A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030

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Institute for Governance & Sustainable Development

About the Institute for Governance & Sustainable Development

IGSD's mission is to promote fast climate mitigation to slow near-term warming and self-propagating climate feedbacks, avoid or at least delay catastrophic climate and societal tipping points, and limit global temperatures to 1.5 °C—or at least keep this temperature guardrail in sight and limit overshoot.

IGSD's research confirms that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5 °C or even the more dangerous 2 °C guardrail and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions from decarbonizing the energy system with the sprint to rapidly cut non-CO_2 super climate pollutants and protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

Combining the fast mitigation sprint with the decarbonization marathon also helps address the ethical issues of intra-generational equity by giving societies urgently needed time to adapt to unavoidable changes and build resilience. The latest science suggests that the window for exceeding the 1.5 °C guardrail could close as soon as the early 2030s, making this the decisive decade for fast action to slow warming.

The fastest way to reduce near-term warming in the next decade or two is to cut SLCPs. Because they only last in the atmosphere from days to 15 years, reducing them will prevent 90 percent of their predicted warming within a decade. Strategies targeting SLCP reductions can avoid four times more warming at 2050 than targeting CO_2 alone. Reducing HFCs can avoid nearly 0.1 °C of warming by 2050 and up to 0.5 °C by the end of the century. The initial HFC phasedown schedule in the Kigali Amendment to the Montreal Protocol will capture about 90 percent of this. Parallel efforts to enhance the energy efficiency of air conditioners and other cooling appliances during the HFC phasedown can double the climate benefits at 2050. Cutting methane emissions can avoid nearly 0.3 °C by the 2040s, with the potential for significant avoided warming from emerging technologies to remove atmospheric methane faster than the natural cycle.

Combining the fast mitigation sprint with the decarbonization marathon would reduce the rate of global warming by half from 2030 to 2050, slow the rate of warming a decade or two earlier than decarbonization alone, and make it possible for the world to keep the 1.5 °C guardrail in sight and reduce overshoot. It would also reduce the rate of Arctic warming by two-thirds. This would help slow self-amplifying climate feedbacks in the Arctic, and thus avoid or at least delay the cluster of projected tipping points beyond 1.5 °C. Reducing climate risks and staying within the limits to adaptation are critical to building resilience.

IGSD approaches to fast mitigation includes science, technology, law and policy, and climate finance. IGSD works at the global, regional, national, and subnational levels.

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Executive Summary

It's already too hot. 2023 was likely the warmest year in 125,000 years[1] and warming is expected to accelerate and pass the 1.5 °C guardrail within 10 years or less.[2] Methane[*] is a super-potent planet-warming gas—a kilogram of methane (CH_4) emissions has over 80 times the warming power of a kilogram of carbon dioxide (CO_2) emissions over 20 years. The fastest way we know to slow warming is to make rapid and deep cuts to methane and other super climate pollutants.

The IGSD *Primer on Cutting Methane* provides the scientific and policy rationale for decision-makers to achieve the "strong, rapid, and sustained" cuts to methane emissions needed to slow global warming in the near term,[3] and limit the risk of triggering climate, economic, and social tipping points. While methane is the focus of this *Primer*, slowing warming in the near term also requires deep cuts to the other similarly potent non-CO_2 super climate pollutants,[4] which include the "short-lived climate pollutants" (SLCPs) with atmospheric lifetimes of, on average, under 15 years—black carbon soot, hydrofluorocarbons (HFCs, primarily used as refrigerants), and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O). Deep cuts in these super climate pollutants, including methane, will also reduce the build-up of heat in the ocean that otherwise would continue adding to warming for decades to centuries, extending the warming influence of SLCPs long beyond their atmospheric lifetime.[5] While cutting CO_2 emissions is essential to limit our warming commitment over the long term, strategies that pair decarbonization with aggressively cutting super climate pollutants can slow warming one to two decades sooner than CO_2-focused strategies alone and avoid nearly four times more warming by 2050.[6] Rapidly implementing strategies that target super climate pollutants could cut the rate of global warming in half to avoid, or at least delay, self-amplifying feedbacks and tipping points.[7]

Topics addressed in the *Methane Primer* include the science establishing the need for methane mitigation; current and emerging mitigation opportunities by sector; national, regional, and international efforts building momentum to achieve fast and deep methane reduction; and financing initiatives to secure support for fast methane reduction. The *Methane Primer* also highlights the need for research and development of technologies to remove methane from the atmosphere at scale. Through in-depth analysis of methane science, law, policy, and governance, this *Primer* provides the path for more international collaboration to move away from voluntary commitments and towards a binding global methane agreement.

Key messages in this *Primer* include:

- Every increment of additional warming matters.[8] We are already experiencing a climate emergency with extreme events occurring sooner and with greater severity than anticipated. Because extreme climate impacts depend on the *rate of warming* as well as the total warming,[9] the continued and growing emissions of CO_2 and other super climate pollutants are particularly troubling. Record-shattering extreme events will become increasingly likely as the rate of warming accelerates and more severe as new levels of warming are reached (*see* **Section 2**).[10]

[*] Natural gas is composed of 70–90% methane. Energy production (extraction of oil, gas, and coal), agriculture (livestock and rice), and waste (landfills and wastewater) are the three main sources of methane emissions from human activity.

- Without fast action to slow warming, *global warming** could exceed the 1.5 °C guardrail by the end of the current decade[11] and 2 °C by 2050 due to rising emissions, declining particulate air pollution that masks existing warming, and natural climate variability.[12] Continuing record climate emissions means that the rate of warming could increase from the 0.2 °C per decade trend of the past 40 years to 0.25–0.32 °C per decade over the next 20 years.[13]
    - There is a 66% chance that annual average near-surface global temperatures will exceed 1.5 °C for at least one year between 2023 and 2027 and a 32% chance that the five-year mean from 2023 to 2027 will exceed this threshold.[14] At +1.44 °C above the pre-industrial period,[15] 2023 was likely the hottest year in 125,000 years.[16] With the continuing El Niño, 2024 will likely be as warm,[17] if not warmer (*see* **Section 2**).[18]
    - Exceeding the 1.5 °C guardrail increases the risk that self-amplifying feedbacks further accelerate rising temperatures and trigger a cascade of irreversible tipping points in the climate system (**Box 2**).[19]
    - Over 3 billion people live in vulnerable circumstances. Impacts from warming above 1.5 °C pose very high risks and potentially irreversible impacts to unique and threatened human and natural systems and increase risk from extreme weather.[20]
    - Limiting warming to 1.5 °C would prevent most of the tropics from exceeding the combined heat and humidity conditions beyond the survival limit.[21] Warming of 2.7 °C by the end of the century would leave about one-third of the global population outside of the climate niche (2–2.5 billion people), while limiting warming to 1.5 °C would halve the number of people exposed to unprecedented heat.[22]
- Methane is the second largest contributor to global warming after CO_2, responsible for nearly 45% of current net warming.[23]
    - Methane pollution has already caused 0.51 °C of the 1.06 °C of total observed warming (2010–2019) compared to pre-industrial.[24]
    - Warming caused by methane will continue to increase if methane emissions continue to rise. Under current policy scenarios, anthropogenic methane emissions are expected to increase by 24–30% by 2050.[25]
    - The rate of growth in atmospheric methane concentrations in 2020 and 2021 more than doubled from the 2007–2019 average.[26] Recent studies have attributed the surge of atmospheric methane concentrations to continued growth in anthropogenic emissions together with increasing emissions from wetlands and a reduced capacity of the atmosphere to remove methane.[27] Methane concentrations increased 11 ppb in 2023 to reach an average of 1,923 ppb, more than two and half times pre-industrial levels (**Box 1**).[28]

* The Intergovernmental Panel on Climate Change defines the time when global warming exceeds a temperature threshold as "the midpoint of the first 20-year period during which the average [global surface air temperature] exceeds the threshold."

- Cutting methane emissions is the biggest and fastest strategy for slowing warming and keeping the 1.5 °C guardrail* within reach.[29] Pursuing all methane mitigation measures this decade is the only known way to avoid nearly 0.3 °C of warming by the 2040s and slow warming by 30%.[30]
    - The International Energy Agency finds in the *Global Methane Tracker 2024* that cutting methane emissions from fossil fuels by 75% by 2030 is "vital to limit warming to 1.5 °C."[31] The International Energy Agency estimates that if all existing methane policies and pledges made by countries and companies are implemented, methane emissions would only decline by 50% by 2030.[32]
    - The *Global Methane Assessment* from the United Nations Environment Programme and the Climate & Clean Air Coalition finds that cutting methane emissions is the fastest strategy for slowing warming in the near term.[33]
    - The Intergovernmental Panel on Climate Change *Sixth Assessment Report* (AR6) confirms that "strong, rapid, and sustained methane reductions" are key to limiting warming in the near- and longer-term (*see* **Section 3**).[34]
    - AR6 Working Group III further finds that "[d]eep [greenhouse gas] emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century…. Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*)."[35]
    - Limiting warming to 1.5 °C with no or limited overshoot requires reducing global anthropogenic (human-caused) methane emissions by 34% in 2030 and 44% in 2040 relative to modelled 2019 levels, in addition to cutting global CO_2 emissions in half in 2030 and by 80% in 2040, and deep cuts to other SLCPs and N_2O.[36]
    - Estimates of the remaining carbon budget (*i.e.*, the total net amount of CO_2 that can still be emitted while keeping global warming to below 1.5 °C with limited overshoot) assume anthropogenic methane emissions are reduced by 51% between 2020 and 2050.[37] Without these deep reductions in methane, the carbon budget will be further reduced.
- Cutting methane is the fastest way to offset the near-term accelerated warming associated with declining particulate air pollution that masks existing warming.[38]
    - Air pollution that is co-emitted with CO_2 when sulfur-containing coal and oil are burned results in particles that reflect sunlight. These co-emitted sulfate cooling particles currently "mask" warming of about 0.5 °C; and while the accumulated CO_2 in the atmosphere will continue to cause warming for decades to centuries, the cooling particles fall out of the atmosphere within days to months once they are stopped at the source, unmasking more of the existing warming (*see* **Section 3**).[39]

* Keeping the 1.5 °C guardrail within reach requires limiting the magnitude of the temperature peak and how long 1.5 °C is exceeded as part of temporary overshoot.

- The transition away from fossil fuels will not only reduce CO_2 but also will reduce these cooling particles. The loss of this cooling effect will offset reductions in warming from decarbonization until around 2050 and even accelerate warming over the first decade following decarbonization or longer.[40]
- Cutting methane and other SLCPs is key to counteracting this increased rate of warming in the near term.[41] When excluding consideration of unmasking of reflective particles, strategies that target super climate pollutants could avoid as much as 0.6 °C by 2050 compared to 0.1–0.2 °C for CO_2-focused strategies alone.[42]

- Only 13% of methane emissions are covered by direct methane mitigation policies.[43] Measures specifically targeting methane sources are essential, as broader decarbonization measures can only achieve 30% of the needed methane reductions (*see* **Section 4**).[44] Moving from voluntary to more binding commitments and expanding coverage and enforcement of methane mitigation policies is essential to achieving the climate benefits of cutting methane. This could include building on, strengthening, and coordinating existing national measurement, monitoring, reporting, and verification schemes and/or border adjustment and methane-fee mechanisms (*see* **Section 6**).
- The ***Global Methane Pledge*** launched by the U.S. and EU in 2021 established a collective target to reduce global anthropogenic methane emissions by at least 30% from 2020 levels by 2030.[45] Achieving this target would reduce warming by at least 0.2 °C by 2050 and keep the planet on a pathway consistent with staying below 1.5 °C.[46]
- Around 60% of global methane emissions come from human activities in three main sectors: energy production (oil, gas, and coal), agriculture (livestock and rice), and waste (landfill and wastewater).[47] Energy production accounts for about 35% of anthropogenic methane emissions (*see* **Section 4A**),[48] agriculture accounts for about 40% (*see* **Section 4B)**,[49] and waste accounts for about 20% (*see* **Section 4C**),[50] with biomass burning and biofuels as minor sources.
- Technologies exist to cut methane emissions from energy production, agriculture, and waste by 45% by 2030 (**Table 2**) to achieve nearly 0.3 °C in avoided warming by the 2040s (*see* **Section 4**).[51]
  - Roughly 60% of the available targeted measures have low mitigation costs (defined as less than US$21 per tonne of carbon dioxide equivalent (CO_2e) based on a 100-year global warming potential (GWP_{100}) and US$7 per tonne of CO_2e for GWP_{20}).[52] Over 50% of those measures have negative costs in that they pay for themselves.[53]
  - The International Energy Agency's *Global Methane Tracker 2024* finds that methane mitigation in the fossil fuel industry is one of the "most pragmatic and lowest cost options" to reduce greenhouse gas emissions.[54] Low-cost technology options are available now to curb more than 75% of methane emissions from oil and gas operations.[55] The International Energy Agency calculates that if all countries achieved the intensity of methane emissions (emissions per unit of production) similar to Norway's performance, methane emissions from oil and gas operations would fall by more than 90%.[56] Norway's performance can be attributed to strict regulation of the oil and gas sector,[57] as well as the imposition of a methane fee within its broader carbon taxes.[58]

- In the energy production sector, the greatest potential for mitigation is in the oil and gas sector.[59] In the waste sector, reducing and managing solid waste holds the most promise.[60] And in the agriculture sector, measures to reduce methane emissions from livestock could have the greatest impact.[61]
- Methane mitigation can also support geographically diverse and well-paying jobs, as shown in U.S. states that are leading methane mitigation efforts for positions ranging from field technicians to chemical engineers to data scientists.[62]

- Cutting methane also increases resilience and promotes environmental justice.[63] By slowing near-term warming and reducing associated hazards, methane mitigation provides climate-vulnerable communities with more time to adapt while also decreasing communities' adaptation burdens.[64] Additionally, because methane is oxidized in the atmosphere to form tropospheric ozone (also known as photochemical smog), cuts to methane reduce harm to public health,[65] as well as to crops, supporting food security (*see* **Section 4**).[66]
    - Achieving net-zero CO_2 emissions by accelerating the transition to clean energy is essential to stabilizing the climate. In addition, during the time it takes for a just and equitable transition to a net-zero economy, it is essential to stop methane leaks to slow warming, protect the health of local communities, and ensure food security.[67]
- About 40% of global methane emissions are from natural sources.[68] These natural sources include tropical wetlands, peatlands, and Arctic permafrost, all of which are warming and appear to be increasing emissions as part of self-propagating feedbacks as microbes increase their methane-producing activity and wildfires accelerate thaw.[69] In addition to the need to slow the rate of warming to reduce emissions from natural sources and lower risks associated with the release of seabed methane hydrates, the National Academies of Sciences, Engineering, and Medicine (NASEM) completed the first report of a two-phase study to assess the need and potential for atmospheric methane removal (*see* **Section 5**).[70]
- Many national and subnational governments,[71] including major methane-emitting countries and regional organizations, are already pursuing mandatory and voluntary methane mitigation measures (*see* **Section 6**). In addition, public and private organizations and initiatives around the world are collaborating on methane mitigation. These international, regional, and national efforts strengthen and expand methane mitigation action and leadership, but more action is needed at the international level (*see* **Section 7**).
- Systems to measure and monitor methane emissions already exist, and others are under development. Satellite-based systems are rapidly increasing our understanding of major emitting sources, including a small number of "ultra-emitters" who are responsible for 8–12% of global oil and gas sector methane emissions (*see* **Section 8**).[72] These monitoring systems, when coupled with an accountability and enforcement strategy, are essential to ensuring the world is on track to secure maximum reductions in methane emissions. This includes encouraging use of accurate metrics that better reflect temperature impacts of strategies to stay below 1.5 °C, such as the 20-year global warming potential (GWP_{20}) for methane and other SLCPs (**Box 3**) (*see* **Section 9**).[73]
- Securing the appropriate funding and finance is essential to support governments and organizations committed to fast methane reductions. Private philanthropies, multilateral

banks, governments, and other financial sector stakeholders all have roles to play in enabling fast methane mitigation to respond to the climate emergency. Methane mitigation solutions, however, remain severely underfunded.[74] At the 28th Conference of the Parties (COP28) in Dubai, governments, philanthropies, and the private sector announced more than $1 billion in new grant funding for methane reduction had been mobilized since COP27.[75] Yet, as the *Global Methane Tracker 2024* emphasizes, more is needed to bridge the current funding gap in methane finance to deliver the required reductions this decade. In the fossil fuel industry, the International Energy Agency estimates that around US$170 billion in spending is needed to deliver methane mitigation to stay below 1.5 °C (around US$100 billion in the oil and gas sector and US$70 billion in the coal industry).[76]

  - COP29 should establish a global methane fund of at least $10 billion a year for the next five years. The fund should be capable of adapting to the needs of international, regional, national, and subnational actors, as well as non-state actors, to provide the funds necessary to pursue policies, initiatives, and projects to rapidly reduce methane (*see* **Section 11**).

- As cutting methane emissions is the single most important action humanity can take to slow near-term warming, multilateral action must move from pledges to mandatory measures.[77] Governments should build on the national, regional, and international efforts that establish a robust technical and policy foundation for global methane control. Key international efforts include the Global Methane Pledge (endorsed by 156 countries and the European Union),[78] the Nationally Determined Contributions (NDCs) under the Paris Agreement from 95% of countries that directly reference or plan to reference methane mitigation,[79] and bilateral agreements such as the *U.S.-China Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis (“Sunnylands Statement”)*.[80]

  - The COP28 *Summit on Methane and Non-CO_2 Greenhouse Gases (“COP28 Methane Summit*”) was a significant step forward in building momentum towards a global methane agreement.[81] The final decision outcome of COP28 on the Global Stocktake (“Global Stocktake Agreement”) further illustrates the inevitability of a global methane agreement, recognizing the urgent need to accelerate and substantially reduce “non-carbon-dioxide emissions globally … in particular methane emissions by 2030” (*see* **Section 10A**).[82]

- The approach to the design of a global methane agreement should take inspiration from the Montreal Protocol on Substances that Deplete the Ozone Layer, widely acknowledged as the best environmental agreement ever created,[83] while adapting to the geopolitical dynamics of the climate emergency. Similar to the Montreal Protocol, a global agreement could begin with a framework methane agreement and a parallel protocol on the energy sector.[84] Separate protocols could then follow on the waste and agricultural sectors. Any agreement must also embrace mandatory targets in a way that accounts for emerging crises for peace, democracy, and food security (*see* **Section 10D**).

- Bilateral and multilateral climate events, particularly COP29, offer opportunities to build upon the progress made at COP28 and move towards a global methane agreement. This international collaboration should involve unprecedented speed and ensure mandatory commitments are science-based, equitable, and effective. Rapid and aggressive methane mitigation must occur this decade; it is the only way to keep the critical temperature threshold of 1.5 °C within reach.[85]

1. Introduction: Building on the Global Methane Pledge

The world is in a state of climate emergency requiring fast-acting solutions that move beyond current paradigms of inadequate climate action. Ending dependence on fossil fuels, including fossil gas, by shifting to clean energy is essential to protect the climate and ensure peace and security. But during the time it takes to shift the world's energy system to clean energy, it is essential to simultaneously reduce methane emissions as fast as possible to address the climate emergency. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) affirms this, stating that "[s]trong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone. (*high confidence*)."[86]

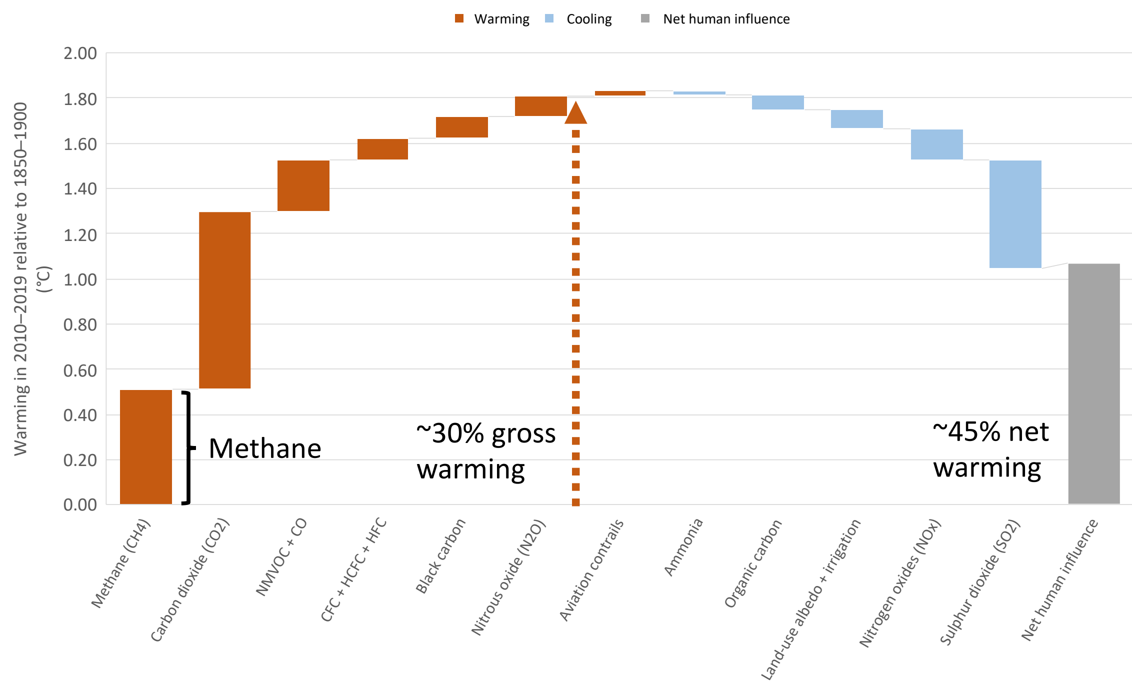
Methane (CH_4) is a super-potent planet-warming greenhouse gas with over 80 times the warming power of carbon dioxide (CO_2) over 20 years (**Box 3**).[87] As described in the *Financial Times*, "[i]f you think of fossil fuel emissions as putting the world on a slow boil, methane is a blow torch that is cooking us today."[88] Methane is also a major precursor of tropospheric ozone, an air pollutant responsible for millions of premature deaths, billions of dollars' worth of crop losses annually,[89] and weakening of carbon sinks.[90]

Methane pollution has already caused 0.51 °C of the total observed warming in 2010–2019 of 1.06 °C compared to 1850-1900 (**Box 1**);[91] and warming will increase, if methane emissions continue to rise. Methane concentrations peaked above 1,900 ppb for the first time in September 2021,[92] and reached an average of 1,923 ppb in 2023, more than two and half times pre-industrial levels.[93] Over the 2020–2022 period, the amount of methane in the atmosphere increased 1.5–2.5 times faster than model averages projected, which indicates that "policies may have to be even stronger than those in existing analyses to reach the Paris Agreement's goals."[94]

Box 1. Methane's contribution to current warming

Methane emissions from human activity are responsible for nearly 45% of current net warming.[95] According to the IPCC AR6, methane pollution caused 0.51 °C (0.29–0.84 °C) of warming in 2010–2019 relative to 1850–1900, and CO_2 caused 0.79 °C (0.52–1.25 °C) of warming (**Figure 1**). The total current net anthropogenic warming is about 1.06 °C (0.88–1.21 °C) through 2019.[96] While emissions of greenhouse gases and black carbon aerosols contribute about 1.8 °C of warming, about 0.7 °C of this warming is currently masked due to the cooling effect of reflective aerosols that are primarily co-emitted along with CO_2 during coal and diesel combustion. This assessed net warming of 1.07 °C is very close to the observed warming of 1.06 °C (0.88–1.21 °C). If we don't account for these cooling aerosols and only consider gross warming due to greenhouse gas emissions in terms of radiative forcing (how much extra heat do the added gases trap in the atmosphere), methane contributes about 30% of anthropogenic radiative forcing (approximately 1.2 out of 3.8 Watts per square meter, Wm^{-2}). This emissions-based radiative forcing of methane of 1.2 (0.90 to 1.51) Wm^{-2} accounts for the direct effect of methane emissions (0.54 Wm^{-2}) and for indirect positive forcing from the contribution of methane emissions to increased background tropospheric ozone and stratospheric water vapor;[97] it also reduces the formation of cooling sulfate aerosols by acting as a sink for the hydroxy radical (OH).[98] Methane from fossil fuel sources has slightly higher emissions metric values than those from biogenic sources.[99]

Figure 1. Contributions to observed warming in 2010–2019 relative to 1850–1900



Adapted from Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Data for Figure SPM.2 (v20210809). *See also* NERC EDS Centre for Environmental Data Analysis (2021).

Cutting methane emissions is the fastest and best strategy to slow warming and keep 1.5 °C within reach.[100] Limiting warming to 1.5 °C would prevent most of the tropics from exceeding the combined heat and humidity conditions beyond the survival limit.[101] Warming of 2.7 °C by the end of the century would leave about one-third of the global population outside of the climate niche (2–2.5 billion people), while limiting warming to 1.5 °C would halve the number of people exposed to unprecedented heat.[102]

The *Global Methane Assessment* from the Climate & Clean Air Coalition (CCAC) and United Nations Environment Program (UNEP) concludes that currently available mitigation measures could reduce human-caused methane emissions by 45% by 2030, compared to projected business-as-usual 2030 levels, and avoid nearly 0.3 °C warming by the 2040s.[103] Fast and aggressive methane mitigation is critical because the window to reduce warming enough to slow self-amplifying feedbacks and avoid tipping points may close by the end of this decade.[104] Many feedbacks are showing signs of activation, and there is evidence that we are nearing or have already crossed multiple climate tipping points.[105]

The IPCC defines a "tipping point" as "a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly."[106] The "evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute," according to Tim Lenton and colleagues.[107] Earth system models project a cluster of six such abrupt shifts between 1 °C and 1.5 °C of warming and another eleven between 1.5 °C and 2 °C,[108] as confirmed by two IPCC Special Reports.[109] A 2022 assessment finds that exceeding 1.5 °C increases the likelihood of triggering or committing to six self-amplifying climate tipping points.[110] Domino-like interactions among these systems risk triggering a global cascade of tipping points.[111] Climate models either ignore or under-estimate key feedbacks and tipping point risks.[112] Additionally, climate models do not account for other circumstances that have been shown to lower thresholds for triggering tipping points, including increasing rates of warming,[113] pressure from multiple drivers (like droughts, wildfires, deforestation), or increased variability in a single driver.[114] Further, as-yet-undiscovered tipping points are possible due to limitations in current models and the exclusion from these models of certain processes, including those related to biogeochemical feedbacks involved in processes such as permafrost thaw.[115]

Box 2. Self-propagating feedbacks and tipping points

AR6 defines a *climate feedback* as "an interaction in which a perturbation in one *climate* quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first." AR6 examples of climate feedbacks include carbon cycle feedback, cloud feedback, and ice-albedo feedback, among others. AR6 defines a *tipping point* as "a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly."[116] Some feedbacks, like the ice-albedo feedback, are self-propagating: initial warming reduces the volume and extent of reflective Arctic summer sea ice, exposing the darker ocean surface that absorbs more heat, and providing an additional feedback that sustains the loop through further reduction of the sea ice. Key elements of the climate system have tipping points that, once exceeded, commit the system to change, even if this change is projected to take decades to hundreds of years to fully play out, as in the case of melting of the Greenland Ice Sheet.[117] Other systems may tip abruptly. An example would be the shift of the terrestrial biosphere from a net sink for CO_2 to a net source of CO_2 as warming increases respiration rates and decreases photosynthesis rates.[118]

For a fuller discussion of feedbacks and tipping points and fast-mitigation solutions, *see* Institute for Governance & Sustainable Development (2023) THE NEED FOR FAST NEAR-TERM CLIMATE MITIGATION TO SLOW FEEDBACKS AND TIPPING POINTS.

Decarbonizing the energy system and achieving net-zero CO_2 emissions is critical for stabilizing the climate and keeping temperatures below 1.5 °C by the end of this century.[119] However, phasing out CO_2-emitting fossil fuels, such as coal and diesel, also stops emissions of co-emitted cooling aerosols such as sulfur dioxide (SO_2).[120] Unlike CO_2, which remains in the atmosphere for decades to centuries, these cooling aerosols fall out of the atmosphere within days to months. The loss of this cooling effect will offset reductions in warming from decarbonization until around 2050 and *likely even accelerate warming over the first decade of decarbonization or longer*.[121]

> "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO_2, will result in an increase in the resulting rate of warming.… The only measures that can counteract this increased rate of warming over the next decades are methane reductions." -- IPCC author Joeri Rogelj[122]

The *Global Methane Assessment* and IPCC AR6 both highlight "strong, rapid, and sustained methane reductions" as key to counteracting this increased rate of warming from unmasking over the next decades.[123] Further, AR6 finds that reducing methane emissions is key to effectively reducing peak warming and lowering the costs of climate change in the near term by limiting the likelihood of overshooting 1.5 °C.[124]

As noted, in addition to causing global warming on its own, methane is also a major precursor to tropospheric ozone,[125] which also causes warming and is linked to significant human respiratory and cardiovascular morbidity and mortality,[126] and agricultural crop damage (estimated at US$63 billion annually in East Asia alone).[127] Damage to plants due to increased tropospheric ozone may reduce their ability to absorb carbon and may negate some of the carbon fertilization effect from increased CO_2 concentrations with a potentially significant effect on indirect radiative forcing.[128] A recent study estimated methane's contribution to the present-day tropospheric ozone burden at 35%.[129] Methane is likely to play a greater role in tropospheric ozone formation as emissions of other precursors decrease due to air pollution controls.[130] Reducing global methane emissions by 45% by 2030 would prevent 255,000 premature deaths, 775,000 asthma-related hospital visits, 73 billion hours of lost labor from extreme heat, and 26 million tonnes of crop losses globally.[131] Eliminating all anthropogenic methane emissions could avoid 690,000 premature deaths per year in 2050.[132] Each tonne of methane reduced generates US$4,300 in health, productivity, and other benefits.[133] In addition, methane mitigation strategies provide further cost reductions and efficiency gains in the private sector, create jobs, stimulate technological innovation, and help reduce climate vulnerability in the most disadvantaged communities.

The *COP28 Methane Summit*, convened by the United States, China, and United Arab Emirates on 2 December 2023,[134] recognized methane's essential role in rapidly cutting emissions to ensure peak-warming reduction and limit the likelihood of overshooting 1.5 °C. In addition, the first Global Stocktake Agreement recognizes "the need for deep, rapid, and sustained reductions" in GHG emissions to stay below 1.5 °C, including accelerating and substantially reducing methane emissions by 2030.[135] These recent developments build upon an impressive and increasingly strong foundation for methane mitigation, as detailed in this *Primer*, at the subnational, national, regional, and international levels. Many of these efforts are discussed in this *Primer*, including:

- Research on the best approaches for the removal of methane from the atmosphere (**Section 5**);
- Domestic efforts, including from major-emitting countries, to implement methane measures, including border adjustment mechanisms (**Section 6**);
- Governmental, quasi-governmental, and private sector initiatives, including methane metrics and monitoring programs (**Section 7** and **Box 6**);
- Multilateral and bilateral methane initiatives (**Section 10**); *and*
- Key international financial initiatives addressing methane mitigation (**Section 11**).

Yet, the majority of existing efforts to cut methane are not mandatory and are not sufficient to cut warming quickly enough[136] to avoid tipping points that would lock in devastating global warming and make it much more difficult to avoid an existential threat to a liveable planet Earth.[137] Governments must fully implement[138] and build on these existing commitments and initiatives to further open the door for a global methane agreement drawing inspiration from treaties such as the Montreal Protocol[139] and responding to a growing chorus of calls for such actions.[140]

This *Primer* provides an overview of the science underpinning the need for fast climate-mitigation action this decade, why cutting methane emissions is the fastest and best way to slow climate change in the near term, and the natural sources of methane and related atmospheric removal research. The *Primer* also reviews methane emissions in the energy production, agricultural, and waste sectors, as well as the current technologies to cut nearly half of these emissions. Further, the *Primer* outlines methane mitigation efforts in selected major methane-emitting countries and reviews the methane-abatement-related activities of governmental, quasi-governmental, and industry-led organizations and initiatives. A summary of methane-emissions monitoring systems follows, as does a summary of key elements that are needed to build an accountability and enforcement strategy using such monitoring information. The *Primer* then describes international efforts, including the Global Methane Pledge and recent *COP28 Methane Summit*, that are catalyzing other bilateral and multilateral actions to curb methane, including calls for mandatory national and multilateral methane emissions mitigation measures. This is followed with a summary of key financial and philanthropic organizations initiatives to provide crucial financial support for methane ambition and action.

Although this *Primer* focuses on methane, deep cuts to similarly potent short-lived climate pollutants (SLCPs)—including black carbon soot, hydrofluorocarbons (HFCs), and tropospheric ozone (for which methane is a major precursor) are also critical to slowing warming in the near term.[141] Such cuts will reduce the build-up of heat in the ocean that otherwise will continue adding to warming for decades to centuries, long after the lifetime of the pollutant.[142]

Box 3. Time and temperature methane metrics: GWP_{20} is an improvement, temperature is even better!

Reducing the risks associated with accelerating warming requires mitigation strategies that can slow warming in the near term, like cutting methane emissions. Assessing how strategies affect near-term warming requires considering individual emissions by pollutant in units of mass, as required under the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines and recommended by climate scientists.[143] It also requires accounting for co-emissions by source, since policies act on sources, not on individual pollutants.

An ideal option for assessing temperature impact is to convert emissions by source in terms of pollutant and co-emissions to temperature impacts using tools such as the Assessment of Environmental and Societal Benefits of Methane Reductions Tool or the CCAC Temperature Pathway Tool. Alternatively, using the 20-year global warming potential (GWP_{20}) better captures near-term warming impact than the 100-year GWP, in addition to being more aligned with meeting the 1.5 °C target.[144] While the UNFCCC currently requires using the GWP_{100} metric when reporting aggregated emissions or removals, which systematically undervalues the near-term climate impact of methane, reporting Parties may use other metrics in addition, such as GWP_{20} or absolute temperature potentials.[145] Indeed, using GWP_{100} alone systematically underestimates the importance of methane emissions and "can lead to suboptimal policies and priorities by misleading climate actors from the top levels of governments (e.g., U.S. NDC) to grassroots organizations."[146]

Box 3 continued

IPCC AR6 has updated the metrics for methane as follows: GWP_{20} is 81.2 and GWP_{100} is 27.9.[147] **Table 1** below summarizes GWP values for methane from IPCC reports.

Table 1. GWP values for methane from IPCC reports

		AR6	AR5		AR4	TAR	SAR
Methane (CH_4)	**GWP_{20}**	81.2	84	86*	72	62	56
	GWP_{100}	27.9	28	34*	25	23	21
Fossil CH_4	**GWP_{20}**	82.5 ± 25.8	85		--	--	--
	GWP_{100}	29.8 ± 11	30		--	--	--
Non-fossil CH_4	**GWP_{20}**	80.8 ± 25.8	--		--	--	--
	GWP_{100}	27.2 ± 11	--		--	--	--

* With carbon cycle feedback. All methane AR6 values include carbon cycle feedback.
AR6 = 2021 Sixth Assessment Report WGI (Table 7.SM.7; Table 7.15); **AR5** = 2013 Fifth Assessment Report WGI (Table 8.A.1; Table 8.7); **AR4** = 2007 Fourth Assessment Report (Table 2.14); **TAR** = 2001 Third Assessment Report (Table 6.7); **SAR** = 1995 Second Assessment Report (Table 2.9).

Most aggregation metrics are designed for comparison with long-lived CO_2. Metrics such as CO_2-equivalence in terms of GWP and GWP* ("GWP star") are based on mathematical relationships that are intended to make SLCPs like methane comparable to the longer-term warming impact of CO_2 emissions.[148] These aggregate metrics generally ignore co-emitted pollutants with significant near-term climate impacts such as cooling aerosols. The GWP* metric seeks to account for the shorter lifetime of methane by differentiating historical emissions from changes in the rate of emissions.[149] One criticism of this approach is that it essentially "grandfathers" historical emissions, so when applied at the scale of regional or individual methane emitters, sources with high historical emissions can claim negative GWP* by reducing their rate of emissions. This is the case even if their emissions in a given year are equivalent to a new source with no historical emissions. This has led to misuse of these metrics to claim that some sectors with large historical emissions and stable or decreasing current rates of emissions have contributed less to global warming.[150]

For these reasons, this *Methane Primer* follows the convention of the *Global Methane Assessment* in using mass-based metrics, such as million metric tonnes of methane (Mt CH_4), and temperature impacts rather than GWP metrics where possible.

2. The need for speed: Winning the sprint to 2030 is critical to avoiding climate catastrophe

Every increment of additional warming matters.[151] We are already experiencing the climate emergency, with extreme events occurring sooner and with greater severity than anticipated. As the rate of warming accelerates, record-shattering extreme events will become increasingly common and more dangerous.[152] We have, at most, until the end of the decade, and probably less, to radically slow global warming or face an existential threat to a liveable planet Earth. The world could hit the 1.5 °C guardrail by 2030 because of rising emissions, declining particulate air pollution that unmasks existing warming, and natural climate variability.[153]

While the 20-year average temperature is not expected to exceed 1.5 °C before 2030, there is a 66% chance that annual average near-surface global temperatures will exceed 1.5 °C for at least one year between 2023 and 2027 and a 32% chance that the five-year mean from 2023–2027 will exceed this threshold, according to the World Meteorological Organization (WMO).[154] The 2011–2020 temperature average over land has already crossed the 1.5 °C threshold,[155] and warming has been increasing at an unprecedented rate of over 0.2 °C per decade since the mid-2010s.[156]

According to the Copernicus weather service, "we have already entered uncharted territory" in global temperature extremes.[157] At +1.44 °C above the pre-industrial average,[158] 2023 was the warmest year in the historical record,[159] likely from a combination of natural variabilities (such as the start of warmer El Niño conditions in the middle of the year) and external forcing (from continuing climate emissions and declining aerosol pollution).[160] 2024 will likely be as warm, with the potential for exceeding 1.5 °C at least temporarily.[161]

Speed must become a key factor in the selection of climate solutions, to quickly limit warming, slow self-propagating feedbacks, avoid tipping points, and protect the most vulnerable people and ecosystems. Therefore, we need fast climate solutions, meaning measures that can begin within two to three years, be substantially implemented within five to ten years, and produce a climate response within the next decade or two.[162] These strategies also are critical to increasing resilience by providing communities more time to adapt to global warming and by reducing the amount of adaptation needed.[163]

The scientific community has failed to adequately communicate the need for speed. As Yangyang Xu, V. Ramanathan, and David Victor noted in their Comment in *Nature*,[164]

> "[The IPCC Special Report on 1.5 °C] underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution [which is quickly reducing the reflective sulfate particles that mask warming], and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there is a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report…. The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."

A. Current climate impacts are bad, and worse is on the horizon from the growing risk of self-propagating feedback loops pushing the planet past tipping points

Rapid warming over the near term threatens to accelerate a vicious cycle—self-propagating feedbacks where the planet starts to warm itself. These feedback mechanisms could set off a domino-like cascade of tipping points in the Arctic and elsewhere, many of them irreversible and potentially catastrophic,[165] and could lead to uncontrollable warming, becoming the dominant force regulating the climate system.[166]

A prestigious group of climate scientists, in their 2019 *Nature* Comment, *Climate Tipping Points—Too Risky to Bet Against*, explain that "the clearest emergency would be if we were approaching a global cascade of tipping points" and that such "cascading effects might be common."[167]

Evidence from the latest review of feedbacks and tipping points suggests that we are already "in a state of planetary emergency: both the risk and urgency of the situation are acute."[168] At about 1.2 °C of warming, there is a non-negligible risk that one or more cryosphere tipping points have already been passed.[169] Best estimates indicate that critical thresholds for the Greenland Ice Sheet, West Antarctic Ice Sheet, warm-water corals, and abrupt permafrost thaw occur around ~1.5 °C.[170] Limiting warming below 2 °C and the duration, or overshoot, of warming above 1.5 °C may avoid collapse of the ice sheets and prevent tipping of the Amazon.[171]

The melting Greenland Ice Sheet Is the largest single contributor to the rate of global sea-level rise,[172] and is already committed to lose 110 trillion tons of ice by the end of the century, which would raise global sea levels by nearly a foot.[173] Recent observations have shown that the rate of retreat was as high as 610 m per day during the last interglacial period, and current levels of ocean-driven melting can trigger 100 m of ice sheet loss each day.[174] The IPCC's AR6 Working Group I report (AR6 WGI) was unable to exclude the possibility of sea level rise of up to 7.5 feet (2.3 meters) by 2100 due to uncertainties in ice sheet processes.[175]

Delaying mitigation increases the risk of crossing one or more temperature thresholds from higher peak temperatures. More importantly, stabilization of temperatures above 1.5 °C dramatically increases the risk of crossing multiple climate tipping points.[176] At 2 °C of warming the risks of triggering "relatively large, abrupt and sometimes irreversible changes in systems" become high, according to IPCC AR6.[177] Fast action to slow warming in both the near- and longer-term is critical to avoid committing the planet to weather and climate extremes that pose an existential threat to civilization.[178]

B. Reducing fossil-fuel burning is essential but does not slow near-term warming

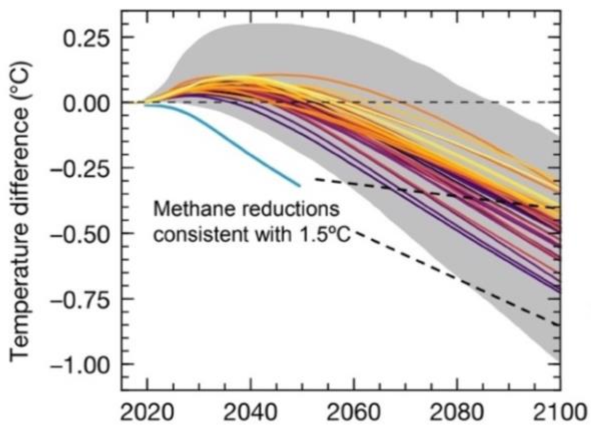
Decarbonizing the energy system and achieving net-zero CO_2 emissions is critical for stabilizing the climate and keeping temperatures below 1.5 °C by the end of this century, but cutting CO_2 alone is not able to achieve this target.[179] In fact, reducing the burning of fossil fuels like coal and diesel also cuts co-emitted cooling aerosols, primarily in the form of sulfates and nitrates. Co-emitted cooling aerosols are reflective particles that currently mask warming of about 0.5 °C.[180] While the accumulated CO_2 in the atmosphere will continue to cause warming for decades to centuries, these cooling aerosols fall out of the atmosphere in days to months, which "unmasks" or offsets reductions in warming from decarbonization until around 2050 and even adds warming over the first decade following decarbonization or longer (**Figure 2**).[181] Even without accounting for the unmasked warming from reducing cooling aerosols, peaking CO_2 emissions in 2030 and reaching carbon neutrality in the 2060s would only avoid 0.1 °C of warming by 2050,[182] although the benefits of this strategy accrue quickly starting around 2060 through the end of the century.

AR6 confirms that the shift from fossil fuels to clean energy is unmasking hidden warming of up to 0.5 °C[183] that cancels out the cooling benefits of decarbonization until around 2050, underscoring the importance of cutting non-CO_2 super climate pollutants (**Figure 1**):

> "Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).… Additional [methane] and

[black carbon] mitigation would contribute to offsetting the additional warming associated with [sulfur dioxide] reductions that would accompany decarbonization (*high confidence*)."[184]

Figure 2. Decarbonization-only strategies accelerate near-term warming by reducing both CO_2 and cooling aerosols (SO_2) compared to mitigation strategies targeting methane reductions that result in avoiding warming in the near term



Source: Shindell D. (25 May 2021) *Benefits and Costs of Methane Mitigation*, Presentation at the CCAC Working Group Meeting. *Updating* Figure 3d from Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411.

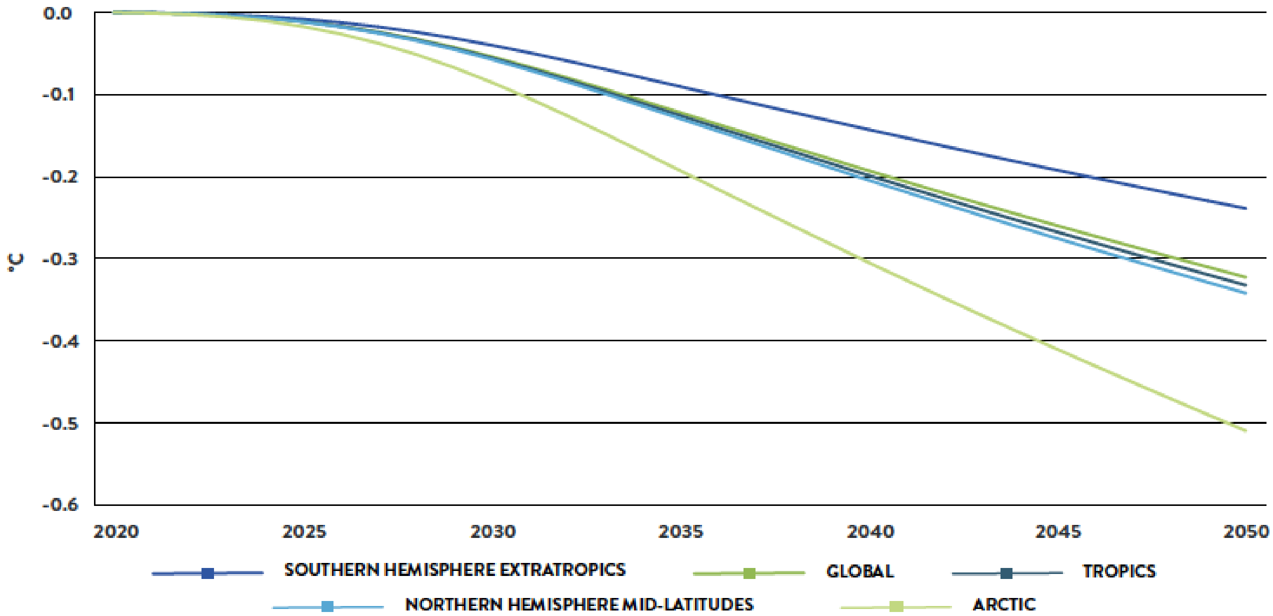
3. Cutting methane emissions is the fastest and best way to slow warming in the near-term

The *Global Methane Assessment* confirms that cutting methane emissions is the fastest strategy to limit warming over the next 20 years.[185] Pursuing all methane mitigation measures this decade is the only known way to avoid nearly 0.3 °C of warming by the 2040s and slow warming by 30%.[186] AR6 confirms that "strong, rapid, and sustained methane reductions" are key to limiting warming in the near- and longer-term.[187] Further, the most recent IPCC AR6 Working Group III contribution (AR6 WGIII) on climate solutions reinforces that deep and rapid cuts to methane emissions are essential to limiting warming in the near-term and shaving peak warming from overshooting 1.5 °C.[188] Limiting warming to 1.5 °C with no or limited overshoot requires reducing emissions by 34% below 2019 levels in 2030 and 44% below 2019 levels in 2040.[189]

A. Pursuing all available methane mitigation measures is the only plausible way to limit warming over the next 20 years

The *Global Methane Assessment* calculated that strategies to cut methane emissions 40–45% by 2030 could avoid nearly 0.3 °C by the 2040s, and 0.5 °C in the Arctic by 2050, 60% more than the global average (**Figure 3**).[190] This is consistent with AR6, which confirmed that cutting methane (by 35% or more) together with other SLCPs could slow warming globally by 0.2 °C (0.1–0.4 °C) in 2040.[191] Strategies to cut methane emissions achieve 60% more avoided warming in the Arctic than the global average, with the potential to avoid 0.5 °C by 2050.[192] Every 10-year delay in methane mitigation after 2040 would cause further peak warming of around 0.1 °C, and would further amplify surface air temperature levels due to biogeochemical feedbacks.[193]

Figure 3. Temperature response to methane abatement from 2020–2050 based on mitigation levels consistent with 1.5 °C scenarios



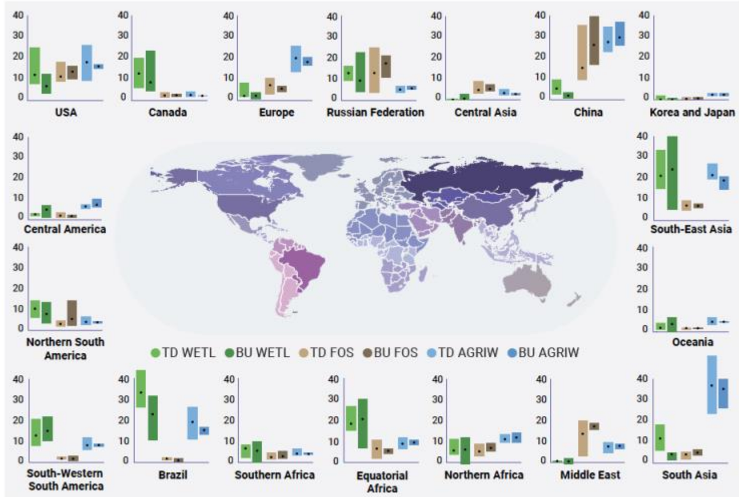
Source: United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Figure 5.1. *Note*: In addition to global mean responses, values are given for the southern hemisphere extratropics (90–28 °S), the tropics (28 °S–28 °N), the northern hemisphere mid-latitudes (28–60 °N) and the Arctic (60–90 °N).

Current climate pollutant emission levels place global average temperatures on a trajectory to exceed 2 °C by 2050, with anthropogenic methane emissions accounting for up to one-third of the temperature increase.[194] The 2011 *Integrated Assessment of Black Carbon and Tropospheric Ozone* calculated that fully implementing measures targeting methane and black carbon could reduce the rate of global warming by half and reduce Arctic warming by two-thirds.[195] Pursuing all available methane mitigation measures would cut the global rate of warming by 30% by mid-century.[196] If all anthropogenic methane emissions were eliminated, surface methane levels could drop below pre-industrial levels within 15 years.[197]

Rapid reductions in methane emissions this decade could also reduce the risk of losing all of the summer Arctic sea ice.[198] The former "ecosystem of ice" in the Arctic no longer exists: half of the Arctic's September sea ice is already gone,[199] and the rest could disappear within 10 to 15 years.[200] If Arctic summer sea ice were to disappear for the sunlit months, as could happen as early as mid-century,[201] it would be the warming equivalent of 1,000 billion tonnes of CO_2 and up to three times this if cloud cover dissipates.[202]

In sum, due to the long lifetime of CO_2 and the unmasking of warming associated with decarbonization, cutting methane together with the other SLCPs is the only plausible way to limit warming in the near term,[203] absent solar radiation management or other still speculative climate interventions.

Figure 4. Average methane emissions for 2008–2017 in Mt CH_4 per year for 18 continental



regions

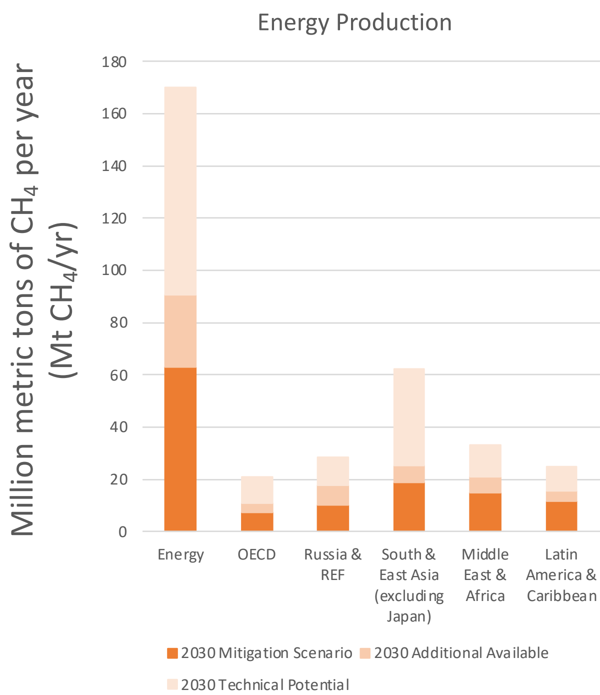
Source: United Nations Environment Programme (2021) EMISSIONS GAP REPORT 2021: THE HEAT IS ON – A WORLD OF CLIMATE PROMISES NOT YET DELIVERED, Figure 6.1. *Note*: Emissions are shown for three main emission categories: wetlands (WETL), fossil fuel-related (FOS) and agriculture and waste (AGRIW). Colored bars represent the minimum and maximum range of available estimates from top-down (TD) and bottom-up (BU) approaches. Black dots show the average for each approach (based on Saunois *et al.* 2020 data sets). The colors in the map indicate regions only.

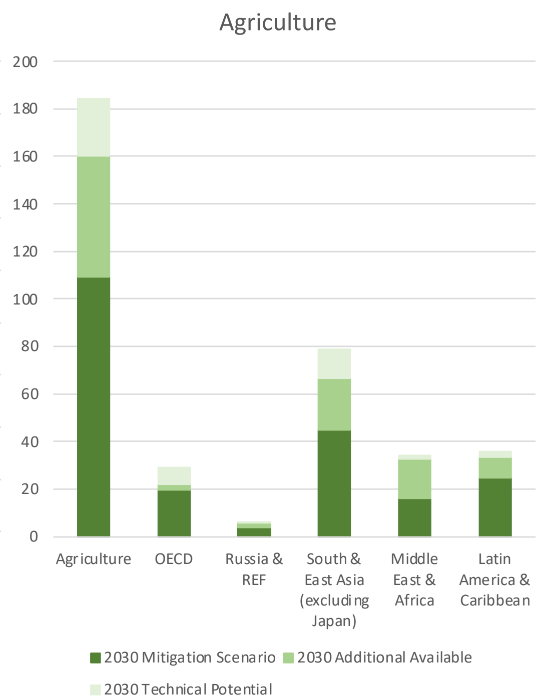
B. Anthropogenic sources are responsible for about 60% of global methane emissions

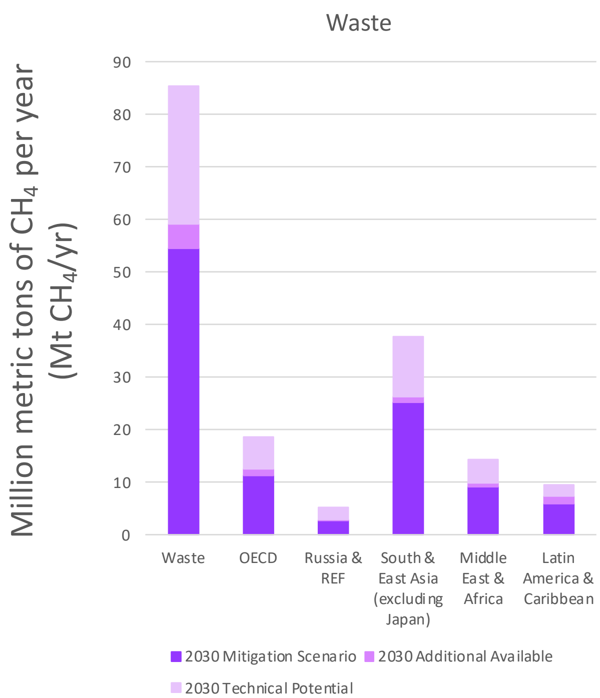
Human activity is responsible for about 60% (estimates range from 50–65%) of total global methane emissions.[204] Three sectors are primarily responsible: energy production (~35%), agriculture (~40%), and waste (~20%), with regional differences and uncertainties in estimates shown in **Figure 4**.[205] In comparison, biomass burning and biofuels are minor sources.[206] Currently available mitigation measures could reduce emissions from these sectors by about 180 million metric tonnes of methane per year (Mt/yr), approximately 45%, by 2030 (

Figure 5). Of those reductions, around 75 Mt (roughly 60%) could be reduced at no or low cost (less than US$600 per tonne of methane reduced, or about US$21 per tonne of CO_2-equivalent using 100-year GWP of 28) (**Box 3**).[207] While anthropogenic emissions are likely the main cause of increasing atmospheric methane levels over the last two decades, natural sources of methane appear to be increasing emissions as part of wetlands and permafrost feedbacks.[208] Recent studies attribute the record-breaking increase of methane emissions in 2020, when the average rate of methane concentration growth doubled from the 2007–2019 average, to reduced oxidative capacity of the atmosphere and increased wetland emissions, in addition to anthropogenic emissions; the cause of the surge in atmospheric methane concentration continued into 2022 and is under investigation.[209] (**Section 5** discusses important early-stage research underway on removing methane from the atmosphere.)

Figure 5. Indicative baseline emissions in 2030 and mitigation potential from technical and additional measures consistent with a 1.5 °C pathway







Source: 2030 Business As Usual Scenarios (limited climate policy; SSP3-7.0) *adapted from* Fujimori S., *et al.* (2017) *SSP3: AIM implementation of Shared Socioeconomic Pathways*, GLOB. ENVIRON. CHANGE 42: 268–283. Technical Potentials in 2030 are adapted from the maximum abatement in: Environmental Protection Agency (2019) *Non-CO_2 Greenhouse Gas Emission Projections and Mitigation: 2010-2050*. Additional measures are the difference between technical potentials and the 1.5 °C consistent mitigation Scenario (SSP1-1.9) *from* van Vuuren D. P., *et al.* (2017) *Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm*, GLOB. ENVIRON. CHANGE 42: 237–250.

i. *The energy production sector accounts for ~35% of anthropogenic methane emissions*

About 35% of anthropogenic methane emissions come from energy production activities related to oil, gas, and coal.[210] Emissions in 2020 were estimated at close to 130 Mt CH_4 globally, with about 80 Mt CH_4 from oil and gas and 40 Mt from coal, with the IEA estimating a 5% increase in emissions in 2021.[211] Each fuel is similarly responsible for around one-third of methane emissions associated with energy production.[212] Most emissions from oil and gas come from onshore extraction, followed by downstream activities such as refining and distribution.[213] These emissions include accidental leaks as well as purposeful venting of methane. When these leaks and fugitive emissions (gas that escapes during the drilling, extraction, and transportation process)[214] are considered, methane emissions from the energy production sector are about 70% higher than in reported data.[215] Note, however, these estimates generally do not include likely significant emissions from abandoned coal mines and oil and gas wells.[216]

Methane occurs naturally in coal mines and many mitigation measures are taken to ensure worker safety, including those mentioned in **Section 6**. Emissions occur from active underground mines, abandoned mines that continue to leak methane, and some surface mines.[217] Recent analysis of coal mine emissions from Australia, including surface mines, found that methane emissions had been significantly underestimated in official reporting.[218] Even in the case of forecasted declining coal production,[219] methane from coal is expected to remain an important focus of mitigation efforts, because absent intervention, emissions from abandoned mines will increase as more mines are abandoned.[220] The IEA estimates that methane emissions from operating coal mines in 2020 had a larger short-term impact on climate than the European Union's combined CO_2 emissions, and that coal power generation would need to be reduced by 75% by 2030 to limit warming to 1.5 °C.[221] However, coal demand is on track to meet the 2023 annual record and set a new, all-time high in 2023, as the result of extreme heatwaves and the continuing replacement of Russian gas in Europe.[222]

Abandoned coal mine methane can also be a significant source of methane, making up 12.5% of methane emissions from coal mining in the U.S.[223] These emissions may be underestimated as typical aerial surveillance of methane emissions is not as effective with abandoned mines, and certain parameters needed to estimate methane emissions are not available for each abandoned coal mine.[224]

ii. *The agriculture sector accounts for ~40% of anthropogenic methane emissions*

Agriculture accounts for around 40% of anthropogenic emissions. These agricultural emissions arise primarily from livestock and rice cultivation.[225] The largest contribution within agriculture is from cattle, sheep, and other ruminant animals that generate methane through their digestion processes (enteric fermentation),[226] with cattle accounting for 77% of these emissions.[227] Current manure management practices, especially for pigs and cattle, also release methane.[228] Emissions in 2020 were estimated at approximately 117 Mt CH_4 from livestock and manure management.[229] Population increases will continue to drive agricultural emissions, particularly from livestock, which are expected to rise to about 11 million tonnes per year by 2030 (range 6–23 million tonnes).[230]

Flooded fields used for rice cultivation are another major source of methane, especially in regions with high rice production.[231] In Asia, rice cultivation contributes around 20% of the region's methane emissions.[232] In 2020, emissions from global rice cultivation were estimated at around 30 Mt CH_4.[233]

iii. The waste sector accounts for ~20% of anthropogenic methane emissions

Approximately 20% of anthropogenic emissions come from the waste sector.[234] This includes both landfills and wastewater treatment where decomposition of organic waste produces methane. Waste sector emissions in 2017 are approximately 68 Mt CH_4.[235] However, traditional methods likely continue to underestimate emissions from landfills. A recent multi-satellite study found that city-level methane emissions in Buenos Aires, Delhi, Lahore, and Mumbai were 1.4 to 2.6 times larger than estimated, with landfill emissions contributing 6% to 50% of those emissions.[236] Currently, an estimated 2.0 billion metric tons of global municipal solid waste is generated annually, and this amount is expected to increase by 70% to 3.4 billion metric tons by 2050.[237]

Box 4. Self-amplifying methane emissions from natural sources and sinks

In addition to anthropogenic sources, warming-driven feedbacks, such as thawing of permafrost, wetland emissions, and seabed methane hydrates increase atmospheric concentrations of methane; Arctic amplification, increased wildfires, and other biogeochemical processes can accelerate these emissions.

- Permafrost contains nearly twice the amount of carbon than is already in the atmosphere and is found below about a quarter of the N. Hemisphere's land area.[238] The thawing of permafrost,[239] a process which releases methane, could amplify warming over a century or longer,[240] is irreversible at a human time-scale.[241] For each °C of global warming at 2100, the permafrost feedback could release 66 Gt CO_2 (11 to 150) and 10 Gt CO_2-eq (2.6 to 27) of methane, in addition to nitrous oxide (N_2O), which model-based estimates do not account for.[242] This has the potential to add 0.05–0.7 °C of warming by 2100, of which 50% would be due to methane emissions.[243] The magnitude of the permafrost carbon feedback strengthens under a high-emissions scenario.[244]
    - According to AR6 WGI, permafrost CO_2 feedback can be as high as 4.1 billion tonnes through 2100.
    - Of the approximately 15 million square kilometers of permafrost on land,[245] 3.4 million square kilometers have already thawed; and with a warming of 1.5 °C approaching, another 4.8 million square kilometers could thaw gradually.[246]
- In addition, up to 20% of the permafrost area accounting for half of permafrost carbon could experience abrupt local thaw events, such as the deep sinkholes observed in the Beaufort Sea.[247] These abrupt thaw events could cumulatively emit up to nearly 11 Gt carbon in the form of CO_2 (40 Gt CO_2) and 6.8 Gt carbon in the form of CH_4 (9 Gt CH_4) by 2100, in addition to the 92 Gt carbon that could be released by gradual thaw over this period under a high-emission scenario.[248]
    - Some of the emissions from thawing permafrost are expected to be offset by the expanded growth of biomass, only if human emissions are curbed.[249]
    - In addition to accelerating soil carbon feedbacks due to permafrost thaw, heatwaves in the Siberian Arctic (such as those in 2020 that peaked at 6 °C above normal temperatures) may be causing "surprise" fossil methane gas to leak from rock formations.[250]
    - Increasingly frequent Arctic wildfires are accelerating permafrost thaw.[251]

Box 4 continued

- Another concern is the risk that warming ocean waters will destabilize seabed methane hydrates.[252]
  - Such destabilization likely occurred off the coast of Guinea 125,000 years ago during the previous interglacial, with ice core records suggesting a sufficient amount of methane was released to the atmosphere to affect CO_2 and CH_4 concentrations.[253]
  - With a rapidly warming Arctic, the shallow seabed of the East Siberian Arctic Shelf poses significant concerns due to its potential to speed up other global warming impacts.[254]
  - Although there is debate on the possibility and rate of a potential release,[255] it has been confirmed that the rate of methane release in the Chukchi Sea, a marginal sea of the Arctic Ocean, was higher in the 2010s compared to the 1990s.[256]
  - The release of land-based methane hydrates as glaciers recede could further amplify the permafrost feedback.[257]
- Recent studies have also identified feedback mechanisms from natural sources and sinks, which accelerated the growth of methane between 2020 and 2022, including increased emissions from wetlands and reduced capacity of the atmosphere to remove methane.[258]

4. The technologies exist to cut nearly half of anthropogenic methane emissions from the energy production, waste, and agriculture sectors

According to the CCAC, currently available measures could reduce anthropogenic methane emissions from the energy production, waste, and agriculture sectors by 45% by 2030.[259] The Global Methane Pledge commits participants to collectively reduce anthropogenic methane emissions across all sectors by at least 30% reductions below 2020 levels by 2030, equivalent to at least 150 Mt CH_4 reduction below 2030 baseline levels (**Figure 6**).[260] Measures specifically targeting methane sources are essential, as broader decarbonization measures can only achieve 30% of the needed methane reductions.[261] Roughly 60% of the available targeted measures have low mitigation costs (less than US$21 per tonne of CO_2e for GWP_{100} and US$7 per tonne of CO_2e for GWP_{20}), and just over 50% of those have negative costs in that the measures pay for themselves.[262] In the IEA net zero emissions by 2050 scenario, total methane emissions from human activity are reduced by 45% and the energy sector by 75% between 2020 and 2030, costing less than 3% of net income from oil and gas in 2022.[263] Methane mitigation also supports geographically diverse and well-paying jobs as shown in U.S. states that are leading methane mitigation efforts, for positions ranging from field technicians to chemical engineers to data scientists.[264]

Table 2 summarizes technical and additional methane emissions control measures by sector. There are many compilations of technology-based solutions and costs, including reports by the International Institute for Applied Systems Analysis, the International Energy Agency, the U.S. Environmental Protection Agency, McKinsey, and others.[265] Several groups are tracking and assessing novel and innovative approaches, such as the Solar Impulse Foundation's compilation of 1000+ efficient, clean, and profitable solutions for the environment.[266]

Table 2. Emissions control measures by sector

Technical Controls		
Fossil Fuels	**Waste**	**Agriculture**
Oil and gas: upstream and downstream leak detection and repair (LDAR); blowdown capture; recovery and utilization of vented gas with vapor recovery units and well plungers; installation of flares. **Oil and gas by existing devices:** replace pressurized gas pumps and controllers with electric or air systems; replace gas-powered pneumatic devices and gasoline/ diesel engines with electric motors; early replacement of devices with lower-release versions; replace compressor seals; cap unused wells. **Coal mining:** flooding abandoned mines; pre-mining degasification; air methane oxidation with improved ventilation.	**Municipal solid waste:** composting; source separation with recycling and reuse; no landfill of organic waste; use of biocovers; treatment with energy recovery or collection of landfill gas. **Industrial solid waste:** recycling or treatment with energy recovery; no landfill of organic waste. **Residential wastewater:** upgrade primary treatment to secondary/ tertiary anaerobic treatment with biogas recovery and utilization; use wastewater treatment plants instead of latrines and disposal. **Industrial wastewater:** upgrade to two-stage treatment, *i.e.*, anaerobic treatment with biogas recovery followed by aerobic treatment.	**Enteric fermentation (cattle, sheep, & other ruminants):** feed changes and supplements; breeding to improve productivity, animal health, and fertility. **Manure management (ruminants & pigs):** treatment in biogas digesters; decreased manure storage time; improved manure storage covering, housing systems and bedding; manure acidification. **Rice cultivation:** improved water management or alternate flooding/ drainage wetland rice; direct wet seeding; phosphogypsum and sulphate addition to inhibit methanogenesis; composting rice straw; use of alternative hybrids. **Agricultural waste burning:** bans and enforcement of existing bans.
Behavioral and Technological Changes		
Fossil Fuels	**Waste**	**Agriculture**
- Emissions pricing - Fuel switching to renewables - Energy demand management - Energy efficiency improvement	- Emissions pricing - Reduced food waste	- Emissions pricing - Reduced crop losses and food waste - Dietary change

Adapted from United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 107 (Table 4.1 Emissions control measures included in at least one of the mitigation analyses).

A. Energy production sector

The greatest potential for mitigating methane emissions from energy production is in the oil and gas sector, where the mitigation potential is 29–57 Mt CH_4/yr,[267] representing 20–40% of the reductions needed to meet the Global Methane Pledge target in 2030 (**Figure 6**). Together with additional mitigation from coal, the fossil fuel sector represents slightly more than half of the emissions reductions to meet the Global Methane Pledge target. The IEA identified pathways for achieving 75% reductions from the energy production sector, as called for in the IEA's Net Zero Emissions by 2050 (NZE) Scenario,[268] with 40–50% of the measures having no net cost, based on average energy prices in 2023.[269] If methane leaks from fossil fuel operations in 2021 had been captured and marketed, the additional 180 billion cubic meters (bcm) of gas would have been equivalent to all the gas used in Europe's power sector and significantly eased price pressures.[270] The IEA highlights in the *Global Methane Tracker 2024* that while methane emissions intensity of oil and gas production varies widely, high emissions intensities are not inevitable and can be addressed cost effectively through a combination of best practice high operational standards, policy action, and technology deployment.[271] The IEA calculates that if all countries achieved the intensity of methane emissions (emissions per unit of production) similar to Norway's performance, methane emissions from oil and gas operations would fall by more than 90%.[272] The IEA has also reported that in the NZE Scenario, emissions fall by over 60 Mt (a 75% reduction) to 2030.[273] One-third of this drop would occur because of reductions in oil and gas use to 2030 in the NZE Scenario, with the remaining two-thirds stemming from widespread efforts across all parts of the supply chain to reduce the emissions intensity of oil and gas operations the methane emissions intensity of oil and gas production falls by more than 70% to 2030).[274] By 2030, the IEA predicts that under this scenario, all oil and gas producers have an emissions intensity similar to the world's best operators today.[275]

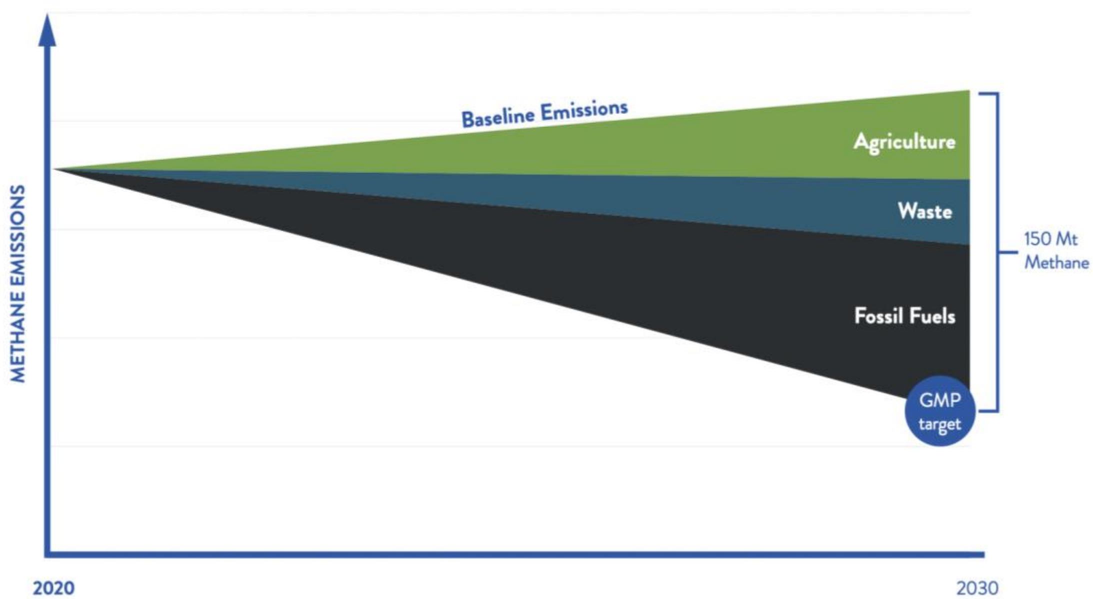
Additionally, a report from the Global Climate and Health Alliance has found that implementing solutions to reduce methane emissions in the energy production sector would have significant co-benefits for human health, such as by avoiding respiratory and cardiovascular illness.[276]

Measures to address leaks,[277] and reduce flaring and venting,[278] of methane are critical to lowering absolute methane emissions, and methane intensity, in the oil and gas sector.[279] These actions include ramping up leak detection and repair programs (LDAR) and replacing leaking devices and older equipment with modern low-emitting equipment.[280] Prohibiting venting of natural gas at oil wells can reduce emissions by 95%.[281] The World Bank Global Gas Flaring Reduction Partnership estimates that 144 bcm of gas was wastefully flared in 2021, an amount that, if captured, could power all of sub-Saharan Africa.[282] In 2020, the top 100 U.S. oil and gas producers contributed to 74% of reported methane emissions and 77% of reported GHG emissions, led by Hilcorp Energy, Exxon Mobil, Occidental Petroleum, and ConocoPhillips, according to an analysis by Ceres and the Clean Air Task Force.[283] This analysis confirmed that equipment operations relating to flaring and venting is a major determinant of emissions intensity, with pneumatic controllers comprising 62% of reported methane emissions and gas flaring and venting comprising 58% of total reported GHG emissions in the Williston basin.[284] The Oil and Gas Methane Partnership 2.0 Reporting Framework requires companies to report methane emissions from sources across the entire oil and gas value chain with a target to reduce emissions by 50–75% by 2030.[285] At COP28, the World Bank re-launched the Global Gas Flaring Reduction Partnership as the Global Flaring and Methane Reduction Partnership and set as a requirement to access project development and financing support a commitment through the Oil and Gas Methane Partnership 2.0 framework to achieve near-zero absolute methane emissions by 2030 by reducing methane intensity to below 0.2%, and to achieve zero-routine flaring by 2030.[286] These initiatives are discussed further in **Section 7**.

Reducing fugitive emissions of methane and associated air pollutants also promotes environmental justice. For example, over 18 million people in the U.S. live within one mile of wells and they are disproportionately marginalized groups; unemployment near wells is also found to be 4 to 12 times higher than the national average.[287] Efforts to plug and decommission the millions of abandoned and idle oil and gas wells would further reduce emissions while creating jobs and smoothing the energy transition.[288]

To reduce methane emissions from the oil and gas sector, it is critical to update and improve monitoring of methane emissions to identify hot spots and super-emitters. This is particularly important when considering that methane emissions from this sector are likely significantly higher than currently estimated, especially when estimates are based on inventory methods using emissions factors.[289] An airborne study of the Permian Basin in New Mexico estimated emissions 6.5 times larger than in an emissions factor-based inventory.[290] New satellite data revealed a significant amount of leaking methane from Australia's largest coal mines, raising concerns of a "large underreporting of methane emissions in the national inventory."[291] Satellites have also observed over 1800 "ultra-emitters" from 2019–2020, primarily associated with the oil and gas production sector, with a total emissions contribution equivalent to 8 to 12% (about 8 million metric tons of methane per year) of global oil and gas production methane emissions.[292] Taking satellite observations and scaled emissions intensities into consideration, IEA estimates that emissions from the energy sector were 70% higher than officially reported.[293] Researchers from the Rocky Mountain Institute (RMI), Stanford University, the University of Calgary, and Koomey Analytics developed the Oil and Climate Index Plus (OCI+) tool, which determined that the most climate-damaging oil and gas fields were in Russia's Astrakhanskoye field, Turkmenistan's South Caspian Basin, and the U.S. Permian Basin in Texas.[294] One challenge to reconciling these estimates is identifying how to integrate "top-down" measurements with "bottom-up" approaches to estimating methane emissions to allow for a more accurate depiction of overall emissions.[295] Under-reporting of methane emissions in NDCs from leading emitters can also lead to an underestimation of methane emissions, which in turn justifies greater monitoring efforts.[296] Methane monitoring efforts are discussed further in **Section 8**.

Figure 6. Mitigation pathways by sector consistent with the Global Methane Pledge target



Reproduced from United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: *2030 BASELINE REPORT*, 10 (Figure ES6: "Illustrative example of the GMP-consistent methane emissions reduction pathway to 2030. Mitigation in all three main anthropogenic sectors is required to achieve the GMP target in 2030 with slightly more than half of the mitigation expected to come from the fossil fuels sector.").

In addition to reductions in the oil and gas sector, measures to cut emissions from coal mining can provide additional mitigation of 12–25 Mt CH_4/yr.[297] Methane released due to mining activity can come from coalbed methane, a production method that taps coal seams and coal mine methane.[298] Coalbed methane can be linked to leakage in gas supply chains, while coal mine methane is attributed to coal production systems.[299] The IEA estimates that eliminating the worst performing quartile of operating coal mines would remove about 25 Mt CH_4 by 2050.[300] The primary methods for reducing coal emissions from active underground coal mines are oxidation of ventilation air methane and the recovery and use of methane through pre-mining degasification.[301] Although methane is recoverable before mining operations begin, the methane vented from mines is dilute and thus more expensive to use.[302] Additionally, because abandoned mines continue to leak methane, the CCAC recommends the flooding of abandoned coal mines to eliminate these emissions.[303] In some situations, abandoned mine methane can be recovered and used before flooding occurs.[304] In some limited instances, abandoned coal mine methane may be appropriate to use as a clean or alternative source of energy.[305] Efforts to mitigate methane emissions from abandoned mines can ameliorate negative health and environmental impacts for the local community.[306]

The climate and economic benefits of reducing methane emissions from the energy production sector are significant. Transitioning to renewable energy and addressing methane from abandoned fossil fuel facilities[307] are essential to reducing methane emissions in the coming decades.[308]

B. Agriculture sector

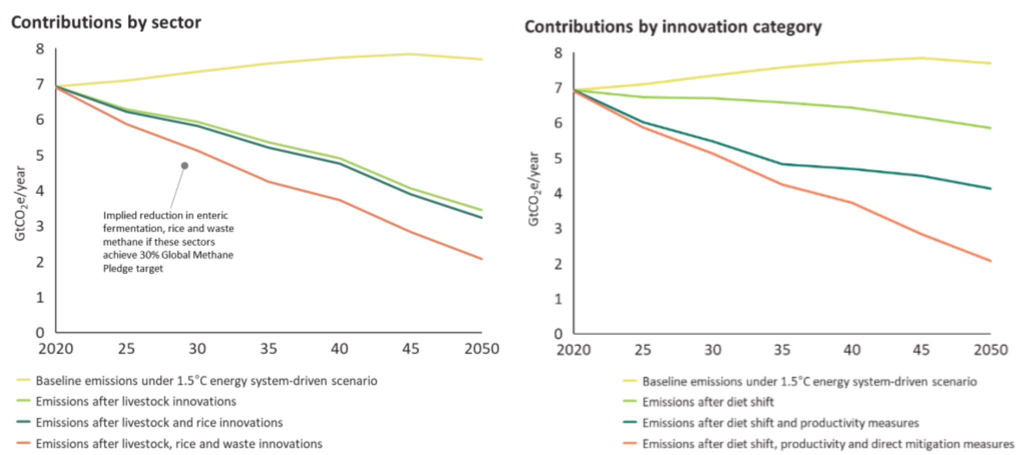
The agriculture sector can provide mitigation of 4–50 Mt CH_4/yr from the livestock subsector and 6–9 Mt CH_4/yr from rice cultivation,[309] representing 7–39% of the reductions needed to meet the GMP target in 2030 (**Figure 6**).[310] Across the entire food system, from agricultural production to food's end-of-life stages and every step in between, methane emissions could be further reduced by up to 75% by 2050 (**7**).[311] There is a considerable range in these projected mitigation percentages because the magnitude of methane mitigation from each subsector largely depends on a variety of factors—including farm type, variations among local and regional markets, and local and regional socio-economic considerations. The low end of the range assumes limited adoption of productivity, direct mitigation abatement measures and no shift in diets. Nonetheless, mitigation of methane in food systems is achievable, and aggressive strategies are needed as part of a comprehensive strategy to slow warming in the near term. Future projections show that food consumption emissions alone could add nearly 1 °C to warming by 2100, largely driven by high-methane foods (60% of the increase).[312] It is especially important to consider vulnerabilities across the sector and regional differences in order to design and implement effective, equitable mitigation strategies. For example, smallholder farmers (who produce over one-third of food for global consumption)[313] commonly live under the poverty line and experience food insecurity.[314] This socio-economic precarity is in stark contrast to multinational farming operations.

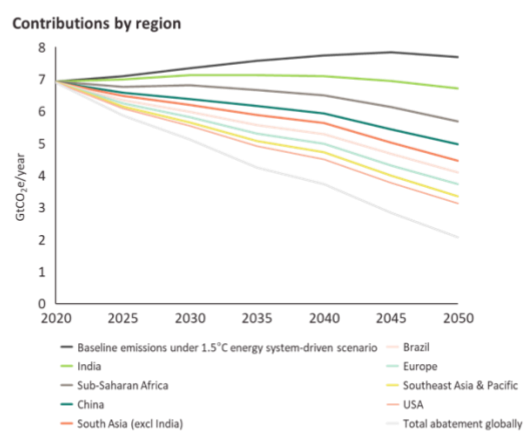
While the food system is a major contributor to climate change (30% of global GHG emissions),[315] and a major methane emitter (60% of anthropogenic methane emissions when food waste is included),[316] it is also a sector that is vulnerable to the impacts of climate change. This vulnerability severely impacts food security. The 2023 United Nations Food and Agriculture Organization (FAO) annual report on food security indicates that global hunger levels are rising, exacerbated by climate change shocks and other factors.[317] At COP28, the FAO released part one of a series of publications outlining a roadmap to sustainably achieve an end to world hunger (Sustainable Development Goal 2), including a target of reducing methane emissions from livestock by 25% of 2020 levels by 2030.[318] Methane emissions can significantly harm food production, in particular. As an illustration of this harm, methane, as a precursor to ozone, can contribute to the annual loss of ~580 million tonnes of staple crops like rice and maize.[319]

Furthermore, the entire food system will come under increasing stress in the next three decades, necessitating a system-wide transformation to meet the needs of future generations. Due to emissions impacts, expected population increases,[320] food-demand increases of 30–62% by 2050,[321] and expansion of global trade to address rising protein demands,[322] the food system is not expected to adequately provide for the needs of future generations. Only by adopting aggressive mitigation strategies can we reduce the risk that emissions from food systems will cause an overshoot of the 1.5 °C guardrail by 2050.[323] Key aggressive mitigation strategies include diet shifts; increases in productivity, efficiency, and food-systems resilience (such as improving soil health); direct mitigation (through feed and manure additives); and reductions in food loss and waste.[324]

We provide further detail below on measures to mitigate methane in livestock production, rice production, and outline prospects for agricultural methane mitigation in general.

Figure 7. Methane emissions reduction potential by sector, innovation category and region





Reproduced from Global Methane Hub & Climateworks Foundation (2023) *The Global Innovation Needs Assessments: Food System Methane, Technical Report*, 20 (Figure 3.1: "Methane emissions reduction potential by sector, innovation category and region." Footnote 28: Baseline emissions under 1.5°C energy system-driven scenario refers to food system emissions in scenario that meets a 1.5°C climate objective using emissions reduction in the energy system, without relying on interventions to reduce emissions in the food system.").

i. Livestock operations constitute a majority of food system methane emissions

Meat and animal products generate a majority of the GHG emissions (>60%) from the food system.[325] After 2030, consumption of meat and animal products will contribute more than half of food-consumption warming through the end of the century.[326] This large contribution comes from enteric-fermentation and manure-management methane emissions, as well as the land-use impacts from raising livestock.[327] Reducing methane emissions in the livestock sector can therefore mitigate the majority of food-system warming.

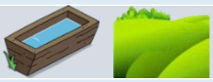
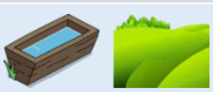
Mitigation measures in this sector are divided below into "productivity," "direct mitigation," and "behavioral" strategies. Productivity measures aim to generate more products per animal to lower methane emissions intensity; direct mitigation aims to inhibit methanogenesis (the process by which methane is generated) in the animal's stomach or manure; and behavioral strategies change either the supply- or demand-side of animal product market and consumption. Further strategies are summarized in **Table 3**. To accurately evaluate the mitigation potential of each livestock sector strategy, it is necessary to consider the local context, as the solutions best suited to each farm may vary substantially,[328] and to measure both the total methane abatement across the chain of production and any related environmental and emissions impacts.[329] It is also critical to consider the potentially perverse economic incentives to expand and further industrialize the meat and dairy sectors.[330]

a. Productivity strategies for cattle to reduce methane-emissions intensity

Increasing animal productivity, so that the same amount of milk or meat is produced with fewer cattle, can be an effective strategy to reduce the methane emissions intensity (emissions per kg of milk or meat).[331] The overall effectiveness of productivity measures depends largely upon their implementation in the local context.[332] In addition to methane mitigation, improving animal productivity generally may support countries' food security and other development goals.[333]

Key methods to increase animal productivity include improving feed digestibility, animal health and breeding, and grazing management.[334] Improving feed digestibility by reducing lignin (an organic polymer cattle cannot digest) can increase cattle consumption of feed, resulting in greater production of milk and meat per animal unit, reducing methane emissions per animal.[335] Maintaining high animal health standards, including by reducing heat stress,[336] minimizes the need to replace diseased, low-producing animals[337] and can directly reduce methane emissions by lowering methane emissions per product.[338] Breeding improvement schemes, such as breeding selectively for genes that increase productivity and reduce methane emissions, are another effective strategy.[339] Adopting new grazing strategies may improve feed digestibility, which in turn increases animal productivity. Some of these strategies may be more effective at reducing methane emissions when implemented at certain life stages of livestock, because the metabolic needs of meat and dairy production change over the animal's life cycle.[340] However, the climate and environmental impacts of novel grazing strategies are particularly dependent on local context. In some contexts, implementing these strategies can lead to unintended negative consequences, including land-use changes that defoliate native flora and exacerbate climate change.[341] In other contexts, the implementation of these strategies can lead to net-positive results, such as improving feed by decreasing total production costs.[342] When paired with livestock herd reduction, productivity increases may lead to reduced methane emissions intensity and an overall reduction of methane emissions.[343]

Table 3. Key emerging mitigation technologies for livestock methane, their applicability and key constraints across systems, relative emissions reduction, impact on animal performance, estimated global mitigation potential including constraints on adoption, and timing and confidence in commercial availability

Technology	Applicability	Key Constraint	Relative Emissions Reduction†	Impact on Animal Performance	Mitigation Potential in 2050‡	Widespread Commercial Availability§
Rumen Modification						
CH_4 inhibitors[a,b]		cost, regulatory approval	30%	no/limited effect[b]	0.8	2025 (*high*)
	*	cost	20–30%		5–8	2030 (*medium*)
CH_4 vaccine[a]		"sustained R&D, veterinary services, cost"[b]	30% (assumed)[a]	--	11–28	2050 (*medium*)
nitrate electron sink[b]		effect on enteric and manure N_2O emissions, potential negative animal health, cost	15[b]–42%[c]	neutral effect:[b] decreased intake & increased milk yield	not assessed	--
seaweed[a]	 *	"global-scale production, cost, toxicology, regulatory and market acceptance"[a]	20–50%	unknown[b]	0.5–1 1–10	2030 (*insufficient to determine*)
Diet Formulation						
tanniferous forages[b]		effect on manure CH_4, decreased palatability and feed intake, and incomplete digestion[c]	10[a]–32%[c]	no/limited effect[b]	not assessed	--
oil/oilseeds and fat inclusion[b]		effect on manure CH_4, cost, impaired feed digestibility,[d] effect on upstream emissions	14–15%	negative effect[b] (at high inclusion levels)	not assessed	--
decreasing dietary forage-to-concentrate ratio[b]		disease risk, risk of producing volatile fatty acids in the rumen,[c] feed over food competition	9% (intensity)	positive effect:[b] increased weight gain & milk yield	not assessed	--
Animal and Feed Management						
increasing feeding level[b]		effect on manure CH_4	17% (intensity)	positive effect:[b] increased weight gain & digestibility	not assessed	--
decreasing grass maturity[b]		effect on manure N_2O	13% (intensity)	positive effect:[b] increased milk yield & digestibility	not assessed	--
low-emissions breeding[b]		breeding programme	15[a]–31%[c]	limited positive effect[b]	2–9	sheep: 2030 (*high*) cattle: 2035 (*medium*)

 Feedlot and Mixed Systems  Grassland Systems ** intensive grazing systems*[a] *† absolute unless noted* *‡ in Mt CH_4 yr^{-1}* *§ confidence level*

Adapted from [a] Reisinger A., *et al.* (2021) *How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?*, PHILOS. TRANS. R. SOC. A 379(2210); [b] Arndt C., *et al.* (2022) *Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050*, PROC. NAT'L. ACAD. SCI. 119(20); [c] Harmsen M., *et al.* (2023) *Uncertainty in non-CO_2 greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility*, NAT. COMMUN. 14(2949); *and*

[d] Palangi V., *et al.* (2022) *Strategies to Mitigate Enteric Methane Emissions in Ruminants: A Review*, SUSTAINABILITY 14(20). Relative emissions reductions are assessed as CH_4 per unit of feed dry matter intake, g kg^{-1}.

b. *Direct mitigation measures, like feed and manure additives, can reduce absolute methane emissions*

New feed and manure additives, and other new technologies, are being developed to improve livestock health and productivity, manage enteric fermentation, and directly reduce emissions from manure.[344] The UK has also proposed the feeding of insect protein to animals to reduce overall GHG emissions from feed production.[345] Several of these new technologies are described below. *See also* **Section 6** for more information on additives acting to prevent methane emissions.

Enteric fermentation accounts for the majority of methane emissions from the agricultural sector. **Table 3** presents the main types of technologies that are being explored to reduce enteric fermentation, including feed and vaccine interventions on the rumen, such as red algae (*Asparagopsis taxiformis*) and methane-inhibitor 3-nitrooxypropanol (3-NOP, marketed as Bovaer®), and other dietary interventions. These technologies show promise but multiyear studies are needed to observe sustained effects, including effects that are potentially negative to cattle and human health, efficiencies, and the additives' production streams.[346] Meanwhile regulators have begun approving use of proprietary versions of these technologies in several geographies but face hurdles in others,[347] and some additive-fed meat and dairy products are on the market.[348] This is a rapidly developing area of research that received a $200 million public-private coordinated investment as part of the Enteric Fermentation R&D Accelerator announced at COP28.[349]

Manure additives, such as biochar (black carbon produced from the heating of organic material),[350] acids,[351] straw,[352] and SOP® Lagoon technology (based on calcium sulphate dihydrate, also known as gypsum)[353] can also reduce methane and other pollutant emissions such as ammonia, while storing the manure for a longer period. Manure emissions can also be addressed via anaerobic digestion (*i.e.*, a technology that converts organic waste to methane biogas and nutrient-rich digestate that may be used for fertilizer application),[354] and alternative management options (*i.e.*, separating sludge into solid and liquid components, and speedy removal of manure from barns).[355] However, the implementation of anerobic digestion technology or alternative management measures should be assessed based on the characteristics of individual farms.[356] Any use of biogas technology must also be monitored to prevent leaks and to address climate and environmental justice concerns. This is critical as biogas production facilities extend fossil fuel infrastructure and potentially increase pollution and odor.[357]

c. *Supply and demand-side behavior changes can further promote methane reductions in the food system*

Behavioral changes in livestock producers and consumers can also mitigate methane emissions in the sector. These changes include producer decreases in herd sizes and consumer shifts of diets from traditional high-methane intensive animal proteins (*e.g.*, red meat and milk) to alternative proteins. Changing various farming practices can achieve significant methane mitigation if done at a sufficiently large scale. For example, incentivizing operators to use organic farming practices may result in fewer methane emissions compared to large, intensified operations (also known as "feedlots" or concentrated animal feeding operations).[358]

On the demand side, a shift to lower meat consumption, especially in countries and regions with higher than health-recommended meat consumption rates, would reduce methane emissions from livestock by decreasing herd size and associated land use emissions and avoid 0.19°C by the end of the century.[359] Cultivating alternative proteins—plant-based, fermentation-derived, and cultivated meats—alleviates some of the greatest climate impacts of traditional animal agriculture (unsustainable land use, methane emissions, length of supply chain, etc.).[360] For example, replacing half of traditional animal proteins with alternatives by 2050 could decrease agriculture and land use emissions (*i.e.*, methane, nitrous oxide, carbon dioxide) by 31%.[361] While studies continue to demonstrate the reduced GHG impact of alternative protein diets versus traditional animal-sourced diets,[362] regional differences in meat consumption and protein-deficiencies must be considered to ensure a more equitable and sustainable approach to diet shifts globally.

Alternative proteins could contribute to achieving large-scale dietary shifts away from animal-based proteins while meeting global protein demand.[363] However, alternative proteins face several challenges on the way to scale to levels compatible with significant emissions avoidance.[364] In many countries there is a considerable gap in price between alternative and traditional proteins, although the gap is narrowing.[365] In addition to the challenge of meeting taste and price parity with animal-based proteins to achieve consumer acceptance, some cultivated and fermentation-derived alternative proteins face regulatory and research and development (R&D) hurdles.[366] Achieving taste and price parity at scale for alternative proteins will require massive investment but could deliver large net climate, job, and economic benefits.[367]

Governments at the national and subnational levels, as well as non-profit and private-sector organizations, have introduced mechanisms to inform consumers and incentivize industry to minimize methane emissions from beef and dairy operations. For example, the U.S. Department of Agriculture certifies some products which implement methane reduction strategies as "climate-smart."[368] California has awarded several grants directed to climate-smart animal production projects specifically addressing methane.[369] The private sector is creating mechanisms to reduce livestock methane emissions as part of a company's "Scope 3" GHG emission reduction reporting. (Scope 3 includes indirect GHG emissions from parts of the corporate value chain that the company does not control).[370] Large livestock operators, including Danone, have submitted targets to reduce methane emissions across all operations.[371] The U.S.-based think tank, the Institute of Agriculture and Trade Policy, has called for independent verification of these operations to ensure methane reductions are aligned with the Global Methane Pledge.[372] Use of GWP* to claim climate neutrality from large methane emitters is a misuse of this metric, which should only be used at the global level to relate sustained changes in methane emissions to additional warming beyond a reference level.[373]

ii. Rice production is the next highest methane-emitting activity in the food system

Rice production constitutes a smaller proportion of global methane-emitting activities from food production when compared with livestock production.[374] However, there are several strategies to improve rice production and future resiliency, while mitigating rice cultivation emissions. For rice paddy fields, improved water management, alternate flooding and drainage of wetland rice, direct seeding, and improved yield gains can greatly reduce emissions and improve productivity.[375] Although the key mitigation strategy is to reduce the time that fields are flooded,[376] this strategy requires tracking of responsive increases in N_2O emissions—another powerful GHG.[377] Experts estimate that alternate wetting and drying of fields (as opposed to continuous flooding during the growing season) could reduce methane emissions by as much as 48%.[378] Rice yield gains may be improved through crop breeding (to select for breeds that are more productive) and the application of biochar to crops,[379] as well as mechanization of what is otherwise manual work.[380] A 2021 study estimates that for every 1% increase in rice yield, methane emissions are reduced by 1%.[381] In addition to offering methane mitigation, selective breeding for rice can also offer adaptive benefits, such as increasing productivity in areas that will face worsened drought conditions in a changing climate.[382] Removal of rice straw may also reduce methane emissions.[383]

Certain strategies outlined above may be eligible to receive assistance through regulatory programs such as California's Air Resource Board Compliance Offset Protocol.[384] Several international projects have been deployed to sustainably produce rice, including the United Nations Development Programme (UNDP)'s alternative wetting and drying projects in Ghana,[385] and the World Bank's loan to Hunan province in China to pursue improved irrigation techniques and produce climate-resilient rice.[386]

iii. Future prospects for agricultural methane mitigation include new research, strengthening monitoring systems, and setting commitments and implementing policies aligned with the Global Methane Pledge

A wide range of research is assessing prospects for agricultural methane mitigation, including:

- adoption of indigenous practices;[387]
- use of regenerative agriculture (*e.g.*, silvopasture, agroecology,[388] and solar grazing[389]);
- integration of rice and animals[390] or animals and other crops;[391]
- introducing certain additives and processes to manure lagoons;[392]
- application of dung beetles[393] or worms (vermafiltration)[394] to cattle dung;
- use of electricity to convert livestock waste into fertilizer with reduced methane emissions;[395]
- use of captured methane as fish food;[396]
- use of brewer's yeast to suppress enteric methane while promoting animal growth;[397]
- genetically modifying yeast to inhibit methanogenic activity in the rumen;[398]
- application of anti-methanogenic vaccines to cattle;[399] *and*
- use of CRISPR, or gene-editing technology, to culture soil microbes in labs to better understand soil interactions that produce methane in rice paddy fields.[400]

Apart from measures derived from Indigenous practices, each of the above measures is still at an early stage of development and all are yet to be formally scientifically evaluated.

Improving monitoring systems across the agricultural sector is critical to measure and verify the impact of all mitigation measures (*see* **Section 8** on monitoring systems, including satellite and data integration). For example, methane emissions from cattle were observed for the first time in

California's San Joaquin Valley via GHGSat.[401] Machine-learning algorithms are also becoming faster at estimating GHG emissions, including N_2O (which has previously been difficult to quantify), from complex interactions in the soil.[402] Research is also finding systematic errors in current monitoring approaches for rice paddies, informing the implementation of new approaches that more accurately quantify and assess emissions from rice production.[403] Further improvements in monitoring systems are continuing to identify emitters in the agricultural sector, which are small in number but great in the magnitude of methane emissions.[404]

To develop effective methane mitigation plans in the agriculture sector, local and regional contexts and potential increases in other GHGs must be considered. While more countries have been including food system GHG mitigation in their NDCs,[405] more work needs to be done to include food system methane mitigation commitments. These commitments must be targeted, ambitious, and aligned with the Global Methane Pledge and Paris Agreement targets. In particular, these methane mitigation strategies must be designed to take account of both adaptation and mitigation needs at a regional and local level.[406] In some cases, tackling mitigation of emissions in one part of the food system could result in increased emissions from another part of the food system,[407] which could detract from overall climate goals.

C. Waste sector

The waste sector can provide mitigation of 29–36 Mt CH_4/yr,[408] representing 19–24% of the reductions needed to meet the Global Methane Pledge target in 2030 (**Figure 6**). Solid waste mitigation makes up the bulk of the mitigation potential from the waste sector.[409] Landfill operators can capture and convert to energy the methane emitted from existing landfills.[410] Collecting landfill gas requires costly equipment (*e.g.*, extraction wells and internal dumpsite piping)[411] construction and operation, although there are financial benefits in producing a biogas product fit for energy use.[412] McKinsey estimates that the maximum technical opportunity for inclusion of capture technology where applicable may lead to 4.50 Mt CH_4/year abatement by 2030.[413] As an alternative to combustion, which can contribute to air pollution, landfill gas can generate electricity using fuel cells.[414] In addition, improvements to landfill methane gas capture are emerging to optimize such capture while minimizing infrastructural needs and frequent human intervention.[415] Such technology should be assessed per landfill basis, as infrastructural needs may make landfill gas capture development more costly.

Discarded food and other organic waste releases methane as it decomposes in landfills under low-oxygen (anaerobic) conditions. The diversion of organic waste from landfills can significantly reduce methane emissions.[416] Programs to reduce food waste can decrease methane emissions from the food system, including both the waste and agriculture sectors.[417] Recent studies find that halving food loss and waste could result in the equivalent of quartering the total emissions from the global food system.[418] This can be done by promoting strategies to manage extreme heat exposure and increasing cooling access for small-scale farm managers to reduce food waste from earlier harvests caused by warmer weather,[419] and by turning food waste into chicken feed.[420] Emissions from food loss and waste are expected to rise in the future, due to increased population and consumption of food, and increased international trade, which lengthens the food supply chain, but may be combatted with compost and anaerobic digestion.[421] Cutting food loss and waste in half, combined with improving crop and livestock productivity, will also help to improve global food security.[422] More broadly, improving solid waste management reduces methane emissions and provides tremendous co-benefits for health including helping to close the nutritional gap between diet and optimal nutrient intake, especially for marginalized and vulnerable populations that reside close to waste treatment or disposal sites, or work in the waste sector.[423]

For organic waste already present in a landfill, biologically active covers or "biocovers," composed of greenwaste/compost, limit methane emissions by stimulating microbial methane oxidation.[424] Methane oxidation rates range depending on landfill type, location, and composition/thickness of biocover, but use of biocovers may yield impressive results—studies yielded over 60% improvements, and in some cases nearly 80% improvements,[425] in methane oxidation.[426] Biocovers may be used in inactive landfills as a control technology for remaining methane emissions following closure.[427] Due to their relatively low cost (compared to landfill gas collection), simple technical applicability,[428] and potential lifetime of 6–7 years with limited performance declines,[429] biocovers may be a solution to reduce methane emissions in landfills operated in low-income countries with limited management.[430] Biocovers have also proved to be successful in developed jurisdictions, such as in Denmark, with landfill gas capture technology employed simultaneously to optimize methane reductions.[431] Additional landfill biocover studies are underway, including at the University of California, Berkeley's Center for Law, Energy, and the Environment.[432] Odor mitigation measures have also been found to correlate with reduced methane emissions.[433] When combined with improved landfill management, these measures could reduce landfill emissions in the U.S. by 50% by 2030.[434]

Aerial remote sensing is a proven option for landfill methane monitoring that is more likely to accurately quantify emissions that are difficult to capture in traditional models.[435] In particular, aerial remote sensing is more flexible with landfill infrastructure changes and can identify important trends in emissions that could lead to new mitigation strategies.[436] Recent satellite data has found that landfill emissions in Buenos Aires, Delhi, Lahore, and Mumbai have been underestimated in common emissions inventory calculations.[437] The Waste Methane Assessment Platform (WasteMAP) launched in November 2022 will provide an open-source platform with information and best practices for operators, policymakers, and financiers.[438] Landfill methane emissions estimates and monitoring could also be improved by incorporating site-specific factors and cover-soil qualities into model estimates.[439]

For wastewater, McKinsey estimates that mitigation measures could reduce wastewater emissions by 27% by 2030 and 77% by 2050.[440] Methods to achieve this emissions reduction include improving the treatment of wastewater through upgraded processes, infrastructure, and technology.[441]

5. Natural sources of methane are responsible for about 40% of global emissions and research is underway on removing atmospheric methane and preventing methane formation

Natural sources of methane contribute approximately 40% (35–50%) of emissions and include wetlands and other freshwater systems, thawing permafrost, geological seeps, wild animals, forests, and oceanic sources including seabed methane hydrates.[442] While increasing anthropogenic emissions were likely the main cause of rising atmospheric concentrations over the past two decades, increases in emissions from natural sources are likely a major contributor to the recent rapid growth in methane concentrations.[443] As discussed in **Section 3**, the rate of growth of atmospheric methane concentrations surged between 2020 and 2022,[444] with evidence of increasing emissions from natural sources of methane principally in warmer and wetter wetlands over the Northern Hemisphere, accounting for about half of the increase.[445] AR6 WGI assesses that the methane release from a permafrost feedback could be as high as 4.1 billion tonnes through 2100 under current climate commitments.[446] The higher estimate is consistent with consideration of abrupt thaw that could affect half of permafrost carbon with about 20% released as methane, noting that models considering only gradual permafrost thaw likely underestimate carbon emissions by 40%.[447]

Some of these natural sources of methane are expected to increase and act as self-propagating feedbacks to human-caused warming.[448] While the permafrost methane feedback is well-established if poorly constrained,[449] new feedbacks have been suggested to explain the recent acceleration in atmospheric methane concentration. This includes a combination of strengthened positive feedbacks due to interactions between surface temperature, wetland emissions and wildfires, as well as reduced methane removal through negative hydroxyl radical feedbacks.[450] In addition, recent studies find that tropical wetland sources may explain more than 80% of the rapid increase in atmospheric methane concentrations over 2010–2019, potentially the result of a feedback between warming and strength in the Indian Ocean dipole and rainfall over East Africa.[451] However, AR6 WGI finds *low confidence* in multi-decadal trends in the Indian Ocean dipole due to limited data prior to the 1960s.[452]

Another concern is the risk that warming ocean waters will destabilize seabed methane hydrates. Such destabilization likely occurred off the coast of Guinea 125,000 years ago during the previous interglacial, with ice core records suggesting a sufficient amount of methane was released into the atmosphere to affect CO_2 and CH_4 concentrations.[453] With a rapidly warming Arctic, the shallow seabed of the East Siberian Arctic Shelf poses significant concerns due to its potential to speed up other global warming impacts.[454] Release of land-based methane hydrates as glaciers recede could further amplify the permafrost feedback.[455]

Research is underway on the best approach for removing methane directly from the free atmosphere.[456] Such a strategy could prove vital as a means of addressing growing methane from natural sources and their self-amplifying feedbacks, as well as from hard-to-abate anthropogenic sources.[457] On a molecular basis, methane is 220 times more dilute than CO_2 in the free atmosphere,[458] but its high global warming potential and the relative simplicity of accelerating the natural degradation of methane to CO_2 without carbon storage make it an attractive target,[459] with the potential to reduce warming much faster than CO_2 removal.[460] Removing methane, as a precursor of tropospheric ozone, also benefits public health, agriculture, and natural ecosystems, in a way that CO_2 removal does not.[461] However, care would need to be taken to avoid unintended atmospheric chemistry effects.[462]

Potential approaches for removing methane are listed below:[463]

- **Atmospheric oxidation enhancement** includes approaches that would accelerate the natural conversion of methane to CO_2 by enhancing the oxidative capacity of the atmosphere. For example, iron salt aerosols have been proposed as a cost-effective mechanism for augmenting the natural chlorine sink to oxidize atmospheric methane.[464]

Additional early-stage proposals for this approach include hydrogen peroxide dispersal and photocatalytic aerosols.

- **Terrestrial methanotrophy enhancement** considers the potential to safely enhance ecosystem methane sinks. The approach includes soil management practices such as soil amendments and engineered methanotrophs.[465] Experiments with filters containing methane-eating microbes have been used to process relatively concentrated methane, such as that found in coal mines and above landfills and manure lagoons.[466]
- **Methane reactors** pass air through catalytic systems using heat, sunlight, or radicals to break down methane. Photoreactors are being tested for low-concentration waste methane sources.[467] A research group at MIT identified a clay material capable of oxidizing atmospheric levels of methane at relatively low temperatures.[468] Gathering and flaring natural emissions or using more efficient thermal oxidation designs could also develop into viable strategies at higher methane concentrations near sources.[469]
- **Surface treatments** consider application of photocatalysts to surfaces, building on approaches that have been investigated to improve air quality.[470]

Many strategies and technologies are being explored within each category, with most in early stages of research. It is important to distinguish between methane removal technologies that have the potential to remove methane from the atmosphere and have the potential to contribute to drawing down atmospheric methane concentrations from technologies applied to reducing emissions from methane sources. Reducing emissions from sources should be considered methane mitigation as opposed to atmospheric methane removal.

The U.S. National Academies of Sciences, Engineering, and Medicine just published a consensus study report, *A Research Agenda Toward Atmospheric Methane Removal* (2024), that describes priority research that should be addressed within the next 3-5 years to lay the groundwork for a second-phase study that will address "technical, economic, and social viability of technologies to remove atmospheric methane at climate-relevant scales."[471] In theory, removing the equivalent of three years' worth of current anthropogenic methane emissions (and continuing to remove about 10% of current annual emissions) would reduce warming by 0.21 °C; further, removing one year's worth of methane emissions would reduce transient warming almost four times more than removing one year's worth of CO_2 emissions (0.07 °C for methane compared to 0.02 °C for CO_2).[472] However, these estimates should be considered preliminary, given the early stage of research on all forms of atmospheric methane removal, and there are no technologies currently available that can remove the amount of methane necessary to achieve these levels of avoided warming.[473]

6. Major-emitting countries are pursuing and must strengthen methane mitigation measures

National and subnational governments are increasingly developing and implementing methane mitigation policies and initiatives.[474] However, these measures must be expanded and strengthened to achieve the 50% reduction in methane emissions by 2050 assumed in calculations of the remaining carbon budget for 1.5°C.[475] A recent study has found that only 13% of methane emissions are covered by direct methane mitigation policies.[476] Governments can strengthen methane mitigation policies by implementing readily available technologies, laws, and governance structures to their fullest and considering ways to expand methane mitigation through other available avenues. The IEA produced a Regulatory Roadmap and a Toolkit on Driving Down Methane Leaks from the Oil and Gas Industry.[477] The IEA policies database includes methane abatement policies from its member countries around the world.

Examples of specific methane mitigation measures in Australia, Brazil, Canada, China, the European Union, India, Iraq, Mexico, Nigeria, the United Kingdom, and the United States are described below. These countries' policies are included because of their status as major emitters and in most cases, noteworthy ambition in the context of methane mitigation. Also noteworthy is Colombia's finalization of regulations in February 2022, making it the first country in South America to regulate emissions from oil and gas.[478] In light of border adjustment and methane-fee initiatives in the U.S., EU, and elsewhere, as described in this section, it is useful to note the 2023 XV BRICS Summit declaration (comprising Brazil, Russia, India, China, South Africa, Egypt, Ethiopia, Iran, and the United Arab Emirates) signaling that members of the BRICS organization oppose "trade barriers introduced under the pretext of tackling climate change."[479]

A. Australia

Australia contributes to approximately 1.6% of global methane emissions.[480] These emissions primarily derive from agriculture (44%), energy (44%), and waste (8.7%).[481] While these are the official figures, a report released in August 2023 found that Australia is vastly underestimating its emissions from the oil and gas sector.[482] Fugitive methane emissions from coal mining and oil and gas supply have likely been grossly underestimated to date—by about 80% for coal and 90% for oil and gas.[483]

Australia joined the Global Methane Pledge in October 2022.[484] Australia also passed the Climate Change Act in 2022. This Act legislates Australia's targets to reduce greenhouse gas emissions by 43% on 2005 levels by 2030 and net zero greenhouse gas emissions by 2050.[485] Australia does not have a higher or more specific domestic methane emission reduction target than the 30% reduction set out in the Global Methane Pledge.[486] However, recent amendments to climate legislation passed in March 2023 place greenhouse gas emissions caps on major oil, gas, coal, and other polluting facilities and mandates that these facilities reduce their emissions by a minimum of 4.9% per year.[487] The New South Wales State Parliament has also legislated a target to reduce greenhouse gas emissions by 70% by 2035.[488]

In energy, flaring and venting is predominantly regulated at the State and Territory level.[489] In Queensland, venting is only allowed where flaring is not technically possible or for safety reasons.[490] In Northern Territory, the code of practice for petroleum producers mandates that venting and flaring should be either eliminated or minimized to as low as reasonably practicably.[491] However, in Western Australia, which is the primary source of Australia's domestic petroleum production,[492] emissions from venting and flaring need to be reported, but there is no further policy or regulation to mandate that these emissions be reduced and eliminated.[493]

In agriculture, Australia is funding the $6 million Methane Emissions Reduction in Livestock (MERiL) Stage 1 program to support research and development of methane-reducing livestock feed technologies.[494] The federal government is providing a further $5 million to Stage 2 of

MERiL, which consists of grants to develop and determine the feasibility of low emission delivery technologies.[495] Further, the federal government is providing $15 million to Stage 3 of MERiL, which allocates grants to undertake trials to validate the delivery technology and demonstrate its emissions reduction and productivity impacts.[496] The federal government is also providing $8.1 million to support the commercialization of seaweed as a low emissions feed technology and lower barriers to market entry.[497] An additional $9.3 million is being directed to scale-up production of the red seaweed, *Asparagopsis*.[498]

In waste, the 2018 National Waste Policy pledged to reduce organic waste, including garden and food waste, by avoiding their generation and supporting diversion away from landfill into soils and other uses, supported by appropriate infrastructure.[499] The government has set the goal to halve Australia's food waste, and halve the amount of organic waste sent to landfill by 2030.[500]

Policies that have been implemented to achieve this goal include:

- State and Territory governments expanded Garden Organic and Food Organics and Garden Organics curbside collection services to households and businesses in Australia.[501]
- Stop Food Waste Australia began working to deliver a voluntary commitment program called the Australian Food Pact. It will work with organizations across the food supply chain to develop tailored plans to help them achieve their food waste goals.[502]
- The National Food Waste for Healthy Soils Fund was announced, to support recycling infrastructure that will create consistent, safe, and high-quality recycled organic products for use in soil.[503]
- New South Wales ran a pilot *Scrap Together* campaign, drawing on results of bin audits and social research, to improve the rate of food waste recycling in three council areas. The pilot campaign increased food waste recycling by an average of 10% and the campaign has since been expanded to other council areas.[504]
- South Australia released a State Food Waste Strategy 2020–2025 to reduce and divert household and business food waste, outlining 38 actions including policy measures, behavioral change actions and continued support for industry across three program areas to capture material and return to productive use.[505]
- South Australian implemented a Kerbside Performance Plus Food Organics Incentives Program, which provided financial support for local government to roll out area-wide high performing food waste diversion systems.[506]

B. Brazil

Brazil is the fifth largest methane emitter in the world,[507] owing to its cattle industry, which accounts for 14% of the global bovine herd.[508] Brazil's total methane emissions amounted to approximately 400 Mt CO_2e in 2020, with ~285 Mt CO_2e coming from the livestock sector alone.[509]

Brazil is a signatory to the GMP. To fulfill its obligations in the GMP and the UNFCCC, Brazil enacted a decree in 2022 that created the Federal Strategy to Incentivize the Sustainable Use of Biogas and Biomethane.[510] The decree establishes guidelines to encourage the development of carbon markets, the use of biomethane as a renewable energy and fuel source, and investment in scientific-technological research.[511] Further, it provided a non-exhaustive list of urban and rural waste that may be used to produce biogas and biomethane, including waste disposed in landfills.[512]

The Federal Strategy, which includes the Methane Zero Program, will introduce methane credits into existing market mechanisms.[513] Methane credits representing tons of methane not emitted will generate additional income for biogas and biomethane projects. Prior to the Methane Zero Program, Brazil encouraged development of biofuels through RenovaBio, a regulated market for decarbonization credits that require fossil fuel distribution companies to meet their targets by investing in biofuel enterprises.[514]

In 2019, the U.S. and Brazil launched the U.S.-Brazil Energy Forum as a mechanism for cooperation in carbon and methane management, civil nuclear power, renewable energy, energy efficiency, and grid modernization. In its second ministerial meeting in 2022, the two governments agreed to "exchange expertise in carbon and methane management, and carbon sequestration and storage."[515] More recently, in August 2022, the U.S. and Brazil also launched the Clean Energy Industry Dialogue to collaborate on renewable energy and sustainable fuels, including offshore wind energy and clean hydrogen.[516]

At COP28, Brazil announced that its National Council of Energy Policy will establish guidelines on methane reduction in the oil and gas sector by the end of 2024, and that the National Agency for Petroleum, Natural Gas, and Biofuels aims to finalize regulations by the end of 2025 based on these guidelines.[517]

C. Canada

Canada committed to reduce emissions by 40–45% below 2005 levels by 2030, including a 40–45% reduction in methane emissions from the oil and gas sector, and reach net-zero emissions by 2050.[518] As part of its participation in the GMP, Canada aims to reduce oil and gas methane emissions by 75%.[519] Current Canadian regulations, issued in 2018, cover new and existing upstream oil and gas facilities, and include enhanced leak detection and repair requirements, and when fully implemented, quantitative limits on natural gas venting.[520] In November 2022, the Canadian government proposed a regulatory framework to reduce oil and gas emissions in line with the 2030 target.[521] The proposed regulation will require methane destruction to operate at a control efficiency of 99% or higher,[522] prohibit flaring at all oil sites,[523] and require all facilities to have a fugitive emission management plan with monthly inspections.[524] In advance of COP28, the federal government indicated that it would announce new methane regulations and funding.[525] These regulations are intended to ensure a reduction of methane emissions in the upstream oil and gas sector by at least 75% below 2012 levels by 2030.[526] This would be achieved by expanding the scope of the current regulations, introducing a focus on maximizing emission reductions, removing some exclusions, and ensuring all practical actions to lower emissions that are considered both achievable and cost effective are in place by 2030.[527]

Canada governs its oil and gas methane emissions primarily through provincial-level regulations that supplant the national regulation in accord with equivalency agreements. The Canadian federal government has equivalency agreements in place with the provinces of Alberta, British Columbia, and Saskatchewan,[528] which together produce about 99.8% of Canada's gas, and more than 92%

of its oil.[529] Most gas comes from Alberta, which produces nearly twice as much as British Columbia, and more than 25 times as much as third-place Saskatchewan.[530]

Alberta has set a goal for 45% reduction in methane emissions by 2025 across all sectors, and an additional goal of reducing methane emissions from conventional oil and gas by 75–80% by 2030.[531] Alberta is reported to be on track to surpass the 2025 target.[532] In order to reach its target, Alberta has established a Methane Working Group comprised of academic and industry experts, as well as members of indigenous communities to assess the effectiveness of methane policies.[533] Additionally, Alberta has developed the Alberta Methane Emissions Program to support methane emission reductions in the oil and gas industries.[534] This program is funded by Alberta's Technology Innovation and Emissions Reduction Fund.[535] The Alberta Methane Emissions Program is a three-year $17 million initiative to promote technology and data sharing for the purpose of developing methane-efficient technology for the oil and gas sector.[536] With continued reliance on the Methane Working Groups' assessments and the MTIP's support, Alberta hopes to achieve its 2030 target, though studies show that current estimates of methane emissions in Alberta differ from independent estimates.[537]

Saskatchewan has implemented its own Methane Action Plan in 2019 with the target of 40% methane emission reductions by 2025.[538] Currently, Saskatchewan reports that it has surpassed these targets with emission reductions of 60%.[539] Despite the national pledge and target, studies have suggested that oil and gas emissions in Alberta and Saskatchewan are 60% higher than reported in Canada's national inventory, due to inconsistencies found in short-scale testing used by the national inventory.[540]

For landfills, Canada has committed to increasing the number of landfills that collect and effectively capture methane, as well as to pilot improved monitoring systems in these landfills.[541] The federal government in Canada works with provincial and local governments to bring awareness to food waste and disposal options with the goal of reducing the amount of organic waste that is landfilled.[542] In turn, local and provincial governments developed goals,[543] plans,[544] and tax incentives[545] to reduce food waste.

Furthermore, the federal government implements programs to incentivize climate-smart agriculture and reductions in agricultural GHG emissions. Canada's Agricultural Climate Solutions program invests in natural climate solutions, such as increasing carbon storage on farms.[546] The Agricultural Clean Technology Program supports methane reductions in the agricultural sector by investing in green energy and technologies that use manure and other waste for energy.[547] In December 2023, Canada announced its Reducing Enteric Methane Emissions from Beef Cattle (REME) protocol which will offer offset credits at beef cattle operations for actions which either directly decrease methane, or the methane intensity of the national herd, such as animal diet improvements, animal management improvements, and reduction of waste.[548] Canada has also recently announced market authorization for Bovaer, a methane reducing feed ingredient for cattle.[549]

In February 2021, Canada and the U.S. declared a "shared commitment to reducing oil and gas methane emissions to protect public health and the environment, as guided by the best science."[550] Additionally, Canada is a Party to the LRTAP Convention, which is examining the impacts of methane on ozone formation, as explained further in **Section 10**.[551]

D. China

During the September 2020 UN General Assembly, China announced its target of achieving carbon neutrality before 2060.[552] This longer-term goal covers all GHGs, including methane. For the near term, China's Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035 provides that China will "strengthen the control of other GHGs such as methane, HFCs, and perfluorocarbons (PFCs)."[553] The prominent mention of methane in this Plan provides China's national ministries and agencies with authority to include detailed requirements for methane in their 14th Five-Year implementation plans covering the period 2021–2025. Additionally, China has made the commitment to include actions/targets to address economy-wide emissions of all GHGs in its 2035 Nationally Determined Contributions (NDCs) in the *Sunnylands Statement*.[554] In this regard, recall also that the U.S. and China mentioned that "[b]oth countries intend to communicate 2035 NDCs in 2025" in the *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s* ("*Joint Glasgow Declaration*").[555]

More specifically on methane, China released the Methane Emissions Control Action Plan in November 2023.[556] This Action Plan highlights as key priorities the improvement of the monitoring, reporting, and verification (MRV) system for methane emissions, as well as methane emissions control actions in the energy, agriculture, and waste sectors. It is also noteworthy that the Action Plan aims to strengthen the synergistic control of methane and other pollutants, such as volatile organic compounds. As an incentive mechanism, the Action Plan also promotes the inclusion of methane mitigation and reutilization projects in the greenhouse gas voluntary emission trading system.[557]

China's annual utilization of coal mine gas will reach 6 billion cubic meters by 2025.[558] This indicates a decrease from the coal-mine gas utilization goal by 2020. China's targets for the 13th Five-Year period include: "by 2020, the coalbed methane (coal-mine gas) extraction volume shall reach 24 bcm, within which the production of on-ground coalbed methane shall reach 10 bcm with a utilization rate of over 90%; and the extraction of coal-mine gas shall reach 14 bcm with a utilization rate of over 50%."[559] At a State Council press conference on 27 April 2021, the Ministry of Ecology and Environment announced a plan to revise emission standards for coalbed methane and coal mine gas.[560] The Chinese government has also been providing special funding to support coalbed methane extraction and utilization projects during 2023–2025.[561] At the provincial level, Shanxi Province announced that it had extracted 7.16 billion cubic meters of coalbed methane in the first eight months of 2023, a record high for the January–August period.[562]

Importantly, China's methane emissions reduction success or failure is closely linked to its ability to transition away from fossil fuels, including coal. For example, China has announced that it will strictly control coal consumption during 2021–2025 and gradually reduce coal consumption during 2026–2030.[563] Key regional targets include reducing the coal consumption in Beijing, Tianjin, Hebei, and surrounding areas by about 10%, reducing the coal consumption in the Yangtze River Delta region by about 5%, and achieving negative growth in coal consumption in the Fenwei Plain region by 2025.[564] In China's updated NDCs, China incorporated its goal of increasing the share of non-fossil fuels in primary energy consumption to around 25% by 2030 and noted that funds have already been expended on a major project, "Development of Large Oil and Gas Fields and Coal-Bed Methane."[565] In its Mid-Century, Long-Term Low Greenhouse Gas Emission

Development Strategy, China included its target of further increasing the percentage of non-fossil fuels to over 80% by 2060.[566]

For the oil and gas sector, China sets targets to reach the plateau stage for oil/petroleum consumption during 2026–2030,[567] and aims to peak land-transportation petroleum consumption by 2030.[568] Additionally, China aims to have the collection rate of associated gas from oilfields be on par with international advanced standards by 2030.[569] China's updated NDCs incorporate actions to reduce methane emissions in this sector, including through the deployment of technologies for the recovery of associated gas.[570] The China Oil and Gas Methane Alliance, an association of seven Chinese companies, has pledged to reduce the companies' average methane emissions intensity in natural gas production to below 0.25% by 2025, and cooperate and share technical experience on methane-emissions control, including LDAR and gas-recovery systems.[571] However, China has not yet applied mandatory methane intensity requirements to fossil oil and gas production and import. Additionally, China's efforts to promote green and clean transportation are also expected to reduce petroleum consumption and contribute to methane emissions mitigation. Examples of key targets in the transportation sector are to increase new-energy and clean-energy powered transportation to about 40% of total new transportation per year in 2030 and to achieve a deployment rate of no less than 70% for green transportation in cities with populations of one million or more by 2030.[572]

For the agriculture sector, China set targets for achieving "comprehensive reutilization" of over 80% of livestock and poultry manure nationwide by 2025.[573] China's Methane Emissions Control Action Plan further raises the goal to over 85% by 2030.[574] Furthermore, China will increase the efficiency of chemical fertilizers and pesticides to 43% by 2025,[575] which may also have implications for methane emissions reduction. To help address GHG emissions from cropland, China also aims to achieve zero growth in the use of chemical fertilizers and pesticides for major crops and achieve comprehensive utilization of 85% of crop straw by 2020.[576] China lays out key action items for emissions reduction and carbon sequestration in the agriculture sector as part of China's efforts to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. These key actions include, among others, reducing methane emissions from rice farming and livestock manure management, promoting the replacement of fossil fuel with biogas, and improving methane emissions monitoring from agricultural sources.[577] Importantly, China is also looking into low-carbon compensation mechanisms to incentivize methane mitigation action in the agricultural sector.[578] Additionally, the CCAC is working together with China to, among other things, research and develop effective methane mitigation strategies "such as carefully controlling the water, fertilizer, antibiotics, and type of feed, which can not only reduce emissions but can also increase agricultural production."[579]

For the waste sector, China set targets including reaching, by 2025, 90% harmless disposal of urban sludge,[580] 25% sewage resource utilization in water-scarce cities at the prefectural level and above,[581] 40% domestic sewage treatment in rural areas,[582] and more than 95% of county sewage treatment.[583] Furthermore, by 2030, the national average utilization rate of urban recycled water will be increased to 30%.[584] For selected regions, China is requiring that, by 2025, the utilization rate of recycled water shall reach over 35% in the Beijing, Tianjin and Hebei regions, and strive to reach a utilization rate of 30% in water-scarce cities at the prefecture level and above in the middle and lower reaches of the Yellow River basin.[585] Additionally, China committed to increase the reutilization of urban household waste to around 60% by 2025 and 65% by 2030.[586] By the end of 2025, China plans to reach a domestic waste incineration treatment capacity in cities and townships of about 800,000 tonnes per day; about 65% of this incineration treatment capacity is for treatment of domestic waste in cities.[587] China is also promoting the recycling and reuse of industrial solid waste with the goal of increasing the comprehensive reutilization rate of bulk industrial solid waste to 57% by 2025.[588] At the subnational level, China announced a plan to build 100 zero-waste cities by 2025.[589] The construction of zero-waste cities will contribute to methane emissions reduction through planned improvements in solid waste disposal in industrial sources, reduction of household waste landfills, management and reuse of livestock waste, and control of chemical fertilizer and pesticide application.[590]

China's Methane Emissions Control Action Plan also prioritizes the improvement of the MRV system in the current 14th Five-Year period (2021–2025) and the upcoming 15th Five-Year period (2026–2030).[591] This Action Plan lays out the plan for establishing a sky-earth methane monitoring system, including ground-based monitoring, unmanned aerial vehicles, and satellite remote sensing. To support the development and implementation of national methane mitigation policies and targets, China has announced the plan to strengthen satellite remote sensing technology development and deployment for GHG emission data monitoring,[592] and launched a number of emissions monitoring pilots involving enterprises, municipalities, and regions.[593] Particularly, these include pilot projects in the coal mining, oil and gas production, and waste sectors focused on methane emissions monitoring. During its January 2023 press conference, China's Ministry of Ecology and Environment (MEE) noted that the oil and gas industry pilots have established a methane leakage detection mechanism that involves an integrated "satellite + unmanned aerial vehicle + cruise" monitoring system for tracking methane leakage in production processes. For the coal mining industry pilots, MEE observed that a collaborative methane emissions monitoring technology has been developed using existing coal mine safety monitoring systems. MEE also commented that it has established a preliminary understanding of the concentrations and the spatial and temporal distributions of global methane emissions through analysis of satellite remote sensing data.[594] The China Council for International Cooperation on Environment and Development also commissioned IGSD to provide methane metrics and measurement research for MEE and other Chinese government authority and expert consideration.[595]

In addition to the national methane-emission reduction policies and targets described above, China has taken several steps to mitigate the climate and other environmental impacts of its overseas investments. These include the commitment to stop building new coal-fired power plants[596] and the issuance of government guidelines recommending that Chinese enterprises comply with prevailing international standards or China's own standards if the country receiving the Chinese investment: 1) lacks environmental standards applicable to the investment and project in question; or 2) has in place environmental standards for the investment or project in question that are lower than prevailing international standards or those applied to such investments and projects in China.[597]

E. European Union

The European Union (EU) addresses methane in its existing policies and is working to strengthen them. The European Climate Law includes a binding target for Europe to become climate-neutral by 2050 with an interim target to reduce all greenhouse gas emissions by 55% by 2030, compared to 1990 levels.[598] The European Commission presented a methane strategy in October 2020 and noted that the 55% target would require that the European Union reduce methane emissions by 35–37% by 2030.[599] Additionally, the methane strategy prioritizes ensuring more accurate measurement and reporting of private-sector emissions.[600]

In July 2021, the European Commission adopted a set of proposals, known as the "Fit for 55" package, that would achieve the 55% GHG reduction target by 2030.[601] The Fit for 55 package would enhance ambition for sectors not covered by the Emissions Trading System, including waste management, buildings, and agriculture, by increasing the overall emissions-reduction target from 30% to 40%.[602] The package also would amend the EU Land Use, Land-Use Change and Forestry regulation to include non-CO_2 emissions, including methane, by 2031.[603] More than half of the European Union's domestic methane emissions occur in the agriculture sector,[604] with most methane emissions from energy use occurring abroad.[605] Some analysts have concluded that the European Union will not achieve large reductions in domestic methane emissions without "policies that drive the uptake of behavioral and technical measures in the livestock agriculture sector."[606]

In December 2021, the Commission proposed regulations and a directive[607] based on a proposed 2050 energy mix in which biogas, biomethane, renewable and low-carbon hydrogen (*see* **Box 5**), and synthetic methane would represent two-thirds of gaseous fuels, with the remainder from fossil gas accompanied with carbon capture and storage (a reduction from the 95% share of fossil gas in 2021). The directive proposes to limit long-term natural gas contracts from running beyond 2049.[608]

The Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942 for the fossil fuel sector would require operators to report on source-level methane emissions, including a phase-in of direct measurements and site-level measurements of non-operated assets.[609] The regulations would also require operators to institute LDAR programs, and ban routine venting and flaring.[610] Regulatory inspections and information from relevant internationally available sources would verify compliance with these regulations.[611]

Furthermore, the proposed regulations would require that Member States publicly inventory inactive oil and gas wells. They would also require that either Member States or other responsible parties monitor methane emissions and develop mitigation plans for remediation, reclamation, and permanent plugging.[612] The regulations would similarly compel Member States to publicly inventory closed and abandoned coal mines, and require that Member States with jurisdiction over abandoned mines and operators of closed mines monitor and report methane concentrations at those closed or abandoned within the previous 50 years.[613]

The proposed regulations also specify that underground coal mines and drainage stations perform continuous emission measurements, whereas surface mines would be required to employ deposit-specific emission factors to quantify emissions.[614] Underground and surface mines estimate post-mining emissions based on relevant factors and report all emissions to regulators.[615] Underground mines would be prohibited from routine venting and flaring with a destruction efficiency below 98%, except during exigent situations, and required to report flare events.[616] A report from Ember has identified that new amendments that increased the venting thresholds for thermal coal, and delayed action on coking coal will only cut methane emissions from coal mines by around 47%, well below the stated climate goal of a 58% reduction.[617]

The proposed regulations do not include specific, binding target reductions.[618] The EU instead reiterated a call for transparency and referred the matter to the Agency for the Cooperation of Energy Regulators and Committee of European Securities Regulators.[619] The proposed regulations would require EU importers to report additional information on exporters' and producers' methane mitigation efforts, and establish a Methane Transparency Database and global methane monitoring tool.[620] Additionally, the proposed regulation would empower the Commission to pursue appropriate legislative amendments to extend reporting requirements to third countries, following a report on the impact of the extension on the energy supply chain and the production of imported fossil fuels.[621] The regulations will also ensure that equivalent monitoring, reporting, and verification measures should be applied by exporters to the EU by 1 January 2027, and maximum methane intensity values by 2030.[622] Importers will face financial penalties if they buy from foreign suppliers that don't comply with the limit—effectively imposing a fee on non-compliant fuels.[623]

In 2023, the European Parliament adopted a series of amendments to the Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942. Key amendments include heightened leak and detection requirements,[624] an expansion of monitoring requirements to the petrochemical sector,[625] and requiring that from 2026, importers of coal, oil, and gas demonstrate that exporters of coal, oil, and gas into the EU comply with the regulatory requirements for the measurement, monitoring, reporting and verification, leak detection and repair, and venting and flaring.[626]

In November 2023, the Council of Europe reached a provisional agreement with the European Parliament on the final version of these regulations, paving the way for their enactment and implementation.[627] The European Parliament formally adopted the regulations on 10 April 2024, followed by the Council of Europe on 27-28 May 2024.[628] As part of implementation of the regulations, equivalent monitoring, reporting and verification measures should be applied by exporters to the EU by 1 January 2027, and maximum methane intensity values by 2030.[629]

The EU has also made broader efforts to regulate methane emissions from landfills. The EU Landfill Directive requires Member States to separate biodegradable waste and establishes a target to landfill only 10% of municipal solid waste by 2035.[630] Requirements to divert organic waste helped to achieve a 47% drop in EU landfill emissions between 1990 and 2017.[631]

The 2023 launch of the EU's revised Common Agriculture Policy (CAP) increases emphasis on climate actions within the agriculture sector and dedicate 40% of funding to climate-related measures.[632] The specific goals within the CAP, as reflected in CAP Strategic Plans, include increasing targets to reduce food waste, and a focus on methane reducing ruminants.[633]

The newly adopted Carbon Border Adjustment Mechanism (CBAM), designed to prevent outsourcing of carbon-intensive industries and incentivize sustainable practices abroad,[634] does not address imported methane. However, some have called for methane to be addressed in future measures.[635] CBAM entered into effect on a transitional basis in October 2023, only applying during this transitional phase to imports of cement, iron and steel, aluminum, fertilizers, electricity and hydrogen.[636] CBAM and similar measures like the proposed U.S. carbon border adjustment charge discussed above are opposed by many developing countries.[637] CBAM may evolve in time to allow for broader EU-U.S. alignment on a global methane border adjustment mechanism.[638]

Prior to the February 2022 Russian invasion of Ukraine, the European Union imported more than 40% of its total gas consumption from Russia.[639] In 2019, the European Union imported nearly 90% of its natural gas, mostly from Russia.[640] A July 2022 regulation controversially allowed the certification, under limited circumstances, of some natural gas under the EU sustainable investment taxonomy.[641] The European Union has responded to this changing geopolitical situation by announcing the acceleration of its transition from fossil energy.[642] On 23 March 2022, the European Commission tabled a legislative proposal to increase its gas storage levels to 80% by November 2022.[643] Further, it issued a communication stating its plans to form a Task Force on Common Gas Purchases that will "prepare the ground for energy partnerships with key suppliers of LNG, gas, and hydrogen in the Mediterranean, Africa, the Middle East, and the U.S.[644] On 25 March 2022, the White House and European Commission on European Energy Security announced that they would ensure expeditious regulatory procedures for LNG infrastructure, but also emphasized their efforts to reduce the emissions intensity of such infrastructure.[645] Notably, on 8 May 2022, the G7 committed "to phase out our dependency on Russian, energy, including phasing out or banning the import of Russian oil," but did not specifically mention gas.[646]

Additionally, the United Nations Economic Commission for Europe (UNECE) is studying methane's role as a precursor for ozone formation in the UNECE region as part of its work under LRTAP.[647] The UNECE includes all of Europe, as well as countries in North America, Central Asia, and Western Asia. For more information, *see* **Section 10**.

The Joint Communication on EU External Energy Engagement, which was published on 18 May 2022, outlines the region's current efforts and plans to diversify its energy supply. This includes partnerships to increase imports of liquefied natural gas from other countries, like Egypt, Israel, Japan, and Korea,[648] and a commitment to "ensure that gas supplies from existing and new gas suppliers are coupled with targeted actions to tackle methane leaks and to address venting and flaring."[649] The European Union has since signed memoranda of understanding on energy cooperation with Israel, Egypt, and Azerbaijan, aimed "enabling a stable delivery of natural gas to the EU that is consistent with long-term decarbonization objectives and is based on the principle of market-oriented pricing."[650] The European Union does not yet specify any intent to promulgate regulations to control methane emissions from energy imports, but will increase support to develop a global hydrogen market, beginning with partnerships with "reliable partner countries to ensure open and undistorted trade and investment relations for renewable and low carbon fuels."[651] Further, it will prioritize energy savings and energy efficiency to achieve its target of 5% reduction in short-term demand for oil and gas.[652] The European Union has also committed to a Memorandum of Understanding alongside Egypt and Israel, in which it pledged to promote the reduction of methane leakages, and in particular examine new technologies for reducing venting and flaring and explore possibilities for the utilization of captured methane throughout the entire supply chain.[653]

In a Joint Statement released by the EU and U.S. in April 2023 following a meeting of the EU-U.S. Energy Council, the Council confirmed their intention to continue advancing the reduction of global methane emissions.[654] The Council stated that they intend to promote domestic and international measures for reinforced monitoring, reporting, and verification, as well as transparency, for methane emissions data in the fossil energy sector, such as through the Oil and Gas Methane Partnership 2.0 (OGMP 2.0) standard (*see* **Section 7**) and the development of a common tool for life cycle analysis (LCA) of methane emissions for hydrocarbon suppliers and purchasers.[655]

Box 5. Risks and limited climate benefits from switch to hydrogen

Hydrogen is being proposed as a clean energy alternative, especially for hard-to-decarbonize sectors like heavy industry, shipping, and aviation. The climate benefits of hydrogen as a replacement for fossil fuels depends on several factors: 1) the source of the energy used to generate the hydrogen and its emissions and extent of carbon capture in the case of "blue hydrogen" (natural gas with carbon capture); 2) leakage rate of methane if used as the source of hydrogen or energy source, with even low methane leakage rates of about 1% resulting in higher GHG emissions than burning natural gas for power;[656] and 3) the leakage rate of the hydrogen itself, which can contribute to warming by extending the lifetime of methane and other GHGs, significantly reducing the climate benefits of even "green hydrogen" (renewable-based electrolysis).[657] Similar concerns apply to net climate benefits of proposed "green e-methane" (synthetic methane produced from "green hydrogen" and captured CO_2).[658] Preliminary estimates suggest that a 10% leakage rate of hydrogen under a high deployment scenario could cause at least 0.1 °C of warming, potentially offsetting the avoided warming in 2050 from deploying all currently cost-effective methane mitigation options globally.[659] High hydrogen leakage combined with increasing methane emissions could add as much as 0.4 °C of warming.[660]

F. India

According to India's third Biennial Update Report (BUR) to the UNFCCC, methane accounted for 19.5 million tonnes (409 Mt CO_2e, using GWP_{100} of 21 per Indian reporting), or 14.43% of India's total GHG emissions in 2016.[661] The agriculture sector accounted for 73.96% of India's methane emissions (14.4 million tonnes), the waste sector 14.46% (2.8 million tonnes), the energy sector 10.62% (2.0 million tonnes), and industrial processes and product uses accounted for 0.96% (0.1 million tonnes).[662]

India is working to cut methane emissions across key sectors, particularly in the agriculture sector. Two methods of rice cultivation in India aim to reduce water usage and methane emissions: the system of rice intensification and direct-seeded rice. The system of rice intensification is being used in 24 of India's 28 states,[663] and cultivation using the direct-seeded rice method is being deployed in India on nearly 100,000 hectares of land.[664] India also is shifting land used for paddy crops to other crops that require less water and thus enable reductions of methane emissions.[665] Furthermore, India is implementing methods, including feed additives, that increase productivity of milk-producing animals and reduce GHG emissions.[666]

India's strategy to reduce methane emissions from the energy sector appears focused on transitioning to renewable energy and improving energy efficiency.[667] Under the 2022 *U.S.-India Strategic Clean Energy Partnership*, the U.S. and India agree to abate methane emissions from oil and gas, and specifically in India's city gas distribution sector, through the public-private U.S.-India Low Emissions Gas Task Force.[668] The Low Emissions Gas Task Force is led by the U.S. Department of Energy and the Indian Ministry of Petroleum and Natural Gas,[669] and aims to implement best practices for natural gas development as India strives to achieve its goal of increasing the share of natural gas in the primary energy supply to 15% by 2030.[670]

India has also launched a pair of biogas programs, called Galvanising Organic Bio-Agro Resources (Gobar-Dhan) and the New National Biogas and Organic Manure Programme.[671] Prime Minister Narendra Modi launched the Global Biofuels Alliance (GBA) on the sidelines of the G20 Summit in New Delhi in September 2023, aiming to bring together the biggest consumers and producers of biofuels as a key to energy transition.[672] Such biorefinery programs may address challenges of waste disposal and fertilizer shortages aligned to the structure of farms in India.[673]

In addition to methane from oil and gas, India is working to reduce methane from coal. India's coalbed methane amount is estimated to be 91.8 trillion cubic feet spread over 11 states.[674] Further, India identified 233.30 trillion cubic feet of shale gas and oil, the commercialization of which can dramatically increase methane emissions.[675]

The Government of India formulated its Coal Bed Methane (CBM) policy in July 1997 to harness CBM potential in the country and reduce methane emissions from coal mining. Through this policy, CBM is converted to natural gas under the provisions of the Ministry of Petroleum and Natural Gas 1948 Oil Fields (Regulation & Development) Act and the 1959 Petroleum and Natural Gas Rules.[676] To harness CBM potential, coalbed methane-producing blocks have been offered to companies through competitive bidding. Thus far, India awarded 30 CBM blocks under four rounds of bidding to national, private, and joint venture companies.[677]

India reported 17 Mt CO_2e of fugitive emissions from coal mining and post-mining operations as of 2016 in its Third Biennial Update Report to the UNFCCC (2021 BUR).[678] The U.S. EPA used India's 2016 emissions data to project 22 Mt CO_2e of Indian coal mine methane emissions annually at 2020, and 48 Mt CO_2e of such emissions at 2050.[679] According to the 2021 BUR, fugitive methane emissions dropped 2 percent between 2014 and 2016, "mainly due to a relative reduction in underground mining activities."[680] The 2021 BUR estimates that, between 2014 and 2016, methane emissions from surface mining increased 7 percent, whereas emissions from underground mining decreased by 3 percent. India's data on fugitive methane emissions is based on country-specific emissions factors on file at the IPCC Emission Factor Database.[681]

The 2021 BUR further mentions that "the upcoming projects of [CBM] extraction will also reduce the liberation of methane into the atmosphere during coal mining, which will be taken up in future."[682] Furthermore, Coal India Limited, the largest coal-mining company in India and the world, refers in its 2020-2021 environmental, social, and governance (ESG) report to three "clean coal" strategies: coal mine methane, coalbed methane, and coal-to-liquid (coal liquefaction) technology.[683]

Planned coal mine methane and coalbed methane exchanges, training, and projects are aimed at further reducing methane.[684]A pre-drainage project is under development at one underground mine,[685] and studies have been conducted to determine the feasibility of additional coal mine methane abatement projects.[686] Despite these efforts to reduce coal bed methane, India announced the auction of 67 new coal mines in 2021,[687] with an estimated 36 billion tons of coal.[688] These blocks represent fewer than a third of the 214 that the Ministry of Coal is statutorily obligated to develop.

Other methane reduction policies include comprehensive waste management. There are various policies in India, including the National Action Plan on Climate Change,[689] Swachh Bharat

Mission,[690] Solid Waste Management Rules 2016,[691] and National Clean Air Program,[692] that play a role in reducing methane emissions from the waste sector through climate change adaptation and mitigation, universal sanitation coverage, and segregation and minimization of waste. Although these policies do not explicitly address methane, they include goals such as making urban areas garbage-free,[693] segregating waste at source,[694] and capturing GHGs at landfills—each of which are directly or indirectly reducing methane emissions.[695] Moreover, Swachh Bharat Mission 2.0 has been instrumental in promoting scientific treatment of all the fractions of municipal solid waste and remediation of existing dumpsites.[696] More than 87 million tonnes of waste has been remediated all over the country, reclaiming 3,440 acres of land.[697]

In May 2022, the Indian government made an announcement that may have implications for enhanced methane mitigation, given the critical role of methane mitigation in meeting the goals of the Paris Agreement.[698] This announcement was that three ministry-level authorities—the Ministry of Earth Sciences, the Department of Science and Technology, and the Ministry of Environment, Forest and Climate Change—will form a consortium to "work cohesively towards climate action and towards realizing India's Nationally Determined Contributions under the Paris Agreement."[699]

According to Schedule 7 of the Indian Constitution,[700] India is a quasi-federal nation, meaning that ultimately all the commitments made by the Government of India on the international stage have to be implemented by the Indian states. In 2009, the Government of India directed all state governments and union territories to prepare State Action Plans on Climate Change, consistent with the strategy outlined in the 2008 National Action Plan on Climate Change.[701] All States have since prepared State Action Plans on Climate Change, and some have published multiple iterations. While most states have identified methane as a more potent gas than carbon dioxide, a few have included strategies to reduce methane emissions in their State Action Plans. Haryana,[702] Goa,[703] Odisha[704] and Jammu & Kashmir have included methane reduction strategies as part of their state plans in the agricultural sector.[705] The states of Kerala,[706] Karnataka[707] and Rajasthan have additionally identified strategies to improve methane emissions from livestock, agriculture and landfills.[708] In addition to the State Action Plans, States' Vision 2047 policies guide their overall policy development towards 2047, the centennial of Indian independence. Punjab's 2047 vision document recommends a dual strategy focusing on CO_2 and SLCP reduction measures across highest emitting sectors.[709] These include strategies for SLCP emissions reduction in rice cultivation and biomass burning in the agricultural sector, manure management and enteric emissions in industries, solid waste from landfill sites and wastewater in the waste sector, specifically for methane.

G. Iraq

Iraq's oil and gas sector is a large contributor of methane emissions, amounting to approximately 9% of global methane emissions from the sector in 2019.[710] Iraq has also been among the top 9 flaring countries for the last 10 years.[711]

In 2020, Iraq announced that its Ministry of Health and Ministry of Environment and Oil will establish an inter-ministerial technical task force to focus on the nature and scale of methane emissions from the country's oil and gas sector.[712] Since then, Iraq has included methane in its NDC submission, joined the CCAC's Oil and Gas Methane Partnership, and became a signatory to the GMP.[713] In 2022, Iraq's Ministry of Environment announced that they are working with the World Bank's Global Gas Flaring Reduction Partnership to develop its roadmap with a target of zero flaring in oil and gas production by 2030.[714] The Iraqi government reportedly introduced a new law in October 2022 to encourage investment in producing electricity from methane gas generated by solid waste.[715]

In February 2023, diplomats from the U.S. and Canada expressed their interest in assisting Iraq with reducing flaring.[716] They expressed a commitment from the U.S. and Canada to investing in gas capture technology, to boost power production and reduce the adverse health implications of the methane emissions.[717]

In a statement at COP28 to S&P Global Commodity Insights, Abdulbaqi Alsalait, energy adviser to the Iraq Ministry of Oil, indicated that Iraq is focused on eliminating gas flaring by 2028 and reducing methane output by 30% by 2030.[718] Alsalait also stated that it is "impossible" for Iraq to eliminate methane output by 2030 and that Iraq was opposed to a phaseout or phasedown of fossil fuels.[719]

H. Mexico

In addition to the methane targets arising from the 2016 North American Climate, Clean Energy, and Environment Partnership, in 2018, Mexico published comprehensive regulations for methane emissions reductions in the oil and gas sector that acknowledge the potential to reduce emissions in the sector by up to 75% by 2025.[720] These regulations include standards for quarterly leak detection and repair, the use of vapor-recovery systems to capture gas, the move to low- and zero-bleed pneumatics, and less-wasteful practices.

Mexico also joined the Global Methane Pledge and participates in the Global Methane Pledge Energy Pathway.[721] In July 2022, President Lopez Obrador agreed with U.S. president Joe Biden to cooperate with Mexico's national oil company, Petróleos Mexicanos (PEMEX), to eliminate routine flaring and venting.[722] In January 2023, however, PEMEX was identified as lagging behind its obligations to identify, report, and mitigate methane emissions from its installations.[723]

Mexico's most recent NDC under the Paris Agreement include goals to capture and manage biogas from livestock waste, and to improve waste management to reduce methane emissions.[724] The NDC also mentions intent to develop a Gas Exploitation Strategy, which will include using 98% of fugitive methane gas in new and existing oil and gas fields.[725] These goals are part of Mexico's commitment to reduce GHG emissions by at least 35% and up to 75% below projected business-as-usual scenario by 2030.[726]

A priority for methane reductions in Mexico is to improve methane monitoring for accurate emissions reporting. For example, recent satellite-based measurements found 45% higher emissions from anthropogenic sources than estimated in the national GHG inventory, with the largest discrepancy between inferred and estimated emissions coming from the oil and gas sector.[727] A separate Environmental Defense Fund (EDF)-led study found that for onshore processing facilities, methane leaks were 10 times higher than reported, while offshore processing facilities had emissions that were 90 percent lower than reported. According to EDF, this finding suggests that the offshore gas was piped inland, where it later would be flared or leaked. Emissions from a single facility that received offshore gas were found to emit the equivalent of half of Mexico's residential gas consumption.[728]

President Andrés Manuel López Obrador and other Mexican officials met with Special Presential Envoy for Climate John Kerry on 9 February 2022 to continue the U.S.-Mexico dialogue on climate collaboration and clean energy action. During this visit, the two sides agreed that the policy focus of their actions "will include tackling methane emissions from oil and gas, waste, and agriculture," among other areas.[729] In June 2022, President López Obrador announced that PEMEX will be spending $2 billion to lower its methane emissions by up to 98%.[730] The following month, the U.S. and Mexico committed to "tackle methane emissions from oil and gas and other sectors," and for the U.S. to cooperate with Mexico and PEMEX on a plan to eliminate routine flaring and venting.[731] Satellites recently detected large methane plumes from an offshore oil platform in one of Mexico's major oil-producing fields, highlighting the urgency of tackling these emissions.[732]

I. Nigeria

Nigeria is at the forefront of countries experiencing climate change, as it has been for more than 50 years.[733] Nigeria's ongoing and increasing climate crisis is prominently reflected in the farmer-herder crisis resulting in huge loss of lives and livelihoods across the country. For example, Nigeria's development and adoption of a national strategy for transforming the Nigeria livestock sub-sector to address the impacts of climate change resulting in the migration of herders induced desertification of the north of the country, which led to conflicts with farmers and deadly violence.[734] It is appropriate, then, that Nigeria became the first African country to regulate methane emissions in its energy sector.[735]At the same time, Nigeria—together with Sudan, the Democratic Republic of Congo, and Egypt—contribute to half of the African continent's total methane emissions.[736]

Nigeria has made broad progress beyond security and economic programs to respond to international climate mitigation agreements and policies. For instance, to fulfill its responsibilities under the UNFCCC and its Kyoto Protocol and Paris Agreement, Nigeria enacted the national Climate Change Act in 2021[737] to help drive responses to the need for climate change adaptation and mitigation, including cutting methane.[738]

During the period leading up to and following the passage of the National Climate Change Act, efforts were made at formulating climate-related policies and plans, including those relevant to cutting climate super pollutants such as methane. These include the 2017 National Gas Policy,[739] 2018 National Action Plan to Reduce Short-Lived Climate Pollutants,[740] National Climate Change Policy 2021–2030,[741] and the 2050 Long-Term Vision for Nigeria.[742]

Key sector-specific legal measures that are in progress, or that have been issued and are important for assessment of methane-reduction activities, include:

- 2004 Associated Gas Re-injection Act ("AGRA");[743]
- 2016 Nigerian Gas Flare Commercialization Program ("NGFCP");[744]

- 2023 Gas Flaring, Venting and Methane Emissions (Prevention of Waste and Pollution) Regulations;[745]
- 2023 Midstream Gas Flare Regulations;[746]
- 2021 Petroleum Industry Act;[747]
- 2020 Gas Flaring (Prohibition and Punishment) Bill (draft, which has recently passed through its second reading in the Nigerian Senate);[748] *and*
- 2022 Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria.[749]

The World Bank 2022 Global Gas Flaring Tracker Report indicated that of the top 10 flaring countries, seven of the countries have held the top 10 position consistently for the previous decade, including Nigeria.[750] Nevertheless, this report also noted that Nigeria reduced its flaring, a major source of methane contribution to the planet, by 31% between 2012 and 2021, placing Nigeria in the "promising reduction" category.[751]

Nigeria has been a CCAC partner since 2012.[752] It was one of the original 31 countries that joined the GMP in 2021.[753] Largely in response to their partnership with the CCAC, Nigeria developed its National Action Plan to Reduce Short-Lived Climate Pollutants, which includes the incorporation of targets for the oil and gas sector to eliminate 100% of routine gas flaring by 2020,[754] control fugitive methane emissions and leakage by 50%, and reduce methane leakage by 50%, by 2030.[755] Targets for the waste sector include recovering 50% of methane from landfills by 2030 and achieving a 50% reduction in open burning of waste by 2030. For the agriculture sector, the Plan contains targets such as achieving a 30% reduction in methane emissions intensity from enteric fermentation by 2030.

However, while Nigeria did reduce its flaring emissions by 70% between 2000 and 2020, it did not achieve its target of an overall 100% reduction in flaring.[756] In August 2022, Nigeria launched its Energy Transition Plan outlining its plan to achieve net zero emissions by 2060.[757] This plan focused on reducing emissions across five prominent areas: power, cooking, oil and gas, transport and industry.[758] It aims to achieve a 100% reduction of flaring emissions by 2030.[759]

At COP27, Nigeria announced new Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations. The Guidelines established Nigeria's place as the first African country to regulate methane emissions in the energy sector, and contained revised targets for elimination of routine gas flaring (100% of gas flaring eliminated by 2030) and control of fugitive emissions and leakages (60% methane reduction by 2030).[760] Notably, these targets are subject to the Petroleum Industry Act (also mentioned above), which provides exemptions in Section 104 and 107 (e.g., for emergencies, exemptions granted by Commission, acceptable safety practice under established regulations, and where Commission or Authority grants permit to licensee or lessee to allow flaring or venting of natural gas for a specific period where required for facility start-up or for strategic operational reasons, including testing). It should be noted that Nigeria has repeatedly revised its flaring elimination targets shifting them first in 2004, then in 2008, then in 2012, and now in 2020.[761] Achieving the flaring target will thus require greater action on behalf of the government to ensure that this is the final time that the target needs to be revised.[762]

Nigeria's methane mitigation ambition also figures prominently in its NDCs. Zero gas flaring by 2030 is included in Nigeria's 2021 update to its NDC.[763] The updated NDC integrates measures from Nigeria's National Action Plan to Reduce Short-Lived Climate Pollutants aiming to reduce black carbon, methane, and hydrofluorocarbon emissions by 42%, 28% and 2%, respectively, by 2030 compared to a baseline scenario.[764]

At COP28, Nigeria showcased major steps taken this year under the Nigeria Gas Flare Commercialization Program, including advancing projects it estimates will capture over half of all gas flaring volumes in Nigeria.[765]

In January 2024, the Nigerian Upstream Petroleum Regulatory Commission announced that it had entered a partnership with the Climate & Clean Air Coalition.[766] This collaboration will encompass a multifaceted approach, including knowledge sharing, technological support, and joint research efforts aimed at devising effective methane mitigation strategies.[767]

While it remains to be seen if Nigeria will meet all its targets, including those in its NDCs, Nigeria's ambition, provided it accompanies its targets with the implementation of best practices, is helpful to other developing countries seeking leadership models and inspiration from an African methane mitigation champion.

J. United Kingdom

Methane emissions make up 13% of the United Kingdom's total greenhouse gas emissions.[768] The majority of methane emissions in the United Kingdom stem from agriculture (53%), waste (32%), and the energy sector (15%).[769]

The United Kingdom was one of the first countries to sign the GMP.[770] The United Kingdom is also a state partner of the CCAC, and a member of the Oil and Gas Methane Partnership Steering Group.[771] It has also committed to the World Bank's Zero Routine Flaring by 2030 initiative.[772] The UK government has aligned domestic policy with the Global Methane Pledge target of a 30% reduction in methane by 2030,[773] and has not set a higher or stricter target.

In the six years from 2015 to 2021, methane emissions have fallen by an average of 1.5% per year.[774] According to the Climate Change Committee, an independent non-departmental public body formed under the Climate Change Act 2008, this reduction will need to accelerate to 4% per year if the United Kingdom is to achieve the target of a 30% reduction by 2030.[775] However, in 2023, a study from researchers at Princeton University and Colorado State University found that the current method for estimating methane emissions from offshore oil and gas production in the United Kingdom systematically and severely underestimate methane emissions.[776] The study finds that about five times more methane is being emitted from UK oil and gas production than what the government has reported.[777] This may mean that existing figures, estimates, and policies need to be revised and reconsidered.

In 2022, the UK government published a Methane Memorandum, which outlined how the 1.5% annual reduction in methane emissions had been achieved.[778] In March 2023, the UK government published its Carbon Budget Delivery Plan, which outlined in further detail, current and future policies for additional reductions in greenhouse gas emissions, including methane.[779]

In the energy sector, the UK government has adopted an Iron Mains Risk Reduction Programme (IMRRP), which is a plan to upgrade the gas network from iron pipes to plastic pipes.[780] This reduces leakages of methane where the pipes have been changed.[781] In 2021, the North Sea Transition Authority, which regulates flaring and venting for UK energy operators, laid out new guidelines for flaring and venting to align with the UK's wider Net Zero Strategy.[782] These new guidelines stipulate that all operators should have, or work towards, credible plans to achieve zero routine flaring and venting by 2030 or sooner,[783] and that all new all new developments should be planned and developed on the basis of zero routine flaring and venting.[784] The government has stated that it will not accelerate the end to routine flaring from 2030 to 2025, citing the difficulty with the cost and technological associated with a quicker end to flaring, as well as the "maturity" of the North Sea basin.[785]

For the waste sector, a landfill tax has been in place since October 1996 and is levied on disposal of waste in landfills, with very limited exemptions.[786] The UK government has indicated that additional policies will be needed to meet the aim of preventing biodegradable waste from going to landfill, still the largest source of emissions in the sector.[787] Some of these proposed policies involve further R&D to refine emissions estimates,[788] to explore further methane gas capture from landfill, and new collection and packaging reforms to support the reduction of biodegradable municipal waste going to landfills.[789]

For the agriculture sector, proposals have been announced to increase the use of robust Monitoring, Reporting and Verification (MRV) of GHG emissions,[790] to burn methane emitted generated during storage of liquid manure to convert it to carbon dioxide,[791] and the feeding of insect protein to animals to reduce overall global emissions from feed production.[792] There are additional plans to mandate retrofitting slurry tanks with a permeable or impermeable cover,[793] to employ genetic testing to improve livestock breeding goals and deliver permanent low emissions traits,[794] and to encourage the use of methane suppressing feed products to reduce methane emissions from livestock.[795]

In a parliamentary report prepared by the Climate Change Committee, the UK government was criticized for a "weak" contribution to progress on the Global Methane Pledge.[796] The report further noted that "the Government has not set out a UK-specific 30% reduction on 2020 levels by 2030 commitment to support the Global Methane Pledge and the Methane Memorandum brought forward high-level intentions rather than detailed plans for sectoral reductions."[797] Under current plans, it is unlikely to meet its commitments under the Global Methane Pledge.[798]

The parliamentary report lays out a series of recommendations to ensure that the UK meets its international commitments. These recommendations include:

- Set out plans for reducing domestic methane emissions in line with the collective aims of the GMP and announce an intention to set a longer-term pathway for these emissions.[799]
- Strengthen and bring forward targets for methane flaring and venting. For all facilities that will remain in operation post 2030, flaring and venting should only be permitted beyond 2025 when necessary for safety reasons.[800]
- Introduce regulations under the Clean Air Strategy to reduce enteric methane emissions, specifically under environmental permitting to the dairy and intensive beef sector.[801]

- Set out how methane capture and oxidization rates at landfill sites will be improved.[802]

In December 2023, the UK government announced that it would implement a carbon pricing mechanism by 2027.[803] Similar to the EU CBAM, goods imported into the UK from countries with a lower or no carbon price will have to pay a levy by 2027, ensuring products from overseas face a comparable carbon price to those produced in the UK.[804] As of now, the proposed mechanism makes no mention of methane, but, similar to the EU border adjustment mechanisms, it may evolve in time to apply a similar methane fee.[805]

K. United States

The U.S. has set a target of reaching net-zero GHG emissions by no later than 2050, with an interim target of reaching 50–52% reduction from 2005 levels of GHG emissions by 2030.[806] This section will first discuss domestic methane mitigation efforts before turning to the wider U.S. role in bilateral and multilateral methane commitments.

i. Domestic action

In November 2021, the White House published the *U.S. Methane Emissions Reduction Action Plan*, a whole-of-government initiative and model for taking a sectoral approach to reducing methane emissions.[807] The U.S. has subsequently introduced a number of leading domestic methane regulations and initiatives as well as having led on, or helped to develop, a number of bilateral and multilateral methane commitments. Key actions to implement the Action Plan's whole-of-government approach are described below.

On 31 January 2022, the Biden administration announced the next steps of the *U.S. Methane Emissions Reduction Action Plan*, starting with allocating $1.15 billion for states to clean up orphaned oil and gas wells.[808] The next steps include enforcing the Protecting Our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act to ensure that pipeline operators minimize methane leaks, emphasizing current research efforts and investments to reduce methane from cattle, and allocating $11.3 billion in funding for abandoned mine-land reclamation and $1 billion for natural gas pipeline modernization. As part of the Plan, the Biden administration announced the creation of an inter-agency group to coordinate methane measurement, monitoring, reporting and verification, and convened a workshop for energy communities on repurposing fossil fuel infrastructure.[809] Alongside the reduction in emissions that will come with these measures, a study from the BlueGreen Alliance has found that the full implementation of the new proposed regulations for oil and gas facilities could create over 136,000 jobs over the next 13 years.[810]

In July 2023, the White House convened the first-of-its-kind Methane Summit.[811] At the Summit, the White House announced that it was establishing a Cabinet-level Methane Task Force to advance a whole-of-government approach to proactive methane leak detection and data transparency, and to support state and local efforts to mitigate and enforce methane emissions regulations.[812] The Task Force is designed to accelerate the *U.S. Methane Emissions Reduction Action Plan*.[813] The White House also committed to leveraging domestic action to raise global ambition and to coordinate international efforts to mitigate methane emission.[814]

The passage in August 2022 of the Inflation Reduction Act (IRA) of 2022 is key to wider U.S. efforts on climate mitigation, including methane. The IRA contains nearly $370 billion in climate funding, including $1.55 billion to monitor and reduce emissions from oil and gas.[815] The legislation includes a Methane Emission Reduction Program with a methane waste fee (called the Waste Emissions Charge) of up to $1,500 per ton of methane by 2026,[816] and raises royalty fees for oil and gas extracted from federal lands and waters, including fees on gas avoidably lost by non-emergency flaring or venting.[817] In addition, the IRA will provide about $20 billion in agricultural conservation grants, which would prioritize climate issues including methane mitigation.[818] The IRA is estimated to reduce U.S. greenhouse gas emissions by 40% below 2005 levels by 2030.[819]

The Infrastructure and Investment Jobs Act enacted in November 2021 authorized the U.S. government to invest in methane mitigation solutions and distribute significant grants to bolster methane mitigation. The Act also includes an Orphaned Well Site Plugging, Remediation, and Restoration program, which authorizes over $4.5 billion in appropriations to plug, remediate, and reclaim orphaned wells.[820] Key rulemaking and other initiatives are described below.

a. Energy production sector

In November 2021, under § 111 of the Clean Air Act, the U.S. Environmental Protection Agency (EPA) proposed regulations for more stringent controls on emissions of methane and other air pollutants from new and existing oil and gas operations.[821] The proposal was subsequently updated to include more thorough life-cycle controls, tighter supervision of marginal wells, and a Super Emitter Response Program, among other measures.[822] The EPA estimates that for covered sources, the proposed rule would reduce emissions 87% below 2005 levels by 2030.[823] A finalized version of this rule was released at COP28.[824] Another proposed EPA rule under the Clean Air Act, released in May 2023, would strengthen requirements on fossil fuel-fired electric generating units.[825]

The EPA has taken several regulatory actions to align with the Clean Air Act regulations and to implement the Methane Emissions Reduction Program under the IRA.[826] The EPA issued a proposal in July 2023 to amend reporting requirements for petroleum and natural gas systems which will improve the accuracy of reported emissions of GHGs, including methane, consistent with the Methane Emissions Reduction Program under the IRA.[827] In January 2024, the EPA issued a proposed rule to implement the requirements of the Waste Emissions Charge discussed above. This proposed rule interacts with other methane policies under the Clean Air Act and would affect oil and gas operators and facilities that report more than 25,000 Mt CO_2e. The rule would impose and collect an annual charge on methane emissions that exceed specified waste emissions thresholds.[828] The current proposal would charge these operators $900 for every ton of methane emissions that exceed levels set by the federal government, beginning in 2024. The fee would increase to $1,200 in 2025 and $1,500 per ton in 2026.[829]

The EPA Office of Enforcement and Compliance Assurance (OECA) has announced six priority areas as National Enforcement and Compliance Initiatives for Fiscal Years 2024–2027.[830] One of these areas is mitigating climate change. As part of this, OECA has stated that they will use OECA's criminal and civil enforcement authorities to address three separate and significant contributors to climate change: (1) methane emissions from oil and gas facilities; (2) methane emissions from landfills; and (3) the use, importation, and production of hydrofluorocarbons (HFCs).[831] By focusing on enforcement of long-standing air pollution requirements, such as New Source Performance Standards at oil and gas facilities and landfills, OECA plans to achieve the ancillary benefit of reducing methane emissions.[832]

Other federal departments and agencies are undertaking regulatory action to mitigate methane across the energy production sector.

Under the Infrastructure and Investment Jobs Act, the Department of Energy will distribute almost $11 billion in Abandoned Land Mine grants to eligible states and tribes over 15 years.[833] States with unclaimed mines listed in the EPA's Methane Coal Mine Opportunities Database are encouraged to prioritize reclamation of said mines, eliminating methane emissions "to the greatest extent possible."[834] In August 2022, the Department of Energy announced up to $32 million in funding towards research and development of monitoring, measurement, and other mitigation technologies to detect and reduce methane emissions in the oil and gas sector.[835] In July 2023, the EPA and Department of Energy released a notice of intent announcing the upcoming availability of up to $350 million for mitigating methane emissions from marginal conventional wells.[836] In January 2024, the Department of Energy's loan office conditionally approved a $189 million loan to support the build-out of a methane monitoring network in key oil-producing basins that would provide real-time data for tens of thousands of oil and gas sites.[837]

As authorized by the Infrastructure and Investment Jobs Act, the Department of Agriculture is also investing $10 million in a Bioproduct Pilot Program to "advance development of cost-competitive bioproducts with environmental benefits compared to incumbent products,"[838] including products that have lower carbon footprints.[839]

The U.S. Bureau of Land Management, on 18 November 2023 published a proposed rule under the Mineral Leasing Act to extend royalty fees to avoidably vented, flared and leaked methane, and require operators to submit waste minimization plans.[840] The Bureau of Land Management estimates that the proposed rule could save $55 million a year in recovered gas, raise $39 million a year in fees, and provide $427 million a year in benefits to society from reduced emissions.[841]

The Department of Transportation is finalizing rules to reduce leaks throughout the gas pipeline system, and is working on a new proposed rule.[842] On 18 May 2023, the Pipeline and Hazardous Materials Safety Administration, a Department of Transportation agency, published a Notice of Proposed Rulemaking on pipeline safety which aims to reduce methane emissions from transmission pipelines, distribution pipelines, gas gathering pipelines, underground natural gas storage facilities, and liquefied natural gas facilities.[843] The proposed rule includes strengthened requirements on leakage survey, leak detection, leak grading and repair, blowdown emissions mitigation, and pipeline facility maintenance. The Pipeline and Hazardous Materials Safety Administration estimates the proposed rule would result in $341 to $1,440 million per year in net benefits.[844]

In the coal sector, the EPA documented 53 current coal-mine methane recovery projects and profiles project opportunities at other gas-emitting mines.[845] The EPA estimated in 2019 that recovery projects at some of the gassiest mines were capturing or oxidizing more than 700,000 tonnes of methane per year.[846] However, overall coal-mine methane production has halved since 2008, falling from approximately 57 bcm in 2008 to 22 bcm in 2021.[847]

While reports indicated that the Biden administration was approving more drilling permits on public lands than previous administrations,[848] in January 2024, the White House announced a temporary pause on pending approvals of Liquefied Natural Gas (LNG) exports until the Department of Energy can update the underlying analyses for authorizations.[849] As part of this update the Department of Energy must consider the impact on climate change, as well as the economy and national security of the U.S.[850]

The U.S. has also increased its funding for methane mitigation efforts from fossil fuels. On 2 December 2021, the Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) announced 12 selectees to receive a total of $35 million in grants to reduce methane emissions from the oil, gas, and coal sectors. These projects include research on reducing methane emissions from natural gas engines, gas flares, and coal mine shafts.[851] According to ARPA-E, these three sources contribute to at least 10% of U.S. anthropogenic methane emissions.[852] In developing the REMEDY (Reducing Emissions of Methane Every Day of the Year) program, ARPA-E recognized the need for further research on methane capture from the air in parallel with efforts to capture CO_2.[853] In July 2022, the CHIPS and Science Act doubled ARPA-E's budget[854] and expanded funding for climate and Earth systems research, including for a Center for Greenhouse Gas Measurements, Standards, and Information.[855]

b. Agriculture sector

There are a number of upcoming legislative bills and proposals with the potential to increase U.S. methane mitigation efforts in the agriculture sector. The upcoming 2023 Farm Bill may provide an additional opportunity for increased ambition in methane abatement projects through revised livestock management and crop production subsidies and incentives.[856] In the 2023 progress report towards the *U.S. Methane Emissions Reduction Action Plan*, the U.S. was confirmed to have achieved $500 million of methane agriculture finance through Partnerships for Climate-Smart Commodities,[857] and an annual $8 million in USDA's Agriculture Research Service methane research projects.[858] However, there has been some opposition to the use of spending bills to increase the obligation on the agricultural sector to report their methane emissions.[859]

c. Waste sector

The *U.S. Methane Emissions Reduction Action Plan* also includes regulations and programs to reduce methane from landfills and the waste sector.[860] The EPA is implementing updated emissions-reduction standards and requirements for municipal solid waste landfills (originally estimated to reduce methane emissions by over 300,000 metric tons of methane per year).[861] In January 2024, the U.S. Senate Committee on Environment & Public Lands conducted a hearing on landfill methane emissions and the Committee Chair called on the waste industry, White House, and federal agencies, including the EPA, to deploy "innovative methods" to address methane.[862]

The EPA is also tracking multiple other efforts to reduce methane, including livestock anaerobic-digester and landfill gas-capture projects.[863] In October 2023, the EPA released a report entitled *Quantifying Methane Emissions from Landfilled Food Waste*.[864] This report constituted the first peer-reviewed national reference point for the amount of methane emissions attributable to food waste in U.S. municipal solid waste landfills.[865] It found that while total emissions from municipal solid waste landfills are decreasing, methane emissions from landfilled food waste are increasing.[866] At COP28, the U.S. announced that the EPA is planning a rulemaking to review and, if appropriate, revise its Clean Air Act emission standards for new and existing municipal solid waste landfills, considering new monitoring technology, incentivization of organics waste diversion, and emissions controls at landfills not covered by current regulations. In 2024, EPA will release updates on emissions estimates for MSW landfills. In addition, the U.S. released for public comment a draft national strategy for Reducing Food Loss and Waste and Recycling Organics in line with its 2030 goal of 50% food loss and waste reduction.[867]

The EPA's 2024 review of the New Source Performance Standards and Emissions Guidelines for municipal solid waste landfills under the Clean Air Act provides an opportunity to include additional methane abatement measures.[868] Several groups have called for stronger standards and guidelines that include expansion and regulation of gas capture systems for smaller landfills, increased frequency of methane monitoring, and increased source reduction and waste diversion from landfills.[869] Some states have already begun including these recommendations into their regulations and guidelines,[870] or are planning to do so,[871] going beyond currently mandated U.S. EPA requirements.[872]

ii. Other initiatives and proposals

The U.S. federal government operates a host of voluntary initiatives that incentivize methane reductions and provide technical support to abate methane emissions. These include the Food Waste Challenge to reduce food waste by 50% by 2030 (supported by businesses and organizations across the food chain through the Food Loss and Waste 2030 Champions initiative),[873] the Landfill Methane Outreach Program that promotes the capture and use of landfill gas,[874] the Coalbed Methane Outreach Program that promotes the use of coal mine methane,[875] and the AgStar Program that aims to reduce methane emissions from livestock waste.[876] The U.S. Department of Agriculture also announced $3.1 billion in Partnerships for Climate-Smart Commodities funding to encourage implementation of climate-smart practices, including practices that mitigate methane emissions, such as manure management, feed management to reduce enteric emissions, and alternative wetting and drying of rice fields.[877] Several U.S.-funded programs were announced at COP27 to further livestock methane research and support projects that mitigate methane.[878] In 2023, the U.S. Department of Commerce released an open-access plain language handbook for policymakers on reducing methane from oil and gas operations, entitled *Methane Abatement for Oil and Gas – Handbook for Policymakers*. The Handbook is a starting point for understanding the policies, rules, and best practices that countries can adopt and implement to effectively abate methane when producing oil and gas.[879]

A wider focus on methane emissions has also been seen in the context of corporate disclosure. Rules proposed by the U.S. Securities and Exchange Commission would require publicly listed companies to disclose climate emissions and related risks, including those related to methane.[880] The U.S. oil and gas industry has also founded multiple voluntary initiatives related to methane emissions. The Environmental Partnership is an association of over 100 U.S. oil and natural gas companies designed to improve environmental performance through information-sharing, including best practices for LDAR, flaring, and other technologies.[881] The ONE Future Coalition is an association of more than 50 natural gas companies with the collective goal of reducing methane emissions across the natural gas value chain to 1% or less by 2025.[882] The Natural Gas Sustainability Initiative, launched by the Edison Electric Institute, American Gas Association, and other industry organizations, published a protocol for reporting methane emissions intensity.[883]

In August 2023, a bipartisan proposal called the Providing Reliable, Objective, Verifiable Emissions Intensity and Transparency (PROVE IT) Act was introduced to the U.S. Senate. The Act would direct the Department of Energy to conduct a comprehensive study comparing the emissions intensity of certain goods produced in the United States to the emissions of those same goods produced in the other countries.[884] If legislated, the PROVE IT Act would be the first U.S. effort to comprehensively assess the relative carbon efficiency of goods produced in the world's major economies. On 18 January 2024, the U.S. Senate Committee on Environment and Public Works passed the PROVE IT Act. It is anticipated that a companion Act will be introduced in the U.S. House of Representatives.[885]

In December 2023, Senator Sheldon Whitehouse introduced his Clean Competition Act bill with the support of House champions.[886] The Act would impose a carbon border adjustment charge based on carbon intensity.[887] While the Act is focused on carbon intensity, it opens the door for further consideration of whether a similar border adjustment charge could be applied to methane.

Box 6. Subnational governments demonstrating leadership on methane mitigation

U.S. states also are working to decrease methane emissions in the oil and gas sector. California set a legislative target to reduce methane emissions by 40% by 2030.[888] In 2014, Colorado approved the first methane regulations in the country, requiring energy companies to reduce methane emissions from both new and existing oil and natural gas facilities. Colorado continues to strengthen its oil and gas regulations, banning routine flaring and venting in 2020.[889] At the Summit of the Americas in June 2022, California unveiled the California Climate Commitment, which includes a budget proposal for remediating idle oil wells ($200 million) and launching methane-detecting satellites ($100 million).[890] In 2021, Colorado adopted standards to reduce methane emissions from pneumatic controllers.[891] New Mexico followed suit, issuing stringent regulations for the oil and gas sector, and also banning all routine flaring and venting. A more recent New Mexico rule is expected to reduce emissions still further. Most recently, the Colorado Air Quality Control Commission adopted a new rule requiring direct measurement of methane emissions, building on Colorado's 2021 standards.

Members of the U.S. Climate Alliance, which includes the governments of 23 states and Puerto Rico aim to reduce methane emissions across all sectors by 40–50% by 2030. This target includes reducing emissions from the energy sector by 40–45% by 2025, and from the waste sector by 40–50% by 2030. Members also plan to reduce methane emissions from the agricultural sector, including reducing emissions by 30% from enteric fermentation, and up to 70% from manure management, by 2030. Moreover, states and municipalities have enacted policies that ban or divert organic waste from landfills and aim to reduce food waste. There has been some backlash to state initiatives, with the state of New York facing a lawsuit for its decision to ban natural gas stoves from 2026.[892]

U.S. states are also leading outreach to other states serve as models for methane and other climate actions. For example, the California-China Climate Institute has completed Memoranda of Understanding (MOU) with, Guangdong Province,[893] Hainan Province,[894] Jiangsu Province,[895] and the municipalities of Beijing[896] and Shanghai.[897] California also launched a Subnational Methane Action Coalition to empower subnational governments to progress toward their climate goals through methane mitigation in the energy, agricultural and waste sectors.[898]

Research and other institutions are also developing tools for subnational jurisdictions, such as sectoral protocol frameworks for methane emission reductions, that engage governments in actions such as inventories, baselines, target setting, policy implementation, and information sharing.[899]

iii. International action

The U.S., alongside the EU, led the development of the Global Methane Pledge.[900] The U.S. was also a leading convenor alongside China and the UAE of the *COP28 Summit on Methane*.[901] Further, the U.S. is a party to the Convention on Long-range Transboundary Air Pollution (LRTAP), which is examining the impacts of methane on ozone formation and is discussed further in **Section 10**.[902]

The North American Climate, Clean Energy, and Environment Partnership that the U.S., Canada, and Mexico created in 2016 has agreed to reduce methane emissions from the oil and gas sector by 40–45% by 2025.[903] Partners committed to develop and implement federal regulations to reduce emissions from existing new sources in the oil and gas sector, as well as national methane reduction strategies for key sectors as soon as possible, including for oil and gas, agriculture, and waste and food management.[904] *See* subsections above on Canada and Mexico actions to meet this target. In July 2022, the U.S. and Mexico committed together to "tackle methane emissions from oil and gas and other sectors."[905]

In response to the global energy impact of the ongoing Russian invasion of Ukraine, the White House agreed to aid the EU transition from dependence on Russian gas by attempting to ensure additional shipments of 15 bcm of liquefied natural gas in 2022, in addition to "maintaining an enabling regulatory environment" toward new LNG export capacities. However, it also agreed to "undertake efforts to reduce the greenhouse gas intensity of all new LNG infrastructure and associated pipelines."[906] The Federal Energy Regulatory Commission also rolled back a new policy on assessing the climate impact of pipeline emissions.[907] There is also concern about the methane emissions that will arise should the Biden administration continue to export LNG.[908] This highlights the importance of immediate action to require progressive reductions in methane emission rates from "replacement methane gas" provided in response to changes in countries' methane gas imports, keeping in mind GMP commitments.[909]

In May 2022, leaders from the U.S. and the Association of Southeast Asian Nations (ASEAN) agreed at the U.S.-ASEAN Special Summit in Washington, DC, to raise their collective ambition to, among other things, reduce methane emissions. The Fact Sheet for the Special Summit indicates:

> "The United States is committed to working with the nations of Southeast Asia to reduce the region's methane emissions. The United States welcomed Indonesia, Vietnam, Malaysia, the Philippines, and Singapore joining the GMP at COP-26, and we are accelerating technical assistance, financial resources, and project pipeline development for methane mitigation in GMP countries, including through the EPA, USTDA [U.S. Trade and Development Agency], DFC [Development Finance Corporation], and EXIM [Export-Import Bank], as well as the newly-created Global Methane Hub, a philanthropic fund that can support methane mitigation priorities in the region."[910]

The U.S. also has collaborative arrangements with Brazil on energy. The U.S.-Brazil Energy Forum is a mechanism for the two governments to exchange technical, regulatory, and policy expertise, including carbon and methane management.[911] In August 2022, the U.S. and Brazil launched the Clean Energy Industry Dialogue, a bilateral forum led by the private sector and industry to promote clean energy, including offshore wind and clean hydrogen.[912] A discussion of these developments can also be found in **Section 6K.**

In April 2023, U.S. Secretary of State Anthony Blinken met with the Foreign Minister of Turkmenistan. They stated their intentions for the U.S. and Turkmenistan to cooperate on deploying leak detection and repair solutions as well as developing a methane reduction investment plan in 2023 to control methane emissions in the oil and gas sector.[913] They also pledged to form a working group methane mitigation and will endeavor to feature methane mitigation outcomes by COP28.[914]

Also in April 2023, President Biden highlighted the need for a Methane Finance Sprint at the Major Economies Forum on Energy and Climate[915] and announced a $1 billion contribution to the UN's Green Climate Fund at the Forum (*see* **Section 11B**).[916]

In July 2023, U.S. Climate Envoy John Kerry visited China to advance climate cooperation. Kerry had previously indicated that methane was particularly important for cooperation.[917] At a subsequent bilateral meeting in November, the U.S. and China signed the *Sunnylands Statement*. The Statement stipulates, among other measures to cooperate to reduce methane emissions, that "the two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress."[918]

Additionally, in all methane-emitting sectors, the U.S. State Department, in partnership with U.S. Agency for International Development (USAID), has launched a new USAID Methane Accelerator program to mainstream and scale up methane abatement projects.[919]

7. International collaboration is critical for combatting methane emissions

Public and private organizations and initiatives around the world, such as those described briefly below, are collaborating on methane mitigation. Their collaboration is critical to strengthening the consensus that supports methane action, including at the bilateral and multilateral levels. Initiatives that rate methane performance may be an increasingly important part of this collaboration as the world re-aligns around changes in global gas supply and focuses on assessing the methane intensity of available gas volumes and associated producer performance.[920]

A. Governmental and Quasi-governmental organizations and initiatives

i. Agriculture Innovation Mission for Climate

The Agriculture Innovation Mission for Climate (AIM4C), co-created by the U.S. and UAE, is an initiative to increase funding and participation in climate-smart agriculture and food system innovation from 2021–2025. AIM4C "innovation sprints" will guide participants to address specific goals using coordinated funding. Methane-related innovation sprints include: "Enteric Fermentation R+D Accelerator," "AgMission: Cultivating Climate-Smart Solutions," "Cellular Agriculture: Addressing Climate Change and Promoting Resilience in the Protein Sector," "Accelerating Sustainable Protein Innovation through Research," "Livestock, Climate and System Resilience," "Climate Smart Rice Technology Project," "Greener Cattle Initiative: Addressing Enteric Methane Emissions," and "Satellite monitoring of quantity and quality of available biomass in pastoral livestock systems."[921] Over 40 countries and nearly 300 organizations have partnered with this initiative.[922]

ii. Alliance of Champions for Food Systems Transformation

At COP28, Brazil, Norway, Sierra Leone, Cambodia, and Rwanda launched the Alliance of Champions for Food Systems Transformation. The Alliance aims to transform national food systems to deliver universal access to sustainable, affordable, and nutritious food and to achieve major progress across ten priority action areas this decade.[923] One of the priority action areas is reducing methane emissions from agriculture.[924] Each country is pledging to: strengthen national plans and food systems transformation pathways, including in the priority action areas and consistent with science-based targets; update NDCs, National Adaptation Plans, Long-Term Low Emission Development Strategies, and National Biodiversity Strategies and Action Plans in line with these national plans and pathways by 2025 at the latest; and report annually on targets and priority action areas.[925]

iii. ASEAN Energy Sector Methane Leadership Program

The ASEAN Energy Sector Methane Leadership Program, established in July 2023, is an 18-month initiative, delivered through masterclasses and workshops, which will focus on capability building to strengthen ASEAN energy companies' plans, targets, and financing options for reducing methane emissions.[926] The Program is launched as a collaboration between PETRONAS and ASEAN energy operators, governmental agencies, and international organizations.[927]

iv. The Breakthrough Agenda

Initially launched at COP26 by a coalition of 45 world leaders, the Breakthrough Agenda aims to halve global emissions by 2030 through a multi-country clean technology plan. Countries endorsed goals to make clean technologies and sustainable practices more affordable, accessible, and attractive than their alternatives by 2030 in the power, road transport, steel, hydrogen and agriculture sectors. At COP28, it was announced that the Breakthrough Agenda goals now also cover the buildings and cement sectors.[928] The Breakthrough Agenda has an annual cycle to track developments towards these goals, identify where further coordinated international action is needed to galvanize public and private international action to make these transitions quicker, cheaper, and easier.[929] At COP27, leaders set 28 priority actions within this framework and agreed to review and share progress and improvements on these actions. The 2023 Breakthrough Agenda report assessed annual progress on these priority actions and found only modest progress has been made in strengthening international collaboration in critical areas. The report's recommendations span financial assistance, research and development, demand-creation, infrastructure, and standards and trade, to accelerate the transition in each of the seven sectors.[930]

v. The Climate & Clean Air Coalition to Reduce Short-Lived Climate Pollutants

The CCAC facilitates methane mitigation and information sharing at all levels, including through publication of leading science. The CCAC is a voluntary partnership with over 80 State and regional partners, and a similar number of non-state partners as of the end of 2023.[931]

As of September 2023, the CCAC acts as the Secretariat for the Global Methane Pledge.[932] The CCAC assists countries with developing plans to reduce SLCPs.[933] The CCAC also helps countries increase the ambition of the SLCP-reduction targets that they include in their NDCs under the Paris Agreement. Increasing support and funding for the CCAC would strengthen information-sharing and technical support for countries leading to a concerted increase in ambition. This could include further ambition concerning methane reporting under the CCAC's Oil and Gas Methane Partnership, described in **Section 7B(ix)**. This could also include coordinating support for

"National Methane Offices," and other methane mitigation architecture, adopting the institutional strengthening approach that has been "a major factor in the success" of developing countries achieving Montreal Protocol objectives (*see* **Section 11**).[934] The November 2022 Ministerial communiqué raised the possibility of establishing a Technology and Economic Assessment Panel on Methane (since established),[935] to advise partners on "innovative methane mitigation technologies, including methane removal and sector-specific methane reduction technologies."[936]

In November 2021, the CCAC Ministerial launched the CCAC Methane Flagship, "which, starting in 2022, will foster and strengthen high level commitments to reduce methane, amplify and raise awareness, support planning and delivery of strategies and plans, provide analysis and tools to support action, and scale up financing."[937] The CCAC's efforts resulting in the *Global Methane Assessment* raised awareness of and brought political attention to the opportunities of methane abatement.[938] In addition to their work with the *Global Methane Assessment*, the CCAC's work with Shindell's group at Duke University resulted in a publicly accessible, online methane mitigation tool.[939] The CCAC plans to improve this tool to make it more user-friendly, including by continuously updating methane emissions and existing metrics for quantifying co-benefits. This will enable a national level overview of the relevant measures and related co-benefits, including job creation.

The CCAC is also planning to develop a *Global Methane Policy/Implementation Tracker* to record and quantify progress on the implementation of methane-related measures, policies, and regulations. In addition, the CCAC is hosting three hubs that will be working with governments and other stakeholders on agriculture, waste, and oil and gas. Notably, the UN Economic Commission for Europe (UNECE) joined the CCAC in 2015 with the aim of contributing to CCAC's work by sharing experience, knowledge, and best practices, including with respect to UNECE's amended Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) to LRTAP.[940] This relationship can help inform efforts to develop a binding global methane agreement to address climate emergency and promote peace and security. The LRTAP Convention and the Gothenburg Protocol are discussed further below in **Section 10**.

In September 2022, the CCAC and the Global Methane Initiative (GMI) convened a Global Methane, Climate and Clean Air Forum with the goal of bringing together policymakers, industry leaders, technical experts, and researchers from around the world.[941] Discussion included opportunities to protect the climate and improve air quality, with a special focus on methane, in all emitting sectors. Several announcements of new financing projects were made following this forum, which have been described throughout **Section 7**, **Section 10A**, and **Section 11**. Discussion highlighted the need for science-based fast climate action "given the narrow window to achieve the goals of the Paris Agreement on climate change,"[942] policy approaches that will catalyze adoption of mitigation technology, and financial support to make the necessary transitions.

In November 2022, the CCAC hosted a ministerial meeting at COP27 wherein ministers and leaders of CCAC partners reaffirmed and renewed their commitment to reduce methane and other SLCPs and to launch new collaborative actions to further drive emissions reductions.[943] The CCAC partners welcomed the possibility of exploring the formation of a Technology and Economic Assessment Panel on Methane to advise them on methane mitigation technologies[944] and requested the CCAC Scientific Advisory Panel to develop a proposal to highlight and better calculate near-term climate benefits of methane action.[945] The CCAC board has since approved the formation of a pilot Technology and Economic Assessment Panel (TEAP) on Methane to develop and share knowledge with countries about promising, innovative, and underfinanced SLCP mitigation strategies.[946] The TEAP launched its first report in November 2023.[947] The CCAC is also continually strengthening its Scientific Advisory Panel (SAP) to provide needed support, including on methane mitigation science.[948]

In October 2023, the CCAC co-released a report with the IEA on *The Imperative of Cutting Methane from Fossil Fuels*. The report outlined in detail the necessity of rapid cuts to methane from fossil fuels, as well as the benefits for health and climate of such reductions.[949]

In December 2023, the CCAC co-hosted the Global Methane Pledge Ministerial at COP28.[950] The Global Methane Pledge Ministerial, which showcased national actions and catalytic grant funding to deliver on the goal to cut methane at least 30% by 2030. Among the announcements made were over $1 billion in new grant funding for methane action mobilized since COP27, the full launch of the Methane Alert and Response System, a new Data for Methane Action Campaign, and a new platform to better track waste methane emissions in cities around the world. Also announced was the joining of Canada, Federated States of Micronesia, Germany, Japan, and Nigeria as Global Methane Pledge Champions, while Turkmenistan, Kazakhstan, Kenya, Kosovo, Romania, and Angola joined the Global Methane Pledge (*see* **Section 10** for further details).[951]

The CCAC also hosted the CCAC Ministerial at COP28, which focused on financing SLCPs as well as immediate action to reduce methane and other SCLPs. Ministers announced the pilot work of the new TEAP which highlights context-specific, practical mitigation measures aimed at closing finance gaps.[952] The ministerial meeting also announced that a global assessment on the cost of inaction on SLCPs and an assessment on the integrated agriculture and food systems will be prepared in advance of COP30.[953] Additionally, Ministers called for increased efforts to support highly vulnerable Small-Island Developing States (SIDS), especially in the context of rapid mitigation of methane and black carbon to slow sea level rise and increasing frequency and intensity of climate-exacerbated weather events.[954] Further contributions to the CCAC Trust Fund were announced from the European Commission, Finland, Germany, Ireland, Japan, Monaco, and Sweden amounting to an estimated $15 million (*see* **Section 10** for further details).[955]

The Lowering Organic Waste Methane (LOW-Methane) initiative was also launched at COP28. The ambition of LOW-Methane is to deliver at least 1 million metric tons of annual waste-sector methane reductions well before 2030 with 40 subnational jurisdictions and their national government counterparts, including by working to unlock over $10 billion in public and private investment. The consortium effort will be supported by a coordination group housed within the CCAC (*see* **Section 10** for further details).[956]

In addition, CCAC launched the CCAC Clean Air Flagship at COP28. The Flagship will bring more attention to the global air pollution crisis, highlight readily available solutions, elevate ongoing regional collaboration, amplify and strengthen multi-level government cooperation, and offer direct support to countries including through policy and integrated climate and clean air planning activities and sector specific action via CCAC Sector Hubs, and capacity support for integrated inventories, monitoring and air pollution modelling, and implementation of related priority measures and action plans.[957] The Flagship will support science cooperation and information-sharing initiatives, especially with respect to methane,[958] and strengthen and support regional and sub-regional cooperation, and the implementation of political commitments to achieve the WHO Air Quality Guidelines and GMP.[959]

vi. The Global Waste Initiative 50 by 2050

Egypt, which held the COP27 Presidency in 2022, launched the *Global Waste Initiative 50 by 2050* in November 2022. This initiative estimates that the waste sector contributes 20% of global methane emissions.[960] Methane emissions from landfilling of solid waste reached about 1.3 Mt CH_4 in 2010, which was projected to increase if waste management practices did not improve.[961] The Global Waste Initiative will develop a platform for partnerships and projects on mitigation and adaptation and support knowledge and innovation transfer of infrastructure for waste management.[962] The COP27 also hosted a session on creating a "Green Africa," including the goal of cutting waste by 50% in African countries.[963]

vii. International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP)

At COP28, the International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP) announced that it will, with funding from the U.S. State Department and Global Methane Hub, support 15 governments to incorporate agricultural methane into their nationally determined contributions and 10 governments to build investment pipelines in low-methane agricultural development.[964]

viii. International Working Group to Establish Universal Approach to Measuring, Monitoring, Reporting, and Verifying Greenhouse Gas Emissions Across the Natural Gas Supply Chain

At COP28, the U.S., the European Commission, and 12 other natural gas importing and exporting countries formed an international working group to advance comparable and reliable information about methane and CO_2 emissions across the natural gas supply chain to drive global emissions reductions.[965]

ix. United Arab Emirates Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action

At COP28, 159 countries signed the UAE's Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action. The Declaration affirmed that "agriculture and food systems must urgently adapt and transform in order to respond to the imperatives of climate change."[966] While there is no explicit mention of the need to reduce methane emissions from the agriculture sector, the signatories to the Declaration pledged to work collaboratively and expeditiously on a number of objectives including maximizing "the climate and environmental benefits - while containing and reducing harmful impacts - associated with agriculture and food systems by conserving, protecting and restoring land and natural ecosystems, enhancing soil health, and biodiversity, and shifting from higher GHG-emitting practices to more sustainable production and consumption approaches." Countries committed to report annually on their progress and increase finance to adapt and transform agriculture and food systems to address climate change.[967]

x. Net-Zero Producers Forum

In April 2021, Canada, Norway, Qatar, Saudi Arabia, and the United States announced their intention to establish the Net-Zero Producers Forum, which convened its first ministerial meeting in March 2022.[968] The Forum is designed to "develop pragmatic net-zero emission strategies, including methane abatement, advancing the circular carbon economy approach, development and deployment of clean-energy and carbon capture and storage technologies, diversification from reliance on hydrocarbon revenues, and other measures in line with each country's national circumstances."[969] In May 2022, the UAE joined as a member of the Forum.[970] At COP28, the Forum launched the Upstream Methane Abatement Toolkit.[971] The Upstream Methane Abatement Toolkit is a resource developed to highlight current measures and lessons learned regarding the implementation of methane abatement technologies.[972]

xi. World Bank Global Gas Flaring Reduction Partnership and Zero Flaring Initiative/Global Flaring and Methane Reduction (GFMR)

At COP28, the World Bank re-launched the Global Gas Flaring Reduction Partnership as the Global Flaring and Methane Reduction Partnership (GFMR), a new multi-donor trust fund focused on helping developing countries cut CO_2 and methane emissions from the oil and gas industry.[973]

Evolving from its predecessor, the Global Gas Flaring Reduction Partnership, GFMR develops country-specific flaring reduction programs, conducts research, shares best practices, raises awareness, and secures global commitments to end routine flaring, which results in methane emissions, and advances flare measurement and reporting.[974] Access to project development and financing support through the re-launched GFMR will be subject to a commitment to measure and report emissions through the Oil and Gas Methane Partnership 2.0 Framework, to achieve near-zero absolute methane emissions by 2030 by reducing methane intensity to below 0.2%, and to achieve zero routine flaring by 2030.[975] The GFMR has $255 million in new grant funding supported by financial contributions from the UAE, U.S., Norway, BP, ENI, Equinor, Occidental, Shell, and TotalEnergies.[976]

The GFMR also seeks commitments to the Zero Routine Flaring by 2030 Initiative. Governments and companies that participate in the World Bank Zero Routine Flaring Initiative commit to end routine flaring by 2030.[977] A wide range of stakeholders, including 34 governments, 54 oil and gas companies, and 15 development organizations, support the Zero Routine Flaring by 2030 Initiative.[978] The GFMR is developing a Global Gas Flaring Explorer, an online platform that will deliver real-time monitoring of gas flaring globally, in collaboration with the Oil and Gas Climate Initiative and the Payne Institute (Colorado School of Mines).

The 2022 Global Gas Flaring Tracker Report found that ten countries account for 75% of all gas flaring and 50% of global oil production: "Seven of the top 10 flaring countries have held this position consistently for the last 10 years: Russia, Iraq, Iran, the U.S., Venezuela, Algeria, and Nigeria. The remaining three (Mexico, Libya, and China) have shown significant flaring increases in recent years."[979]

xii. World Bank Global Methane Reduction Platform for Development (CH4D)

At COP28, the World Bank launched the Global Methane Reduction Platform for Development (CH4D) to support low-and mid-income countries to realize the "methane triple-wins" of abating emissions, enhancing resilience, and empowering livelihoods. Through partnerships, including with the CCAC Methane Roadmap Action Programme (M-RAP), CH4D will mobilize expertise, affordable technologies, and catalytic finance for methane abatement in the agriculture and waste sectors.[980]

B. Industry-led initiatives

i. American Petroleum Institute Methane Action Plan

In 2023, the American Petroleum Institute released its Methane Action Plan.[981] The Plan highlights the work done by the oil and gas industry's Environmental Partnership to reduce methane. The Environmental Partnership aims to reduce methane through the following actions:[982]

- Reducing flaring through facility design, takeaway capacity planning and alternative beneficial use.
- Replacing, removing or retrofitting high-bleed pneumatic controllers with low- or zero-emitting devices.
- Monitoring manual liquids unloading to minimize emissions by ensuring all wellhead vents are closed to the atmosphere.
- Minimizing compressor emissions by implementing design and operation changes.
- Detecting and repairing leaks through regular component inspections.
- Minimizing pipeline blowdown emissions through operational changes prioritizing alternative beneficial use of gas that would otherwise be vented.

ii. Coalition for LNG Emission Abatement Towards Net Zero (CLEAN)

In July 2023, the European Commission, alongside the U.S., Japan, South Korea, and Australia agreed to form a new monitoring mechanism for methane emissions from the LNG sector.[983] The Coalition for LNG Emission Abatement Towards Net Zero (CLEAN) was announced at a conference in Tokyo.[984] The Coalition of LNG buyers—including the Korean Gas Corporation (KOGAS) and JERA—will ask major LNG producers to provide basic data on emissions such as volume and intensity as well as reduction targets and measures being taken.[985] Participation will be voluntary and the results will be disclosed by the government-backed Japan Organization for Metals and Energy Security, known as Jogmec.[986]

iii. Dairy Methane Action Alliance

At COP28, a group of global food companies, led by the Bel Group, Danone, General Mills, Kraft Heinz, Lactalis USA, and Nestlé, was convened by the EDF to launch the Dairy Methane Action Alliance (DMAA).[987] Members of the DMAA commit to reporting their methane emissions by mid-2024 and producing methane action plans by the end of 2024.[988]

iv. Global Methane Initiative

The Global Methane Initiative (GMI) is a public-private partnership that covers the three major sectors (energy production, agriculture, and waste) and promotes methane capture and use.[989] GMI facilitates the international exchange of information and technical assistance. GMI includes 46 countries that represent around 75% of the world's anthropogenic methane emissions, including the U.S., Canada, Argentina, Brazil, Russia, China, India, and Australia.[990] GMI claims that its support has enabled partner countries to reduce methane emissions by more than 500 Mt CO_2e since 2004.[991]

v. Methane Abatement in Maritime Innovation Initiative (MAMII)

The Methane Abatement in Maritime Innovation Initiative (MAMII) was launched in September 2022 by a coalition of shipping leaders, aims to reduce the environmental impact of liquefied natural gas (LNG) in shipping, MAMII was formed to identify, accelerate, and advocate technology solutions for the maritime industry to measure and manage methane emissions activity.[992] Energy companies TotalEnergies and Chevron, and gas carrier Seapeak joined MAMII in February 2024. These three companies join the now more than 20 members of MAMII.[993]

vi. The Methane Guiding Principles

The 50 oil and gas industry signatories to the Methane Guiding Principles have committed to reporting publicly on how they are meeting the intent of five principles: including, continual reduction of methane emissions; improving the accuracy of emissions data; advocating sound policy and regulations on methane emissions, and increasing transparency.[994] The commitment to reducing methane emissions includes the implementation of LDAR programs and reduction of venting and fugitive emissions. The group also released a toolkit for policymakers.[995]

At COP28, along with the International Association of Oil and Gas Producers, the Oil and Gas Climate Initiative, and the Environmental Dense Fund, the Methane Guiding Principles announced an intention to build a framework to share expertise to help companies reduce methane emission and flaring in line with the Oil and Gas Decarbonization Charter (i.e. achieving near-zero methane emissions and eliminating routine flaring by 2030).[996] In addition, the Methane Guiding Principles launched the Advancing Global Methane Reductions initiative, which aims to accelerate 20 countries' methane emissions reductions.[997]

vii. Oil and Gas Climate Initiative

The Oil and Gas Climate Initiative (OGCI) is a CEO-led initiative in which member companies agree to several commitments and principles. In particular, OGCI members commit, by 2025, to a collective average methane intensity of aggregated upstream oil and gas operations of well below 0.20%, from a 2017 baseline of 0.30%. They also commit to reduce aggregate upstream carbon intensity from 23 kg of GHG per barrel of oil or gas in 2017 to 17 kg by 2025 and to support explicitly the aims of Zero Routine Flaring by 2030.[998] OGCI reported a collective methane intensity of 0.17% in 2021,[999] and in 2022 launched the Aiming for Zero Methane Emissions Initiative, with plans to eliminate the oil and gas industry's methane footprint by 2030.[1000] The Chair of the OGCI Executive Committee, Bjorn Otto Sverdrup, underscored the need for further action at Global Energy Transition in June 2023: "It's time to move beyond incremental improvement," Sverdrup said, pointing to "zero-tolerance" policies already in place for oil spills and safety incidents. "Let's try to deploy that mindset. All methane emissions can and should be avoided."[1001] OGCI, together with industry associations Ipieca and IOGP have released a recommended practices guide to help operators select and deploy methane detection and quantification technologies.[1002] At COP28, OGCI announced that it will be expanding its Satellite Monitoring Campaign to provide data to reduce emissions from large-scale methane plumes and flares, supported by in-kind contributions from OGCI companies.[1003]

viii. Oil and Gas Decarbonization Charter (OGDC)

At COP28, companies representing more than 40% of global oil companies signed on to a voluntary decarbonization initiative called the Oil and Gas Decarbonization Charter (OGDC). National Oil Companies represent over 60% of the signatories to the Charter.[1004] Signatories have pledged to reduce their emissions to be net-zero operations by 2050 at the latest, and to end routine flaring by 2030, as well as to achieve near-zero upstream methane emissions by 2030.[1005] The Charter has come under criticism from a number of NGOs for its failure to impose mandatory targets and standards on the oil and gas industry.[1006]

ix. Oil and Gas Methane Partnership

The Oil and Gas Methane Partnership (OGMP), a CCAC initiative (with UNEP, the European Commission, and EDF), advances methane emissions reporting, including through the OGMP 2.0 Reporting Framework. The Partnership now represents over 120 companies with assets in more than 60 countries on five continents and covers over 35% of the world's oil and gas production and over 70% of LNG flows.[1007]

The OGMP 2.0 Reporting Framework requires companies to report methane emissions from sources across the entire oil and gas value chain with a target to reduce emissions by 50–75% by 2030.[1008] OGMP 2.0 members are expected to provide continually updated implementation plans showing continuous improvement in measurement, coverage, and technical guidelines.[1009] The EU intends to build on this framework in developing its measurement, reporting, and verification requirements for the energy sector.[1010] To achieve the OGMP 2.0 Gold Standard (the highest possible standard under the framework) companies must demonstrate an explicit and credible path to required reporting levels within the required period.[1011]

x. The World Biogas Association

The World Biogas Association serves as a global trade association for biogas, landfill gas, and anaerobic digestion industry sectors.[1012] The Association provides members with publications such as a Global Biogas Industry Directory, data on the size and growth of global biogas markets, and analyses demonstrating the industry's environmental and economic potential.[1013] The Association convenes the World Biogas Summit, which in 2021 focused on methane mitigation.[1014]

At COP28, the World Biogas Association co-hosted side events on the role of the waste sector in delivering the Global Methane Pledge, including an event in partnership with the CCAC, the International Solid Waste Association, and IGSD.[1015]

C. Performance rating and certification initiatives

Increased attention to fugitive methane emissions from the oil and gas sector is driving interest in lower methane-intensity sources. This has prompted a rise in certification programs using a range of approaches that require scrutiny and the development of criteria for assessing credibility and a framework for improving the validation of methane intensity claims.[1016] It is useful to note that the Payne Institute for Public Policy (Colorado School of Mines) has published a glossary of terminology of oil and gas production operations to assist in promoting a common understanding and interpretation of terms.[1017]

i. MiQ, Veritas, Equitable Origin, Trustwell

RMI and SYSTEMIQ established MiQ, an independent not-for-profit organization. MiQ developed a certification system based on methane intensity that grades natural gas volumes produced and producer performance. MiQ indicates that it is the only major certification system based largely on bottom-line methane intensity, and estimates that it already certifies 4% of the global gas market.[1018] MiQ maintains a digital registry of these certificates to avoid double-counting.[1019] MiQ incorporates the Natural Gas Sustainability Initiative protocol or alternate "robust alternative methodologies" for calculating methane intensity.[1020] It requires monitoring at source and facility level, and it specifies frequencies and minimum detection levels for such monitoring, with grade increases linked to "more robust emissions management." Qualification for certification is based on methane intensity, company practices, and monitoring technology deployment, and methane intensity must be less than or equal to 2% to qualify.[1021] In June 2023, MIQ-Highwood released an index in the U.S. for integrating inventory and direct measurement data for national-level emissions intensity quantification.[1022]

Additional voluntary certification schemes have been developed by Veritas (led by GTI Energy), Equitable Origin,[1023] and Trustwell (by Project Canary).[1024]

ii. Natural Gas Sustainability Initiative (NGSI)

The Natural Gas Sustainability Initiative (NGSI) developed the NGSI Methane Emissions Intensity Protocol as a voluntary approach for companies to calculate methane emissions intensity.[1025]

iii. Project Canary

Project Canary is a company of scientists, engineers, financial analysts, and industry experts focused on measuring, analyzing, and visualizing corporate emissions profiles and environmental risk assessments, to provide auditable emissions data and information for gas and gas-source certifications, including the Trustwell Responsible Gas certification.[1026] Project Canary's emissions management program provides a platform for 24/7 real-time quantification and understanding of emissions data.[1027] For example, the Project Canary platform can "provide an inventory of emissions generated by all sources on a pad, from consistent flux of small emissions off tanks, to the larger discrete emissions events."[1028] Project Canary's environmental assessment program includes qualitative and quantitative Trustwell operational performance reviews of wellbores/facilities around the world.[1029] The environmental assessment program includes Colorado State University Center for Energy Water Sustainability-validated freshwater-use metrics, to enable certification of freshwater resource use as part of a responsibly sourced gas environmental social governance strategy.[1030] Further, the Project Canary SENSE platform combines data from all sensors, equipment, inventory, and emissions factors, using ML-based regression and Gaussian plume models to quantify total site operational and fugitive methane emissions.[1031] The Project Canary continuous emissions monitoring platform and technologies are being deployed around the world, including at Kellas Midstream, the "company responsible for transporting 40 percent of the UK's domestic gas production."[1032]

8. Monitoring, data, and measurement systems add transparency and accountability

Methane emissions are currently estimated based on a range of existing reporting regimes and protocols, including the UNFCCC, the Global Reporting Initiative (GRI), and national reporting programs. Increasingly sophisticated systems to measure and monitor methane emissions will add transparency and accountability to global methane reduction efforts. In particular, these systems will be essential to ensuring the world is on track to securing the 30% (or greater) reductions in methane emissions necessary to slow the world's near-term warming as called for in the GMP. Monitoring systems help provide critical information that the public can use to hold companies and countries accountable.[1033]

Monitoring systems include satellites, aircraft-based flyover technologies that are being deployed to identify more exact infrastructure emissions source points, and on-the-ground handheld infrared and other monitoring devices to pinpoint emitting machinery.[1034]

The rapid improvement in methane detection technologies and data analytics is fueling a boom in private monitoring and data analytics companies.[1035] Below is a non-comprehensive list of initiatives aimed at improving methane monitoring and accounting. These examples suggest how a combination of public and private monitoring services could provide a "system of systems" for companies, regulators, researchers,[1036] and citizens interested in tracking and mitigating methane emissions.[1037]

Methane measurement and monitoring initiatives include the following:

A. Carbon Mapper

In April 2021, Carbon Mapper, a philanthropically funded not-for-profit organization, announced a plan to launch a satellite constellation to pinpoint methane emissions, in partnership with the State of California, NASA's Jet Propulsion Laboratory, Planet, the University of Arizona, Arizona State University, High Tide Foundation, and RMI.[1038] The first two satellites are in development and will be launched in early 2024.[1039] Expansion to an operational multi-satellite constellation will start in 2025.[1040] Additionally, Carbon Mapper is developing a data portal in collaboration with California's Air Resources Board to make the data publicly available.[1041] In 2023, Carbon Mapper is conducting remote-sensing surveys of more than 1,000 managed landfills and open dumpsites across the U.S., Canada, and locations in Latin America, Africa, and Asia, with the intent to expand coverage in 2024 using satellites.[1042] At COP28, Carbon Mapper announced plans for new satellite launches in 2024.[1043]

B. Copernicus

Copernicus is the EU's Earth observation program that provides information services with data drawn from satellite observation and in-situ (non-space) systems.[1044] The European Commission manages Copernicus and implements the program in partnership with Member States, European agencies, and centers.[1045] In addition to collecting information from in-situ systems, the European Union will place a constellation of about 20 satellites in orbit before 2030.[1046] Among the six information services, the Copernicus Atmosphere Monitoring Service,[1047] the Copernicus Land Monitoring Service,[1048] and the Copernicus Climate Change Service[1049] are closely relevant to methane monitoring. All of these information services are open for free access.

C. Climate Trace

Climate TRACE is a non-profit coalition of organizations working together to create an inventory of greenhouse gas emissions.[1050] The inventory uses satellites, other remote sensing techniques, and artificial intelligence to deliver a detailed look at global emissions including methane.[1051]

D. Data to Methane Action Campaign

At COP28, the Global Methane Hub, in collaboration with IMEO and its partners, launched the Methane Action Campaign to comprehensively deliver increased funding to enable governments, businesses, and other actors to radically reduce methane emissions, including harmful leaks, and drive effective policy change through never-before-leveraged data. At COP28, the Global Methane Hub announced $10 million in seed funding toward the Campaign and a funding target of $300 million by COP29.[1052]

E. Earth Surface Mineral Dust Source

The National Aeronautics and Space Administration developed the Earth Surface Mineral Dust Source (EMIT) mission to map key minerals in deserts and advance understanding of the effect of airborne dust on climate but it also detects methane.[1053] EMIT's monitoring, which covers the oil and gas production, waste, and energy sectors, has the capability to detect far larger emissions than those measured by previous airborne surveys.[1054] Since being installed on the International Space Station in July 2022, EMIT identified more than 50 methane super-emitters in Central Asia, the Middle East, and the Southwestern U.S.[1055] As EMIT monitors areas that are also methane hotspots, it is expected to detect more super-emitters in the future.[1056] The capabilities of EMIT will be used to inform the design of higher-resolution instrumentation launched on two satellites in late 2023.[1057]

F. Environmental Defense Fund's MethaneSAT

The EDF's MethaneSAT program launched a new methane satellite on 4 March 2024 to provide regular monitoring of global oil and gas operations, including to identify emissions across large geographic areas and to measure emissions at predetermined locations.[1058]

G. GHGSat

GHGSat, a global emissions monitoring company, signed a memorandum of intent in 2019 with the Canadian Space Agency and the European Space Agency.[1059] GHGSat will be collaborating with the International Methane Emissions Observatory by providing free data on methane emissions from their satellites.[1060] On 4 May 2022, GHGSat shared its first findings using satellite technology of livestock methane emissions from a farm in Joaquin Valley, California.[1061] In August 2022, GHGSat detected emissions from landfills in Buenos Aires, Delhi, Lahore, and Mumbai, finding that landfills contribute 6–50% of reported city-level emissions.[1062] At COP28, GHGSat announced a strategic collaboration with Al Yah Satellite Communications Company (ADX: YAHSAT) and Abu Dhabi National Oil Company (ADNOC), aimed at reducing methane emissions from the global energy sector.[1063]

H. Greenhouse Gas Observing Satellite

The Japanese Ministry of Environment, National Institute for Environmental Studies, and the Japanese Aerospace Exploration Agency jointly manage the Greenhouse Gas Observing Satellite (GOSAT) program, consisting of two satellites that have already been launched (GOSAT ["Ibuki"] and GOSAT-2) and a third (Global Observing SATellite for Greenhouse gases and Water cycle "GOSAT-GW") that is scheduled to launch March 2024.[1064] The satellites are used for GHG emissions monitoring and meteorological studies.[1065]

I. International Energy Forum's Methane Initiative and Methane Measurement Methodology Project

The International Energy Forum (IEF)'s Methane Initiative will develop a methane emissions measurement methodology that can standardize data collection.[1066] IEF's Methane Measurement Methodology Project aims to assist IEF Member States in their development of credible methane reduction plans for the energy sector based on best available data for methane emissions.[1067]

J. International Methane Emissions Observatory

Launched on 31 October 2021 at the G20 Summit, the International Methane Emissions Observatory (IMEO) is a UNEP initiative with support from the European Commission and other governments that will integrate methane emission data from multiple sources into a coherent dataset that will describe the confidence in each data element.[1068] The IMEO will initially focus on the energy sector and later expand to waste and agriculture.[1069] Additionally, the IMEO will play an important role in implementing the GMP by helping countries prioritize actions and by monitoring commitments.[1070] UNEP hosts the IMEO, with public funding support of €100 million over five years (including funding from the European Commission as a founding member).[1071] IMEO will closely coordinate with the CCAC, among other organizations, including on incorporation and analysis of data from OGMP 2.0, mentioned in **Section 7**.[1072] The IMEO has published three annual reports, *An Eye on Methane*, which describe progress on OGMP 2.0 and remaining challenges in methane monitoring and measurement.[1073] In November 2022, UNEP and IMEO launched the Methane Alert and Response System (MARS) to enhance detection of methane super-emitters, alert relevant stakeholders, and support and track methane mitigation progress.[1074] MARS is supported with a data from various stakeholders including as an example, Karryos, a global technology company acting as a platform to access consolidated data from methane detecting satellites into one platform.[1075]

At COP28, results of the MARS pilot period went live, publicly sharing satellite data for notified emissions events.[1076] As a result of the work of the IMEO, a large methane leak in Argentina has been halted.[1077] IMEO is also supporting 34 new science studies to fill existing knowledge gaps about the location and magnitude of emissions, including the first scientific measurement campaigns in sub-Saharan Africa (Angola and Gabon) and the Middle East (Oman).[1078]

K. Oil and Climate Index Plus

Researchers from RMI, Stanford University, the University of Calgary, and Koomey Analytics developed the Oil and Climate Index Plus (OCI+) tool as a response to opaque, self-reporting of GHG emissions from the oil and gas sector.[1079] The OCI+ presents a full life-cycle assessment of GHG emissions for half of global oil and gas production. The OCI+ tool and the accompanying report conclude that significant fossil fuel emissions occur not only at the point of combustion but also at the wellhead, and during processing, refining, and transportation.[1080] The report also refers to cutting methane as "the highest priority for the oil and gas sector.[1081] OCI+ could be useful for financial institutions to inform near-term investment decisions that reduce methane in their energy portfolios.[1082]

L. U.S. Greenhouse Gas Center

The U.S. launched the Greenhouse Gas Center at COP28. The Center will serve as a hub for collaboration between agencies across the U.S. government as well as non-profit and private sector partners.[1083] Data, information, and computer models from observations from the International Space Station, various satellite and airborne missions, and ground stations are available online. The Center's data catalogue includes a curated collection of data sets that provide insights into greenhouse gas sources, sinks, emissions, and fluxes.[1084] Initial information in the Center's website is focused on estimates of greenhouse gas emissions from human activities, naturally occurring greenhouse gas sources and sinks on land and in the ocean, and large methane emission event identification and quantification, using aircraft and space-based data.[1085]

M. Veritas

GTI has created a series of protocols to ensure adequate assessment of methane from natural gas.[1086] The Veritas protocols provide a guiding framework for operators across the natural gas supply chain to use measurements to estimate their methane emissions. As part of protocol development, 14 operators from across the natural gas supply chain participated in pilot demonstrations of the protocols in 2022. These operators executed draft versions of the protocols to examine their expected emissions and deploy a variety of detection and quantification technologies, from handheld instruments to aircraft surveys.[1087]

N. Waste Methane Assessment Program

The Waste Methane Assessment Platform (WasteMAP), was created by the Rocky Mountain Institute and Clean Air Task Force, with funding from the Global Methane Hub, to improve waste methane emissions transparency, highlight mitigation opportunities and best practices to reduce solid waste methane emissions.[1088] WasteMAP consolidates modeled and reported waste data and methane emissions data from Carbon Mapper, Climate TRACE, EDGAR, RMI, SRON, UNFCCC, UN-Habitat, and the World Bank.[1089] A key feature of WasteMAP is the decision support tool (DST), which allows users to estimate baseline methane emissions from current waste management practices in a given city and project alternative methane emission scenarios with improved waste management practices.[1090]

9. Building an accountability and enforcement strategy using robust emissions monitoring systems

As discussed in **Section 8**, emissions monitoring systems add transparency and accountability to emissions reduction efforts. The technologies underpinning these systems are poised to revolutionize the information available by making once invisible emissions visible to the public, to regulatory agencies, and to owners and operators of methane sources across all sectors. These monitoring systems, when coupled with an accountability and enforcement strategy, will be essential to ensuring the world is on track to secure maximum reductions in methane emissions.

Effective accountability and response mechanisms to tackle emissions sources would include several components. At the most basic level, these include: 1) inventory by emissions total, sector, and location; 2) baseline emissions level by jurisdiction; 3) reduction goal by emissions total and sector; and 4) monitoring and reporting, providing for full transparency. In addition, these components include the abilities: 1) to identify and alert organizations responsible for the emitting assets; 2) to make responsible regulatory agencies aware of the emissions; and 3) to ensure that the emissions data is available in an accessible and timely manner to civil society watchdogs, media, and affected communities.

An effective accountability and enforcement strategy should incorporate "carrot" (incentive) and "stick" (e.g., regulatory, "name and shame") mechanisms. The strategy should encompass operators of methane sources, responsible government agencies, including prosecutors, and civil society, including affected communities. Further, the strategy should also identify solutions for addressing detected emissions and connect operators to technical capacity and financial resources, as appropriate. Additional capacity building that reflects training and other proper incentives are needed for stakeholders involved in the accountability aspects of the strategy. Such stakeholders include emissions-source operators, regulatory agencies, financial risk agencies, and watchdogs.

An accountability strategy could have several components, including:

- An asset map and inventory of methane sources with geospatial coordinates that allow detailed identification of sources and related contacts for operators;
- A "phone book" of the corresponding control agents for each source point of emissions (federal, state, local, private sector, etc.) based on location and type of asset;
- A mechanism for accessing emissions data from monitoring systems and rapidly converting the data into usable formats for accountability actors; *and*

- A coordination and communications network of civil-society actors by region, country, subnational jurisdiction where emissions are significant, to strengthen collective civil-society capacity to act as emissions data emerges.

The National Academies of Sciences recently published a framework for evaluating greenhouse gas emissions information, which advocates for the following pillars: (1) usability and timeliness; (2) information transparency; (3) evaluation and validation; (4) completeness; (5) inclusivity; and (6) communication.[1091]

At the government level, National Methane Offices or equivalent responsible units could be established and assume responsibility for developing and maintaining emissions inventories and for identifying and monitoring key source points of emissions. These Offices would also liaise with corresponding subnational agencies to build effective accountability systems, establish procedures, and identify specialists and other stakeholders that can be relied upon for assistance with the deployment of accountability actions and systems. These Offices would be arranged regionally and at the subnational level, to encourage cooperation and share information and mitigation strategies.

A key component of incentivizing mitigation actions is for sources of identified methane emissions to have access to technologies and financing to implement mitigation solutions. The CCAC's new methane TEAP is a valuable tool to assess and recommend technology solutions on a regular basis to encourage continued innovation and support for implementation of best practices. A CCAC-housed Methane Tracker could also support this work.

10. International efforts, including the COP28 Methane Summit and the Global Methane Pledge, are catalyzing bilateral and multilateral actions to curb methane

Methane emissions from any source anywhere affect the global climate, as well as public health and environment, because methane is a well-mixed greenhouse gas and contributes to increasing background tropospheric ozone pollution. Methane mitigation by any and all countries is therefore the best means to achieve rapid and effective reductions of methane emissions wherever these emissions occur.[1092]

There have been numerous international agreements, commitments, pledges, initiatives, and measures seeking to bolster bilateral and multilateral efforts to cut methane emissions. A detailed description of these efforts is described in this section (*see also* **Section 7**). Key international efforts include the Global Methane Pledge (now endorsed by 156 countries and the European Union),[1093] the 95% of countries that directly reference or plan to reference methane mitigation in its Paris Agreement NDCs,[1094] and bilateral agreements such as the *Sunnylands Statement*.[1095] The recent *COP28 Methane Summit* recognized methane's essential role in rapidly cutting methane emissions to ensure peak-warming reduction and limit the likelihood of overshooting 1.5 °C.[1096] COP28's Global Stocktake Agreement, including recognition of the urgent need to accelerate and substantially reduce "non-carbon-dioxide emissions globally … in particular methane emissions by 2030," further illustrates the inevitability of a global methane agreement.[1097] International efforts build upon impressive and increasingly strong domestic efforts to curb methane detailed in this *Primer* (*see also* **Section 6**).

Yet the majority of wider methane international commitments, including the Global Methane Pledge, are not mandatory. Voluntary commitments are not sufficient to quickly cut warming and avoid tipping points that would lock in devastating global warming and make it much more difficult to avoid an existential threat to a liveable planet Earth.[1098] There is therefore a growing chorus of support for binding national and international commitments.[1099] Because cutting methane emissions is the single most important action humanity can take to slow near-term warming, it is critical to move from a pledge to mandatory measures with bilateral, plurilateral, and regional efforts as the foundation for a binding global methane agreement. Governments must fully implement[1100] and build on the existing commitments and initiatives to open the door for a binding global methane agreement.

The Montreal Protocol provides inspiration for a global methane agreement.[1101] Negotiated in nine months,[1102] the Montreal Protocol not only solved the first great threat to the global atmosphere by putting the stratospheric ozone on the path to recovery by 2065, but also has done more to avoid climate warming than any other agreement,[1103] avoiding an amount of warming that otherwise would have equaled or even exceeded the warming that CO_2 is causing today.[1104]

There are further discussions below of the Global Methane Pledge, COP28's Global Stocktake Agreement, the Convention on Long-Range Transboundary Air Pollution's Gothenburg Protocol, the United States-China *Sunnylands Statement* and *Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, and a global methane agreement to address the climate emergency and promote peace and security.

A. The Global Methane Pledge, the COP28 first Global Stocktake Agreement, and the Global Methane Pledge's Energy, Agriculture and Food, and Waste Pathways

The Global Methane Pledge was formally launched at the Head-of-State level at the high-level segment of COP26 on 2 November 2021 in Glasgow.[1105] The United States and European Union first announced the GMP at the Major Economies Forum on 17 September 2021.[1106] The Global Methane Pledge commits governments to a collective global goal of reducing global methane emissions by at least 30% from 2020 levels by 2030.[1107] Signatories also commit to moving towards using the highest-tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources.[1108] The Global Methane Pledge marked the first time that Heads of State have committed to fast action to cut super climate pollutants to meet the 1.5 °C temperature target of the Paris Agreement. In September 2023, Canada, Federated States of Micronesia, Germany, Japan, and Nigeria joined the United States and the European Union as Champions of the Global Methane Pledge to advocate for accelerated methane action to achieve the Pledge.[1109] During COP28, Turkmenistan, Kazakhstan, Kenya, Romania, and Angola were welcomed as new members of the GMP. In March 2024, Azerbaijan announced it had joined the Pledge, bringing total participation to 156 governments and the European Union.[1110] At COP28, a GMP Ministerial was held to welcome efforts to deliver action and funding needed to achieve the 30% reduction target of the Global Methane Pledge.[1111]

Successful implementation of the Global Methane Pledge would reduce warming by at least 0.2 °C by 2050.[1112] Achieving the Global Methane Pledge's emissions-reduction target would keep the planet on a pathway consistent with staying within 1.5 °C, according to the *Global Methane Assessment*.[1113] This is roughly equivalent to an emissions reduction of 35% below projected 2030 levels. Deploying all available and additional measures could lead to a 45% reduction below 2030 levels to achieve nearly 0.3 °C in avoided warming by the 2040s.[1114]

At COP28, Parties agreed to the first Global Stocktake Agreement, which "recognizes the need for deep, rapid, and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts."[1115] One of the proposed methods in the Global Stocktake Agreement to achieve these deep, rapid, and sustained reductions in greenhouse gas emissions is "accelerating and substantially reducing non-carbon-dioxide emissions globally, including in particular methane emissions by 2030."[1116] The reference to methane in the first Global Stocktake Agreement builds upon momentum starting at COP26, where former U.S. President Barack Obama reminded those in attendance that "curbing methane emissions is currently the single fastest and most effective way to limit warming."[1117] The Glasgow Climate Pact, agreed to at COP26, "invites Parties to consider further actions to reduce by 2030 non-carbon dioxide greenhouse gas emissions, including methane."[1118]

At the U.S.-ASEAN Special Summit in Washington, DC, on 12 May 2022, the U.S. committed to "accelerating technical assistance, financial resources, and project pipeline development for methane mitigation in GMP countries, including through the EPA, USTDA [U.S. Trade and Development Agency], DFC [Development Finance Corporation], and EXIM [Export-Import Bank], as well as the newly-created Global Methane Hub."[1119]

On 27 May 2022, the G7 Climate, Energy, and Environment Ministers reaffirmed their commitment to the Global Methane Pledge and noted the importance of responding "to the current crisis, in a manner consistent with our climate objectives and without creating lock-in effects."[1120] In June 2022, G7 Leaders reaffirmed their commitment to the Global Methane Pledge.[1121]

There are three Global Methane Pledge Pathways: the Global Methane Pledge Energy Pathway, the Global Methane Pledge Food and Agriculture Pathway, and the Global Methane Pledge Waste Pathway. The subsections below will address developments that have occurred in each Pathway, starting with developments from COP27, and then developments from COP28. This is followed by a brief overview of methane finance announcements from COP28.

i. Global Methane Pledge Energy Pathway

In June 2022, the U.S., EU, and 11 other countries launched the Global Methane Pledge Energy Pathway, which includes $59 million in funding to support methane reductions in the oil and gas sector.[1122] The funding includes $4 million to support the World Bank Global Gas Flaring Reduction Partnership (re-launched at COP28 as the GFMR), $5.5 million to support the GMI, up to $9.5 million from the IMEO to support scientific assessments of methane emissions and mitigation potential, and up to $40 million annually from the philanthropic Global Methane Hub to support methane mitigation in the fossil energy sector.

Global Methane Pledge Energy Pathway developments that took place during COP27 in November 2022 include the following:[1123]

- The U.S., EU, Japan, Canada, Norway, Singapore, and UK issued a *Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels*, in which the signatories commit to work towards creating an international market for fossil energy that minimizes flaring, methane, and carbon dioxide emissions across the value chain to the fullest extent possible.[1124] The Joint Declaration covers over half of global gas import volumes and more than one-third of global gas production.
- UNEP and IMEO launched the Methane Alert and Response System (MARS) to augment detection of methane super emitters, notify relevant stakeholders, and support and track methane mitigation progress (*see* **Section 8**).[1125]
- The World Bank Global Gas Flaring Reduction Partnership announced the launch of the 2023 phase of its trust fund, with plans to become the GFMR Partnership to address methane emissions across the oil and gas value chain (*see* **Section 7**).[1126]

During COP28, a number of Global Methane Pledge Energy Pathway developments were welcomed and addressed at the Global Methane Pledge COP28 Ministerial,[1127] including:

- New policies, regulations, and national commitments to cut methane from some of the world's largest oil and gas methane emitters, including:
    - U.S. announcing final standards to sharply reduce methane emissions from oil and gas operations, expected to reduce over 1.5 Gt CO_2e and reduce nearly 80% below future methane emissions expected without the rule (*see* **Section 6**);[1128]
    - EU adopting its first-ever methane regulations, setting ambitious monitoring and abatement criteria for domestically produced and imported fossil oil, gas, and coal, including establishing a methane import standard by 2030 (*see* **Section 6**);[1129]
    - Canada unveiling draft regulations to achieve an ambitious reduction of methane emissions in the upstream oil and gas sector by at least 75% below 2012 levels by 2030 (*see* **Section 6**);[1130]
    - Brazil announcing that its National Council of Energy Policy will establish guidelines on methane reduction in the oil and gas sector by the end of 2024, and the National Agency for Petroleum, Natural Gas and Biofuels aims to finalize regulations by the end of 2025 based on these guidelines (*see* **Section 6**);[1131]
    - Egypt announcing its intention to develop domestic methane regulations in its oil and gas sector by the end of 2024, as part of developing the sector's detailed methane emissions reduction roadmap;[1132]
    - Nigeria showcasing major steps taken this year under the Nigeria Gas Flare Commercialization Program, including advancing projects estimated to capture over half of all gas flaring volumes in Nigeria. Nigeria committed to accelerate implementation of these projects and to ensure robust enforcement of its oil and gas methane guidelines launched at COP27 (*see* **Section 6**);[1133] *and*

- Kazakhstan joining the Global Methane Pledge and announced cooperation with the U.S. to develop national standards to eliminate non-emergency venting of methane and require LDAR in the oil and gas sector as soon as possible before 2030.[1134]

- New OGMP 2.0 members. The Partnership now represents over 120 companies with assets in more than 60 countries on five continents and covers over 35% of the world's oil and gas production and over 70% of LNG flows (*see* **Section 7**). [1135]
- The launch of the World Bank GFMR with $255 million in new grant funding to catalyze oil and gas methane and flaring reduction in developing countries (*see* **Section 7**).[1136]
- The U.S., European Commission, and 12 other natural gas importing and exporting countries establishment of an international working group to advance comparable and reliable information about methane and CO_2 emissions across the natural gas supply chain (*see* **Section 7**).[1137]
- The OGCI announcement that is expanding its Satellite Monitoring Campaign to provide actionable data to reduce emissions from large-magnitude methane plumes and flares, supported by in-kind contributions from OGCI companies. ExxonMobil also announced its intention to provide up to $25 million in-kind assistance to address capability shortcomings to reduce methane emissions (*see* **Section 7**).[1138]

ii. Global Methane Pledge Food and Agriculture Pathway

At COP27, Global Methane Pledge countries launched the Global Methane Pledge Food and Agriculture Pathway and Waste Pathway.[1139] The Food and Agriculture Pathway will leverage up to $400 million to help smallholder farmers transition diary systems to lower-emission, climate-resilient pathways[1140] and raise $70 million for a new Enteric Methane Research and Development Accelerator.[1141] The Food and Agriculture Pathway focuses initially on providing funding support to targeted countries for transitioning their agricultural sector to low-emission and climate-resilient pathways, supporting methane mitigation research and innovation, and highlighting ambitious methane mitigation actions taken by the U.S. and EU.

During COP28,[1142] the Global Methane Pledge Ministerial welcomed several new developments in the Global Methane Pledge Food and Agriculture Pathway, including:

- The Global Methane Hub formal launch of the Enteric Fermentation R&D Accelerator with $200 million in funding, making it the largest ever globally coordinated research effort into livestock methane reduction.[1143]
- The World Bank launch of the Global Methane Reduction Platform for Development (CH4D) to support low- and mid-income countries to realize the "methane triple-wins: of abating emissions, enhancing resilience, and empowering livelihood (*see* **Section 7**; **Section 11**).[1144]
- The International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP) announcement that it will, with funding from the U.S. State Department and Global Methane Hub, support 15 governments to incorporate agricultural methane into their nationally determined contributions and 10 governments to build investment pipelines in low-methane agricultural development (*see* **Section 7**).[1145]

- The launch of Dairy Methane Action Alliance (DMAA), a global initiative to accelerate food industry action to drive down dairy methane emissions, by six major food companies (Bel Group, Danone, General Mills, Kraft Heinz, Lactalis USA [a U.S. affiliate of Lactalis Group], and Nestlé), representing billions of dollars in global annual dairy sales (*see* **Section 7**).[1146]

iii. Global Methane Pledge Waste Pathway

Also launched at COP27, the Global Methane Pledge Waste Pathway aims to scale up subnational action on waste methane[1147] and establish a Food Waste Management Accelerator to develop mitigation projects.[1148] The Waste Pathway focuses initially on advancing methane mitigation measures across the solid waste value chain. Initial components of the Pathway include: enhancing measurement and tracking of methane emissions; supporting accelerated subnational action on waste methane; developing methane mitigation projects to reduce food loss and waste; funding projects with a high regional impact across different countries; and scaling up investment in waste methane mitigation.

During COP28, the Global Methane Pledge Ministerial New also welcomed a number of initiatives in the Global Methane Pledge Waste Pathway, including:

- Lowering Organic Waste Methane (LOW-Methane) initiative launch (*see* **Section 7**).[1149]
- Inter-American Development Bank launch of a new Too Good to Waste initiative, which aims to contribute at least a 30% reduction in methane emissions in solid waste operations in Latin America and the Caribbean financed by the Bank, including three recently approved projects totaling $372.5 million.[1150]
- U.S. announcement of new steps on waste methane. The U.S. EPA is planning a rulemaking to review and, if appropriate, revise its Clean Air Act emission standards for new and existing municipal solid waste (MSW) landfills, considering new monitoring technology, incentivization of organics waste diversion, and emissions controls at landfills not covered by current regulations. In 2024, U.S. EPA will release updates on emissions estimates for MSW landfills. In addition, the United States released for public comment a draft national strategy for Reducing Food Loss and Waste and Recycling Organics in line with its 2030 goal of 50% food loss and waste reduction (*see* **Section 6**).[1151]
- The leaders of Canada, U.S., and Mexico's commitment to reducing methane emissions from the waste sector by at least 15% by 2030 at the 2023 North American Leaders Summit.[1152]
- CCAC's TEAP, co-chaired by Ireland and Senegal, released its first report on *Driving Innovation and Technology in the Waste Sector* (*see* **Section 7**).[1153]

iv. Global Methane Pledge-Related Funding Announcements from COP27 and COP28

Funding announcements at COP27 included a $3.5 million seed grant for further financing of global smallholder farmers led by the Green Climate Fund, a plan for the Global Methane Hub to raise $70 million to develop a new Enteric Methane Research and Development Accelerator, $500 million for methane reduction projects via Partnerships for Climate Smart Commodities launched by USDA, and more.[1154] Prior to COP27, the U.S. announced a $5 million grant to the African

Development Bank to fund methane abatement across Africa[1155] and a $2.8 billion investment in USDA-driven Partnerships for 70 Climate-Smart Commodities and Rural Projects, with methane reduction projects as a priority for the first round of funding distribution.[1156]

At COP28, Minsters welcomed the fact that, in addition to over $1 billion in new grant funding, international financial institutions approved over $3.5 billion in new investments for methane-reducing projects since COP27. Approvals include $375 million from the Green Climate Fund and partners, over $1.9 billion (€1.78 billion) from the European Investment Bank, over $218 million (€200 million) from the European Bank for Reconstruction and Development, and $372.5 million from the Inter-American Development Bank. The World Bank approved at least $700 million in investments, including a $255 million for rice project in China, $300 million for landfill methane reduction in Cote d'Ivoire, and $145 million for wastewater methane reduction in Malawi.[1157]

These initial commitments and activities, as well as those described below, raise awareness of the opportunity to slow warming by cutting methane, the sectors involved, and the level of ambition needed. Governments should build on the GMP and the GMP's multiple Pathways to open the door for a global methane agreement, including acting immediately to require a progressively lower methane emissions rate from providers of "replacement methane gas" in response to shifts in energy sourcing.

B. Methane action under the Gothenburg Protocol to the Convention on Long-Range Transboundary Air Pollution

The *COP28 Methane Summit* and the Global Methane Pledge lay the foundation for more concrete, emergency methane abatement, including in the form of a global methane agreement that also draws from successful models such as the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP), and its 1999 Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone (Gothenburg Protocol),[1158] described further below.

LRTAP is a regional treaty framework between Europe, North America, Russia, and former Eastern Bloc countries for reducing transboundary air pollution and understanding related science.[1159] Methane is the last remaining major ozone precursor not explicitly controlled under the Gothenburg Protocol, as currently amended.[1160]

Including methane in LRTAP is an active area of discussion and this activity should acknowledge and reinforce efforts, including through UNECE's existing collaboration with the CCAC, to develop a global methane agreement to address the climate emergency and promote peace and security. UNECE joined the CCAC in 2015 with the aim of contributing to CCAC work through exchanges of experience, knowledge, and best practices, including with respect to the Gothenburg Protocol.[1161]

Several LRTAP subsidiary bodies are studying methane emissions, including modeling impacts of methane emissions from outside the region on ozone levels within the UNECE region.[1162] LRTAP and its eight protocols[1163] reflect several innovations that can benefit the development of a global methane agreement. These include: the adoption of a technology-based approach that incorporates national measures to reduce pollutants;[1164] a robust scientific body that monitors whether Parties are on track to meet their targets;[1165] and a dual reporting system that requires Parties to report their annual pollutant emissions and progress in implementing their national strategies.[1166] These policy mechanisms recognize, incorporate, and monitor existing national air pollutant emissions control efforts. When developing a global methane emissions control mechanism, it will be worth considering the benefits of LRTAP innovations when determining how to best recognize countries' existing measures to control methane.

While LRTAP could be a valuable regional mechanism for binding methane controls, additional LRTAP considerations from a global perspective include:

- *LRTAP Parties are from North America, Europe, and Central and Western Asia and do not include several countries with significant methane emissions or developing countries that support the* Global Methane Pledge. LRTAP Parties are members of UNECE.[1167] Not all Parties to LRTAP are also Parties to the additional protocols under LRTAP. For example, Russia is a Party to LRTAP but is not a Party to the Gothenburg Protocol. LRTAP Parties do not include major methane-emitting countries[1168] such as China, India, Brazil, and Iran, or other GMP countries in the developing world, such as Argentina, Ghana, Indonesia, Iraq, Mexico, Pakistan, and Nigeria.

- *Methane is under active discussion but is not controlled under LRTAP nor under any of its protocols at this time.* LRTAP controls in-scope pollutants contributing to transboundary air pollution. Eight Protocols further clarify Party obligations regarding specific pollutants and activities. The most recent Protocol, and the most consequential for methane, is the Gothenburg Protocol, which entered into force in 2005.[1169] The objectives of the Gothenburg Protocol include control and reduction of emissions of sulfur, nitrogen oxides, ammonia, volatile organic compounds (other than methane) and particulate matter caused by anthropogenic activities that are likely to cause adverse effects on human health and the environment, natural ecosystems, materials, crops and the climate in the short- and long-term, due to, among other things, ground-level ozone arising from long-range transport of covered pollutants.[1170] Methane is a major source for tropospheric ozone and contributes to background ozone levels globally.[1171] Although methane is recognized as an ozone precursor in the Gothenburg Protocol,[1172] it is not currently a controlled pollutant.

- *UNECE remains focused on methane's role as an ozone precursor and on how methane emissions from outside the UNECE affect ozone formation within the UNECE.* UNECE recognizes that global growth in methane emissions is in large part from countries outside the UNECE (or ECE) region.[1173] UNECE is reviewing sources of global methane emissions, with a focus on how emissions from non-UNECE regions affect ozone transport to and formation within the UNECE.[1174] This review also includes how methane emissions reductions may be better achieved through a future and instrument.[1175]

- *The LRTAP process for formalizing methane controls should support binding targets and move at a pace consistent with the climate emergency and the role of methane mitigation in slowing warming, while providing opportunities for input, collaboration, and support for global methane controls.* Since 2018, several LRTAP subsidiary bodies have been considering whether and how to address methane. In September 2021, a Joint Progress Report found that methane is the main driver behind increasing background ozone levels, and that the waste sector in Europe and the oil and gas sector in Eastern Europe, Asia, and the U.S. have the greatest abatement potential in those regions.[1176] The LRTAP Gothenburg Protocol Review Group, established under the Working Group on Strategies and Review pursuant to decision 2020/2,[1177] concluded its work in the form of a report presented to the Executive Body in December 2022. In the report, the Review Group found that expected increases in global methane concentrations offset ozone decreases resulting from other pollution controls in Europe and North America.[1178] The report also indicated that even with full implementation of the Protocol, background ozone levels within the UNECE region will continue to increase due to increases in external ozone precursor emissions, particularly methane.[1179] The Review Group concluded that the methane contribution to transboundary ozone is "significant enough" that the LRTAP Executive Body should consider potential policy action under the Convention.[1180] As a result of these recommendations, the LRTAP scientific bodies updated their strategy to include *further investigation* of methane emissions, their contribution to air pollution,[1181] and the feasibility of adopting control technology among its priorities.[1182] The Task Forces have since drafted a guidance document on technical measures for reduction on methane emissions from landfills, the natural gas grid, and biogas facilities,[1183] and a policy brief on co-mitigation of methane and ammonia and methane emissions from agricultural sources.[1184]

- *LRTAP Parties decided to amend the Gothenburg Protocol in response to the findings of the review at the 43rd Meeting of the Executive Body in December 2023*. In the draft decision, Parties acknowledged that global methane reductions are necessary to reduce ground-level ozone within the ECE region and decided to include addressing methane emissions in the revision process.[1185] The options for revisions include amending the Protocol text and annexes, adopting non-binding instruments to encourage voluntary actions to fulfill the goal of the Global Methane Pledge, and increasing collaboration with other entities like the WHO, the UNFCCC, and the CCAC to amplify action on air pollution globally.[1186]

Taking all the above considerations into account and recognizing that controlling methane calls for urgent action, Parties should consider both rapidly moving to include methane commitments within the Gothenburg Protocol and calling for a binding global methane agreement to account for the global nature of methane emissions and impacts and to promote global security and peace.

C. U.S.-China Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis and the Joint Glasgow Declaration on Enhancing Climate Action in the 2020s

i. The Sunnylands Statement

The *Sunnylands Statement* underscores the renewed U.S. and China commitment to climate leadership announced in advance of COP28.[1187] This commitment was also reflected in China's hosting, with the U.S. and the UAE, the *COP28 Methane Summit*.[1188] The *Sunnylands Statement* is an important additional step to implement the new climate architecture that President Biden and his then climate envoy John Kerry articulated at the Major Economies Forum on Energy and Climate in April 2023.[1189]

Importantly, the *Sunnylands Statement* paves the way for U.S.-China engagement and cooperation on key climate priorities starting with the run up to COP28. The "Sunnylands legacy" includes the meeting in 2013 between President Obama and President Xi which helped build the consensus needed to adopt the Kigali Amendment to the Montreal Protocol on HFCs in 2016 and chart a path toward eventual HFC phaseout.[1190] In the same way, the *Sunnylands Statement* reflects a "start and strengthen" approach to address the climate crisis.[1191]

At the 15 November 2023 meeting between President Biden and President Xi Jinping, "[t]he two leaders underscored the importance of working together to accelerate efforts to tackle the climate crisis in this critical decade. They welcomed recent positive discussions between their respective special envoys for climate, including on national actions to reduce emissions in the 2020s, on common approaches toward a successful COP28, and on operationalizing the Working Group on Enhancing Climate Action in the 2020s to accelerate concrete climate actions."[1192]

To realize the potential of the *Sunnylands Statement* to address the climate emergency, there is still a massive amount of work to be done. The *Statement* identifies opportunities for further understanding and ambition-strengthening actions in these top two GHG-emitting countries, including on the energy transition from fossil fuels,[1193] the mitigation of methane, HFCs, N_2O, and other non-CO_2 climate pollutants,[1194] the development of resource efficiency and a circular economy,[1195] the synergistic control of GHGs and other air pollutants,[1196] on climate cooperation at the subnational level,[1197] on combating deforestation,[1198] and on 2035 NDCs.[1199]

In addition to action adopted at the national and subnational levels, the *Sunnylands Statement* underscores the role of multilateralism in solving the climate crisis.[1200] It echoes the provisions on strengthening global methane governance and cooperation in the China Methane Emissions Control Action Plan.[1201] It also points to the importance of international advocacy, including discussions at the COP28 Methane and Non-CO_2 GHGs Summit and other activities which can build the foundation for commitments that can contribute to a binding global methane agreement.[1202]

ii. The Joint Glasgow Declaration

Earlier, at COP26 on 10 November 2021, the U.S. and China issued the *Joint Glasgow Declaration*, which commits the two largest economies and emitters of climate pollutants to jointly tackle the climate crisis through "accelerated actions in the critical decade of the 2020s,"[1203] including additional measures to reduce methane emissions. This *Declaration* provides key background for understanding the *Sunnylands Statement.* For example, in the *Declaration*, China agreed to develop a "comprehensive and ambitious National Action Plan" to achieve methane emissions control and reductions in the 2020s.[1204] The U.S. and China also committed to "cooperate to enhance the measurement of methane emissions," to meet during the first half of 2022 to focus on methane measurement and mitigation issues,[1205] and to establish a Working Group on Enhancing Climate Action in the 2020s to address the climate crisis, which would meet regularly.[1206] Further, the United States and China indicated their intention to communicate 2035 NDCs in 2025,[1207] which helps reinforce the *Sunnylands Statement* reference that "both countries' 2035 NDCs will be economy-wide, include all GHGs, and reflect the reductions aligned with the Paris temperature goal of holding the increase in global average temperature to well below 2 degrees C and pursuing efforts to limit the temperature increase to 1.5 degrees C."[1208]

China's announcement in the *Declaration* of a National Action Plan on methane to reduce methane emissions in the 2020s,[1209] later released on 7 November 2023,[1210] reflected at the time significant progress towards achieving the objectives of the Global Methane Pledge, although China has not joined the Global Methane Pledge.[1211] Notwithstanding, as a result of the *Sunnylands Statement* and the *Joint Glasgow Declaration*, national and subnational methane-mitigation activities that Global Methane Pledge countries undertake will serve as models to help inform and potentially strengthen the implementation of China's Methane Emissions Control Action Plan. It is also significant that both China's updated NDCs and Mid-Century Strategy list policy actions for reductions of non-CO_2 GHGs, including methane.[1212]

D. A Global Methane Agreement to Address the Climate Emergency and Promote Peace and Security

In the run-up to COP26 in Glasgow, the European Parliament called on the Commission and the Member States to "negotiate a binding global agreement on methane mitigation at the COP26 meeting in Glasgow in line with the modelled pathways that limit global warming to 1.5 °C."[1213] There already is a strong and evolving foundation for negotiating such an agreement, as described below, including an appetite among key leaders for multilateralism to solve unprecedented global challenges and keep democracy alive.[1214] This includes acting immediately to negotiate a progressively lower methane emissions rate from providers of "replacement methane gas" in response to shifts in sourcing as the availability of Russian gas is reduced.

The outcome of COP28 on the Global Stocktake Agreement further illustrates the inevitability of a global methane agreement. The decision states that parties to the UNFCCC recognize "the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts, in a nationally determined manner, taking into account the Paris Agreement and their different national circumstances, pathways and approaches."[1215] One of the actions expressly needed to achieve this deep, rapid, and sustained reduction is "[a]ccelerating and substantially reducing non-carbon-dioxide emissions globally, including in particular methane emissions by 2030."[1216] This language in the final decision outcome establishes a critical building block towards a binding global methane agreement to expand on and fulfill this objective. As noted by CCAC High-level Advocate for Finance Rachel Kyte at the COP28 CCAC Ministerial: "It's 2023. With peak oil, peak coal, and peak emissions, we are also 'peak-pledge.'"[1217]

i. The Montreal Protocol provides inspiration and a model for a global methane agreement

The Montreal Protocol provides inspiration and a model for a mandatory, sector-focused global methane agreement. The Montreal Protocol is widely regarded as the world's most successful environmental agreement because it has not only put the stratospheric ozone layer on the path to recovery by 2065, but also prevented global warming at least equal to the current warming from CO_2 emissions.[1218]

The Montreal Protocol has several features that could contribute to the success of a global methane agreement, even though a different approach may be needed for methane associated with fossil fuel production and consumption,[1219] or responses to crises involving food security or opportunities such as the growth of border adjustment and methane-fee regimes.

First, the treaty imposes mandatory obligations on all Parties, both those from the developed countries, and those from developing countries. At the same time, the Protocol implements the principle of "common but differentiated responsibilities and respective capabilities."[1220] This principle is implemented by giving developing-country Parties a grace period, often five or ten years, before requiring them to phaseout or phasedown a controlled substance.[1221] This principle also is given effect through a dedicated funding mechanism, the Multilateral Fund, where developed countries pay the "agreed incremental costs" that developing countries incur when implementing controlled-substance phaseouts and phasedowns.[1222] In addition to financial support for replacement technologies, the Montreal Protocol provides financial support to strengthen the National Ozone Units that operate in every one of the 147 developing-country Parties.[1223] The UNEP OzonAction office also provides regular training and capacity-building for developing-country Parties, expanding in-country action and awareness of the importance of achieving ozone-depletion and climate mitigation associated with the Montreal Protocol.

Additional important features of the Montreal Protocol are its assessment panels, particularly the Scientific Assessment Panel (SAP)[1224] and the Technology and Economic Assessment Panel (TEAP).[1225] The SAP assesses the status of ozone-layer depletion and relevant atmospheric science. The TEAP reviews the technologies and economics of alternatives to the chemicals being phased out by bringing together experts from industry, government, and academia to find solutions and report independently without government censorship.[1226]

The Montreal Protocol was preceded by an underlying framework treaty, the Vienna Convention for the Protection of the Ozone Layer.[1227] A strategy involving the development of a global methane agreement should contemplate and anticipate the sudden prioritization and acceleration of action to cope with crises and opportunities to drive down global methane emissions, including crises involving food security and energy, as well as potential opportunities such as the growth of carbon border adjustment mechanisms and methane-fee initiatives. Nonetheless, a framework-protocol structure could be suitable for a global methane agreement: a framework agreement followed by a series of protocols on the energy, waste, and agricultural sectors,[1228] while also addressing research and development of strategies to remove methane from the atmosphere to counter natural emissions.[1229]

ii. *The scientific, policy, and technical foundation already exists for the negotiation of a global methane agreement inspired by the Montreal Protocol*

The urgency of slowing warming in the near term means that speed must become the key factor in the selection of climate solutions[1230] to quickly limit warming, slow self-propagating feedbacks, avoid tipping points, and protect the most vulnerable people and ecosystems.[1231] The UNEP, the IPCC,[1232] the CCAC,[1233] and the Arctic Council[1234] have all contributed to this scientific understanding. The IPCC's AR6 Working Group II contribution (AR6 WGII) underscores the dire consequences of further delays in global action and the urgency of slowing warming in the near term.[1235] The *Global Methane Assessment* confirms that cutting methane emissions is the fastest and only plausible mitigation strategy to limit warming over the next two decades.[1236]

Responding to this call to action, governments, organizations, and collaborative initiatives at all levels have built a robust policy and technical foundation for global methane control. In addition to the developments at COP28 described in **Section 10A**, this foundation includes:

- *International commitments and initiatives involving critical methane action*. For instance, as of November 2023, 95% of NDCs of the Parties under the Paris Agreement include methane within the scope of their overall mitigation target and 40 Parties include methane as a supplementary target or assessment of the mitigation potential of the measure(s) identified.[1237] At the COP28 Global Methane Pledge Ministerial, U.S. Special Presidential Envoy for Climate John Kerry issued a challenge to all governments to include all greenhouse gases from all sectors in their revised 2035 NDC target.[1238] The U.S. and EU anchored support for the Global Methane Pledge at the leadership level during the Major Economies Forum on Energy and Climate in September 2021.[1239] In June 2022, the U.S., EU, and 11 other countries launched the Global Methane Pledge Energy Pathway, which includes funding to support methane reductions in the oil and gas sector. In November 2022, the U.S. and the EU launched the Global Methane Pledge Food and Agriculture Pathway and Global Methane Pledge Waste Pathway to advance methane mitigation in the agriculture and waste sectors. The Global Methane Pledge has since expanded to 157 participants (156 countries plus the EU) as of COP28, with developing countries such as Argentina, Ghana, Indonesia, Iraq, and Mexico, among the earliest supporters.[1240] The G20 has recognized that methane is "one of the quickest, most feasible and most cost-effective ways to limit climate change and its impacts" and agreed to promote cooperation and transparency.[1241] The EU has committed to reduce all GHG emissions by 55% by 2030,[1242] and the European Commission has emphasized the need for unified, global action on methane.[1243] Parties to the Economic Commission LRTAP—and specifically the Gothenburg Protocol—are undertaking a process that will hopefully formalize binding methane mitigation while providing opportunities for input, collaboration, and support for global methane controls.[1244] International Monetary Fund staff recognized that cutting methane emissions is critical to stabilizing the global climate and that financing would need to be part of an international agreement aimed at mitigating methane "given that mitigation costs would fall disproportionately on emerging market economies."[1245] The CCAC is actively strengthening global understanding and ambition for methane control though initiatives such as its Methane Flagship, as well as its establishment of a TEAP and helping countries with the development of national methane action plans.[1246] The CCAC and the UNEP have partnered on the Global Methane Assessment.[1247] UNEP also launched the Oil & Gas Methane Partnership 2.0.[1248] In November 2022, the Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels emphasized the "dramatically reducing methane" is a necessary complement to global decarbonization to limit warming to 1.5 °C.[1249] In October 2023, Ministers gathered at the International Climate and Energy Summit, with the aim of strengthening ambition and implementation ahead of COP28. There the Ministers agreed to highlight the critical role of, and opportunity for, the fossil fuel industry to reduce methane emissions from their operations, with the aim of cutting them 75% by 2030.[1250] Twelve countries, the European Commission, and the East Mediterranean Gas Forum established the International Working Group to Establish a Greenhouse Gas Supply Chain Emissions Measurement, Monitoring, Reporting, and

Verification (MMRV) Framework for Providing Comparable and Reliable Information to Natural Gas Market Participants.[1251] The China Council for International Cooperation on Environment and Development is developing research on methane metrics and measurement and initiatives for major methane-emitting sectors.[1252] The Peterson Institute for International Economics has also called on the United States and the European Union to align their current efforts to introduce carbon border adjustment mechanisms to create an international methane border adjustment mechanism.[1253] *See also* **Section 6**, **Section 7**, and **Section 11**.

- *Bilateral commitments and actions on methane mitigation*. For instance, the U.S. and China, in their *Joint Glasgow Declaration*, demonstrated the capability of economic and political rivals to find common ground on methane mitigation.[1254] The landmark *Sunnylands Statement* has also seen the U.S. and China agree to further cooperate on methane reduction.[1255] These policy initiatives and the growing climate emergency underscore the importance, even during a time of increased political crises, for cooperation—and even some ambition-promoting competition—among methane mitigation champions in China and other countries.[1256] Canada[1257] and Mexico,[1258] as additional examples, have established regulations for energy-sector methane emissions, and joined the U.S. in pledging to enhance cooperation.[1259] Nigeria stands out as the first African country to regulate its energy-sector methane emissions (*see* **Section 6**).[1260]

- *National methane mitigation measures*. Examples include, for instance, the China National Methane Emissions Control Plan;[1261] the U.S. Methane Emissions Reduction Action Plan and Methane Summit to Tackle Dangerous Climate Pollution, while Creating Good-Paying Jobs and Protecting Community Health;[1262] and the European Union methane regulation and border adjustment mechanisms (*see* **Section 6**).[1263]

- *Subnational efforts inspiring national measures*. These include regulations in U.S. states such as California,[1264] New Mexico,[1265] and Colorado,[1266] and in Canadian provinces such as British Columbia.[1267] Climate-focused initiatives such as the C40 Cities network[1268] and Under2 Coalition[1269] have united subnational entities around the world in addressing methane emissions. California launched a Subnational Methane Action Coalition in 2023 with 15 jurisdictions around the world to empower subnational governments to make concrete progress towards their climate goals through methane mitigation in the energy, agricultural and waste sectors (*see* **Box 5**).[1270]

- *Methane monitoring, data, and measurement initiatives*. Multiple satellite-based efforts and the IMEO[1271] are already informing global understanding of the levels of methane emissions contributing to the climate emergency. These initiatives are essential to understanding whether the world is on track to meet existing commitments (*see* **Section 8**). They also provide critical information needed for successful and robust accountability and enforcement mechanisms in a global methane agreement.

- *Methane funding initiatives*. The Word Bank's and International Monetary Fund's increased interest in methane funding and mitigation efforts demonstrate an increased interest from multilateral financial institutions in methane. Key efforts include the World

Bank's Global Flaring and Methane Reduction (GFMR) Partnership,[1272] the International Monetary Fund's analysis of a global methane fee,[1273] and the International Monetary Fund's Resilience and Sustainability Trust.[1274] The Global Methane Hub acts as a central focus point for wider philanthropic commitments on methane. These financial initiatives and other funding efforts are discussed further in **Section 11**. These financial initiatives lay the groundwork for a multilateral fund that can be used within a Global Methane Agreement to bolster financial support for the achievement of binding methane targets.

- *Public and private collaborations across all levels on methane mitigation.* These efforts, discussed further in **Section 7**, are strengthening awareness of effective methane mitigation measures that must underpin a successful global methane agreement. These encompass, in addition to the CCAC initiatives, the Global Methane Initiative,[1275] the OGCI,[1276] and methane emissions mitigation performance-rating and certification initiatives such as MiQ,[1277] the Canary Project, and the Natural Gas Sustainability Initiative.[1278]

This scientific, technical, and policy foundation, added to the inspiration of the Montreal Protocol, provides the understanding, ambition, examples, and solutions necessary to develop a binding global methane agreement.

iii. Creating and strengthening the organizations necessary to support a global methane agreement can and should start immediately within the CCAC

With speed as a key factor for climate solutions, work on organizations that will later support a global methane agreement should not wait for negotiations to commence. The climate emergency and its impacts have no analog in the history of humankind. Therefore, the strategy for developing such an agreement should contemplate and anticipate the sudden prioritization and acceleration of action to cope with crises and methane mitigation opportunities, including crises involving food security and energy and opportunities such as the growth of border adjustment and methane-fee regimes. This work can and should start immediately. This includes strengthening or creating scientific, technical assessment, financial, and capacity-building organizations similar to those associated with the Montreal Protocol, such as the CCAC, which is now the Secretariat for the Global Methane Pledge.[1279] This could build upon existing commitments under the CCAC. For example, the CCAC launched the CCAC Clean Air Flagship at COP28. The Flagship will bring more attention to the global air pollution crisis, highlight readily available solutions, elevate ongoing regional collaboration, amplify and strengthen multi-level government cooperation, and offer direct support to countries including through policy and integrated climate and clean air planning activities and sector specific action via CCAC Sector Hubs, and capacity support for integrated inventories, monitoring and air pollution modeling and implementation of related priority measures and action plans.[1280] The Flagship will support science cooperation and information-sharing initiatives, especially with respect to methane,[1281] and strengthen and support regional and sub-regional cooperation, and the implementation of political commitments to achieve the WHO Air Quality Guidelines and Global Methane Pledge.[1282] Building off of this Flagship model, but ensuring it focuses on methane, would allow the CCAC to play a critical role in a Global Methane Agreement.

The CCAC has also established a TEAP, which released its first report on *Driving Innovation and Technology in the Waste Sector* in November 2023.[1283] The TEAP will form a useful advisory component of a global methane agreement. The creation of a methane control regime based on the successful Montreal Protocol would help ensure that it lives up to its mandate.[1284]

*iv. **Building upon the existing strong scientific, technical, and policy foundation and CCAC organizations, negotiations on a global methane agreement should start at the head-of-State level***

Building upon the strong foundations already in place, using the Montreal Protocol as an inspiration and model, and employing organizations developed within an organization such as the CCAC, a global methane agreement should be launched at the Head of State level. Negotiations for the agreement should be concluded with the need for unprecedented speed in mind. The Montreal Protocol was negotiated in just nine months.[1285] In March 2022, UNEP launched negotiations with the ambition of completing a global agreement to address plastic pollution two years later, in 2024.[1286]

11. Financial and philanthropic organizations can provide crucial financial support for methane ambition and action

Securing the appropriate funding and finance is essential to support governments and organizations committed to fast methane reductions. Private philanthropies, multilateral banks, governments, and other financial sector stakeholders all have roles to play in enabling fast methane mitigation to respond to the climate emergency. A stable climate system is a condition *sine qua non* for global financial system stability. Therefore, investment in methane mitigation at scale makes financial sense. In other words, the ability to capture the full temperature abatement of methane mitigation is the best insurance to secure investments.

Notably, however, methane mitigation solutions remain severely underfunded.[1287] In February 2024, the President of the World Bank said "[m]ethane is 80 times more dangerous than carbon dioxide. It gets 2% of climate financing. When something that is 80 times more dangerous gets 2% of financing, something is not right."[1288] While the momentum coming out of the COP28 announcements described below and in **Section 10A(iv)** is promising, more needs to be done across all sources of climate finance to facilitate methane mitigation at the scale and speed required to address the climate emergency.

A first-of-its-kind assessment of the landscape of methane mitigation finance from the Climate Policy Initiative tracked about US$11.6 billion in annual 2019/2020 investments, just 2% of total tracked climate finance (public development finance and private climate-related finance, excluding philanthropy), and 10 times less than the US$119 billion needed each year through 2050 based on the cost of readily available mitigation measures consistent with a 2 °C warming scenario.[1289] Among sectors receiving funding, the waste sector accounts for about 66% of abatement financing while the agriculture and energy sectors collectively receive about 33% of available financing.[1290] Increased investments to reduce methane emissions in the energy and agricultural sectors are essential as these two sectors emit around 82% of anthropogenic methane.[1291]

In the lead-up to COP28, the Climate Policy Initiative released its 2023 version of its landscape of methane abatement finance report. The report found that, at US$13.7 billion, methane abatement finance is at its highest level yet, but annual flows need to be at least 3.5 times larger until 2030.[1292] A 2023 report by the Clean Air Task Force identified that a lack of donor interest in methane mitigation financing, the absence of a dedicated international methane funding mechanism, and the failure to prioritize methane mitigation projects are all barriers to the ability to ensure adequate and available financing to mitigate methane at scale.[1293] The IEA's *Global Methane Tracker 2024* estimates that around US$170 billion in spending is needed to deliver methane mitigation in fossil fuel production to stay below 1. 5 °C (around US$100 billion in the oil and gas sector and US$70 billion in the coal industry).[1294]

At the highest level, multilateral development banks can support countries to achieve at least 30% of methane reduction consistent with the Global Methane Pledge and the *Global Methane Assessment*, including through the following:

- Ensure the availability of financing mechanisms for projects that reduce methane emissions from fossil fuel, waste, and agriculture;
- Promote an evaluation of climate risk that includes climate tipping points and feedbacks;[1295]
- Avoid investments that will precipitate climate tipping points and are not aligned with keeping global temperature under 1.5 °C in the next decade;
- Introduce GWP_{20} in climate impact evaluation to more accurately value near-term temperature impacts of action to reduce methane and other SLCPs;
- Assess the best way to leverage private finance for methane mitigation, including methane markets, policies, and regulation; *and*
- Assess how a global methane agreement can facilitate methane mitigation finance.

While integrating these climate emergency responses into bank processes, multilateral financial institutions can immediately build on their existing commitments to help countries invest in methane abatement. For example, the European Bank for Reconstruction and Development (EBRD) endorsed the GMP.[1296] The EBRD already finances green projects in large methane-emitting sectors, including energy and agribusiness.[1297] At the launch of the GMP, EBRD committed to assisting their countries of operation with efforts to reduce methane, including through technical assistance and funding for methane abatement projects.[1298] The European Investment Bank and Green Climate Fund also committed to providing technical assistance and project finance to support the GMP.[1299]

In September 2022, during a high-level breakfast held on the margins of the 18th African Ministerial Conference on the Environment, the U.S. government announced a US$5 million grant to the African Development Bank to support efforts to abate methane gas emissions across Africa. The CCAC and Global Methane Hub also promised US$1.2 million and US$5 million, respectively.[1300] At the conference, the Vice President of Power, Energy, Climate and Green Growth at the African Development Bank stated:

> “With the support of the U.S. government, and other donors and non-state actors, we intend to create a dedicated pillar of activities within our Africa Climate Change Fund to support methane abatement including working with countries to include methane in their Nationally Defined Contributions and develop pipelines of methane abatement projects for further investment.”[1301]

During COP27, the African Development Bank released a high-level assessment of anthropogenic methane emissions in Africa that outlines the methodology for quantifying methane in Africa to develop 2020 baselines for each country and sector, as well as case studies on possible abatement options and costs.[1302]

It will also be important for donor governments to provide financial support, including through a dedicated mechanism similar to the Montreal Protocol’s Multilateral Fund. Support from the Multilateral Fund for “institutional strengthening” that finances dedicated national ozone units in developing-country governments “is recognized as a major factor in the success of [developing countries] achieving compliance with the Montreal Protocol’s control measures.”[1303] A similar model supporting a network of National Methane Offices could rapidly build the capacity of governments to assess and act on methane mitigation opportunities across sectors and countries, including developing methane emission baselines, tracking and inventorying emitters, providing methane education, implementing national methane action plans, and providing a linkage to global and other major methane mitigation funding.

Philanthropy also has an important role to play to facilitate countries’ achieving the Global Methane Pledge. Soon after the creation of the Global Methane Pledge was launched more than 20 leading philanthropies pledged over US$328 million in support of efforts to drastically reduce methane emissions, including diplomatic efforts building on the Pledge.[1304] The philanthropies committed to quickly deploy grants and ensure that funding is flexible.[1305] As a result, the Global Methane Hub (discussed further in this section) was launched in March 2022 to “support and sustain action from civil society, government, and private industry” in the countries that have signed onto the GMP by “meaningfully investing in methane reduction solutions.”[1306]

Numerous new methane funding announcements were made at the COP28 Methane Summit (*see* **Section 7** and **Section 10(A)**), including that the Global Methane Pledge secured over $1 billion in new grant funding. In addition, international financial institutions approved over $3.5 billion in new investments for methane-reducing projects since COP27.[1307] These approvals included $375 million from the Green Climate Fund and partners, over $1.9 billion (€1.78 billion) from the European Investment Bank, over $218 million (€200 million) from the European Bank for Reconstruction and Development, and $372.5 million from the Inter-American Development Bank.[1308]

This momentum must continue, and finance must ramp up to enable countries to achieve the GMP. COP29 should establish a global methane fund of $10 billion a year for the next five years. This will help bridge the gap in methane finance. The fund could include financing and investment from sovereign wealth funds, the private sector, and the World Bank and other international financial institutions,[1309] as well as penalties collected from non-compliance, similar to the methane fee provision in the U.S.’ Inflation Reduction Act,[1310] and the methane fee proposed in a staff paper released by the International Monetary Fund.[1311] (It is important to note this staff paper does not necessarily represent the views of the International Monetary Fund.)[1312] There is an opportunity to make a specific methane funding announcement at the next Spring meeting of the IMF and World

Bank. The G20 could also direct the IMF and World Bank to address some of the actions set out above and discussed in this Section.

The efforts of key financial institutions and philanthropic organizations to address methane mitigation are discussed below, along with proposals for methane taxes and fees and reform of the global climate finance architecture.

A. Global Methane Hub

The Global Methane Hub was launched in March 2022 with the mandate to support and sustain action from civil society, government, and private industry to achieve the Global Methane Pledge through targeted and effective investment in methane mitigation solutions."[1313] The Global Methane Hub focuses on the energy, agricultural, and waste sectors and supports ambitious catalytic investments and long-term transformation of challenging sectors.[1314] The Hub's funding focuses on cross-cutting emissions in the highest methane emitting regions and sources around the world.[1315]

As of December 2023, the Global Methane Hub had raised over $200 million in pooled funds from more than 20 of the largest climate philanthropies to accelerate methane mitigation.[1316] The funding work of the Global Methane Hub is an important part of enabling countries to achieve the GMP. In addition, the Hub performs a critical role in facilitating effective and targeted collaboration on methane mitigation between private and public finance.

In June 2022, the U.S., the EU, and 11 other countries launched the Global Methane Pledge Energy Pathway (*see also* **Section 10A(i)**), which includes $59 million in funding to support methane reductions in the oil and gas sector.[1317] This funding included up to $40 million annually from the Hub to support methane mitigation in the fossil energy sector.

At COP28, the Global Methane Hub formally launched the Enteric Fermentation R&D Accelerator with $200 million in funding, making it the largest ever globally coordinated research effort into livestock methane reduction.[1318] The Global Methane Hub also launched the Waste Methane Assessment Platform (WasteMAP), a global initiative in collaboration with Rocky Mountain Institute and Clean Air Task Force and with support from Google.

In addition, the Global Methane Hub announced funding initiatives to deliver resources to governments, businesses, and local climate organizations as they implement their methane mitigation strategies.[1319] For example, the Data to Methane Action Campaign in collaboration with the UNEP International Methane Emissions Observatory and its partners. The Global Methane Hub also provided $10 million in funding to help support governments and businesses identify and reduce methane leaks through better data monitoring; and supported the International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP), along with the U.S. State Department, which will develop agricultural methane strategies in 25 countries.[1320]

B. The Methane Finance Sprint

In April 2023, Major Economies Forum participants, the U.S., EU, Canada, Norway, Ireland, France, Germany, and Japan, launched the Methane Finance Sprint.[1321] A handful of entities administering the Methane Finance Sprint, including the World Bank and the Global Methane

Hub, set out to mobilize, by COP28, at least $200 million in new public and philanthropic support for methane abatement activities, with a view to developing a pipeline of projects.[1322]

As announced at COP28, governments, the European Commission, philanthropies, and the private sector significantly exceeded that target, announcing over $1 billion in new grant funding committed since COP27 (*see* **Section 10A(iv)**).[1323] This funding includes $255 million for the re-launch of the World Bank GMFR, $200 million for the launch of the Enteric Fermentation Accelerator, and additional support for the CCAC, the IMEO, and other programs (*see* **Section 7**).[1324]

C. International Monetary Fund-World Bank Climate Advisory Group

In September 2023, the IMF and the World Bank announced the formalization of regular meetings of the IMF-World Bank Climate Advisory Group. This Group will meet every two months to discuss global and country level engagements, including the results of Country Climate and Development Report (CCDRs), country level climate analytical work, and the pipeline of key projects and lending (*see below*).[1325] In addition, the IMF and WBG committed to incorporate climate considerations into their revised joint *Low Income Country Debt Sustainability Framework*.[1326]

These regular meetings between the IMF and World Bank present an opportunity to regularly co-ordinate and consider ways to better facilitate methane mitigation measures across the IMF's and WBG's efforts to address the climate emergency.

D. International Monetary Fund

The IMF recognizes that climate change is a long-term structural challenge that will make countries more prone to severe balance of payment problems by raising the likelihood and impact of future shocks and undermining growth prospects.[1327] IMF staff recognized that cutting methane emissions is critical to stabilizing the global climate and financing would need to be part of an international agreement aimed at mitigating methane "given that mitigation costs would fall disproportionately on emerging market economies."[1328]

i. Resilience and Sustainability Trust

In August 2021, the IMF Board of Governors approved the anticipated general allocation of $456 billion worth of Special Drawing Rights (SDR) (equivalent to US$605 billion).[1329] While this was a historic accomplishment by the International Monetary Fund under the direction of the International Monetary Fund's Managing Director, Kristalina Georgieva, because of the IMF's quota system, the vast majority of SDRs flow to high-income countries. Recognizing this shortcoming, the G7 leaders previously pledged to redirect $100 billion worth of SDRs for countries most in need of resources to address the COVID-19 pandemic, stabilize their economies, and mount a green and global recovery that is aligned with shared development and climate goals.[1330]

In October 2021, at the G20 meeting in Rome, world leaders issued the Leaders' Declaration requiring the International Monetary Fund to establish a Resilience and Sustainability Trust (RST). In this Declaration, the G20 Leaders elaborated that the RST would "provide affordable long-term financing to help low-income countries…. and vulnerable middle-income countries to reduce risks to prospective balance of payments stability, including those stemming from pandemics and climate change."[1331] This was the first time the G20 Heads of State called on the IMF to play a role in reducing economic risks due to climate change.

The Executive Board of the IMF approved the establishment of the RST on 13 April 2022.[1332] Upon its establishment the IMF estimated total resource needs for the RST as SDR 33 billion (equivalent to US$45 billion). The RST was designed to complement IMF's existing lending toolkit that focuses on longer-term structural challenges, including climate change and pandemic preparedness. It aims to enhance economic resilience and sustainability by: 1) supporting policy reforms to reduce macro-critical risks associated with longer-term structural challenges; and 2) augmenting policy space and financial buffers to mitigate the risks arising from such longer-term structural challenges—thereby contributing to *prospective balance of payments stability*.[1333]

The IMF Executive Board conducted an annual review of the resource adequacy of the RST in April 2023. As at that date, the IMF announced that five countries had received loans from the RST and 44 countries had expressed an interest in borrowing from the RST.[1334] As of end of December 2023, 18 countries, including China, France, Germany, Japan, the UK, Canada, Italy, and the Netherlands, had pledged the equivalent of US$42.8 billion on SDRs to the RST.[1335] At COP28, the UAE announced a commitment to provide $200 million to the RST.[1336] It is also noteworthy that in December 2022, the U.S. Congress' approved an appropriation $20 million to either the IMF's Poverty Reduction and Growth Trust or the RST.[1337]

The RST may finance, *inter alia*, costs of climate-related public and/or private investments, like energy efficient retrofitting of existing buildings, costs associated with transitioning to green technologies, and offsetting costs of policies to ensure a just transition, like providing social assistance as governments unwind carbon subsidies.[1338] RST disbursement is linked to the country's financial reform progress. RST measures are informed and consistent with country diagnostics tools developed by both the IMF (the and the World Bank (discussed below) relevant to the RST's purposes.[1339] About three quarters of IMF's membership are eligible for RST financing, including low-income countries, developing and vulnerable small states, and lower middle-income countries.[1340] Access is capped at SDR 1 billion. The loans have a 20-year maturity and a 10.5-year grace period.[1341]

After becoming operational in December 2022, it remains to be seen how effectively the RST can contribute to supporting countries efforts on methane reductions. The IMF expects that the "RST support for the development and implementation of overarching policy frameworks such as green public financial management would improve the integration of climate in policy formulation and enhance governance, thereby giving more comfort to other public and private lenders and donors to provide project financing and technical assistance."[1342] This could present an opportunity for countries that are contributing SDRs to the RST to ensure private sector engagement on methane mitigation. According to the RST framework document, "the RST would focus on downside scenarios associated with select longer-term challenges. It would aim to lower the probability of such scenarios and/or reduce the severity of the [balance of payment] problems that would materialize should such a scenario come to pass."[1343]

The RST framework does not specifically mention methane emissions mitigation among the projects that could benefit from RST financing. However, the language of the framework is sufficiently broad to cover methane action. The IMF and its members, with guidance from the World Bank, should be encouraged to divert funding to methane emissions mitigation policy reforms.[1344] Focusing on methane, the RST could provide financial support to countries in their efforts to reduce methane and create the market conditions for private-sector investment in methane reductions. For example, the RST could include the possibility of allocating SDRs to middle-income countries that have the capacity to catalyze low-cost financing to implement the GMP. The RST should also enhance the ability of middle-income countries to mobilize longer-term financing for just transitions in high methane-emitting sectors. These design aspects must be done without increasing the debt burden of the SDR recipient.

As the IMF continues the RST to reduce climate risk, the IMF must keep climate science as the core of its efforts. The IMF should consider including tipping points and feedbacks in IMF climate modeling. The RST scenarios should use GWP_{20} and include the climate, economic, and social benefits of undertaking methane mitigation. The RST's design, implementation, and measure of its success should be guided by the latest science on climate emergency, climate risk, and pathway to a climate safe zone, including through fast, near-term methane mitigation. It is noteworthy that IMF staff published a paper on *How to Cut Methane Emissions*, specifically calling for a global agreement on methane pricing.[1345]

National climate-risk scenarios cannot be done in isolation because climate is a global challenge. Therefore, such national scenarios should be linked with the global scenario and the 1.5 °C temperature and GMP goals.

E. World Bank Group

The World Bank Group (WBG) is the largest provider of climate finance for developing countries. In 2018, the WBG announced a new set of climate targets for 2021–2025, "doubling its current 5-year investments to around US$200 billion in support for countries to take ambitious climate action."[1346] The US$200 billion consists of "approximately US$100 billion in direct finance from the World Bank, and approximately US$100 billion in combined direct finance" from the International Finance Corporation, the Multilateral Investment Guarantee Agency, and WBG-mobilized private capital.[1347] As part of this action plan, the WBG committed to align all of its financing operations with the Paris Agreement. The World Bank announced it was on track to align 100% of new operations with the Paris Agreement goals from 1 July 2023. For the International Finance Corporation and Multilateral Investment Guarantee Agency, 85% of new operations will be aligned from 1 July 2023 and 100% from 1 July 2025.[1348]

The latest IPCC reports offer an opportunity for the WBG to review its Climate Action Plan (2021–2025) and to ensure its portfolio aligns with the 1.5 °C temperature goal of the Paris Agreement, focusing on the climate emergency, tipping points, and feedback loops, and prioritizing investments in fast mitigation strategies as essential to build resilience and reduce climate risk.[1349] The WBG could also begin incorporating the use of metrics that capture the near-term temperature impacts of methane and other SLCPs, such as GWP_{20}, in all its work to promote carbon markets.[1350]

In 2012, the G8 agreed to commission the WBG to evaluate innovative pay-for-performance mechanisms to address methane.[1351] A report by the Methane Finance Study Group supported the establishment of a methane facility.[1352] In its design and development phase, the Pilot Auction Facility for Methane and Climate Change Mitigation (PAF) benefited from the support of the Climate & Clean Air Coalition.[1353] The PAF completed three auctions to allocate a guaranteed price for future carbon credits in the form of a tradable put option, two for the abatement of methane emissions from the waste sector and one for the abatement of nitrous oxide emissions from nitric acid production.[1354] The three auctions allocated up to US$54 million, resulting in abatement of up to 20.6 million metric tons of CO_2e (using GWP_{100}, thus undervaluing methane climate impact). The main PAF contributors were Germany, Sweden, Switzerland (through a joint contribution of the State Secretariat of Economic Affairs and the Climate Cent Foundation), and the United States.[1355] The GMP might provide an opportunity to further explore this kind of finance mechanism.

Over the last few years, WBG has significantly increased funding of methane mitigation projects across the energy, agriculture, and waste sectors.[1356]

The International Finance Corporation, the WBG's private sector arm, finances methane mitigation projects. For example, in 2021, the International Finance Corporation also announced it had supported one of the largest gas flaring reduction projects in the world in Iraq by arranging a $360 million loan.[1357] In 2022, International Finance Corporation disclosed its funding for 24 landfill gas-to-energy project that will be implemented in 10 provinces in China.[1358] The project is estimated to reduce about 3.4 Mt CO_2e of GHG through methane capture.[1359] Their Green Bond Program offers financing for methane reduction projects focusing on livestock, aquaculture, gas flaring, and waste-to-energy among the list of projects eligible financing.[1360] However, the International Finance Corporation could do more and update its Performance Standards on Environment and Social Sustainability (last updated in 2012) and its Definitions and Metrics on Climate Related Activities (last updated in 2017) with the latest climate emergency science, including climate tipping points and feedback loops in its definition of climate risk so that its financing offerings remain current.

The WBG's International Development Association also funds methane mitigation projects. The International Development Association works in 74 countries and aims to reduce poverty by providing financing and policy advice that boost economic growth, build resilience, and improve the lives of people in the world's lowest income countries.[1361] For example, the International Development Association provided $115 million for an urban sanitation project in Mozambique to improve access to safely managed sanitation to reduce methane emissions,[1362] and provided $200 million for a project in the Logone Valley in Cameroon to improve irrigation and drainage systems to limit methane emissions from rice fields and train farmers on climate-smart agricultural approaches.[1363]

In addition, the Multilateral Investment Guarantee Agency, a WBG member that provides long-maturity guarantees,[1364] can support quick and permanent adoption of methane emission solutions. Many of the actions to reduce methane emission involve long-term investment. The Multilateral Investment Guarantee Agency could produce a plan to scale up its capital optimalization product to support a range of methane mitigation loans and deploy a strategy to attract commercial banks partnership in key projects.

At COP27, the World Bank hosted an event titled "It's Time to Sprint: Targeting Methane Emissions."[1365] Since COP27, the WBG has increased its support of methane mitigation. In addition to direct lending or investment, WBG's support includes analytical work, capacity building, support on regulatory reform, leak detection and monitoring, investment feasibility studies.[1366] At COP28, the WBG announced that since COP27 it had approved at least $700 million in investments, including $455 million for a rice project in China, $300 million for landfill methane reduction in Cote d'Ivoire, and $145 million for wastewater methane reduction in Malawi.[1367] The WBG also launched at COP28 the Global Methane Reduction Platform for Development (CH4D) to support low- and mid-income countries to realize the "methane triple-wins" of abating emissions, enhancing resilience, and empowering livelihoods.[1368] The World Bank also re-launched, the Global Gas Flaring Reduction Partnership (GGFR) as the Global Flaring and Methane Reduction (GFMR) Partnership, a new multi-donor trust fund focused on helping developing countries cut carbon dioxide and methane emissions generated by the oil and gas industry (*see* **Section 7**).[1369]

i. Country Climate and Development Report

As part of the RST architecture, the IMF, and World Bank agreed on "Broad Principles for Bank-Fund Coordination in RST Operations."[1370] One of the key tools of this collaboration is the World Bank's CCDR. The CCDRs are a relatively new WBG diagnostic tool (announced at COP26)[1371] that integrate climate change and development considerations and help countries prioritize the most impactful actions that can reduce greenhouse gas emissions, including methane, and boost adaptation.[1372] As public documents, CCDRs aim to inform governments, citizens, the private sector, and development organizations to engage and implement a climate and development agenda.[1373] The CCDRs may complement the IMF's Climate Macroeconomic Assessments Programs, which is the successor to the Climate Change Policy Assessments (CCPAs).[1374]

Each year key insights from the CCDRs are summarized by the WBG in an annual report.[1375] The 2023 annual report released at COP28 combined results from the CCDRs in 42 countries and highlighted cost-effective opportunities to reduce methane emissions included in numerous CCDRs.[1376] The CCDRs present an opportunity to identify countries' methane mitigation measures that align with meeting the Global Methane Pledge commitments.

F. Private Investment

At COP28, the United Arab Emirates announced the launch of Alterra, a private investment fund for global climate solutions focusing on emerging markets and developing countries.[1377] Alterra seeks to bridge the climate financing gap by raising and investing up to $250 billion of institutional and private capital by 2030. The fund operates in collaboration with BlackRock, Brookfield, and TPG as inaugural partners and had $6.5 billion in committed climate investments, including investments in the Global South, as of December 2023.[1378] The size and focus of this investment fund should facilitate countries' compliance with the Oil and Gas Decarbonization Charter (also announced at COP28 and discussed in **Section 7**).

The IEA notes that investors and insurers are beginning to establish methane performance requirements as a condition on future lending. This includes underwriting standards that include methane reductions. For example, Barclays announced that starting from 2026, energy clients will be required to have 2030 methane emissions reduction targets and a commitment to end all routine venting and flaring by 2030.[1379]

G. Global Methane Tax/Fee

The IMF has modelled the implementation of a methane tax or fee in the top 35 methane-emitting countries.[1380] This tax or fee would work by integrating an initial fee of $10 per tonne of CO_2 equivalent rising to $70 per tonne of CO_2-equivalent in 2030 into existing fiscal regimes.[1381] The European Union's newly adopted CBAM, designed to prevent outsourcing of carbon-intensive industries and incentivize sustainable practices abroad,[1382] does not address imported methane. Some have called for methane to be addressed in future measures,[1383] although concerns have been voiced about the imposition of border adjustment mechanisms from a global trade law and policy perspective.[1384] CBAM entered into effect on a transitional basis in October 2023, only applying during this transitional phase to imports of cement, iron and steel, aluminum, fertilizers, electricity and hydrogen.[1385] CBAM may evolve in time to allow for broader EU-U.S. alignment on a global methane border adjustment mechanism.[1386] The European Union's first-ever methane regulations, however, do include ambitious monitoring and abatement criteria for both domestically produced and imported fossil oil, gas, and coal, and establish a methane import standard by 2030.[1387] **Section 6E** further discusses the European Union's methane regulations and directives. Separately, the Peterson Institute for International Economics has proposed a new global methane border adjustment mechanism where countries would be expected to align with new EU-U.S. methane regulation or pay a methane border adjustment tax.[1388]

H. A Global Financial Strategy to Tackle the Climate Emergency including Methane

At COP26, Prime Minister Mia Mottley from Barbados presented a financial plan to tackle the climate emergency. Prime Minister Mottley, who is also Co-Chair of the Development Committee of the World Bank and the IMF, noted that:

> "The central banks of the wealthiest countries engaged in 25 trillion dollars of quantitative easing in the last 13 years. 25 trillion. Of that, $9 trillion was in the past 18 months – to fight the pandemic. Had we used that $25 trillion to purchase bonds to finance the energy transition, or the transition of how we eat, or how we move ourselves in transport, we would now, today, be reaching that 1.5 degree limit that is so vital to us."[1389]

Prime Minister Mottley proposed an annual increase in the SDRs of $500 billion a year for twenty years to be put in a trust to finance the transition. She pointed out that $500 billion is just 2% of the $25 trillion that central banks from the wealthiest countries engaged in the last 13 years.[1390] The proposal includes a $500 billion trust that would operate on an auction basis for the greatest climate mitigation and include the private sector in its eligibility criteria. Prime Minister Mottley continues to advocate for the creation of this trust which, to truly attenuate the climate emergency, must prioritize methane emissions reductions.[1391] In her address at COP28, Prime Minister Mottley continued to emphasize the need for a different approach to the global capitalization of international financial institutions, including for non-state actors to contribute to this capitalization. She also noted that we have yet to see the global methane agreement that the world needs as part of a change of course on climate action.[1392]

At COP28, major international financial institutions and countries made new commitments to offer climate-resilient debt clauses (CRDCs) in their lending. These clauses allow debt service to be paused to give countries breathing space after climate disasters.[1393] The use of CRDCs was supported by over 70 countries and new commitments to expand the use of CRDCs were made by the UK, France, World Bank, Inter-American Development Bank, European Investment Bank, European Bank for Reconstruction and Development, and African Development Bank.[1394] The IDB announced it had already offered $1.2 billion of loans covered by CRDCs.[1395] Also at COP28, Japan and France announced they would co-lead in supporting the African Development Bank's facility to leverage IMF SDRs for climate and development.[1396]

Earlier, in 2022, Barbados hosted the Bridgetown Initiative with key stakeholders and developed the Bridgetown Agenda.[1397] While the Bridgetown Agenda does not specifically include methane, if implemented, it might present an important opportunity for methane mitigation within the global finance system.

Building upon the Bridgetown Agenda as well as other climate finance flagship initiatives, the UAE Leaders' Declaration on a Global Climate Finance Framework was launched at the start of COP28.[1398] The Declaration seeks to reform the global climate finance architecture by making climate finance available, accessible, and affordable.[1399] The principles in the Declaration emphasize the need for reform of MDBs to better address climate change, widening concessional finance, and for global private and public financial architecture to be made "fit for more frequent, profound shocks" including through wider use of CRDCs and rechallenging IMF SDRs through the RST.[1400] Barbados, Germany, France, Ireland, the Philippines, Colombia, Ghana, Kenya, India, Senegal, UAE, the UK and the United States signed the Declaration.[1401] While the Declaration does not specifically address methane, the high-level principles it contains are a useful framework to unlock public and private finance to fund methane mitigation globally at the scale and speed required.

12. Conclusion

Cutting methane emissions is the best way we know to slow warming in the next 20 years. Achieving the goal of up to 0.3 °C in avoided warming to keep 1.5 °C within reach requires building technical, financial, and governance mechanisms. The COP28 Methane Summit, GMP, and the increasing demand for multilateralism represent important steps along the way to implementing existing commitments and moving to a binding global methane agreement. This includes immediate action to require a progressively lower methane emissions rate from providers that continue to supply "replacement methane gas" in response to changes in countries' methane gas imports, through the full implementation of initiatives such as the CBAM mechanism and methane taxes or fees. Improvements in monitoring systems add transparency but need to be paired with an accountability and enforcement strategy that incentivizes effective emissions reductions by connecting emitters with technical and financial capacity. At the same time, a global methane agreement must be flexible enough to account for growing crises in peace, food security, and global democracy such that it can adapt to the evolving nature of the climate emergency. The Montreal Protocol provides a solid foundation for the architecture of a global methane agreement, with existing methane ambition offering an initial scope for targets, policies, and initiatives that could be pursued under a global methane agreement. This *Methane Primer* lays out the urgency, opportunity, and key pieces to build a solid foundation for a global methane agreement, which should be the ultimate goal if we are going to succeed in slowing global warming in this decade.

Acronyms

AIM4C	Agriculture Innovation Mission for Climate
AR6	Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
AR6 WGI	Working Group I contribution to the IPCC Sixth Assessment Report on the *Physical Science Basis* (2021)
AR6 WGII	Working Group II contribution to the IPCC Sixth Assessment Report on *Impacts, Adaptation, and Vulnerability* (2022)
AR6 WGIII	Working Group III contribution to the IPCC Sixth Assessment Report on *Mitigation of Climate Change* (2022)
ARPA-E	Advanced Research Projects Agency–Energy (U.S.)
ASEAN	Association of Southeast Asian Nations
BRICS	Brazil, Russia, India, China, South Africa
BUR	Biennial Update Report (India)
CATF	Clean Air Task Force
CAP	Common Agriculture Policy (EU)
CBM	coal bed methane
CBAM	Carbon Border Adjustment Mechanism (EU)
CCAC	Climate & Clean Air Coalition
CCDR	Country Climate and Development Reports
CCPA	Climate Change Policy Assessment
CH_4	methane
CH4D	Global Methane Reduction Platform for Development (World Bank)
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP26	26th Conference of the Parties (Glasgow, Scotland) (2021)
COP27	27th Conference of the Parties (Sharm El-Sheikh, Egypt) (2022)
COP28	28th Conference of the Parties (Dubai, United Arab Emirates) (2023)
COP29	29th Conference of the Parties (Baku, Azerbaijan) (2024)
DMAA	Dairy Methane Action Alliance
EDF	Environmental Defense Fund

EMIT	Earth Surface Mineral Dust Source (NASA)
EPA	Environmental Protection Agency (U.S.)
ESG	Environmental, Social, and Governance framework
EXIM	Export–Import Bank of the United States
GBA	Global Biofuels Alliance
GCF	Green Climate Fund
GFMR	Global Flaring and Methane Reduction (World Bank)
GGFR	Global Gas Flaring Reduction Partnership (World Bank)
GFMR	Global Flaring Methane Reduction Partnership (World Bank)
GHG	greenhouse gas
GMI	Global Methane Initiative
GMP	Global Methane Pledge
GOSAT	Greenhouse Gas Observing Satellite (Japan)
Gothenburg Protocol	Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg, Sweden) (1999)
GRI	Global Reporting Initiative
GWP	global warming potential
HFC	hydrofluorocarbons
HoD	Heads of Delegation
IEA	International Energy Agency
IEF	International Energy Forum
IFAD	International Fund for Agriculture Development
IMEO	International Methane Emissions Observatory
IMF	International Monetary Fund
IMRRP	Iron Mains Risk Reduction Programme (UK)
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory (NASA)
Kigali Amendment	Kigali Amendment to the Montreal Protocol (Kigali, Rwanda) (2016)
LDAR	leak detection and repair
LNG	liquefied natural gas

LRTAP	Convention on Long-Range Transboundary Air Pollution
MAMII	Methane Abatement in Maritime Innovation Initiative
MARS	Methane Alert and Response System (UNEP & IMEO)
MEE	Ministry of Ecology and Environment (China)
MERiL	Methane Emissions Reduction in Livestock (Australia)
MLF	Multilateral Fund of the Montreal Protocol
Montreal Protocol	Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal, Canada) (1987)
M-RAP	Methane Roadmap Action Programme (CCAC)
MMRV	measurement, monitoring, reporting, and verification
MRV	measurement, reporting, and verification
MSW	municipal solid waste
Mt	metric ton
N_2O	nitrous oxide
NASA	National Aeronautics and Space Administration (U.S.)
NDC	Nationally Determined Contribution
NGSI	Natural Gas Sustainability Initiative
NZE	Net Zero Emissions by 2050
O_3	tropospheric ozone
OCI+	Oil Climate Index Plus
OGCI	Oil & Gas Climate Initiative
OGDC	Oil & Gas Decarbonization Charter
OGMP	Oil & Gas Methane Partnership
PAF	Pilot Auction Facility for Methane and Climate Change Mitigation
PEMEX	Petróleos Mexicanos
PFCs	perfluorocarbon
PIPES Act	Protecting Our Infrastructure of Pipelines and Enhancing Safety Act (U.S.) (2020)
ppb	parts per billion
PROVE IT Act	Providing Reliable, Objective, Verifiable Emissions Intensity and Transparency Act (U.S.) (2024)

R&D	research & development
RAMP	Reducing Agricultural Methane Program (IFAD)
REME	Reducing Enteric Methane Emissions from Beef Cattle (Canada)
REMEDY	Reducing Emissions of Methane Every Day of the Year (U.S.)
RMI	Rocky Mountain Institute
RST	Resilience and Sustainability Trust (IMF)
SAP	Scientific Assessment Panel (CCAC)
SDR	Special Drawing Rights (IMF)
SLCP	short-lived climate pollutant
SO_2	sulfur dioxide
TEAP	Technology and Economic Assessment Panel (CCAC)
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USTDA	United States Trade and Development Agency
WasteMAP	Waste Methane Assessment Platform (RMI & CATF)
WBG	World Bank Group
WHO	World Health Organization

References

[1] Abnett K. & Dickie G. (8 November 2023) *This year "virtually certain" to be warmest in 125,000 years, EU scientists say*, REUTERS ("This year is "virtually certain" to be the warmest in 125,000 years, European Union scientists said on Wednesday, after data showed last month was the world's hottest October in that period. Last month smashed through the previous October temperature record, from 2019, by a massive margin, the EU's Copernicus Climate Change Service (C3S) said. "The record was broken by 0.4 degrees Celsius, which is a huge margin," said C3S Deputy Director Samantha Burgess, who described the October temperature anomaly as "very extreme". … "When we combine our data with the IPCC, then we can say that this is the warmest year for the last 125,000 years," Burgess said.").

[2] Arias P. A., *et al*. (2021) *Technical Summary*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al*. (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)").

[3] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}").

[4] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}"); 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).").

[5] Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, PROC. NAT'L. ACAD. SCI. 107(43): 18354–18359, 18357 ("In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is

ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions.").

[6] Comparison of strategy targeting CO_2 alone to a reference scenario with limited climate mitigation and when accounting for the reduction in reflective particles that mask warming as a result of decarbonization strategies that phase out fossil fuel use. *See* Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 5 ("Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith, but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020. Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events. By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5)."). When excluding consideration of unmasking of reflective particles, strategies that target super climate pollutants could avoid as much as 0.6°C by 2050 compared to 0.1-0.2°C for CO2-focused strategies alone. Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10321 ("The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1)."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}").

[7] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."), 262 ("Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change."). *See also* Shindell D., *et al.*

(2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065): 183–189, 183–185 ("The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. … Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases. … BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic)."); *and* United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."), 262 ("Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.").

[8] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-19 ("With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*).").

[9] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11(8): 689–685, Supplementary Information ("In the main manuscript, we illustrate a fundamental difference in the behavior of (i) the statistically expected return levels or return periods of extremes traditionally defined as anomalies relative to a reference period, i.e. the probability of exceeding a fixed threshold and (ii) the expected probability of record-shattering extremes. For (i) the statistically expected return periods and levels are largely proportional to the warming level independent of the emission pathway (RCP/SSP), whereas for (ii) the statistically expected probability differs for the same warming level depending on the warming rate of the underlying forced response (i.e. the multi-member mean warming) and thereby on the emission pathway (RCP or SSP).").

[10] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11(8): 689–695, 689 ("Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission

scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades."); Supplementary Information ("In the main manuscript, we illustrate a fundamental difference in the behavior of (i) the statistically expected return levels or return periods of extremes traditionally defined as anomalies relative to a reference period, i.e. the probability of exceeding a fixed threshold and (ii) the expected probability of record-shattering extremes. For (i) the statistically expected return periods and levels are largely proportional to the warming level independent of the emission pathway (RCP/SSP), whereas for (ii) the statistically expected probability differs for the same warming level depending on the warming rate of the underlying forced response (i.e. the multi-member mean warming) and thereby on the emission pathway (RCP or SSP).").

[11] Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 555 ("The threshold-crossing time is defined as the midpoint of the first 20-year period during which the average GSAT exceeds the threshold. In all scenarios assessed here except SSP5-8.5, the central estimate of crossing the 1.5°C threshold lies in the early 2030s. This is in the early part of the *likely* range (2030–2052) assessed in the IPCC Special Report on Global Warming of 1.5°C (SR1.5), which assumed continuation of the then-current warming rate; this rate has been confirmed in the AR6. Roughly half of this difference between assessed crossing times arises from a larger historical warming diagnosed in AR6. The other half arises because for central estimates of climate sensitivity, most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5 (*medium confidence*)."). *See also* Tollefson J. (21 November 2023) *Is it too late to keep global warming below 1.5°C? The challenge in 7 charts*, NATURE ("At this rate, it could be less than a decade — possibly much sooner — before global warming reaches 1.5 °C above pre-industrial levels. Natural variations, such as the current El Niño warming in the tropical Pacific, can significantly influence temperatures in the short term. The Intergovernmental Panel on Climate Change (IPCC) uses 10- and 20-year rolling averages when it calculates Earth's surface temperature. This means there can be a long lag between the official IPCC estimate of global warming and the average temperatures in any given year.").

[12] Diffenbaugh N. S. & Barnes E. A. (2023) *Data-driven predictions of the time remaining until critical global warming thresholds are reached*, PROC. NAT'L. ACAD. SCI. 120(6): 1–9, 2 ("For 1.5 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2035 (2030 to 2040) in the High scenario, 2033 (2028 to 2039) in the Intermediate scenario, and 2033 (2026 to 2041) in the Low scenario (Fig. 3). For 2 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2050 (2043 to 2058) in the High scenario, 2049 (2043 to 2055) in the Intermediate scenario, and 2054 (2044 to 2065) in the Low scenario."), *discussed in* Harvey C. (31 January 2023) *AI Predicts Warming Will Surpass 1.5 C in a Decade*, SCIENTIFIC AMERICAN. *See also* Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Comment, NATURE 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there's a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see 'Accelerated warming'). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu, Ramanathan, and Victor comment was published, the IPCC has updated its estimate for when 1.5 °C will be exceeded: *see* Arias P. A., *et al.* (2021) *Technical Summary*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., et al. (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the

likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"). *See also* Dvorak M. T., Armour K. C., Frierson D. M. W., Proistosescu C., Baker M. B., & Smith C. J. (2022) *Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming*, NAT. CLIM. CHANGE 12: 547–552, 547 ("Following abrupt cessation of anthropogenic emissions, decreases in short-lived aerosols would lead to a warming peak within a decade, followed by slow cooling as GHG concentrations decline. This implies a geophysical commitment to temporarily crossing warming levels before reaching them. Here we use an emissions-based climate model (FaIR) to estimate temperature change following cessation of emissions in 2021 and in every year thereafter until 2080 following eight Shared Socioeconomic Pathways (SSPs). Assuming a medium-emissions trajectory (SSP2–4.5), we find that we are already committed to peak warming greater than 1.5 °C with 42% probability, increasing to 66% by 2029 (340 $GtCO_2$ relative to 2021). Probability of peak warming greater than 2.0 °C is currently 2%, increasing to 66% by 2057 (1,550 $GtCO_2$ relative to 2021). Because climate will cool from peak warming as GHG concentrations decline, committed warming of 1.5 °C in 2100 will not occur with at least 66% probability until 2055.").

[13] Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, NATURE 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes[2]. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of 0.25–0.32 °C per decade[3]. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report."). For historical rates of warming, *see* Lindsey R. & Dahlman L. (18 January 2024) *Climate Change: Global Temperature*, National Oceanic and Atmospheric Administration ("Though warming has not been uniform across the planet, the upward trend in the globally averaged temperature shows that more areas are warming than cooling. According to NOAA's 2023 Annual Climate Report the combined land and ocean temperature has increased at an average rate of 0.11° Fahrenheit (0.06° Celsius) per decade since 1850, or about 2° F in total. The rate of warming since 1982 is more than three times as fast: 0.36° F (0.20° C) per decade.").

[14] World Meteorological Organization (2023) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, 2 ("The chance of global near-surface temperature exceeding 1.5°C above preindustrial levels for at least one year between 2023 and 2027 is more likely than not (66%). It is unlikely (32%) that the five-year mean will exceed this threshold."). For previous years, *see* Madge G. (8 May 2022) *Temporary breaching of 1.5C in next five years?*, UK MET OFFICE ("The chance of at least one year exceeding 1.5°C above pre-industrial levels between 2022-2026 is about as likely as not (48%). However, there is only a very small chance (10%) of the five-year mean exceeding this threshold."); *discussing* World Meteorological Organization (2022) GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE. *See also* Hook L. (9 May 2022) *World on course to breach global 1.5C warming threshold within five years*, FINANCIAL TIMES. World Meteorological Organization (2021) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, 5 ("Relative to pre-industrial conditions, the annual mean global near surface temperature is predicted to be between 0.9°C and 1.8°C higher (90% confidence interval). The chance of at least one year exceeding 1.5°C above pre-industrial levels is 44% and is increasing with time. There is a very small chance (10%) of the five-year mean exceeding this threshold. The Paris Agreement refers to a global temperature increase of 1.5°C, which is normally interpreted as the long-term warming, but temporary exceedances would be expected as global temperatures approach the threshold."); *discussed in* Hodgson C. (26 May 2021) *Chance of temporarily reaching 1.5C in warming is rising, WMO says*, FINANCIAL TIMES; World Meteorological Organization (2020) UNITED IN SCIENCE 2020, 16 ("Figure 2 shows that in the five-year period 2020–2024, the annual mean global near surface temperature is predicted to be between 0.91 °C and 1.59 °C above pre-industrial conditions (taken as the average over the period 1850 to 1900). The chance of at least one year exceeding 1.5 °C above pre-industrial levels is 24%, with a very small chance (3%) of the five-year mean exceeding this level. Confidence in forecasts of global mean temperature is high. However, the coronavirus lockdown caused changes in emissions of greenhouse gases and aerosols that were not included in the forecast models. The impact of changes in greenhouse gases is likely small based on early estimates (Le Quéré et al. 2020 and Carbonbrief.org)."); *and* McGuire B. (12 September 2022) *Why we should forget about the 1.5C global heating target*, THE GUARDIAN.

[15] This value is averaged from five agencies' reported 2023 temperature anomalies. Datasets used by different scientific agencies tend to have fewer data (and thus different baselines) for the pre-industrial period of 1850–1900, and so report slightly different values for the temperature anomaly. For data reported by the five agencies, *see* Hausfather Z. (12 January 2024) *State of the Climate: 2023 smashes records for surface temperature and ocean heat*, CARBON BRIEF.

[16] Abnett K. & Dickie G. (8 November 2023) *This year "virtually certain" to be warmest in 125,000 years, EU scientists say*, REUTERS ("This year is "virtually certain" to be the warmest in 125,000 years, European Union scientists said on Wednesday, after data showed last month was the world's hottest October in that period. Last month smashed through the previous October temperature record, from 2019, by a massive margin, the EU's Copernicus Climate Change Service (C3S) said. "The record was broken by 0.4 degrees Celsius, which is a huge margin," said C3S Deputy Director Samantha Burgess, who described the October temperature anomaly as "very extreme". … "When we combine our data with the IPCC, then we can say that this is the warmest year for the last 125,000 years," Burgess said.").

[17] Hausfather Z. (2024) *State of the Climate: 2023 smashes records for surface temperature and ocean heat*, CARBON BRIEF ("However, 2023 was so exceptionally warm that it suggests that this El Niño might be behaving differently, with global surface temperatures responding more rapidly than in the past. If this is the case, 2024 would not necessarily follow the pattern of past El Niño events and is less likely to be substantially warmer than 2023. … The Met Office, Dr Schmidt, Berkeley Earth and Carbon Brief estimates all have 2024 as more likely than not to be warmer than 2023 – but only by a small margin. In all estimates it is close to a coin flip which will end up as the warmer year. Against a 1880-99 pre-industrial baseline, the central estimate of all four forecasts is just below 1.5C of warming, with ranges suggesting that temperatures could top 1.5C next year."). *See also* Madge G. (8 December 2023) *2024: First chance of a 1.5 °C year*, UK MET OFFICE ("The anticipated two-stage spike in global temperature has received a temporary and partial boost by the current El Niño event warming the tropical Pacific. But, says the Met Office's Prof Adam Scaife: "The main driver for record-breaking temperatures is the ongoing human-induced warming since the start of the Industrial Revolution." … Global average temperatures are measured as the difference between 1850-1900: a proxy for the Industrial Revolution. The global average temperature for 2023 is expected to be below 1.5 °C, but next year's forecast suggests for the first time that values of 1.5 °C or above cannot be ruled out.").

[18] Hansen J., Sato M., & Ruedy R. (12 January 2024) *Global Warming Acceleration: Causes and Consequences*, Columbia University, 1 ("We expect record monthly temperatures to continue into mid-2024 due to the present large planetary energy imbalance, with the 12-month running-mean global temperature reaching +1.6-1.7°C relative to 1880-1920 and falling to only +1.4 ± 0.1°C during the following La Nina. … How do we know global temperature will continue to grow in the next 5-8 months, carrying the 12-month running-mean to at least 1.6-1.7°C? The main reason is the large increase of global absorbed solar radiation (ASR) since 2015 (Fig. 4), which is a decrease of Earth's albedo (reflectivity) by 0.4% (1.4/340).[9] This reduced albedo is equivalent to a sudden increase of atmospheric CO_2 from 420 to 530 ppm. Increase of EEI (Fig. 5) is smaller than the increase of ASR because the warming increases thermal emission to space. The increase of ASR since 2015 is particularly important because it acts as a "fresh forcing," regardless of whether it is a forcing, a persistent feedback, or a combination thereof. Given the absence of monitoring of global aerosol forcing, ASR provides our best clue as to the changing drives for global warming. These assertions warrant discussion.").

[19] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state11. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature."). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s

(23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94).”); Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, EARTH SYST. DYN. 12(2): 601–619, 614 (“In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the climate system as a whole.”); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 (“Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).”).

[20] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-11 (“Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*).”), SPM-13 (“Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*). … SPM.B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*).”).

[21] Zhang Y., Held I., & Fueglistaler S. (2021) *Projections of tropical heat stress constrained by atmospheric dynamics*, NAT. GEO. 14(3): 133–137, 133 (“For each 1 °C of tropical mean warming, global climate models project extreme TW (the annual maximum of daily mean or 3-hourly values) to increase roughly uniformly between 20° S and 20° N latitude by about 1 °C. This projection is consistent with theoretical expectation based on tropical atmospheric dynamics, and observations over the past 40 years, which gives confidence to the model projection. For a 1.5 °C warmer world, the probable (66% confidence interval) increase of regional extreme TW is projected to be 1.33–1.49 °C, whereas the uncertainty of projected extreme temperatures is 3.7 times as large. These results suggest that limiting global warming to 1.5 °C will prevent most of the tropics from reaching a TW of 35 °C, the limit of human adaptation.”). *See also* Vecellio D. J., Kong Q., Kenney W. L., & Huber M. (2023) *Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance*, PROC. NAT’L. ACAD. SCI. 120(42): 1–9, 3 (“In climate change scenarios of 2 °C warming and below, conditions associated with threshold exceedance are limited to the Indus River Valley, east China, the Persian Gulf coastline, and sub-Saharan Africa. Increases in the

number of hours over the threshold in these regions are mild in transitioning from 1.5 °C to 2 °C (Fig. 1 A and B)… . In this study's worst-case scenario of a 4 °C warmer world, around 2.7 billion persons will experience at least 1 wk of daytime (8 h) ambient conditions associated with uncompensable heat stress, 1.5 billion will experience a month under such conditions, and 363.7 million will be faced with an entire season (3 mo) of life-altering extreme heat (Fig. 1F).").

[22] Lenton T. M., Xu C., Abrams J. F., Ghadiali A., Loriani S., Sakschewski B., Zimm C., Ebi K. L., Dunn R. R., Svenning J.-C., & Scheffer M. (2023) *Quantifying the human cost of global warming*, NAT. SUSTAIN. 6(10): 1–11, 7 (calculated based on Supplementary Data 1 "Country-level results for population, land area and land fraction exposed to MAT > 29°C") ("The ~2.7 °C global warming expected under current policies puts around a third of the world population outside the niche. It exposes almost the entire area of some countries (for example, Burkina Faso, Mali) to unprecedented heat, including some Small Island Developing States (for example, Aruba, Netherlands Antilles; Fig. 5b)—a group with members already facing an existential risk from sea-level rise. The gains from fully implementing all announced policy targets and limiting global warming to ~1.8 °C are considerable, but would still leave nearly 10% of people exposed to unprecedented heat. Meeting the goal of the Paris Agreement to limit global warming to 1.5 °C halves exposure outside the temperature niche relative to current policies and limits those exposed to unprecedented heat to 5% of people."), 1 ("By end-of-century (2080–2100), current policies leading to around 2.7 °C global warming could leave one-third (22–39%) of people outside the niche. Reducing global warming from 2.7 to 1.5 °C results in a ~5-fold decrease in the population exposed to unprecedented heat (mean annual temperature ≥29 °C). The lifetime emissions of ~3.5 global average citizens today (or ~1.2 average US citizens) expose one future person to unprecedented heat by end-of-century. That person comes from a place where emissions today are around half of the global average. These results highlight the need for more decisive policy action to limit the human costs and inequities of climate change."), 5 ("Assuming a future world of 9.5 billion, India has the greatest population exposed under 2.7 °C global warming, >600 million, but this reduces >6-fold to ~90 million at 1.5 °C global warming. Nigeria has the second largest population exposed, >300 million under 2.7 °C global warming, but this reduces >7-fold to 20-fold, from ~100 million under 2.7 °C global warming to 80 million exposed under 2.7 °C global warming, there are even larger proportional reductions at 1.5 °C global warming. Sahelian–Saharan countries including Sudan (sixth ranked) and Niger (seventh) have a ~2-fold reduction in exposure, because they still have a large fraction of land area hot exposed at 1.5 °C global warming (Fig. 5b). The fraction of land area exposed approaches 100% for several countries under 2.7 °C global warming (Fig. 5b). Brazil has the greatest absolute land area exposed under 2.7 °C global warming, despite almost no area being exposed at 1.5 °C, and Australia and India also experience massive increases in absolute area exposed (Fig. 4). (If the future population reaches 11.1 billion, the ranking of countries by population exposed remains similar, although the numbers exposed increase.) Those most exposed under 2.7 °C global warming come from nations that today are above the median poverty rate and below the median per capita emissions (Fig. 6)."). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, PROC. NAT'L. ACAD. SCI. 117(21): 11350–11355, 11352 ("Such a calculation suggests that for the RCP8.5 business-as-usual climate scenario, and accounting for expected demographic developments (the SSP3 scenario[15]),∼3.5 billion people (roughly 30% of the projected global population; SI Appendix, Fig. S12) would have to move to other areas if the global population were to stay distributed relative to temperature the same way it has been for the past millennia (SI Appendix, Fig. S13). Strong climate mitigation following the RCP2.6 scenario would substantially reduce the geographical shift in the niche of humans and would reduce the theoretically needed movement to ∼1.5 billion people (∼13% of the projected global population; SI Appendix, Figs. S12 and S13).").

[23] United Nations Environment Programme & Climate & Clean Air Coalition (2022) *Summary for Policymakers, in* GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 5 ("The Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment shows that human-driven methane emissions are responsible for nearly 45 per cent of current net warming. The IPCC has continuously emphasized the critical urgency of reducing anthropogenic emissions – from methane and from other climate pollutants – if the world is to stay below 1.5° and 2°C targets.").

[24] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Masson-Delmotte V., *et al.* (eds.), Figure SPM.2.

[25] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 128 ("The increase in atmospheric CH_4 observed over the past decade has been tracking RCP8.5, the warmest scenario assessed by the IPCC, which yields an estimated 4.3°C of warming globally by 2100 (Jackson et al., 2020; Saunois et al., 2020; Nisbet et al., 2020). Furthermore, there is no reversal of this trend on the horizon: under current policy scenarios, by 2050 CH_4 emissions are expected to increase by 30% compared to 2015 levels (Höglund-Isaksson et al., 2020). Together with recent trends, these prognoses serve to underscore the urgency of mitigating CH_4 emissions."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 34 (Figure 7 shows baseline emissions increasing from about 380 $MtCH_4$ in 2020 to 470 $MtCH_4$ in 2050).

[26] World Meteorological Organization (26 October 2022) *The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2021*, WMO GREENHOUSE GAS BULLETIN ("In 2020 and 2021, the global network of the WMO Global Atmosphere Watch (GAW) Programme detected the largest within-year increases (15 and 18 ppb, respectively) of atmospheric methane (CH_4) since systematic measurements began in the early 1980s (Figure 1). The causes of these exceptional increases are still being investigated by the global greenhouse gas science community. Analyses of measurements of the abundances of atmospheric CH_4 and its stable carbon isotope ratio $^{13}C/^{12}C$ (reported as $\delta^{13}C(CH_4)$) (Figure 2) indicate that the increase in CH_4 since 2007 is associated with biogenic processes, but the relative contributions of anthropogenic and natural sources to this increase are unclear. While all conceivable efforts to reduce CH_4 emissions should be employed, this is not a substitute for reducing CO_2 emissions, whose impact on climate will continue for millennia."). *See also* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 25 January 2023); *and* Allen G. H. (2022) *Cause of the 2020 surge in atmospheric methane clarified*, NATURE 612(7940): 413–14 ("Its atmospheric concentration has nearly tripled since pre-industrial times, from 700 parts per billion (p.p.b.) to more than 1,900 p.p.b. today[3] (see also go.nature.com/3xm1dx4). During 2007–19, the concentration rose at a rate of 7.3 ± 2.4 p.p.b. per year. Then, in 2020, the methane growth rate increased dramatically to 15.1 ± 0.4 p.p.b. per year. … The concentration of atmospheric methane surged again (see go.nature.com/3xm1dx4) to 18.2 ± 0.5 p.p.b. per year in 2021 — another mysterious acceleration without a clear cause, and the fastest rate of increase ever recorded.").

[27] Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 481 ("In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed 53 ± 10% of the MGR anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation."). *See also* Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ENVIRON. RES. LETT. 17(9): 1–8, 6 ("The inversion shows an increase in the methane growth rate from 28 Tg a^{-1} in 2019 to 59 Tg a^{-1} in 2020, consistent with observations. This implies a forcing on the methane budget away from a steady state by 36 Tg a−1 from 2019 to 2020, 86% (82 ± 18% in the nine-member inversion ensemble) of which is from the increase in

emissions between the two years and the rest is from the decrease in tropospheric OH. Changes in methane mass offset the forcing by 5 Tg a^{-1} . The global mean OH concentration decreases by 1.2% (1.6 ± 1.5%) from 2019 to 2020, which could be due to reduced NOx emissions from COVID-19 decreases in economic activity but accounts for only a small fraction of the methane surge. We find that half of the increase in methane emissions from 2019 to 2020 is due to Africa. High precipitation and flooding in East Africa leading to increased wetland methane emissions could explain the increase. We also find a large relative increase in Canadian emissions, also apparently driven by wetlands.").

[28] National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("Atmospheric methane, less abundant than CO_2 but more potent at trapping heat in the atmosphere, rose to an average of 1922.6 parts per billion (ppb). The 2023 methane increase over 2022 was 10.9 ppb, lower than the record growth rates seen in 2020 (15.2 ppb), 2021(18 ppb) and 2022 (13.2 ppb), but still the 5th highest since renewed methane growth started in 2007. … In 2023, levels of nitrous oxide, the third-most significant human-caused greenhouse gas, climbed by 1 ppb to 336.7 ppb. The two years of highest growth since 2000 occurred in 2020 (1.3 ppb) and 2021 (1.3 ppb)."). *See also* National Oceanic and Atmospheric Administration (5 April 2023) *Greenhouse gases continued to increase rapidly in 2022* ("Atmospheric methane, which is far less abundant but much more potent than CO_2 at trapping heat in the atmosphere, increased to an average of 1,911.9 parts per billion (ppb). The 2022 methane increase was 14.0 ppb, the fourth-largest annual increase recorded since NOAA's systematic measurements began in 1983, and follows record growth in 2020 and 2021. Methane levels in the atmosphere are now more than two and a half times their pre-industrial level.").

[29] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years."). *See also* Ross K., Waskow D., & Ge M. (17 September 2021) *How Methane Emissions Contribute to Climate Change*, WORLD RESOURCES INSTITUTE ("Methane is the second most abundant human-caused greenhouse gas (GHG), and is 86 times more powerful than carbon dioxide over 20 years in the atmosphere (34 times more powerful over 100 years). Because it exists for a relatively short time in the atmosphere, cutting methane provides a quick benefit in terms of limiting near-term temperature rise. Studies estimate that ambitious actions to reduce methane can avoid 0.3 degrees C of warming by 2050."); Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 33, 57 ("Global warming will continue to increase in the near term in nearly all considered scenarios and modelled pathways. Deep, rapid and sustained GHG emissions reductions, reaching net zero CO_2 emissions and including strong emissions reductions of other GHGs, in particular CH_4, are necessary to limit warming to 1.5°C (>50%) or less than 2°C (>67%) by the end of century (*high confidence*). … All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*). (CrossSection Box.2)."); Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 9–10 ("Given the smaller role of other non-CO_2 climate pollutants, methane emission cuts therefore provide the strongest leverage for near-term warming reduction (Figure 5)(13, 95). Achievement of methane reductions consistent with the average in 1.5°C scenarios could reduce warming by ~0.3°C by 2050 in comparison with baseline increases (4). A hypothetical complete elimination of anthropogenic methane emissions could avert up to 1°C of warming by 2050 relative to the high emissions Shared Socioeconomic Pathway [SSP; (96)] SSP3–7.0 scenario (97). This large near-term impact partly reflects methane's short lifetime; >90% of increased atmospheric methane would be removed within 30 years of an abrupt cessation of anthropogenic emissions compared with only ~25% of increased CO_2 following CO_2 emission cessation (98)."); *and* Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E.,

Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 11 ("In addition [to cutting CO_2], pricing and reducing methane emissions is critical for effectively mitigating climate change. Methane is a potent greenhouse gas, and unlike carbon dioxide, which persists in the atmosphere for centuries, methane has a relatively short atmospheric lifetime,making reductions impactful in the short term (Shindell et al. 2024). Drastically cutting methane emissions can slow the near-term rate of global warming, helping to avoid tipping points and extreme climate impacts.").

[30] Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S.W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 1–11, 1 ("Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action)."). *See also* Sun X., Wang P., Ferris T., Lin H., Dreyfus G., Gu B.H., Zaelke D., & Wang Y. (2022) *Fast action on short-lived climate pollutants and nature-based solutions to help countries meet carbon neutrality goals*, ADV. CLIM. CHANGE RES. 13(4): 564–577.

[31] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("Cutting methane emissions from fossil fuels by 75% by 2030 is vital to limit warming to 1.5 °C").

[32] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("Taken together, we estimate that if all methane policies and pledges made by countries and companies to date are implemented and achieved in full and on time, methane emissions from fossil fuels would decline by around 50% by 2030. However, in most cases, these pledges are not yet backed up by detailed plans, policies and regulations. The detailed methane policies and regulations that currently exist would cut emissions from fossil fuel operations by around 20% from 2023 levels by 2030.").

[33] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years.").

[34] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}").

[35] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-30–SPM-31 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net

negative CO_2 emissions that reverse warming in the latter half of the century. … Future non-CO_2 warming depends on reductions in non-CO_2 GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] GtCO_2-eq per year, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*) {3.3, AR6 WG I SPM D1.7}").

[36] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}").").

[37] Rogelj J. & Lamboll R. (2024) *Substantial reductions in non-CO_2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget*, COMMUN. EARTH ENVIRON. 5: 1–5, 2 ("Here, we uncover the broader non-CO_2 emissions assumptions that underlie some of the most prominent RCB estimates that are currently available in the literature, and show how shortfall in mitigation ambition for methane (CH_4) and nitrous oxide (N_2O) put achievement of the Paris Agreement targets out of reach. … RCB estimates in line with limiting warming to 1.5 °C assume 1.5 °C-compatible CH_4 reductions from 2020 to 2050 of 51% (47–60%, range between 25th and 75th quantile regressions at 1.5 °C of global warming across scenarios, see Fig. 1, panel a).").

[38] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—

including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.").

[39] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 ("Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73(±0.03) °C could even warm some regions up to 3 °C. Since the temperature increase from past CO_2 emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22)."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 7 (Figure SPM.2c shows that Sulphur dioxide (SO_2) contributes –0.49 °C (–0.10 to –0.93 °C) to observed warming in 2010–2019 relative to 1850–1900); Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestvedt J. S., Osprey S., & Schleussner C.-F. (2018) *Climate impacts from a removal of anthropogenic aerosol emissions*, GEOPHYS. RES. LETT. 45(2): 1020–1029, 1020 ("Limiting global warming to 1.5 or 2.0°C requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Concurrently, emissions of anthropogenic aerosols will decline, due to coemission with GHG, and measures to improve air quality. … Removing aerosols induces a global mean surface heating of 0.5–1.1°C, and precipitation increase of 2.0–4.6%. Extreme weather indices also increase. We find a higher sensitivity of extreme events to aerosol reductions, per degree of surface warming, in particular over the major aerosol emission regions. … "Plain Language Summary. To keep within 1.5 or 2° of global warming, we need massive reductions of greenhouse gas emissions. At the same time, aerosol emissions will be strongly reduced. We show how cleaning up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen those from greenhouse gas warming. The northern hemisphere is found to be more sensitive to aerosol removal than greenhouse gas warming, because of where the aerosols are emitted today. This means that it does not only matter whether or not we reach international climate targets. It also matters how we get there."); *and* Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) *Climate and carbon budget implications of linked future changes in CO_2 and non-CO_2 forcing*, ENVIRON. RES. LETT. 14(4): 1–11.

[40] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.").

[41] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would

accompany decarbonization (*high confidence*)."); *and* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-31 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls.").

[42] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10321 ("The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1)."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}").

[43] Olczak M., Piebalgs A., & Balcombe P. (2023) *A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness*, ONE EARTH 6(5): 519–535, 520 ("Only ~13% (minimum [min.] 10%, maximum [max.] 17%) of global methane emissions are covered by direct methane mitigation policies, while limited policy stringency and reliance on inaccurate emission estimates remain barriers to effective policy. These findings suggest that a consistent approach for accurate identification, quantification, and verification of methane emission sources alongside greater policy coverage and stringency (e.g. measurable objectives and enforcement) must be put into place to realize significant methane emission reduction opportunities").

[44] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 10 ("The levels of methane mitigation needed to keep warming to 1.5°C will not be achieved by broader decarbonization strategies alone. The structural changes that support a transformation to a zero-carbon society found in broader strategies will only achieve about 30 per cent of the methane reductions needed over the next 30 years. Focused strategies specifically targeting methane need to be implemented to achieve sufficient methane mitigation. At the same time, without relying on future massive-scale deployment of unproven carbon removal technologies, expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5°C. (Sections 4.1, 4.2 and 4.3)").

[45] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.").

[46] The *Global Methane Pledge* calls for reducing global methane emissions by at least 30 percent from 2020 levels by 2030, which is comparable to 35 percent reduction below 2030 business-as-usual projections and within the range found to be consistent with 1.5 °C pathways in Figure ES.1 of the *Global Methane Assessment*. *See* United Nations

Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*; *and* United Nations Environment Programme & Climate & Clean Air Coalition (2021) *Briefing on the Global Methane Pledge* ("The Global Methane Pledge is a strong first step as the first-ever Heads-of State global commitment to cut methane emissions at a level consistent with a 1.5 C pathway.").

[47] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, EARTH SYST. SCI. DATA 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH_4 yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH_4 yr^{-1} or ~ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH_4 yr^{-1} or 50 %–65 %).").

[48] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 28 ("Fossil fuels: release during oil and gas extraction, pumping and transport of fossil fuels accounts for roughly 23 per cent of all anthropogenic emissions, with emissions from coal mining contributing 12 per cent.").

[49] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 28 ("Agriculture: emissions from enteric fermentation and manure management represent roughly 32 per cent of global anthropogenic emissions. Rice cultivation adds another 8 per cent to anthropogenic emissions. Agricultural waste burning contributes about 1 per cent or less.").

[50] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 28 ("Waste: landfills and waste management represents the next largest component making up about 20 per cent of global anthropogenic emissions.").

[51] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 8 ("Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts.").

[52] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 10 ("Roughly 60 per cent, around 75 Mt/yr, of available targeted measures have low mitigation costs[2], and just over 50 per cent of those have negative costs – the measures pay for themselves quickly by saving money (Figure SDM2). Low-cost abatement potentials range from 60–80 per cent of the total for oil and gas, from 55–98 per cent for coal, and approximately 30–60 per cent in the waste sector. The greatest potential for negative cost abatement is in the oil and gas subsector where captured methane adds to revenue instead of being released to the atmosphere. (Section 4.2) … Less than US$ 600 per tonne of methane reduced, which would correspond to ~US$ 21 per tonne of carbon dioxide equivalent if converted using the IPCC Fifth Assessment Report's GWP_{100} value of 28 that excludes carbon-cycle feedbacks.").

[53] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 10 ("Roughly 60 per cent, around 75 Mt/yr, of available targeted measures have low mitigation costs[2], and just over 50 per cent of those have negative costs – the measures pay for themselves quickly by saving money (Figure SDM2). Low-cost abatement potentials range from 60–80 per cent of the total for oil and gas, from 55–98 per cent for coal, and approximately 30–60 per cent in the waste sector. The greatest potential for negative cost abatement is in the oil and gas subsector where captured methane adds to revenue instead of being released to the atmosphere. (Section 4.2) … Less than US$ 600 per tonne of methane reduced, which would correspond to ~US$ 21 per tonne of carbon dioxide equivalent if converted using the IPCC Fifth Assessment Report's GWP_{100} value of 28 that excludes carbon-cycle feedbacks.").

[54] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("Methane abatement in the fossil fuel industry is one of the most pragmatic and lowest cost options to reduce greenhouse gas emissions.").

[55] *See generally* International Energy Agency (2023), *THE IMPERATIVE OF CUTTING METHANE FROM FOSSIL FUELS: AN ASSESSMENT OF THE BENEFITS FOR THE CLIMATE AND HEALTH*, 3 ("More than 75% of methane emissions from oil and gas operations and half of emissions from coal today can be abated with existing technology, often at low cost. The oil and gas sector has the greatest share of ready-to-implement and cost-effective technical opportunities to reduce methane emissions.") ; *and* International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("We estimate that around 80 Mt of annual methane emissions from fossil fuels can be avoided through the deployment of known and existing technologies, often at low – or even negative – cost. In our Net Zero Emissions by 2050 (NZE) Scenario – which sees the global energy sector achieving net zero emissions by mid-century, limiting the temperature rise to 1.5 °C – methane emissions from fossil fuel operations fall by around 75% by 2030.").

[56] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 5 ("The best companies and countries are showing what can be done to reduce emissions from oil and gas operations, but the intensity of methane emissions (emissions per unit of production) ranges widely. The best performing countries are more than 100 times better than the worst. Norway and the Netherlands have the lowest emissions intensities in our updated Tracker, and countries in the Middle East such as Saudi Arabia and the United Arab Emirates also have relatively low emissions intensities; Turkmenistan and Venezuela have the highest. If all producing countries were to match Norway's emissions intensity, global methane emissions from oil and gas operations would fall by more than 90%."), 24 ("The methane emissions intensity of oil and gas operations varies greatly across countries, with the best performing countries having an emission intensity over 100 times lower than the worst performers. High emission intensities from oil and gas operations are not inevitable; they are an "above-ground issue" that can be addressed cost-effectively through a well-established combination of high operational standards, firm policy action and technology deployment."). *See also* Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S. W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 1–11, 5 ("For oil and gas, we supplement the IEA (2017) abatement potential of 75% below current levels with voluntary company commitments of capping upstream leakage. This results in an 83% below 2030 level abatement potential rather than 77% without industry targets.").

[57] *See generally* International Energy Agency (2022) NORWAY 2022: ENERGY POLICY REVIEW, 52 ("The government has regulations in place to address emissions in the sector. Direct emissions of methane (venting and fugitive emissions) have long been regulated and flaring is only permitted when necessary for safety reasons. Norway is also part of the Global Methane Pledge of over 100 countries announced at COP26 to reduce global methane emissions by at least 30% from 2020 levels by 2030.").

[58] International Energy Agency (2022) NORWAY 2022: ENERGY POLICY REVIEW, 41 ("The polluter-pays principle is a cornerstone of the Norwegian policy framework on climate change. Norway was one of the first countries in the world to put in place a carbon tax, already in 1991, covering the combustion of fossil fuels and the petroleum sector. Today, approximately 85% of domestic GHG emissions are either covered by the EU ETS or subject to a CO2 tax (or other GHG taxes), or both. And nearly 70% of non-ETS emissions are covered by taxes on GHG emissions. Emissions of nitrous oxide and methane from agriculture constitute two-thirds of non-priced emissions. Methane from landfills is another important source of non-priced emissions. The practice of dumping biological waste on landfills has been banned, and these emissions will phase out.").

[59] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr.").

[60] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: *A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT*, 102 ("Within the waste sector, all cost abatement potential is concentrated within the solid waste subsector which has three to six times the potential found in the wastewater (sewage) subsector (Figure 4.9). Totals in the three available analyses are very similar for the full waste sector, so that the full range is captured by 32 ± 4 Mt/ yr. Hence this sector has about half the potential of the fossil sector for all cost measures and a much narrower uncertainty range. Evaluating this mitigation potential as a share of projected 2030 waste sector emissions is complicated by a large divergence between them, which were ~70 Mt/yr in the Harmsen and US EPA analyses, whereas there was a much larger value of 114 Mt/yr in the IIASA analysis. Hence although all the studies find similar abatement potential, the share of 2030 emissions from waste estimated to be abatable ranges from just 25 per cent in the IIASA analysis to ~40-50 per cent in the US EPA and Harmsen analyses. For low-cost measures in the waste sector, the analyses are again fairly consistent with all falling within the range 16 ±5 Mt/yr.").

[61] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr.").

[62] Lowe M. & Lowe-Skillern R. (2021) *Find, Measure, Fix: Jobs in the U.S. Methane Emissions Mitigation Industry*, DATU RESEARCH, 6 ("Methane emissions mitigation means jobs. A wide and steadily expanding range of skills are required, from field technicians to chemical engineers to data scientists. Interviews with firms indicate that these jobs offer upward mobility. Many firms expect to expand their workforce if new federal and/or state methane rules are put into place. Of the eight states that either have methane rules or are considering them, seven are among the top states for employee locations in the methane emissions mitigation industry, including California, Colorado, Pennsylvania, New York, Wyoming, New Mexico, and Ohio. This would suggest that employee locations are poised to grow if the federal government and/or states roll out new rules on methane emissions.").

[63] von Braun J., Ramanathan V., & Turkson P. K. A. (2022) *Resilience of people and ecosystems under climate stress*, Pontifical Academy of Sciences ("Recommendations: *Resilience building must rest on three pillars*: Mitigation, Adaptation & Transformation. Mitigation: *Reduce climate risks. …* Adaptation: *Reduce exposure and vulnerability to unavoidable climate risks.* Exposure & vulnerability reduction has three faces: Reductions in sensitivity to climate change; Reductions in risk exposure; & enhancement of adaptative capacity. There are limits to adaptation and hence adaptation has to be integrated with mitigation actions to avoid crossing the limits."); where the definition of resilience is taken from Möller V., van Diemen R., Matthews J. B. R., Méndez C., Semenov S., Fuglestvedt J. S., & Resinger A. (2022) *Annex II: Glossary*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), AII-37–AII-38 ("The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (Arctic Council, 2016).").

[64] Zaelke D., Picolotti R., & Dreyfus G. (14 November 2021) *Glasgow climate summit: A glass half full*, THE HILL ("The new architecture also includes cutting not just carbon dioxide but also non-carbon dioxide climate emissions, with a specific focus on methane, a super climate pollutant responsible for 0.5 degrees Celsius of today's observed warming of 1.1 degrees Celsius. Cutting methane presents the single biggest and fastest mitigation action the world can take to keep warming from breaching the 1.5 degrees Celsius guardrail. This makes fast reductions of methane essential for adaptation as well."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts

D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-13 ("Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*)."); *and* Intergovernmental Panel on Climate Change (2018) GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 22 ("Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*).").

[65] International Energy Agency, United Nations Environment Programme, & Climate & Clean Air Coalition (2023) THE IMPERATIVE OF CUTTING METHANE FROM FOSSIL FUELS, 3 ("Immediate, targeted methane abatement in the fossil fuel sector can prevent nearly 1 million premature deaths due to ozone exposure, 90 million tonnes of crop losses due to ozone and climate changes, and about 85 billion hours of lost labour due to heat exposure by 2050, providing roughly U.S.D 260 billion in direct economic benefits.").

[66] Mbow C., *et al.* (2019) *Chapter 5: Food Security*, *in* CLIMATE CHANGE AND LAND, *Special Report of the Intergovernmental Panel on Climate Change on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, Shukla P. R., *et al.* (eds.), 451 ("Methane increases surface ozone which augments warming-induced losses and some quantitative analyses now include climate, long-lived (CO_2) and multiple short-lived pollutants (CH_4, O_3) simultaneously (Shindell et al. 2017; Shindell 2016). Reduction of tropospheric ozone and black carbon can avoid premature deaths from outdoor air pollution and increases annual crop yields (Shindell et al. 2012). These actions plus methane reduction can influence climate on shorter time scales than those of carbon dioxide reduction measures. Implementing them substantially reduces the risks of crossing the 2°C threshold and contributes to achievement of the SDGs (Haines et al. 2017; Shindell et al. 2017)."); ("Ozone causes damage to plants through damages to cellular metabolism that influence leaf-level physiology to whole-canopy and root-system processes and feedbacks. … Using atmospheric chemistry and a global integrated assessment model, Chuwah et al. (2015) found that without a large decrease in air pollutant emissions, high ozone concentration could lead to an increase in crop damage of up to 20% in agricultural regions in 2050 compared to projections in which changes in ozone are not accounted for. Higher temperatures are associated with higher ozone concentrations; C3 crops are sensitive to ozone (e.g., soybeans, wheat, rice, oats, green beans, peppers, and some types of cottons) and C4 crops are moderately sensitive (Backlund et al. 2008)."). *See also* Climate & Clean Air Coalition, *Tropospheric ozone* (*last visited* 5 February 2023) ("79–121 million: Estimated global crop production losses owing to ozone total 79–121 million tonnes, worth USD 11–18 billion annually. … 1 million: Long-term exposure to ozone air pollution is linked to 1 million premature deaths per year due to respiratory diseases.").

[67] Luna M. & Nicholas D. (2022) *An environmental justice analysis of distribution-level natural gas leaks in Massachusetts, USA*, ENERGY POLICY 162(112778): 1–23, 1 ("Using recently available high resolution leak data, this analysis of natural gas leaks across the state of Massachusetts shows that People of Color, limited English speaking households, renters, lower income residents, and adults with lower levels of education are disproportionately exposed to natural gas leaks and that their leaks take longer to repair, as compared to the general population, and particularly as compared to White residents and to homeowners. This pattern is evident for all leaks in the state, for leaks disaggregated by leak class or grade, and for leaks disaggregated by utility. This analysis shows that natural gas leaks are an environmental justice issue warranting further study and policy attention."); *discussed in* Segal E. (17 February 2022) *New Research Shines Light On Natural Gas Leak Crisis*, FORBES. *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 11 ("This assessment found that every million tonnes (Mt) of methane reduced: - prevents approximately 1 430 annual premature deaths due to ozone globally. Of those, 740 would have died from respiratory disease and 690 from cardiovascular disease. Every million tonnes of reduced methane emissions could also avoid approximately 4 000 asthma-related accident and emergency department visits and 90 hospitalizations per year. (Section 3.4) - avoids losses of 145 000 tonnes of wheat, soybeans, maize and rice ozone exposure every year.

This is roughly equivalent to increased global yields of 55 000 tonnes of wheat, 17 000 tonnes of soybeans, 42 000 tonnes of maize, and 31 000 tonnes of rice annually for every million tonnes of methane reduced. (Section 3.5)").

[68] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, EARTH SYST. SCI. DATA 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH_4 yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH_4 yr^{-1} or ~ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH_4 yr^{-1} or 50 %–65 %)."). *See also* Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, EARTH SYST. SCI. DATA 12(3): 1561–1623, 1577 ("Natural methane sources include vegetated wetland emissions and inland water systems (lakes, small ponds, rivers), land geological sources (gas–oil seeps, mud volcanoes, microseepage, geothermal manifestations, and volcanoes), wild animals, termites, thawing terrestrial and marine permafrost, and oceanic sources (biogenic, geological, and hydrate).").

[69] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC $°C^{-1}$. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} $°C^{-1}$ (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2)."). *See also* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH_4 observations and the way forward*, PHILOS. TRANS. R. SOC. A 379(2210): 1–14, 11 ("Explaining the renewed and accelerating increase in atmospheric CH_4 burden since 2007 remains challenging, and the exact causes are not yet clear. But, the observations we describe suggest that increased emissions from microbial sources are the strongest driver, with a relatively smaller contribution from other processes, e.g., fossil fuel exploitation. A more difficult question to answer is the one posed by this special issue: is warming feeding the warming? We cannot say for certain, but we cannot rule out the possibility that climate change is increasing CH_4 emissions. The strong signals from the tropics combined with the isotopic data are consistent with increased emissions from natural wetlands, but large [interannual variability (IAV)] and inter-decadal variability in wetland drivers like precipitation make it difficult to identify small trends. Observations are needed that will help process models capture this variability. The size of the IAV illustrates the potential scope of uncontrollable near-future change and emphasizes the urgency of reducing the global methane burden by mitigating the methane emissions that we can control, from the fossil fuel and agricultural sectors."); *and* Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 481 ("In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed $53 \pm 10\%$ of the MGR anomaly in 2020 relative to 2019."). However, other studies suggest a more limited increase in recent emissions from natural wetlands compared to agriculture and waste and energy production sectors, *see* Zhang Z., *et al.* (2021) *Anthropogenic emissions are the main contribution to the rise of atmospheric methane (1993-2017)*, NAT'L SCI. REV. 9(5): 1–13, 1 ("Our emission scenarios that have the fewest biases with respect to isotopic composition suggest that the agriculture, landfill, and waste sectors were responsible for 53±13% of the renewed growth over the period 2007-2017 compared

to 2000-2006; industrial fossil fuel sources explained an additional 34±24%, and wetland sources contributed the least at 13±9%. The hypothesis that a large increase in emissions from natural wetlands drove the decrease in atmospheric $\delta^{13}C\text{-}CH_4$ values cannot be reconciled with current process-based wetland CH_4 models. This finding suggests the need for increased wetland measurements to better constrain the contemporary and future role of wetlands in the rise of atmospheric methane and climate feedbacks. Our findings highlight the predominant role of anthropogenic activities in driving the growth of atmospheric CH_4 concentrations.").

[70] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, Introductory Summary ("This report identifies priority research that should be addressed within 3-5 years so that a second-phase assessment could more robustly assess the technical, economic, and social viability of technologies to remove atmospheric methane at climate-relevant scales. The research agenda presented in this report includes foundational research that would help us better understand atmospheric methane removal while also filling knowledge gaps in related fields, and systems research that seek[s] to address what developing and/or deploying atmospheric methane removal at scale would entail. A Research Agenda Toward Atmospheric Methane Removal also assesses five atmospheric methane removal technologies that would accelerate the conversion of methane to a less radiatively potent form or physically remove methane from the atmosphere and store it elsewhere."); *see also* Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 1 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."). *See also* Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO_2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03 Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E.").

[71] For example, *see* United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION, 9 ("Given the uncertainty and inaction at the federal level, state leadership on SLCPs is even more necessary and urgent. The U.S. Climate Alliance is stepping up and accepting the mantle of leadership.").

[72] Lauvaux T., Giron C., Mazzolini M., d'Aspremont A., Duren R., Cusworth D., Shindell D., & Ciais P. (2022) *Global assessment of oil and gas methane ultra-emitters*, SCIENCE 375(6580): 557–561, 578 ("On the basis of adjusted emissions, O&G ultra-emitter estimates represent 8 to 12% of global O&G CH4 emissions (according to national inventories; Fig. 2C), a contribution not included in most current inventories (13).… In terms of net climate benefits, eliminating methane emissions from ultra-emitters would lead to 0.005° ± 0.002 °C of avoided warming over the next one to three decades on the basis of linearized estimates from prior modeling (38). Though small, this value is

approximately equal to the total influence from all emissions since 2005 from Australia or the Netherlands (39), or removal of 20 million vehicles from the road for 1 year. The avoided warming would prevent ~1600±800 premature deaths annually due to heat exposure and ~1.3±0.9 billion hours of labor productivity lost annually due to exposure to heat and humidity, with the latter valued at ~$200 million per year."). Note that IEA estimates about 3.5 Mt of methane emissions from the oil and gas sector based on satellite data, representing 6% of IEA's estimate of oil and gas emissions from the 15 countries where such emission events were detected. Recall that IEA uses a scaling approach to estimate emissions and found 70% higher emissions than officially reported. *See also* International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 6, 16 ("Globally, our analysis finds that methane emissions from the energy sector are about 70% greater than the sum of estimates submitted by national governments."), 561 ("Accounting for the level of satellite coverage, very large emitting events detected by satellite are estimated to have been responsible for around 3.5 Mt of emissions from oil and gas operations in 2021 (6% of our estimate of oil and gas emissions in the 15 countries where events were detected)."). Gas has a particularly important role to play in mitigating methane emissions because gas is mostly comprised (70-90%) of methane. So when gas leaks, it is mostly methane that is emitted. This counters the widely promoted and often still accepted argument that gas is an inherently 'cleaner' fuel than coal. *See* Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development, 23. *See also* Gordon D., Reuland F., Jacob D. J., Worden J. R., Shindell D., & Dyson M. (2023) *Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates*, ENVIRON. RES. LETT. 18(8): 1–10; *and* calculator developed by RMI to compare the net GHG emissions parity between gas and coal using varying inputs.

[73] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 1–10, 7 ("Although NDCs and long-term national pledges are currently insufficient to keep warming below 2 °C, let alone 1.5 °C [50–52], the time horizons used for emission metrics should nevertheless be consistent with that central goal of the Paris Agreement. We therefore support the use of the 20 year time horizon over the 100 year version, when binary choices between these two must be made, due to the better alignment of the former with the temperature goals of the Paris Agreement. The 50 year time horizon, not yet in widespread use but now included in IPCC AR6, is in fact the only time horizon that the IPCC presents that falls within the range of time horizons that align with the Paris Agreement temperature goals (24–58 years). However, to best align emission metrics with the Paris Agreement 1.5 ° C goal, we recommend the use of the 24 year time horizon, using 2045 as the end point time, with its associated $GWP_{1.5°C}$ = 75 and $GTP_{1.5 °C}$ = 41."). *See also* Abernethy S. (14 March 2022) *Why don't people realize how bad methane is for climate change? Bad math*, SAN FRANCISCO CHRONICLE; *discussed in* McKenna P. (9 February 2022) *To Counter Global Warming, Focus Far More on Methane, a New Study Recommends*, INSIDE CLIMATE NEWS ("The Environmental Protection Agency is drastically undervaluing the potency of methane as a greenhouse gas when the agency compares methane's climate impact to that of carbon dioxide, a new study concludes. The EPA's climate accounting for methane is 'arbitrary and unjustified' and three times too low to meet the goals set in the Paris climate agreement, the research report, published Wednesday in the journal Environmental Research Letters, found."); *and* Rathi A. (15 February 2022) *The Case Against Methane Emissions Keeps Getting Stronger*, BLOOMBERG. *See also* Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development, 23 ("Reducing intended and unintended emissions to achieve lower-emission goals with a transition to gas, and as we work toward a transition away from gas, requires measurement and MRV along the full well-to-gate scope (producers, processors, and transporters of gas) both for domestic producers and for importers seeking to impose methane emission intensity requirements. Such quantification-based intensity requirements complement established approaches for controlling methane leaks through prescriptive regulations. Measuring methane accurately is key to enabling these types of policies. Further, successful quantification-based emissions policy, such as limits to methane intensity or certification, requires accurate measurement technologies and robust MRV systems coupled with sufficient compliance and enforcement. New investments in the oil and gas sector should build in enhanced MRV systems and methane intensity requirements to limit risks of stranded assets and align with carbon-neutrality goals.").

[74] Rosane P., Naran B., Pastor A. O., Connolly J., & Wignarajah D. (2022) *The Landscape of Methane Abatement Finance*, Climate Policy Initiative & Global Methane Hub, 9 ("Methane abatement solutions are severely underfunded considering their climate change mitigation potential. While also underfunded, other climate change solutions with similar mitigation potential, such as low-carbon transport, received 15 times the investment of methane abatement measures, while solutions such as solar and wind received 26 times the investment. Wind and solar energy have an average of 8.35 $GtCO_2e$ mitigation potential (CO_2) by 2030, and received USD 296 billion in 2019/2020, while targeted methane abatement solutions received only USD 6.3 billion with an average mitigation potential of 3.3 $GtCO_2e$ – the ratio of investment flows to mitigation potential was almost 20 times lower than that of the renewable energy sector (Figure 4). Estimated mitigation potential of methane abatement solutions is 3 $GtCO_2e$ by 2030 over a 100-year timeframe (GWP_{100}). However, if a 20-year timeframe (GWP_{20}) is considered, the mitigation potential would be substantially higher.").

[75] Clean Air Task Force (8 December 2023) *Turning pledges into action: COP28 Global Methane Pledge Ministerial*, ("This year, Global Methane Partners announced: Over $1 billion in new grant funding for methane action mobilized since COP27, more than triple current levels, which will mobilize billions in investment to reduce methane.").

[76] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("Fossil fuel companies and governments around the world now need to deliver clear strategies for how they will implement these pledges effectively and rapidly. This needs to be accompanied by verification and accountability mechanisms to ensure that actors are taking the necessary steps towards their goals. Further commitments – particularly in financing – are needed to deliver the reductions required this decade." …" We estimate that around USD 170 billion in spending is needed to deliver the methane abatement measures deployed by the fossil fuel industry in the NZE Scenario. This includes around USD 100 billion of spending in the oil and gas sector and USD 70 billion in the coal industry. Through 2030, roughly USD 135 billion goes towards capital expenditures, while USD 35 billion is for operational expenditures.").

[77] Zaelke D & Beaugrand M. (26 November 2023) *COP28 Must Set the Stage for a Mandatory Methane Agreement*, THE MESSENGER ("For COP28, and its methane summit, to succeed in preventing climate chaos, it must put the previous pledge on a path to a global methane agreement that moves from voluntary to mandatory measures, with specific numerical targets, tight timelines and a dedicated funding stream — perhaps an "Agreement to Reduce Methane, Avoid Climate Tipping Points, and Eliminate Waste of Fossil Gas.").

[78] AzerNews (7 March 2024) *Azerbaijan's joining Global Methane Pledge aligns with international efforts to limit global warming* ("Methane reduction is of global significance. The fact that 155 countries, contributing to around 50% of global methane pollution, have pledged to reduce emissions underscores the widespread recognition of the urgency to address this potent greenhouse gas. Azerbaijan's decision to join the "Global Methane Pledge" is a notable step. The voluntary commitment to reduce methane emissions by at least 30% by 2030 aligns with the overall goal set by the initiative at COP26. This demonstrates Azerbaijan's recognition of the role it can play in combating climate change and its willingness to contribute to international efforts. On March 4th, Azerbaijan announced its participation in the "Global Methane Pledge," which involves voluntary commitments by states to reduce methane emissions."). *See also* United States Department of State (2 November 2021) *United States, European Union, and Partners Formally Launch Global Methane Pledge to Keep 1.5°C Within Reach*, Press Release ("Today, the United States, the European Union, and partners formally launched the Global Methane Pledge, an initiative to reduce global methane emissions to keep the goal of limiting warming to 1.5 degrees Celsius within reach. A total of over 100 countries representing 70% of the global economy and nearly half of anthropogenic methane emissions have now signed onto the pledge."). The Global Methane Pledge sets a collective target to reduce global methane emissions by at least 30% from 2020 levels by 2030, would reduce warming by at least 0.2 °C by 2050 and keep the planet on a pathway consistent with staying below 1.5 °C. *See* United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.").

[79] Climate & Clean Air Coalition (7 December 2023) *Opportunities for Increasing Ambition of NDCs Through Integrated Air Pollution and Climate Change Planning: Progress & Looking Ahead to 2025*, 3 ("As of November 2023, 95% of NDCs include methane within the scope of their overall mitigation target. The absolute number of NDCs including methane in their overall target has more than doubled, from 90 to 184. Forty countries (~20%) include methane as a supplementary target or assessment of the mitigation potential of the measure(s) identified, growing from a base of two in 2016. Most of the countries who include methane in this way (88%) are GMP partners."). *See also* Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 131 ("A closer look into the NDCs shows that some go beyond simply listing CH_4 under the scope of covered gases and provide more detailed information on CH_4 mitigation. For instance, a number of NDCs include sector-specific policies in the areas of agriculture, waste, oil and gas, and coal that will reduce CH_4 emissions (Ross et al., 2018; Walderdorff, 2020). An even smaller number of NDCs include a quantitative, CH_4-specific reduction target, such as Canada, Japan, and New Zealand. Table 2 provides a summary of NDCs that include a quantitative descriptor of CH_4 mitigation as of January 1, 2021. While some of the NDCs shown in Table 2 include true quantitative CH_4 reduction targets, others quantify the potential for CH_4 reductions, or specify goals expressed in terms of efficiency or intensity. In aggregate, very few NDCs provide concrete or quantitative details on CH_4 mitigation activities – indeed, the NDCs summarized in Table 2 are among those that provide the greatest amount of specificity on CH_4 mitigation, which still tends to be very little."). IGSD makes the following note re: the following three countries included in Mar *et al*. (2022): • Afghanistan: Afghanistan included methane reduction targets within its quantitative emissions reductions goals, but this is not reflected in Mar et al. (2022); • China: China's 2016 Intended NDC included a numeric target for coal-bed methane capture, but this target is absent from its updated 2021 submission; China was therefore not included as a country with a numeric methane target; and • Dominica: Dominica's Intended NDC included plans to install methane capture at a landfill. This project was slated for 2016–2021, but project completion remains unconfirmed. *See* United Nations Framework Convention on Climate Change (2022) *Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat*, Conference of the Parties, Fourth Session, 15 ("All NDCs cover CO_2 emissions, almost all (91 per cent) cover CH_4 and most (89 per cent) cover N_2O emissions, many (53 per cent) cover HFC emissions and some cover PFC and SF_6 (36 per cent) and NF_3 (26 per cent) emissions."); *and* United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release. *See also* Paris Agreement Article 4(2) and Article 4(3) ("2. Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions. 3. Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.").

[80] Unites States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("11. The two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress.").

[81] United Nations Environment Program (2 December 2023) *Bending the warming curve through action on non-CO2 gases at COP28 Summit*. *See also* United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO2 Greenhouse Gases*, Fact Sheet ("The United States, People's Republic of China, and United Arab Emirates today convened a Summit to accelerate actions to cut methane and other non-CO2 greenhouse gases as the fastest way to reduce near-term warming and keep a goal of limiting global average temperature increase to 1.5 degrees Celsius within reach."); *and* Escudero J. (18 December 2023) *COP28: "The Methane COP"*, LEGAL PLANET ("In a high-profile event at the main stage of COP28, the U.S., China, and United Arab Emirates hosted the Summit on Methane and non-CO2 Greenhouse Gases that called on the parties of the Paris Agreement to include methane and other GHGs in their nationally determined contributions (NDC). This statement is

relevant since the parties did not always inform methane emissions; therefore, they were usually ignored in the actions that followed Nationally Determined Contributions, or NDCs. Another significant announcement from the Summit was the incorporation of Turkmenistan – one of the world's top emitters-Kazakhstan, Angola, Kenya, and Romania to the Global Methane Pledge, a commitment to reduce methane emissions by 30% from 202 levels by 2030. With these incorporations, 156 countries have joined the pledge, notably not China. In addition, Kazakhstan and the U.S. announced a cooperation partnership to help the Central Asian country meet the Global Methane Pledge's goals by developing national standards to eliminate non-emergency venting of methane, among other actions.").

[82] United Nations Framework Convention on Climate Change (2023) *First global stocktake, Proposal by the President Draft decision -/CMA.5 Outcome of the first global stocktake*, S28 ("Further recognizes the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts, in a nationally determined manner, taking into account the Paris Agreement and their different national circumstances, pathways and approaches." (f) "Accelerating and substantially reducing non-carbon-dioxide emissions globally, including in particular methane emissions by 2030.").

[83] United Nations Environment Program (1987) *The Montreal Protocol on Substances that Deplete the Ozone Layer*. *See also* Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, NATURE 59 (7872): 384–388, 384 ("About 1.7 °C of the avoided warming comes from the Protocol's mandatory reduction of super polluting chemicals—CFCs, HCFCs, and now HFCs—used primarily as refrigerants in cooling equipment. An additional 0.85 °C of warming will be avoided by protecting forests and other carbon "sinks" from damaging ultraviolet radiation that reduce the ability to pull CO_2 out of the atmosphere and store it safely in terrestrial sinks."). *See also* United Nations Environment Programme, Ozone Secretariat (16 September 2022) *World Ozone Day 2022: Global cooperation protecting life on Earth* ("This action has protected millions of people from skin cancer and cataracts over the years since. It allowed vital ecosystems to survive and thrive. It safeguarded life on Earth. And it slowed climate change: if ozone-depleting chemicals had not been banned, we would be looking at a global temperature rise of an additional 2.5°C by the end of this century. This would have been a catastrophe."); World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, 26 ("New studies support previous Assessments in that the decline in ODS emissions due to compliance with the Montreal Protocol avoids global warming of approximately 0.5–1 °C by mid-century compared to an extreme scenario with an uncontrolled increase in ODSs of 3–3.5% per year."); *and* Andersen S. O., Gonzalez M., & Sherman N. J. (2022) *Setting the stage for climate action under the Montreal Protocol*, EOS 103.

[84] Bledsoe P & Zaelke D. (6 April 2023) *Can the UAE help get a planet-saving methane deal at COP28?*, THE HILL ("The UAE and all nations should make a binding international agreement on methane reductions from the oil and gas sector a key outcome of COP 28.").

[85] United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO2 Greenhouse Gases* ("To keep the goal of 1.5 degrees within reach and reduce the risk of breaching near-term tipping points, the world must take fast action on non-CO2 greenhouse gases, as an essential complement to the energy transition and ending deforestation. While CO2 will determine our long-term climate future, non-CO2 greenhouse gases have an outsized impact on near-term temperatures. Accelerated cuts to methane and non-CO2 gases could avoid up to 0.5 degrees of warming by 2050. Non-CO2 greenhouse gases also cause almost 500,000 deaths every year from respiratory illnesses and 5-7 percent of global crop losses at a time when global production is already strained. Rapidly reducing non-CO2 emissions is a three-in-one solution, advancing global climate, health, and food security objectives simultaneously.").

[86] Intergovernmental Panel on Climate Change (2023) *Summary for Policymakers*, *in* AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the*

Intergovernmental Panel on Climate Change, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 27 ("Strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone. (*high confidence*)"). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 59 ("Mitigation actions will have other sustainable development co-benefits (*high confidence*). Mitigation will improve air quality and human health in the near-term notably because many air pollutants are co-emitted by GHG emitting sectors and because methane emissions leads to surface ozone formation (*high confidence*) The benefits from air quality improvement include prevention of air pollution-related premature deaths, chronic diseases and damages to ecosystems and crops. The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). As methane has a short lifetime but is a potent GHG, strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*).").

[87] The global warming potential (GWP) of a non-CO_2 greenhouse gas compares the amount of warming caused by a GHG with that of CO_2. IPCC reports the 20-year global warming potential (GWP_{20}) of methane as 81.2 times that of CO_2. *See* Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritsen T., Palmer M. D., Watanabe M., Wild M., & Zhang H. (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 7.SM.7.

[88] Hook L. & Campbell C. (23 August 2022) *Methane hunters: what explains the surge in the potent greenhouse gas?*, FINANCIAL TIMES ("If you think of fossil fuel emissions as putting the world on a slow boil, methane is a blow torch that is cooking us today," says Durwood Zaelke, president of the Institute for Governance & Sustainable Development, and an advocate of stricter policies to reduce methane emissions. "The fear is that this is a self-reinforcing feedback loop.... If we let the earth warm enough to start warming itself, we are going to lose this battle.").

[89] Feng Z., Xu Y., Kobayashi K., Dai L., Zhang T., Agathokleous E., Calatayud V., Paoletti E., Mukherjee A., Agrawal M., Park R. J., Oak Y. J., & Yue X. (2022) *Ozone pollution threatens the production of major staple crops in East Asia*, NAT. FOOD 3: 47–56, 47 ("East Asia is a hotspot of surface ozone (O_3) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O_3 by combining O_3 elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O_3-induced annual loss of crop production is estimated at US$63 billion."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 68 ("Methane also plays a significant role in reducing crop yields and the quality of vegetation. Ozone exposure is estimated to result in yield losses in wheat, 7.1 per cent; soybean,12.4 per cent; maize, 6.1 per cent; and rice, 4.4 per cent for near present-day global totals (Mills et al. 2018; Shindell et al. 2016; Avnery et al. 2011a)"); *and* Shindell D., Faluvegi G., Kasibhatla P., & Van Dingenen R. (2019) *Spatial Patterns of Crop Yield Change by Emitted Pollutant*, EARTH'S FUTURE 7(2): 101–112, 101 ("Our statistical modeling indicates that for the global mean, climate and composition changes have decreased wheat and maize yields substantially whereas rice yields have increased. Well-mixed greenhouse gasses drive most of the impacts, though aerosol-induced cooling can be important, particularly for more polluted area including India and China. Maize yield losses are most strongly attributable to methane emissions (via both temperature and ozone).").

[90] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 129 ("Methane is an important contributor to the formation of tropospheric O_3. In addition to acting as a greenhouse gas and being directly harmful to human health (see Section 3.3), it also harms plants by causing cellular damage within the leaves, adversely affecting plant production, reducing the rate of photosynthesis, and requiring increased resource allocation to detoxify and repair leaves (Ashmore, 2005, Sitch et al., 2007). This results in an estimated $11-$18 billion worth of global crop losses annually (Avnery et al., 2011). Beyond this, however, O_3 damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO_2 fertilization that is expected to partially offset rising atmospheric CO_2 concentrations (Sitch et al., 2007, Ciais et al., 2013, Arneth et al., 2010, Ainsworth et al., 2012).").

[91] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 6 ("[FOOTNOTE 10] Contributions from emissions to the 2010-2019 warming relative to 1850-1900 assessed from radiative forcing studies are: CO2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.2.

[92] Vaughan A. (7 January 2022) *Record levels of greenhouse gas methane are a 'fire alarm moment'*, NEW SCIENTIST ("According to data compiled by the US National Oceanic and Atmospheric Administration (NOAA), average atmospheric concentrations of methane reached a record 1900 parts per billion (ppb) in September 2021, the highest in nearly four decades of records. The figure stood at 1638 ppb in 1983.").

[93] National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("Atmospheric methane, less abundant than CO_2 but more potent at trapping heat in the atmosphere, rose to an average of 1922.6 parts per billion (ppb). The 2023 methane increase over 2022 was 10.9 ppb, lower than the record growth rates seen in 2020 (15.2 ppb), 2021(18 ppb) and 2022 (13.2 ppb), but still the 5th highest since renewed methane growth started in 2007. … In 2023, levels of nitrous oxide, the third-most significant human-caused greenhouse gas, climbed by 1 ppb to 336.7 ppb. The two years of highest growth since 2000 occurred in 2020 (1.3 ppb) and 2021 (1.3 ppb)."). *See also* National Oceanic and Atmospheric Administration (5 April 2023) *Greenhouse gases continued to increase rapidly in 2022* ("Atmospheric methane, which is far less abundant but much more potent than CO_2 at trapping heat in the atmosphere, increased to an average of 1,911.9 parts per billion (ppb). The 2022 methane increase was 14.0 ppb, the fourth-largest annual increase recorded since NOAA's systematic measurements began in 1983, and follows record growth in 2020 and 2021. Methane levels in the atmosphere are now more than two and a half times their pre-industrial level.").

[94] Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 3 ("The observed growth rates are roughly 1.5- to 2.5-fold higher than the multi-model mean baseline or bottom-up projections from 2020 to 2022 (Figure 2). The observed growth rates also exceed any individual model's baseline projections during that period. … That real-world methane growth rates exceed baseline projections therefore indicates that policies may have to be even stronger than those in existing analyses to reach the Paris Agreement's goals. Indeed, comparisons of observed atmospheric growth rates with those in 1.5°C-consistent scenarios (using the 2018 IPCC scenarios that did not include observations past 2017) show enormous differences (Figure 2), emphasizing how much stronger policies need to be to reach low-warming goals."); *discussed in* Zaelke D. (2 September 2024) *Mandatory mitigation to meet the methane imperative*, FRONTIERS POLICY LABS ("The *Frontiers in Science* lead article "The methane imperative", by Shindell et al. (5), provides definitive evidence demonstrating methane mitigation's planet-saving ability to reduce near-term warming. This starts with observational

evidence showing that methane growth rates are reaching the greatest values ever recorded—far above levels consistent with the 1.5–2ºC temperature limits of the Paris Agreement—and the recognition that mandatory mitigation measures are therefore needed. The authors explain that failure to cut methane will eat up a sizable portion of the remaining carbon budget for 1.5ºC, which, on current course, will be exhausted by 2030. As the carbon budget shrinks, the need for strategies to reduce CO_2 and methane from the atmosphere grows.").

[95] United Nations Environment Programme and Climate & Clean Air Coalition (2022) *Summary for Policymakers*, *in* GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 5 ("The Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment shows that human-driven methane emissions are responsible for nearly 45 per cent of current net warming. The IPCC has continuously emphasized the critical urgency of reducing anthropogenic emissions – from methane and from other climate pollutants – if the world is to stay below 1.5° and 2°C targets.").

[96] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.2.

[97] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 853–854 ("For methane emissions, in addition to their direct effect, there are indirect positive ERFs from methane enhancing its own lifetime, causing ozone production, enhancing stratospheric water vapor, and influencing aerosols and the lifetimes of HCFCs and HFCs (Myhre et al., 2013b; O'Connor et al., 2021). The ERF from methane emissions is considerably higher than the ERF estimate resulting from its abundance change. The central estimate with the very likely range is 1.21 (0.90 to 1.51) W m^{-2} for emission-based estimate versus 0.54 W m^{-2} for abundance-based estimate (cf. section 7.3.5). The abundance-based ERF estimate for CH_4 results from contributions of its own emissions and the effects of several other compounds, some decreasing CH_4 lifetime, notably NO_x, which importantly reduce the CH_4 abundance-based ERF."). *See also* Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 129 (*see* Table 1 on Present-day anthropogenic radiative forcing directly and indirectly attributable to CH_4 and its chemistry, showing that the radiative forcing contributed by methane to ozone formation, CO_2 formation, increased stratospheric water vapor, and reduction in sulfate aerosol formation are 0.241 W m^{-2}, 0.018 W m^{-2}, 0.05 W m^{-2}, and 0.1 W m^{-2}, respectively, in addition to methane's direct forcing of 0.54 W m^{-2}.).

[98] Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENV. SCI. POL. 134: 127–136, 128–129 ("Methane is a GHG and thereby a direct climate forcer; that is, it absorbs and re-radiates thermal radiation, contributing directly to the greenhouse effect. Unlike CO_2, CH_4 is chemically active, with atmospheric oxidation accounting for approximately 95% of its loss. Among other things, reactions of CH_4 lead to the production of tropospheric O_3 and stratospheric water vapor, and the end product of CH_4 oxidation is CO_2 itself (Forster et al., 2021). In this way, CH_4 also acts as an indirect climate forcer because it leads to the production of other GHGs (Fig. 1). A quantitative overview of radiative forcing due to CH_4 and its associated photochemical products is provided in Table 1. The chemical reactions of CH_4 also alter the atmospheric concentration of oxidants, especially the [hydroxy radical (OH)]. This in turn has an indirect effect on the abundance of other trace gases and aerosols in the troposphere. In particular, increased atmospheric CH_4 provides an increased sink for OH, reducing the formation of sulfate aerosol (via SO_2 +OH). Since sulfate aerosol has a cooling effect on the climate (see also Fig. 2) its reduction can be seen as an additional, indirect positive radiative forcing attributable to CH_4 (Shindell et al., 2009). Shindell et al. (2009) calculate that this effect is equivalent to a radiative forcing of approximately + 0.1 W m^{-2} (Table 1), comparable to the CH_4-induced radiative forcing due to stratospheric water vapor.").

[99] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 927 ("The assessed global warming potentials (GWP) and global temperature-change potentials (GTP) for methane and nitrous oxide are slightly lower than in AR5 due to revised estimates of their lifetimes and updated estimates of their indirect chemical effects (medium confidence). The assessed metrics now also include the carbon cycle response for non-CO2 gases. The carbon cycle estimate is lower than in AR5, but there is high confidence in the need for its inclusion and in the quantification methodology. Metrics for methane from fossil fuel sources account for the extra fossil CO2 that these emissions contribute to the atmosphere and so have slightly higher emissions metric values than those from biogenic sources (high confidence).").

[100] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years."), 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period."); Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 9–10 ("Given the smaller role of other non-CO_2 climate pollutants, methane emission cuts therefore provide the strongest leverage for near-term warming reduction (Figure 5)(13, 95). Achievement of methane reductions consistent with the average in 1.5°C scenarios could reduce warming by ~0.3°C by 2050 in comparison with baseline increases (4). A hypothetical complete elimination of anthropogenic methane emissions could avert up to 1°C of warming by 2050 relative to the high emissions Shared Socioeconomic Pathway [SSP; (96)] SSP3–7.0 scenario (97). This large near-term impact partly reflects methane's short lifetime; >90% of increased atmospheric methane would be removed within 30 years of an abrupt cessation of anthropogenic emissions compared with only ~25% of increased CO_2 following CO_2 emission cessation (98)."); *and* Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 11 ("In addition [to cutting CO_2], pricing and reducing methane emissions is critical for effectively mitigating climate change. Methane is a potent greenhouse gas, and unlike carbon dioxide, which persists in the atmosphere for centuries, methane has a relatively short atmospheric lifetime, making reductions impactful in the short term (Shindell et al. 2024). Drastically cutting methane emissions can slow the near-term rate of global warming, helping to avoid tipping points and extreme climate impacts.").

[101] Zhang Y., Held I., & Fueglistaler S. (2021) *Projections of tropical heat stress constrained by atmospheric dynamics*, NAT. GEO. 14(3): 133–137, 133 ("For each 1 °C of tropical mean warming, global climate models project extreme TW (the annual maximum of daily mean or 3-hourly values) to increase roughly uniformly between 20° S and 20° N latitude by about 1 °C. This projection is consistent with theoretical expectation based on tropical

atmospheric dynamics, and observations over the past 40 years, which gives confidence to the model projection. For a 1.5 °C warmer world, the probable (66% confidence interval) increase of regional extreme TW is projected to be 1.33–1.49 °C, whereas the uncertainty of projected extreme temperatures is 3.7 times as large. These results suggest that limiting global warming to 1.5 °C will prevent most of the tropics from reaching a TW of 35 °C, the limit of human adaptation.").

[102] Lenton T. M., Xu C., Abrams J. F., Ghadiali A., Loriani S., Sakschewski B., Zimm C., Ebi K. L., Dunn R. R., Svenning J.-C., & Scheffer M. (2023) *Quantifying the human cost of global warming*, NAT. SUSTAIN. 6(10): 1–11, calculated based on Supplementary Data 1 "Country-level results for population, land area and land fraction exposed to MAT > 29°C", 7 ("The ~2.7 °C global warming expected under current policies puts around a third of the world population outside the niche. It exposes almost the entire area of some countries (for example, Burkina Faso, Mali) to unprecedented heat, including some Small Island Developing States (for example, Aruba, Netherlands Antilles; Fig. 5b)—a group with members already facing an existential risk from sea-level rise. The gains from fully implementing all announced policy targets and limiting global warming to ~1.8 °C are considerable, but would still leave nearly 10% of people exposed to unprecedented heat. Meeting the goal of the Paris Agreement to limit global warming to 1.5 °C halves exposure outside the temperature niche relative to current policies and limits those exposed to unprecedented heat to 5% of people."), 1 ("By end-of-century (2080–2100), current policies leading to around 2.7 °C global warming could leave one-third (22–39%) of people outside the niche. Reducing global warming from 2.7 to 1.5 °C results in a ~5-fold decrease in the population exposed to unprecedented heat (mean annual temperature ≥29 °C). The lifetime emissions of ~3.5 global average citizens today (or ~1.2 average US citizens) expose one future person to unprecedented heat by end-of-century. That person comes from a place where emissions today are around half of the global average. These results highlight the need for more decisive policy action to limit the human costs and inequities of climate change."), 5 ("Assuming a future world of 9.5 billion, India has the greatest population exposed under 2.7 °C global warming, >600 million, but this reduces >6-fold to ~90 million at 1.5 °C global warming. Nigeria has the second largest population exposed, >300 million under 2.7 °C global warming, but this reduces >7-fold to 20-fold, from ~100 million under 2.7 °C global warming to 80 million exposed under 2.7 °C global warming, there are even larger proportional reductions at 1.5 °C global warming. Sahelian–Saharan countries including Sudan (sixth ranked) and Niger (seventh) have a ~2-fold reduction in exposure, because they still have a large fraction of land area hot exposed at 1.5 °C global warming (Fig. 5b). The fraction of land area exposed approaches 100% for several countries under 2.7 °C global warming (Fig. 5b). Brazil has the greatest absolute land area exposed under 2.7 °C global warming, despite almost no area being exposed at 1.5 °C, and Australia and India also experience massive increases in absolute area exposed (Fig. 4). (If the future population reaches 11.1 billion, the ranking of countries by population exposed remains similar, although the numbers exposed increase.) Those most exposed under 2.7 °C global warming come from nations that today are above the median poverty rate and below the median per capita emissions (Fig. 6)."). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, PROC. NAT'L. ACAD. SCI. 117(21): 11350–11355, 11352 ("Such a calculation suggests that for the RCP8.5 business-as-usual climate scenario, and accounting for expected demographic developments (the SSP3 scenario[15]),∼3.5 billion people (roughly 30% of the projected global population; SI Appendix, Fig. S12) would have to move to other areas if the global population were to stay distributed relative to temperature the same way it has been for the past millennia (SI Appendix, Fig. S13). Strong climate mitigation following the RCP2.6 scenario would substantially reduce the geographical shift in the niche of humans and would reduce the theoretically needed movement to ∼1.5 billion people (∼13% of the projected global population; SI Appendix, Figs. S12 and S13).").

[103] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 8 ("Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5°C. Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts. It would also, each year,

prevent 255 000 premature deaths, 775 000 asthma related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally.").

[104] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 592 ("Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming3, which could happen as soon as 2030. ...The world's remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO_2. Permafrost emissions could take an estimated 20% (100 Gt CO_2) off this budget, and that's without including methane from deep permafrost or undersea hydrates. If forests are close to tipping points, Amazon dieback could release another 90 Gt CO_2 and boreal forests a further 110 Gt CO_2. With global total CO_2 emissions still at more than 40 Gt per year, the remaining budget could be all but erased already. ...We argue that the intervention time left to prevent tipping could already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is 30 years at best. Hence we might already have lost control of whether tipping happens. A saving grace is that the rate at which damage accumulates from tipping — and hence the risk posed — could still be under our control to some extent."). *See also* Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BIOSCIENCE 71(9): 894–898, 894 ("There is also mounting evidence that we are nearing or have already crossed tipping points associated with critical parts of the Earth system, including the West Antarctic and Greenland ice sheets, warm-water coral reefs, and the Amazon rainforest.").

[105] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94)."). *See also* Lenton T. M., Armstrong McKay D. I., Loriani S., Abrams J. F., Lade S. J., Donges J. F., Buxton J. E., Milkoreit M., Powell T., Smith S. R., Zimm C., Bailey E., Dyke J. G., Ghadiali A., & Laybourn L. (2023) GLOBAL TIPPING POINTS SUMMARY REPORT 2023, 13 ("Already, at today's 1.2°C global warming, tipping of warm-water coral reefs is likely and we cannot rule out that four other systems may pass tipping points: the ice sheets of Greenland and West Antarctica, the North Atlantics Subpolar Gyre circulation, and parts of the permafrost subject to abrupt thaw.").

[106] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-78 ("Abrupt change is defined as a change in the system that is substantially faster than the typical rate of the changes in its history (Chapter 1, Section 1.4.5). A related matter is a tipping point: a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly.").

[107] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential

threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 (“Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94).”).

[108] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5777 (“Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit.”). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 593 (“A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic....”); Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-71–TS-72 (“It is *likely* that under stabilization of global warming at 1.5°C, 2.0°C, or 3.0°C relative to 1850–1900, the AMOC will continue to weaken for several decades by about 15%, 20% and 30% of its strength and then recover to pre-decline values over several centuries (*medium confidence*). At sustained warming levels between 2°C and 3°C, there is limited evidence that the Greenland and West Antarctic Ice Sheets will be lost almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss increases with higher surface temperatures (*high confidence*). At sustained warming levels between 3°C and 5°C, near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet is projected to occur irreversibly over multiple millennia (*medium confidence*); with substantial parts or all of Wilkes Subglacial Basin in East Antarctica lost over multiple millennia (*low confidence*). Early-warning signals of accelerated sea-level-rise from Antarctica, could possibly be observed within the next few decades. For other hazards (e.g., ice sheet behaviour, glacier mass loss and global mean sea level change, coastal floods, coastal erosion, air pollution, and ocean acidification) the time and/or scenario dimensions remain critical, and a simple and robust relationship with global warming level cannot be established (*high confidence*)... The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with climate change (*high confidence*). It is *very unlikely* that gas clathrates (mostly methane) in deeper terrestrial permafrost and subsea clathrates will lead to a detectable departure from the emissions trajectory during this century. Possible abrupt changes and tipping points in biogeochemical cycles lead to additional uncertainty in 21st century atmospheric GHG concentrations, but future anthropogenic emissions remain the dominant uncertainty (*high confidence*). There is potential for abrupt water cycle changes in some high-emission scenarios, but there is no overall consistency regarding the magnitude and timing of such changes. Positive land surface feedbacks, including vegetation, dust, and snow, can contribute to abrupt changes in aridity, but there is only low confidence that such changes will occur during the 21st century. Continued Amazon deforestation, combined with a warming climate, raises the probability that this ecosystem will cross a tipping point into a dry state during the 21st century (*low confidence*). {TS3.2.2, 5.4.3, 5.4.5, 5.4.8, 5.4.9, 8.6.2, 8.6.3, Cross-chapter Box 12.1}”); *and* Lee J.-Y., Marotzke J.,

Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4-96 (Table 4.10 lists 15 components of the Earth system susceptible to tipping points).

[109] Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 262 ("Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7."). *See also* Abram N., *et al.* (2019) *Chapter 1: Framing and Context of the Report*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), 1-81 ("While some aspects of the ocean and cryosphere might respond in a linear (i.e., directly proportional) manner to a perturbation by some external forcing, this may change fundamentally when critical thresholds are reached. A very important example for such a threshold is the transition from frozen water to liquid water at around 0 ºC that can lead to rapid acceleration of ice-melt or permafrost thaw (e.g., Abram et al., 2013; Trusel et al., 2018). Such thresholds often act as tipping points, as they are associated with rapid and abrupt changes even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean's large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West Antarctic Ice Sheet though a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al*. 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2ºC (IPCC, 2018).").

[110] Here we distinguish between abrupt shifts, as in Drijfhout *et al.* (2015), and the more restrictive definition of "core climate tipping points" defined by Armstrong McKay *et al.* (2022) as "when change in part of the climate system becomes (i) self perpetuating beyond (ii) a warming threshold as a result of asymmetry in the relevant feedbacks, leading to (iii) substantial and widespread Earth system impacts." *See* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94). … The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C.").

[111] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state11. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature."). *See also* Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, EARTH SYST. DYN. 12(2): 601–619, 614 ("In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the climate system as a whole."); *and* Rocha J. C., Peterson G., Bodin Ö., & Levin S. (2018) *Cascading regime shifts within and across scales*, SCIENCE 362(6421): 1379–1383, 1383 ("A key lesson from our study is that regime shifts can be interconnected. Regime shifts should not be studied in isolation under the assumption that they are independent systems. Methods and data collection need to be further developed to account for the possibility of cascading effects. Our finding that ~45% of regime shift couplings can have structural dependence suggests that current approaches to environmental management and governance underestimate the likelihood of cascading effects.").

[112] McIntyre M. E. (2023) *Climate tipping points: A personal view*, PHYSICS TODAY 76(3): 44–49, 45–46 ("Nearly all the climate system's real complexity is outside the scope of any model, whether it's a global climate model that aims to represent the climate system as a whole or a model that only simulates the carbon cycle, ice flow, or another subsystem…. Changes taking only a few years are almost instantaneous from a climate-system perspective. They're a warning to take seriously the possibility of tipping points in the dynamics of the real climate system.[9] The warning is needed because some modelers have argued that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamic-systems researchers.[3] Other researchers, however, have suggested that such a tipping point may be reached sometime in the next few decades or even sooner.[6,7] Some of its mechanisms resemble those of the Dansgaard–Oeschger warmings and would suddenly accelerate the rate of disappearance of Arctic sea ice. As far as I am aware, no such tipping points have shown up in the behavior of the biggest and most sophisticated climate models. The suggested tipping-point behavior depends on fine details that are not well resolved in the models, including details of the sea ice and the layering of the upper ocean. Also of concern are increases in the frequency and intensity of destructive weather extremes. Such increases have already been observed in recent years. Climate scientists are asking how much further the increases will go and precisely how they will develop. That question is, of course, bound up with the question of tipping points. A failure to simulate many of the extremes themselves, especially extremes of surface storminess, must count as another limitation of the climate models. The reasons are related to the resolution constraints of climate models."). *See also* Spratt D. (19 April 2023) *Faster than forecast, climate impacts trigger tipping points in the Earth system*, BULLETIN OF THE ATOMIC SCIENTISTS ("While observed warming has been close to climate model projections, the impacts have in many instances been faster and even more extreme than the models forecasted. William Ripple and his co-researchers show that many positive feedbacks are not fully accounted for in climate models…. In September 2022, Stockholm University's David Armstrong McKay and his colleagues concluded that even global warming of 1-degree Celsius risks triggering some tipping points, just one data point in an alarming mountain of research on tipping points presented in the last year and a half. … Speaking in 2018, Steffen said that the dominant linear, deterministic framework for assessing climate change is flawed, especially at higher levels of temperature rise. Model projections that don't include these feedback and cascading processes "become less useful at higher temperature levels… or, as my co-author John Schellnhuber says, we are making a big mistake when we think we can 'park' the Earth System at any given temperature rise – say 2°C – and expect it to stay there."); *and* Spratt D. & Dunlop I. (2017) *What lies beneath? The scientific understatement of climate risks*, Breakthrough & The National Centre for Climate Restoration, 21 ("As discussed above, climate models are not yet good at dealing with tipping points. This is partly due to the nature of tipping points, where a

particular and complex confluence of factors abruptly change a climate system characteristic and drive it to a different state. To model this, all the contributing factors and their forces have to be well identified, as well as their particular interactions, plus the interactions between tipping points. Researchers say that "complex, nonlinear systems typically shift between alternative states in an abrupt, rather than a smooth manner, which is a challenge that climate models have not yet been able to adequately meet.").

[113] Ritchie P. D. L., Alkhayuon H., Cox P. M., & Wieczorek S. (2023) *Rate-induced tipping in natural and human systems*, EARTH SYST. DYN. 14(3): 669–683, 669–670 ("However, there is another, less obvious potential consequence of changes in external forcing. When an external forcing changes faster than some critical rate rather than necessarily by a large amount, this can lead to rate-induced tipping points (Stocker and Schmittner, 1997; Luke and Cox, 2011; Wieczorek et al., 2011; Ashwin et al., 2012; Ritchie and Sieber, 2016; Siteur et al., 2016; Suchithra et al., 2020; Arumugam et al., 2020; Pierini and Ghil, 2021; Wiec- zorek et al., 2023; Longo et al., 2021; Kuehn and Longo, 2022; Kaur and Sharathi Dutta, 2022; Hill et al., 2022; Arnscheidt and Rothman, 2022). In contrast to bifurcation-induced tipping, rate-induced tipping occurs due to fast-enough changes in external forcing and usually does not exceed any critical levels as a result of external forcing. Such tipping points are much less widely known and yet are arguably even more relevant to contemporary issues such as climate change (Lohmann and Ditlevsen, 2021; Clarke et al., 2021; O'Sullivan et al., 2022), ecosystem collapse (Scheffer et al., 2008; Vanselow et al., 2019; van der Bolt and van Nes, 2021; Neijnens et al., 2021; Vanselow et al., 2022), and the resilience of human systems (Witthaut et al., 2021)."), 678 ("This paper highlights the importance of considering how fast external forcing is changing as opposed to solely focusing on levels of change. Consequently, the actions taken to control the rate of change in forcing are equally as important as the actions taken to control the level at which forcing is halted."), *discussed in* Morrison A. (14 July 2023) *Tipping Points Can Be Triggered Unexpectedly By Dangerous Rates Of Change*, UNIVERSITY OF EXETER NEWS ("Until now, critical thresholds have been assumed to be a point of no return, but the new study – published in the journal *Earth System Dynamics* – concludes that dangerous rates could trigger permanent shifts in human and natural systems before these critical levels are reached…Whilst the latest Intergovernmental Panel on Climate Change 6th Assessment Report rightly highlighted the urgency to limit global warming levels, it fell short of identifying the rate of warming as a key risk factor for climate tipping points" said joint lead author Dr Paul Ritchie, of Exeter's Global Systems Institute and the Department of Mathematics and Statistics.").

[114] Willcock S., Cooper G. S., Addy J., & Dearing J. A. (2023) *Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers*, NAT. SUSTAIN. 6(11): 1–12, 3 ("In addition to earlier breakpoint dates, extra drivers can also cause ATDCs [Abrupt Threshold-Dependent Change] at levels where it would be resilient to the primary slow driver in isolation (Supplementary Section 2)."), 4 ("The addition of high noise (normalized $\sigma > 0.666$) shows that increasing the variability of the primary slow driver (in isolation) across all four models can bring forward the date of system collapse (Fig. 3). The effects outlined above are synergistic—combining multiple drivers with noise further reduces the breakpoint date beyond the effects of either multiple drivers or noise acting alone (Fig. 4)"), 5 ("Our findings also show that 1.2–14.8% of ATDCs can be triggered by additional drivers and/or noise below the threshold of driver strengths required to collapse the system if only a single driver were in effect.").

[115] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5784 ("Permafrost carbon release (51) and methane hydrates release (52) were not expected in CMIP5 simulations, because of missing biogeochemical components in those models capable of simulating such changes."). *See also* Bathiany S., Hidding J., & Scheffer M. (2020) *Edge Detection Reveals Abrupt and Extreme Climate Events*, J. CLIM. 33(15): 6399–6421, 6416 ("Despite their societal relevance, our knowledge about the risks of future abrupt climate shifts is far from robust. Several important aspects are highly uncertain: future greenhouse gas emissions (scenario uncertainty), the current climate state (initial condition uncertainty), the question whether and how to model specific processes (structural uncertainty), and what values one should choose for parameters appearing in the equations (parametric uncertainty). Such uncertainties can be explored using ensemble simulations. For example, by running many simulations with different combinations of parameter values a perturbed-physics ensemble can address how parameter uncertainty affects the occurrence of extreme events

(Clark et al. 2006). This strategy can be particularly beneficial for studying abrupt events as well since abrupt shifts are associated with region-specific processes, whereas models are usually calibrated to produce a realistic global mean climate at the expense of regional realism (Mauritsen et al. 2012; McNeall et al. 2016). The currently available model configurations are therefore neither reliable nor sufficient to assess the risk of abrupt shifts (Drijfhout et al. 2015). It is hence very plausible that yet-undiscovered tipping points can occur in climate models."); Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-78 ("There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength."); *and* Permafrost Pathways, *Course of Action: Mitigation Policy*, Woodwell Climate Research Center (*last visited* 5 February 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement.... Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish. … 82% [o]f IPCC models do not include carbon emissions from permafrost thaw.").

[116] Intergovernmental Panel on Climate Change (2021) *Annex VII Glossary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.).

[117] Boers N. & Rypdal M. (2021) *Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point*, PROC. NAT'L. ACAD. SCI. 118(21): 1–7, 1 ("A crucial nonlinear mechanism for the existence of this tipping point is the positive melt-elevation feedback: Melting reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. We reveal early-warning signals for a forthcoming critical transition from ice-core-derived height reconstructions and infer that the western Greenland Ice Sheet has been losing stability in response to rising temperatures. We show that the melt-elevation feedback is likely to be responsible for the observed destabilization. Our results suggest substantially enhanced melting in the near future.").

[118] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, SCI. ADV. 7(3): 1–8, 1 ("The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040.").

[119] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J.

(eds.), SPM-22 ("In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}"). *See also* Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-15 ("In model pathways with no or limited overshoot of 1.5 °C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range).... Modelled pathways that limit global warming to 1.5 °C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010).").

[120] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-31 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls.").

[121] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."). *See also* Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, PROC. NAT'L. ACAD. SCI. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); Hansen J. E. & Sato M. (2021) *July Temperature Update: Faustian Payment Comes Due* ("It follows that the global warming acceleration is due to the one huge climate forcing that we have chosen not to measure: the forcing caused by imposed changes of atmospheric aerosols... We should expect the global warming rate for the quarter of a century 2015-2040 to be about double the 0.18°C/decade rate during 1970-2015 (see Fig. 2), unless appropriate countermeasures are taken."); *and* Dvorak M. T., Armour K. C., Frierson D. M. W., Proistosescu C., Baker M. B., & Smith C. J. (2022) *Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming*, NAT. CLIM. CHANGE 12: 547–552, 547 ("Following abrupt cessation of anthropogenic emissions, decreases in short-lived aerosols would lead to a warming

peak within a decade, followed by slow cooling as GHG concentrations decline. This implies a geophysical commitment to temporarily crossing warming levels before reaching them. Here we use an emissions-based climate model (FaIR) to estimate temperature change following cessation of emissions in 2021 and in every year thereafter until 2080 following eight Shared Socioeconomic Pathways (SSPs). Assuming a medium-emissions trajectory (SSP2–4.5), we find that we are already committed to peak warming greater than 1.5 °C with 42% probability, increasing to 66% by 2029 (340 $GtCO_2$ relative to 2021). Probability of peak warming greater than 2.0 °C is currently 2%, increasing to 66% by 2057 (1,550 $GtCO_2$ relative to 2021). Because climate will cool from peak warming as GHG concentrations decline, committed warming of 1.5 °C in 2100 will not occur with at least 66% probability until 2055.").

[122] Climate scientist and IPCC author Joeri Rogelj, *as quoted in* Berwyn B. (15 September 2021) *The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns*, INSIDE CLIMATE NEWS ("James Hansen, a climate scientist who shook Washington when he told Congress 33 years ago that human emissions of greenhouse gases were cooking the planet, is now warning that he expects the rate of global warming to double in the next 20 years. While still warning that it is carbon dioxide and methane that are driving global warming, Hansen said that, in this case, warming is being accelerated by the decline of other industrial pollutants that they've cleaned from it. … In Hansen's latest warning, he said scientists are dangerously underestimating the climate impact of reducing sulfate aerosol pollution. 'Something is going on in addition to greenhouse warming,' Hansen wrote, noting that July's average global temperature soared to its second-highest reading on record even though the Pacific Ocean is in a cooling La Niña phase that temporarily dampens signs of warming. Between now and 2040, he wrote that he expects the climate's rate of warming to double in an 'acceleration that can be traced to aerosols.' That acceleration could lead to total warming of 2 degrees Celsius by 2040, the upper limit of the temperature range that countries in the Paris accord agreed was needed to prevent disastrous impacts from climate change. What's more, Hansen and other researchers said the processes leading to the acceleration are not adequately measured, and some of the tools needed to gauge them aren't even in place…. A doubling of the rate of global warming would put the planet in the fast lane of glacial melting, sea level rise and coral reef ecosystem die-offs, as well as escalating heatwaves, droughts and floods. But that future is not yet set in stone, said Michael Mann, a climate scientist at Penn State. He said Hansen's prediction appears inconsistent with the scientific literature assessed by the Intergovernmental Panel on Climate Change. The IPCC's latest report advises "that reductions of carbon emissions by 50 percent over the next decade and net-zero by 2100, along with a ramp-down in both aerosols and other short-term agents, including black carbon and other trace anthropogenic greenhouse gases, stabilizes warming well below 2 degrees Celsius," Mann said. But the IPCC report also highlighted that declining aerosol pollution will speed warming. "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO2, will result in an increase in the resulting rate of warming," said climate scientist and IPCC report author Joeri Rogelj, director of research at the Imperial College London's Grantham Institute. There's a fix for at least some of this short-term increase in the rate of warming, he said. "The only measures that can counteract this increased rate of warming over the next decades are methane reductions," Rogelj said. "I just want to highlight that methane reductions have always been part of the portfolio of greenhouse gas emissions reductions that are necessary to meet the goals of the Paris Agreement. This new evidence only further emphasizes this need."). *See also* Spring J. & Stanway D. (2 November 2023) *Climate's 'catch-22': cutting pollution heats up the planet*, REUTERS ("[Scientists] stressed the need for more aggressive action to cut emissions of climate-warming greenhouse gases, with reducing methane seen as one of the most promising paths to offset pollution unmasking in the short term.").

[123] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs,

the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}"), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."); *and* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.").

[124] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-30–SPM-31 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century... Future non-CO_2 warming depends on reductions in non-CO_2 GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq per year, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*)").

[125] Fiore A. M., Jacob D. J., Field B. D., Streets D. G., Fernandes S. D., & Jang C. (2002) *Linking ozone pollution and climate change: The case for controlling methane*, GEOPHYS. RES. LETT. 29(19): 25-1–25-4, 25-1 ("Methane is a known major source of the tropospheric O_3 background, but is not generally considered a precursor to regional O_3 pollution episodes in surface air because of its long lifetime (8–9 years).... Our global 3-D model analysis shows that reducing CH_4 emissions enables a simultaneous pursuit of O_3 air quality and climate change mitigation objectives. Whereas reductions in NO_x emissions achieve localized decreases in surface O_3 concentrations, reductions in CH_4 emissions lower the global O_3 background and improve surface air quality everywhere."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT, 45 ("Next, the linearity of the response to different magnitudes of methane concentration change was examined. At the national level,

population weighted ozone changes are extremely linear across a range of methane increases and decreases (Figure 3.4). Though the response itself varies from country to country (i.e. the slopes are different), the ozone change at the national level is directly proportional to the methane concentration change regardless of the ozone metric chosen. This result is consistent with prior studies which also indicate that the ozone/methane relationship is approximately linear (Fiore *et al*. 2008) but its magnitude depends on the local availability of nitrogen oxides, and, through nitrogen oxides, of hydroxyl (West *et al*. 2006; Wang and Jacob 1998).").

[126] Turner M. C., Jerrett M., Pope C. A., Krewski D., Gapstur S. M., Diver W. R., Beckerman B. S., Marshall J. D., Su J., Crouse D. L., & Burnett R. T. (2016) *Long-Term Ozone Exposure and Mortality in a Large Prospective Study*, AM. J. RESPIR. CRIT. CARE MED. 193(10): 1134–1142, 1134 ("We observed significant positive associations between long-term O_3 and all-cause, circulatory, and respiratory mortality with 2%, 3%, and 12% increases in risk per 10 ppb, respectively, in this large-scale study with 22 years of follow-up."). *See also* Global Climate and Health Alliance (2023) MITIGATING METHANE: A GLOBAL HEALTH STRATEGY, 7 ("Methane emissions are directly detrimental to human health by contributing to the formation of tropospheric, or ground-level ozone, an air pollutant and GHG. Tropospheric ozone can damage airways, trigger asthma attacks, and aggravate lung diseases. Long-term exposure to tropospheric ozone can lead to premature mortality from respiratory illnesses, cardiovascular diseases, and cancer1. The 2022 Global Methane Assessment identified a linear relationship in tropospheric ozone responses to methane concentrations — as methane concentrations increase, so does ozone. An estimated 1.04 to 1.23 million respiratory deaths in adults over 30 years old are associated with exposure to ground-level ozone.").

[127] Feng Z., Xu Y., Kobayashi K., Dai L., Zhang T., Agathokleous E., Calatayud V., Paoletti E., Mukherjee A., Agrawal M., Park R. J., Oak Y. J., & Yue X. (2022) *Ozone pollution threatens the production of major staple crops in East Asia*, NAT. FOOD 3: 47–56, 47 ("East Asia is a hotspot of surface ozone (O_3) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O_3 by combining O_3 elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O_3-induced annual loss of crop production is estimated at US$63 billion.").

[128] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 129–130 ("Beyond this, however, O_3 damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO_2 fertilization that is expected to partially offset rising atmospheric CO_2 concentrations (Sitch et al., 2007; Ciais et al., 2013; Arneth et al., 2010; Ainsworth et al., 2012). However, the magnitude of this effect remains the subject of scientific debate, largely due to the complexity of interactions between plant response to O_3 and other environmental variables, including other air pollutants, CO_2 concentrations, temperature, precipitation, and nitrogen availability (Ainsworth et al., 2012; Kvalevåg and Myhre, 2013; Sitch et al., 2007; Simpson et al., 2014). For instance, Sitch et al. (2007) estimated that the present-day indirect radiative forcing due to O_3-induced plant damage could be as high as 0.21–0.38 W m^{-2}, comparable to the direct radiative forcing of tropospheric O_3. However, Kvalevåg and Myhre (2013) argue that this estimate is far too high and that accounting for nitrogen limitation on plant growth reduces the expected impact; they estimate an indirect radiative.").

[129] Butler T., Lupascu A., & Nalam A. (2020) *Attribution of ground-level ozone to anthropogenic and natural sources of nitrogen oxides and reactive carbon in a global chemical transport model*, ATMOS. CHEM. PHYS. 20(17): 10707–10731, 10726 ("As a reactive carbon precursor, methane contributes 35 % of the tropospheric ozone burden and 41 % of the Northern Hemisphere annual average surface mixing ratio, which is more than any other source of reactive carbon.").

[130] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 130 ("Importantly, the role of methane's contribution to O_3 production is expected to increase in the future, as emissions of other anthropogenic precursors

(primarily NO_x and VOCs) are anticipated to decrease as a result of current and planned air quality regulations across much of the globe. For instance, Young et al. (2013) showed that rising CH_4 concentrations could be a major driver of increased surface O_3 by 2100 under the high-emission scenario developed for the IPCC 5th Assessment report. Turnock et al. (2018) showed that increased O_3 production from rising CH_4 concentrations could offset the reduction in surface O_3 due to reductions in emissions of shorter-lived O_3 precursors.").

[131] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 8 (Figure ES1: Current and projected anthropogenic methane emissions and the identified sectoral mitigation potential in 2030 along with several benefits associated with sectoral-level methane emissions mitigation. Avoided warming occurs in the 2040s, other impacts are annual values beginning in 2030 that would continue thereafter).

[132] Staniaszek Z., Griffiths P. T., Folberth G. A., O'Connor F. M., Abraham N. L., Archibald A. T. (2021) *The role of future anthropogenic methane emissions in air quality and climate*, NPJ CLIM. ATMOS. SCI. 5(21): 1–8, 2–3 ("To quantify the air-quality impacts of anthropogenic methane, we calculated the long-term ozone-related mortality for SSP3-7.0 and ZAME for 2050, according to the method in Malley et al.[30]. We found that the ozone associated with anthropogenic methane is responsible for 690,000 premature deaths per year (456,000–910,000, lower and upper bounds of mortality rate) in 2050: 43% from respiratory causes and 57% from cardiovascular causes. This corresponds to around 1270 annual deaths per million tonnes (Tg) of methane emissions, or 65% higher total (ozone-related) deaths per year compared to ZAME.").

[133] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 78 ("The total valuation per tonne of methane for all market and non-market impacts assessed here is roughly US$ 4 300 using a cross-nation income elasticity for WTP of 1.0 and US$ 7 900 using an elasticity of 0.4 (Figure 3.19) – values are ~US$ 150 per tonne larger for fossil-related emissions. This value is dominated by mortality effects, of which US$ 2 500 are due to ozone and ~US$ 700 are due to heat using the more conservative 500 deaths per million tonnes of methane of this analysis' two global-scale estimates and a WTP income elasticity of 1.0, followed by climate impacts.").

[134] United Nations Environment Program (2 December 2023) *Bending the warming curve through action on non-CO2 gases at COP28 Summit*. *See also* United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO2 Greenhouse Gases*, Fact Sheet ("The United States, People's Republic of China, and United Arab Emirates today convened a Summit to accelerate actions to cut methane and other non-CO2 greenhouse gases as the fastest way to reduce near-term warming and keep a goal of limiting global average temperature increase to 1.5 degrees Celsius within reach.") *and* Escudero J. (18 December 2023) *COP28: "The Methane COP"*, LEGAL PLANET ("In a high-profile event at the main stage of COP28, the U.S., China, and United Arab Emirates hosted the Summit on Methane and non-CO2 Greenhouse Gases that called on the parties of the Paris Agreement to include methane and other GHGs in their nationally determined contributions (NDC). This statement is relevant since the parties did not always inform methane emissions; therefore, they were usually ignored in the actions that followed Nationally Determined Contributions, or NDCs. Another significant announcement from the Summit was the incorporation of Turkmenistan – one of the world's top emitters-Kazakhstan, Angola, Kenya, and Romania to the Global Methane Pledge, a commitment to reduce methane emissions by 30% from 202 levels by 2030. With these incorporations, 156 countries have joined the pledge, notably not China. In addition, Kazakhstan and the U.S. announced a cooperation partnership to help the Central Asian country meet the Global Methane Pledge's goals by developing national standards to eliminate non-emergency venting of methane, among other actions."),

[135] United Nations Framework Convention on Climate Change. (2023) *First global stocktake, Proposal by the President Draft decision -/CMA.5 Outcome of the first global stocktake*, S28 ("Further recognizes the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts, in a nationally determined manner, taking into account the Paris Agreement

and their different national circumstances, pathways and approaches." (f) "Accelerating and substantially reducing non-carbon-dioxide emissions globally, including in particular methane emissions by 2030.").

[136] *See generally* (3 December 2021) *Methane matters*, Editorial, NAT. GEOSCI. 14: 875.

[137] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common.. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute…."). *See also* Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254 ("This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. The challenge that humanity faces is to create a "Stabilized Earth" pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System's stability landscape without human stewardship to create and maintain it.").

[138] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050."). It would also keep the planet on a pathway consistent with staying within 1.5 °C, according to the *Global Methane Assessment*. United Nations Environment Programme & Climate & Clean Air Coalition (2021) *Briefing on the Global Methane Pledge* ("The Global Methane Pledge is a strong first step as the first-ever Heads-of State global commitment to cut methane emissions at a level consistent with a 1.5 C pathway."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 9 ("Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1)."). Deploying all available and additional measures could lead to a 45% reduction below 2030 levels to achieve nearly 0.3 °C in avoided warming by the 2040s.[138] Further, implementing the GMP would provide additional benefits, including prevention of approximately 200,000 premature ozone-related deaths, avoidance of ~580 million tons of yield losses of staple crops like rice and maize annually, avoidance of ~$500 billion per year in losses due to non-mortality health impacts, and impacts on forestry and agriculture, and avoidance of ~1,600 billion hours of work per year due to heat exposure. Nearly 85% of targeted measures have benefits that outweigh the net costs. United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: *2030 BASELINE REPORT SUMMARY FOR POLICYMAKERS*, 11 ("Using the results from the 2021 Global Methane Assessment, we calculate that Global Methane Pledge would provide additional benefits worldwide =through 2050, beyond keeping the planet cool, including: - Prevention of roughly 200,000 premature deaths per year due to ozone exposure - Avoidance of ~580 million tonnes of yield losses to wheat, maize (corn), rice and soybeans per year - Avoidance of ~$500 billion (2018 US$) per year in losses per year due to non-mortality health impacts, forestry and agriculture - Avoidance of ~1,600 billion lost work hours per year due to heat exposure."). According to the International Energey Agency,, total methane emissions from human activity are reduced by 45% and the energy sector by 75% between 2020 and 2030, costing less than 3% of net income from oil and gas in 2022. International Energy Agency (2023) *Credible pathways to 1.5 °C - Four pillars for action in the 2020s*, 1–15, 11 ("In the NZE

Scenario, methane emissions from the energy sector fall by around 75% between 2020 and 2030 and total methane emissions from human activity fall by around 45%. The IEA's latest update of its Global Methane Tracker found that methane emissions from oil and gas alone could be reduced by 75% with existing technologies. Around $100 billion in total investment is needed over the period to 2030 to achieve this reduction—equivalent to less than 3% of oil and gas net income in 2022. To address methane emissions from fossil energy production and consumption, countries covering over half of global gas imports and over one-third of global gas exports released a Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels at COP27 calling for minimizing flaring, methane, and CO_2 emissions across the supply chain to the fullest extent practicable.").

[139] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989). For a discussion of the Montreal Protocol on Substances that Deplete the Ozone Layer, *see generally* Miller A. S., Zaelke D., & Andersen S. O. (2021) RESETTING OUR FUTURE: *CUT SUPER CLIMATE POLLUTANTS NOW! THE OZONE TREATY'S URGENT LESSONS FOR SPEEDING UP CLIMATE ACTION*, John Hunt Publishing; *and* Andersen S., Zaelke D., Taddonio K., Ferris R., & Sherman N. (2021) *Ozone Layer, International Protection*, *in* MAX PLANCK ENCYCLOPEDIA OF PUBLIC INTERNATIONAL LAW, Oxford University Press, Peters A., & Wolfrum R. (eds.).

[140] *See, e.g.*, Volcovici V. (27 November 2023) *COP28 climate summit puts spotlight on turning methane pledges into action*, REUTERS ("'If it's just a pledge, it will land with a thump,' said Rachel Kyte, the World Bank's former climate envoy. 'The UAE needs to commit companies and countries to sit down and negotiate a binding agreement to x-out methane' and 'there are a lot of pieces coming together,' said Durwood Zaelke, president of the Institute for Governance and Sustainable Development, a Washington, D.C.-based think tank. 'With major emitters like the U.S., China and EU announcing new rules, the time is right for an agreement.'"). *See also* International Chamber of Commerce (23 November 2023) *Strengthening the Global Methane Pledge to keep 1.5 °C within reach* ("While businesses across our network are firmly committed to reducing methane emissions, clear policy signals from governments – backed by strong accountability measures within the GMP framework – are urgently needed to scale-up the mitigation efforts that are ultimately required by the end of this decade."); *and* Climate & Clean Air Coalition (9 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* ("As CCAC High-level Advocate for Finance Rachel Kyte, who moderated the session, said in her closing: "It's 2023. With peak oil, peak coal, and peak emissions, we are also 'peak-pledge'." This Coalition has proven to turn ambition into action, it set out as the Coalition of the Working.").

[141] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*)"), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).").

[142] Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, PROC. NAT'L. ACAD. SCI. 107(43): 18354–18359, 18357 ("In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has

two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions.").

[143] Parties to the United Nations Framework Convention on Climate Change are required to report emissions on a gas-by-gas basis in units of mass. *See* United Nations Framework Convention on Climate Change, Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶47 (2019) ("47. Each Party shall report estimates of emissions and removals for all categories, gases and carbon pools considered in the GHG inventory throughout the reported period on a gas-by-gas basis in units of mass at the most disaggregated level, in accordance with the IPCC guidelines referred to in paragraph 20 above, using the common reporting tables, including a descriptive summary and figures underlying emission trends, with emissions by sources listed separately from removals by sinks, except in cases where it may be technically impossible to separate information on emissions and removals in the LULUCF sector, and noting that a minimum level of aggregation is needed to protect confidential business and military information."). *See also* Allen M. R., *et al.* (2022) *Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets*, NPJ CLIM. ATMOS. SCI. 5(5): 1–4, 1 ("As researchers who have published over recent years on the issue of comparing the climate effects of different greenhouse gases, we would like to highlight a simple innovation that would enhance the transparency of stocktakes of progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO_2-equivalent emissions of all greenhouse gases, governments and corporations could also indicate the separate contribution to these totals from greenhouse gases with lifetimes around 100 years or longer, notably CO_2 and nitrous oxide, and the contribution from Short-Lived Climate Forcers (SLCFs), notably methane and some hydrofluorocarbons. This separate indication would support an objective assessment of the implications of aggregated emission targets for global temperature, in alignment with the UNFCCC Parties' Decision (4/CMA.1)1 to provide 'information necessary for clarity, transparency and understanding" in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDSs).'").

[144] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 1–10, 7 ("Although NDCs and long-term national pledges are currently insufficient to keep warming below 2 °C, let alone 1.5 °C [50–52], the time horizons used for emission metrics should nevertheless be consistent with that central goal of the Paris Agreement. We therefore support the use of the 20 year time horizon over the 100 year version, when binary choices between these two must be made, due to the better alignment of the former with the temperature goals of the Paris Agreement. The 50 year time horizon, not yet in widespread use but now included in IPCC AR6, is in fact the only time horizon that the IPCC presents that falls within the range of time horizons that align with the Paris Agreement temperature goals (24–58 years). However, to best align emission metrics with the Paris Agreement 1.5 ° C goal, we recommend the use of the 24 year time horizon, using 2045 as the end point time, with its associated $GWP_{1.5°C}$ = 75 and $GTP_{1.5°C}$ = 41."); *discussed in* McKenna P. (9 February 2022) *To Counter Global Warming, Focus Far More on Methane, a New Study Recommends*, INSIDE CLIMATE NEWS ("The Environmental Protection Agency is drastically undervaluing the potency of methane as a greenhouse gas when the agency compares methane's climate impact to that of carbon dioxide, a new study concludes. The EPA's climate accounting for methane is "arbitrary and unjustified" and three times too low to meet the goals set in the Paris climate agreement, the research report, published Wednesday in the journal Environmental Research Letters, found."); *and* Rathi A. (15 February 2022) *The Case Against Methane Emissions Keeps Getting Stronger*, BLOOMBERG.

[145] Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to report emissions on a gas-by-gas basis in units of mass. Framework Convention on Climate Change Dec. 18/CMA.1, FCCC/PA/CMA/ 2018/3/Add.2, at Annex ¶ 37 (March 19, 2019) ("37. Each Party shall use the 100-year time-horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report as agreed upon by the CMA, to report aggregate emissions and removals of GHGs, expressed in CO_2 eq. Each Party may in addition also use other metrics (e.g., global temperature potential) to report supplemental information on aggregate emissions and removals of GHGs, expressed in CO_2 eq. In

such cases, the Party shall provide in the national inventory document information on the values of the metrics used and the IPCC assessment report they were sourced from.").

[146] Cohen-Shields N., Sun T., Hamburg S. P., & Ocko I. B. (2023) *Distortion of sectoral roles in climate change threatens climate goals*, FRONT. CLIM. 5: 1–6, 4 ("Given how GWP100-based CO_2e calculations distort the roles of economic sectors in contributing to future warming, relying solely on GWP100 can lead to suboptimal policies and priorities by misleading climate actors from the top levels of government (e.g., U.S. NDC)[2] to grassroots organizations. This is because the importance of methane emissions in several sectors is systematically underestimated by GWP100. … there are examples of acknowledgment of the metric issue by stakeholders (such as work by the Irish Climate Change Advisory Council to establish multi-gas GHG budgets, as well as the State of New York publishing their emissions inventory using GWP20). Given that prioritizing sectoral mitigation efforts is often necessary under cost and political constraints, the current sectoral share distortion imposed by GWP100/CO_2e risks mis-prioritizing sectors for emissions reductions, undervaluing the benefits of methane-sector mitigation—especially in the near-term—and potentially overlooking important abatement measures. This can have implications for the temperature outcomes of climate policies. For example, if CO_2-dominated sectors are regularly prioritized for mitigation, the realized temperature benefits in the near-term will be lower than anticipated because the remaining warming impact from methane-dominated sectors will be underestimated. The bottom line is that GWP100 should never be singularly relied upon for emissions assessments.").

[147] Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritsen T., Palmer M. D., Watanabe M., Wild M., & Zhang H. (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 7.SM.7.

[148] Lynch J., Cain M., Pierrehumbert R., & Allen M. (2020) *Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants*, ENVIRON. RES. LETT. 15(4): 1–13, 2 ("Following these behaviours, sustained emissions of an SLCP therefore result in a similar impact to a one-off release of a fixed amount of CO_2: both lead to a relatively stable long-term increase in radiative forcing. Thus an alternative means of equivalence can be derived, relating a change in the rate of emissions of SLCPs to a fixed quantity of CO_2...."). *See also* Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 132 ("However, this practice of assigning "equivalence" belies the physical reality, namely that CH_4's impact on climate is distinct from CO_2's in several important ways, as described in Section 3. In effect, only the long-term climate impact of CH_4 (i.e., its radiative forcing over a 100-year time horizon) is robustly taken into account under the Kyoto Protocol and the Paris Agreement. Among other things, this means that CH_4's outsized contribution to near-term climate warming is overlooked.... The focus on CO_2 equivalence under the UNFCCC also leads to an information and transparency gap. The common practice of expressing mitigation targets in terms of aggregate CO_2e, without specifying which reductions come from which GHGs, compromises the ability of modelers to evaluate in detail how the climate will respond to pledged emission reductions; this is because the climate responds differently to the different climate forcers (Fig. 2).").

[149] Cain M., Lynch J., Allen M. R., Fuglestvedt J. S., Frame D. J., & Macey A. H. (2019) *Improved calculation of warming-equivalent emissions for short-lived climate pollutants*, NPJ CLIM. ATMOS. SCI. 2(29): 1–7, 1 ("We have used an empirical method to find a definition of GWP* that preserves the link between an emission and the warming it generates in the medium term up to 2100. The physical interpretation of equation 1 is that the flow term (with coefficient *r*) represents the fast climate response to a change in radiative forcing, generated by the atmospheric and ocean mixed-layer response.30 The timescale of this response is about 4 years here.31 The stock term (with coefficient *s*) represents the slower timescale climate response to a change in radiative forcing, due to the deep ocean response. This effect means that the climate responds slowly to past changes in radiative forcing, and is why the climate is

currently far from equilibrium. We have approximated this response by treating a quarter of the climate response to a SLCP as "cumulative".").

[150] Rogelj J. & Schleussner C.-F. (2021) *Reply to Comment on `Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'*, ENVIRON. RES. LETT. 16(6): 1–8, 2 ("These ethical issues arise from moving away from an emissions centered metric like GWP-100—where every unit of emissions of a certain GHG is treated equally and independent of the emitter or timing of emissions—to metrics like GWP*—which focus on additional warming and where the treatment of a unit of emissions depends on the emitter and their emission history... Meanwhile, a group of the world's biggest diary producers seems happy to consider the grandfathering GWP* perspective and explicitly dismisses other fairness perspectives that would increase their companies' responsibility for reducing methane emissions (Cady 2020)."), *citing* Cady R. (2020) *A Literature Review of GWP*: A proposed method for estimating global warming potential (GWP*) of short-lived climate pollutants like methane*, GLOBAL DAIRY PLATFORM, *discussed in* Elgin B. (19 October 2021) *Beef Industry Tries to Erase Its Emissions With Fuzzy Methane Math*, BLOOMBERG GREEN. *See also* Carter N. & Urbancic N. (2023) *Seeing stars: The new metric that could allow the meat and dairy industry to avoid climate action*, CHANGING MARKETS.

[151] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-19 ("With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*).").

[152] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11(8): 689–695, 689 ("Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades.").

[153] Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Comment, NATURE 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there's a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see 'Accelerated warming'). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu, Ramanathan, and Victor Comment was published, the IPCC has updated its estimate for when 1.5 °C will be exceeded: *see* Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-9 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global

warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"). *See also* Matthews H. D., Tokarska K. B., Rogelj J., Smith C. J., MacDougall A. H., Haustein K., Mengis N., Sippel S., Forster P. M., & Knutti R. (2021) *An integrated approach to quantifying uncertainties in the remaining carbon budget*, COMMUN. EARTH ENVIRON. 2(7): 1–11, 5 ("It is worth noting however, that the spread of our [remaining carbon budget (RCBs)] estimate does include negative values, with a 17% chance that the RCB for 1.5 °C is less than zero (i.e. is already exceeded). This outcome could arise due to current and/or unrealised future warming being at the higher end of their respective distributions, or in the case that the current non-CO_2 forcing fraction is small or negative owing to very strong current aerosol forcing. In this case, we would expect 1.5 °C to be exceeded even in the absence of additional emissions, and any future emissions between now and the time of net-zero CO_2 emissions would cause temperatures to rise further above this threshold.").

[154] World Meteorological Organization (2023) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, 2 ("The chance of global near-surface temperature exceeding 1.5°C above preindustrial levels for at least one year between 2023 and 2027 is more likely than not (66%). It is unlikely (32%) that the five-year mean will exceed this threshold."). For previous years, *see* Madge G. (8 May 2022) *Temporary breaching of 1.5C in next five years?*, UK MET OFFICE ("The chance of at least one year exceeding 1.5°C above pre-industrial levels between 2022-2026 is about as likely as not (48%). However, there is only a very small chance (10%) of the five-year mean exceeding this threshold."); *discussing* World Meteorological Organization (2022) GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE. *See also* Hook L. (9 May 2022) *World on course to breach global 1.5C warming threshold within five years*, FINANCIAL TIMES. World Meteorological Organization (2021) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, 5 ("Relative to pre-industrial conditions, the annual mean global near surface temperature is predicted to be between 0.9°C and 1.8°C higher (90% confidence interval). The chance of at least one year exceeding 1.5°C above pre-industrial levels is 44% and is increasing with time. There is a very small chance (10%) of the five-year mean exceeding this threshold. The Paris Agreement refers to a global temperature increase of 1.5°C, which is normally interpreted as the long-term warming, but temporary exceedances would be expected as global temperatures approach the threshold."); *discussed in* Hodgson C. (26 May 2021) *Chance of temporarily reaching 1.5C in warming is rising, WMO says*, FINANCIAL TIMES; World Meteorological Organization (2020) UNITED IN SCIENCE 2020, 16 ("Figure 2 shows that in the five-year period 2020–2024, the annual mean global near surface temperature is predicted to be between 0.91 °C and 1.59 °C above pre-industrial conditions (taken as the average over the period 1850 to 1900). The chance of at least one year exceeding 1.5 °C above pre-industrial levels is 24%, with a very small chance (3%) of the five-year mean exceeding this level. Confidence in forecasts of global mean temperature is high. However, the coronavirus lockdown caused changes in emissions of greenhouse gases and aerosols that were not included in the forecast models. The impact of changes in greenhouse gases is likely small based on early estimates (Le Quéré et al. 2020 and Carbonbrief.org)."); *and* McGuire B. (12 September 2022) *Why we should forget about the 1.5C global heating target*, THE GUARDIAN.

[155] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 6 ("Global surface temperature was around 1.1°C above 1850–1900 in 2011–2020 (1.09°C [0.95°C– 1.20°C])[7], with larger increases over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88°C [0.68°C– 1.01°C])[8]. Observed warming is human-caused, with warming from greenhouse gases (GHG), dominated by CO_2 and methane (CH_4), partly masked by aerosol cooling (Figure 2.1).").

[156] Forster P. M., *et al*. (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2296 ("The indicators show that human-induced warming reached 1.14 [0.9 to 1.4] °C averaged over the 2013–2022 decade and 1.26 [1.0 to 1.6] °C in 2022. Over the 2013–2022 period, human-induced warming has been increasing at an unprecedented rate of over 0.2 °C per decade.").

[157] Copernicus Climate Change Service (6 July 2023) *Record-breaking North Atlantic Ocean temperatures contribute to extreme marine heatwaves* ("So far this year, discussions of our oceans and climate have largely focused on the onset of El Niño, recently declared by the World Meteorological Organization, and its potential for pushing global temperatures into "uncharted territory" by the end of 2023 and into 2024. But in fact, we have already entered uncharted territory due to the exceptionally warm conditions in the north Atlantic Ocean.").

[158] This value is averaged from five agencies' reported 2023 temperature anomalies. Datasets used by different scientific agencies tend to have fewer data (and thus different baselines) for the pre-industrial period of 1850–1900, and so report slightly different values for the temperature anomaly. For data reported by the five agencies, *see* Hausfather Z. (12 January 2024) *State of the Climate: 2023 smashes records for surface temperature and ocean heat*, CARBONBRIEF.

[159] Copernicus Climate Change Service, *Global Climate Highlights 2023* (*last visited* 10 January 2024) ("2023 is confirmed as the warmest calendar year in global temperature data records going back to 1850 … 2023 was 0.60°C warmer than the 1991-2020 average and 1.48°C warmer than the 1850-1900 pre-industrial level … The year-to-year increase in global-average temperature was exceptionally large from 2022 to 2023. It follows a transition from three years of La Niña in 2020–2022 to El Niño conditions in 2023, although other factors appear to have also played a role.").

[160] Rohde R. (12 January 2024) *Global Temperature Report for 2023*, BERKELEY EARTH ("Over the long-term man-made global warming is responsible for gradually increasing temperatures at a rate of ~0.20 °C / decade. Greenhouse gas emissions, which are the underlying cause of global warming, reached record highs in 2023. While global warming controls the long-term trend, it changes only gradually. Short-term fluctuations in global mean temperature are primarily driven by internal variations in the climate system, such as the state of the El Niño / La Niña oscillation. … The temperature change from 2023 to 2024, +0.29 °C (+0.52 °F) can largely be understood as the combined effect of the transition from La Niña to El Niño, alongside other sources of natural variability (e.g. the North Atlantic) and combined with modest warming from several additional factors. The North Atlantic variations appear to be mostly a form of random natural variability. This is different from El Niño, which is a dynamical process with predictable seasonal variations that can be used for forecasting. However, it does appear likely that the inclusion unforced natural variability in the North Atlantic or elsewhere is necessary to explain the full magnitude of the warming observed in 2024. Other factors likely influencing 2023 climate include the ~11-year solar cycle, which is nearing its expected peak in 2024 or 2025. The current solar cycle appears to be modestly stronger than the previous cycle, but is close to 20th century averages. In addition, we consider it plausible that the 2022 Hunga Tonga eruption is contributing to unusual weather in 2024. Unlike most volcanoes, the eruption of Hunga Tonga was rich in water vapor and low in sulfur. Usually, a large eruption results in a temporary period of cooling due to excess sulfur in the atmosphere, but the Hunga Tonga eruption may have contributed warming instead due to its large water vapor contribution. … Another likely factor in the warmth witnessed during 2023 is the reduction in man-made sulfur aerosols. In 2020, new international rules governing heavy fuels for marine shipping abruptly reduced sulfur emissions from large ships by ~85%. This change was made to preserve human health, due to the toxic nature of sulfur aerosols. However, such aerosols also reflect sunlight, and as a result have a cooling effect. These sulfur aerosols are believed to have masked some of the effects of global warming, especially in the heavily trafficked North Pacific and North Atlantic regions. An analysis suggests that removing the sulfur aerosols may have added ~0.2 °C (~0.4 °F) to the North Atlantic region. This would not explain all of the recent North Atlantic temperature spike, but may have added to its severity.").

[161] Hausfather Z. (12 January 2024) *State of the Climate: 2023 smashes records for surface temperature and ocean heat*, CARBONBRIEF ("However, 2023 was so exceptionally warm that it suggests that this El Niño might be behaving differently, with global surface temperatures responding more rapidly than in the past. If this is the case, 2024 would not necessarily follow the pattern of past El Niño events and is less likely to be substantially warmer than 2023. … The Met Office, Dr Schmidt, Berkeley Earth and Carbon Brief estimates all have 2024 as more likely than not to be warmer than 2023 – but only by a small margin. In all estimates it is close to a coin flip which will end up as the warmer year. Against a 1880-99 pre-industrial baseline, the central estimate of all four forecasts is just below 1.5C of

warming, with ranges suggesting that temperatures could top 1.5C next year."). *See also* Madge G. (8 December 2023) *2024: First chance of a 1.5 °C year*, UK MET OFFICE ("The anticipated two-stage spike in global temperature has received a temporary and partial boost by the current El Niño event warming the tropical Pacific. But, says the Met Office's Prof Adam Scaife: "The main driver for record-breaking temperatures is the ongoing human-induced warming since the start of the Industrial Revolution." … Global average temperatures are measured as the difference between 1850-1900: a proxy for the Industrial Revolution. The global average temperature for 2023 is expected to be below 1.5 °C, but next year's forecast suggests for the first time that values of 1.5 °C or above cannot be ruled out.").

[162] Molina M., Zaelke D., Sarma K. M., Andersen S. O., Ramanathan V., & Kaniaru D. (2009) *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions*, PROC. NAT'L. ACAD. SCI. 106(49): 20616–20621, 20616 ("Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of 'dangerous anthropogenic interference' (DAI). Scientific and policy literature refers to the need for 'early,' 'urgent, 'rapid,' and 'fast-action' mitigation to help avoid DAI and abrupt climate changes. We define "fast-action" to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades."). *See also* Molina M., Ramanathan V. & Zaelke D. (2020) *Best path to net zero: Cut short-lived climate pollutants*, BULLETIN OF THE ATOMIC SCIENTISTS ("And let us be clear: By "speed," we mean measures—including regulatory ones—that can begin within two-to-three years, be substantially implemented in five-to-10 years, and produce a climate response within the next decade or two.").

[163] von Braun J., Ramanathan V., & Turkson P. K. A. (2022) *Resilience of people and ecosystems under climate stress*, Pontifical Academy of Sciences ("Recommendations: *Resilience building must rest on three pillars*: Mitigation, Adaptation & Transformation. Mitigation: *Reduce climate risks… .* Adaptation: *Reduce exposure and vulnerability to unavoidable climate risks.* Exposure & vulnerability reduction has three faces: Reductions in sensitivity to climate change; Reductions in risk exposure; & enhancement of adaptative capacity. There are limits to adaptation and hence adaptation has to be integrated with mitigation actions to avoid crossing the limits."); where the definition of resilience is taken from Möller V., van Diemen R., Matthews J. B. R., Méndez C., Semenov S., Fuglestvedt J. S., & Resinger A. (2022) *Annex II: Glossary*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), AII-37–AII-38 ("The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (Arctic Council, 2016)."). *See also* Zaelke D., Picolotti R., & Dreyfus G. (14 November 2021) *Glasgow climate summit: A glass half full*, THE HILL ("The new architecture also includes cutting not just carbon dioxide but also non-carbon dioxide climate emissions, with a specific focus on methane, a super climate pollutant responsible for 0.5 degrees Celsius of today's observed warming of 1.1 degrees Celsius. Cutting methane presents the single biggest and fastest mitigation action the world can take to keep warming from breaching the 1.5 degrees Celsius guardrail. This makes fast reductions of methane essential for adaptation as well."); Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-13 ("Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*)."); *and* Intergovernmental Panel on Climate Change (2018) GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 22 ("Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and

values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*).").

[164] Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Comment, NATURE 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there's a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see 'Accelerated warming'). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu, Ramanathan, and Victor Comment was published, the IPCC has updated its estimate for when 1.5 °C will be exceeded: *see* Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-9 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)").

[165] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state11. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature."). *See also* Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, EARTH SYST. DYN. 12(2): 601–619, 614 ("In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the climate system as a whole."); *and* Rocha J. C., Peterson G., Bodin Ö., & Levin S. (2018) *Cascading regime shifts within and across scales*, SCIENCE 362(6421): 1379–1383, 1383 ("A key lesson from our study is that regime shifts can be interconnected. Regime shifts should not be studied in isolation under the assumption that they are independent systems. Methods and data collection need to be further developed to account for the possibility of cascading effects. Our finding that ~45% of regime shift couplings can have structural dependence suggests that current approaches to environmental management and governance underestimate the likelihood of cascading effects.").

[166] Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254, 8256 ("This risk is represented in Figs. 1 and 2 by a planetary threshold (horizontal broken line in Fig. 1 on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (***Biogeophysical Feedbacks***) could become the dominant processes controlling the system's trajectory. Precisely where a potential planetary threshold might be is uncertain (15, 16). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements (12, 17), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (***Tipping Cascades***). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. 18). This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. ... Hothouse Earth is likely to be uncontrollable and

dangerous to many, particularly if we transition into it in only a century or two, and it poses severe risks for health, economies, political stability (**12**, **39**, **49**, **50**) (especially for the most climate vulnerable), and ultimately, the habitability of the planet for humans."). Note limitations in current models means IPCC has low confidence in its ability to assess these feedbacks. *See* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-78 ("There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength.").

[167] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575: 592–595.

[168] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575(7784): 592–595, 594 ("In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….").

[169] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94)."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 6 ("Global surface temperature was around 1.1°C above 1850–1900 in 2011–2020 (1.09°C [0.95°C– 1.20°C])[7], with larger increases over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88°C [0.68°C– 1.01°C])[8]. Observed warming is human-caused, with warming from greenhouse gases (GHG), dominated by CO_2 and methane (CH_4), partly masked by aerosol cooling (Figure 2.1).").

[170] Lenton T. M., Armstrong McKay D. I., Loriani S., Abrams J. F., Lade S. J., Donges J. F., Buxton J. E., Milkoreit M., Powell T., Smith S. R., Zimm C., Bailey E., James G. Dyke, Ghadiali A., & Laybourn L. (2023) GLOBAL TIPPING POINTS SUMMARY REPORT 2023, 13 ("Already, at today's 1.2°C global warming, tipping of warm-water coral reefs is likely and we cannot rule out that four other systems may pass tipping points: the ice sheets of Greenland and West Antarctica, the North Atlantics Subpolar Gyre circulation, and parts of the permafrost subject to abrupt thaw.").

[171] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become

widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."). *See also* Lenton T. M., Armstrong McKay D. I., Loriani S., Abrams J. F., Lade S. J., Donges J. F., Buxton J. E., Milkoreit M., Powell T., Smith S. R., Zimm C., Bailey E., James G. Dyke, Ghadiali A., & Laybourn L. (2023) *GLOBAL TIPPING POINTS SUMMARY REPORT 2023*, 13 (At 2°C global warming and beyond, several more systems could tip, including the Amazon rainforest and subglacial basins in East Antarctica, and irreversible collapse of the Greenland and West Antarctic ice sheets is likely to become locked in.").

[172] King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat*, COMM. EARTH & ENV'T.: 1–7, 1 ("The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain.").

[173] Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrlé A., Noël B., van den Broeke M. R., Wouters B., Bjørk A. A., & Fausto R. S. (2022) *Greenland ice sheet climate disequilibrium and committed sea-level rise*, NAT. CLIM. CHANGE: 1–11, 2 ("Application of the average 2000–2019, hereafter 'recent', climatology to Greenland's entire glacierized area of 1,783,090 km^2 gives an AAR/AAR_0 (α) disequilibrium with the current ice configuration corresponding with a $3.3 \pm 0.8\%$ committed area and volume loss. Taken in perpetuity, this imbalance with recent climate results in $59 \pm 15 \times 10^3$ km^2 of committed retreat of Greenland's ice area, equivalent to $110 \pm 27 \times 10^3$ km^3 of the ice sheet volume or 274 ± 68 mm of global eustatic SLR."), 5 ("Given the breadth and potency of those processes, we contend that known physical mechanisms can deliver most of the committed ice volume loss from Greenland's disequilibrium with its recent climate within this century. Nevertheless, we underscore that a SLR of at least 274 ± 68 mm is already committed, regardless of future climate warming scenarios."); *discussed in* Mooney C. (29 August 2022) *Greenland ice sheet set to raise sea levels by nearly a foot, study finds*, THE WASHINGTON POST; *and* Funes Y. (29 August 2022) *The Greenland Ice Sheet's Terrifying Future*, ATMOS.

[174] Nature Research Briefing (2023) *How rapidly can ice sheets retreat?*, NATURE, 1 ("Our results demonstrate that ice sheets can retreat at up to 600 metres per day — 20 times faster than the highest rate observed in Antarctica by satellites1. Furthermore, our findings reveal the vulnerability of regions of ice sheets with flat beds (those shallower than 1°) to pulses of extremely rapid retreat. Notably, we calculate that present-day rates of ocean-driven melting in Antarctica4 could be sufficient to initiate retreat of tens to hundreds of metres per day across similar bed settings. This includes regions of the vast and potentially unstable Thwaites Glacier in West Antarctica, which, in the past few years, has retreated to within about 4 km of a flat area of its bed. Although the rates of ice-sheet retreat revealed in this study are much higher than those detected so far by satellites, we note that they do not necessarily represent the upper limit at which retreat can occur. As such, we would not be surprised if similar landforms record even higher rates of retreat in regions that experienced more substantial ice-sheet melting in the past."); *summarizing* Batchelor C. L., Christie F. D. W., Ottesen D., Montelli A., Evans J., Dowdeswell E. K., Bjarnadóttir L. R., & Dowdeswell J. A. (2023) *Rapid, buoyancy-driven ice-sheet retreat of hundreds of metres per day*, NATURE: 1–6.

[175] Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 9-122 ("[T]he main uncertainty related to high-end sea-level rise is "when" rather than "if" it arises: the upper limit of 1.02 m of *likely* sea-level range by 2100 for the SSP 5-8.5 scenario will be exceeded in any future warming scenario on time scales of centuries to millennia (*high confidence*), but it is uncertain how quickly the long-term committed sea level will be reached (Section 9.6.3.5). Hence, global-mean sea level might rise well above the *likely* range before 2100, which is reflected by assessments of ice-sheet contributions based on structured expert judgment (Bamber et al., 2019) leading to a 95th percentile of projected future sea-level rise as high as 2.3 m in 2100 (Section 9.6.3.3)… High-end sea-level rise can therefore occur if one or two processes related to ice-sheet collapse in Antarctica result in an additional sea-level rise at the maximum of their plausible ranges (Sections 9.4.2.5, 9.6.3.3; Table 9.7) or if several of the processes described in this box result in individual contributions to additional sea-level rise at moderate levels. In both cases, global-mean

sea-level rise by 2100 would be substantially higher than the assessed *likely* range, as indicated by the projections including *low confidence* processes reaching in 2100 as high as 1.6 m at the 83rd percentile and 2.3 m at the 95th percentile (Section 9.6.3.3).”), 9-116 (“While ice-sheet processes in whose projection there is *low confidence* have little influence up to 2100 on projections under SSP1-1.9 and SSP1-2.6 (Table 9.9), this is not the case under higher emissions scenarios, where they could lead to GMSL rise well above the *likely* range. In particular, under SSP5-8.5, *low confidence* processes could lead to a total GMSL rise of 0.6-1.6 m over this time period (17th-83rd percentile range of p-box including SEJ- and MICI-based projections), with 5th-95th percentile projections extending to 0.5-2.3 m (*low confidence*).”). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 19–20 (“Nevertheless, ice-sheet losses may contribute to regional sea level rise under RCP8.5 and worst-case scenarios that reaches 1–2 m for many cities globally by 2100, seriously threatening existing communities and infrastructure (Trisos et al., 2022). Over longer timescales, sustained high rates of global sea-level rise (>1 cm/yr by 2200, with further acceleration to up to a couple centimeters per year beyond) may broadly strain coastal adaptation efforts (Oppenheimer et al., 2019). … As mentioned above, reduction of the GIS will likely require a millennium. Yet the weakening of ice shelf buttressing directly accelerates ice flow and discharge independent of MISI and MICI processes, with immediate implications for observed rates of sea-level rise. Consequently, under our current best understanding, Greenland and Antarctic ice-sheet collapse cannot be considered an abrupt or fast phenomenon in which most sea level impacts manifest within decades. Nevertheless, ice-sheet losses may contribute to regional sea level rise under RCP8.5 and worst-case scenarios that reaches 1–2 m for many cities globally by 2100, seriously threatening existing communities and infrastructure (Trisos et al., 2022). Over longer timescales, sustained high rates of global sea-level rise (>1 cm/yr by 2200, with further acceleration to up to a couple centimeters per year beyond) may broadly strain coastal adaptation efforts (Oppenheimer et al., 2019). … At the same time, models indicate that strong climate mitigation may avert significant fractions of potential sea-level rise and prevent ice-sheet collapse across large regions. In several modeling studies the RCP2.6 scenario prevents collapse of the WAIS (Bulthuis et al., 2019; DeConto & Pollard, 2016) and may reduce the Antarctic contribution to global sea level rise by 2100 to 13 cm (Edwards et al., 2021). … Although significant uncertainties remain regarding the precise temperature thresholds that could trigger ice-sheet collapse, research to date suggests that aggressive climate mitigation could limit risks from ice-sheet instabilities (Table 4).”).

[176] Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2022) *Global warming overshoots increase risk of triggering climate tipping points and cascades*, NATURE 76–82, 78–79 (“We define a high climate-risk zone as the region where the likelihood for no tipping event is smaller than 66% or the risk that one or more elements tip is higher than 33%. We compute this risk and find a marked increase for increasing convergence temperatures (compare Fig. 3d–f). For convergence temperatures of 1.5 °C and above, our results indicate that the high climate-risk zone spans the entire state space for final convergence temperatures of 1.5–2.0 °C. Only if final convergence temperatures are limited to or, better, below today’s levels of global warming, while peak temperatures are below 3.0 °C, the tipping risks remain below 33% (Fig. 3d) … In the worst case of a convergence temperature of 2.0 °C (Fig. 3f), the tipping risk for at least one tipping event to occur is on the order of above 90% if peak temperatures of 4.0 °C are not prevented. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail notable sea-level rise, biosphere degradation or considerable North Atlantic temperature drops.”).

[177] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36 (“At 2°C of global warming, overall risk levels associated with the unequal distribution of impacts (RFC3), global aggregate impacts (RFC4) and large-scale singular events (RFC5) would be transitioning to high (*medium confidence*), those associated with extreme weather events (RFC2) would be transitioning to very high (*medium confidence*), and those associated with unique and threatened systems (RFC1) would be very high (*high confidence*) (Figure 3.3, panel a). With about 2°C warming, climate-related changes in food availability and diet quality are estimated to increase nutrition-related diseases and

the number of undernourished people, affecting tens (under low vulnerability and low warming) to hundreds of millions of people (under high vulnerability and high warming), particularly among low-income households in low- and middle-income countries in sub-Saharan Africa, South Asia and Central America (*high confidence*). For example, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20% (*medium confidence*). Climate change risks to cities, settlements and key infrastructure will rise sharply in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*)."); Footnote 64 ("RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet instability or thermohaline circulation slowing."). *See also* Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2022) *Global warming overshoots increase risk of triggering climate tipping points and cascades*, NATURE 13: 76–82, 78–79 ("We define a high climate-risk zone as the region where the likelihood for no tipping event is smaller than 66% or the risk that one or more elements tip is higher than 33%. We compute this risk and find a marked increase for increasing convergence temperatures (compare Fig. 3d–f). For convergence temperatures of 1.5 °C and above, our results indicate that the high climate-risk zone spans the entire state space for final convergence temperatures of 1.5–2.0 °C. Only if final convergence temperatures are limited to or, better, below today's levels of global warming, while peak temperatures are below 3.0 °C, the tipping risks remain below 33% (Fig. 3d) … In the worst case of a convergence temperature of 2.0 °C (Fig. 3f), the tipping risk for at least one tipping event to occur is on the order of above 90% if peak temperatures of 4.0 °C are not prevented. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail notable sea-level rise, biosphere degradation or considerable North Atlantic temperature drops.").

[178] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10319–10323, 10320 ("Box 2. Risk Categorization of Climate Change to Society. … [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??, implying the possibility of existential threats."). *See also* Kemp L., Xu C., Depledge J., Ebi K. L., Gibbins G., Kohler T. A., Rockström J., Scheffer M., Schellnhuber H. J., Steffen W., & Lenton T. M. (2022) *Climate Endgame: Exploring catastrophic climate change scenarios*, PROC. NAT'L. ACAD. SCI. 119(34): 1–9, 2 ("Despite 30 y of efforts and some progress under the United Nations Framework Convention on Climate Change (UNFCCC) anthropogenic greenhouse gas (GHG) emissions continue to increase. Even without considering worst-case climate responses, the current trajectory puts the world on track for a temperature rise between 2.1 °C and 3.9 °C by 2100 (11). If all 2030 nationally determined contributions are fully implemented, warming of 2.4 °C (1.9 °C to 3.0 °C) is expected by 2100. Meeting all long-term pledges and targets could reduce this to 2.1 °C (1.7 °C to 2.6 °C) (12). Even these optimistic assumptions lead to dangerous Earth system trajectories. Temperatures of more than 2 °C above preindustrial values have not been sustained on Earth's surface since before the Pleistocene Epoch (or more than 2.6 million years ago) (13)."), 3 ("This is particularly alarming, as human societies are locally adapted to a specific climatic niche. The rise of large-scale, urbanized agrarian societies began with the shift to the stable climate of the Holocene ∼12,000 y ago

(42). Since then, human population density peaked within a narrow climatic envelope with a mean annual average temperature of ∼13 °C. Even today, the most economically productive centers of human activity are concentrated in those areas (43). The cumulative impacts of warming may overwhelm societal adaptive capacity.").

[179] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."). *See also* Ou Y., Roney C., Alsalam J., Calvin K., Creason J., Edmonds J., Fawcett A. A., Kyle P., Narayan K., O'Rourke P., Patel P., Ragnauth S., Smith S. J., & McJeon H. (2021) *Deep mitigation of CO_2 and non-CO_2 greenhouse gases toward 1.5 °C and 2 °C futures*, NAT. COMMUN. 12(6245): 1–9, 4 ("CO_2 abatement only cannot achieve the 1.5 °C target under all modeled 1.5 °C pathways but achieves the 2 °C target if reaching net-zero CO_2 by 2030 under 2 °C pathways; CO_2-driven GHG abatement achieves the 1.5 °C target if reaching net-zero CO_2 by 2032 under 1.5 °C pathways or achieves the 2 °C target if reaching net-zero CO_2 by 2045 under 2 °C pathways; Comprehensive GHG abatement achieves the 1.5 °C target if reaching net-zero CO_2 by 2053 under 1.5 °C pathways or achieves the 2 °C target if reaching net-zero CO_2 by 2075 under 2 °C pathways.").

[180] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 ("Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3)."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-2 (Figure SPM.2c shows that Sulfur dioxide (SO_2) contributes –0.49 °C (–0.10 to –0.93 °C) to observed warming in 2010–2019 relative to 1850–1900).

[181] Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, PROC. NAT'L. ACAD. SCI. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."). *See also* United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the near-term warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether

the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here."); Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, 409–410 ("These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO_2. In these more plausible cases, the temperature effects of the reduction in CO_2, SO_2 and CH_4 roughly balance one another until about 2035. After this, the cooling effects of reduced CO_2 continue to increase, whereas the warming induced by a reduction in SO_2 and the cooling induced by the reduction in CH_4 taper off, such that the cooling induced by the reduction in CO_2 dominates (Fig. 3). Examining the effects of CO_2 and SO_2 alone (Fig. 3d), the faster response of SO_2 to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO_2) during the gradual fossil phase-out, as well as the response to historical emissions."), Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period."); Hansen J. E. & Sato M. (13 July 2021) *July Temperature Update: Faustian Payment Comes Due*, Columbia University ("It follows that the global warming acceleration is due to the one huge climate forcing that we have chosen not to measure: the forcing caused by imposed changes of atmospheric aerosols... We should expect the global warming rate for the quarter of a century 2015-2040 to be about double the 0.18°C/decade rate during 1970-2015 (see Fig. 2), unless appropriate countermeasures are taken."); *discussed in* Berwyn B. (15 September 2021) *The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns*, INSIDE CLIMATE NEWS; *and* Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) *Climate and carbon budget implications of linked future changes in CO_2 and non-CO_2 forcing*, ENVIRON. RES. LETT. 14(4): 1–11.

[182] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, Supplemental Information (Table S1). *See also* Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 5 ("Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith (43), but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020 (38, 53). Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events (54, 55). By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[183] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure 6.12 ("Contribution to

effective radiative forcing (ERF) (a) and global mean surface air temperature (GSAT) change (b) from component emissions between 1750 to 2019 based on CMIP6 models (Thornhill et al., 2021b).").

[184] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*)."), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-31 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls.").

[185] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years.").

[186] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S.W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 1–11, 1 ("Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action)."); *and* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum

"Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.").

[187] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).").

[188] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-30–SPM-31 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (high confidence) (Table SPM.1)").

[189] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)").

[190] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Figure 5.1.

[191] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the*

Intergovernmental Panel on Climate Change, Masson-Delmotte V., *et al.* (eds.), 6-7 ("An additional concomitant methane mitigation (consistent with SSP1's stringent climate mitigation policy implemented in the SSP3 world) would not only alleviate this warming but would turn this into a cooling of 0.07 with a likely range of [-0.02 to 0.14] °C (compared with SSP3-7.0 in 2040). Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of GSAT of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}"), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."). *See also* Forster P. M., *et al*. (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2312–2313 ("The RCB for limiting warming to 1.5 °C is becoming very small. It is important, however, to correctly interpret this information. RCB estimates consider projected reductions in non-CO_2 emissions that are aligned with a global transition to net zero CO_2 emissions. These estimates assume median reductions in non-CO_2 emissions between 2020–2050 of CH_4 (50 %), N_2O (25 %) and SO_2 (77 %). If these non-CO_2 greenhouse gas emission reductions are not achieved, the RCB will be smaller (see Supplement, Sect. S8).").

[192] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, Figure 5.1.

[193] Nzotungicimpaye C. M., MacIsaac A. J., & Zickfeld K. (2023) *Delaying methane mitigation increases the risk of breaching the 2 °C warming limit*, COMMUN. EARTH. ENVIRON. 4(250): 1–8, 2–3 ("For every 10-year delay in CH_4 mitigation, our model simulates an additional peak warming of ~0.1 °C (Fig. 2d). Delaying CH_4 mitigation to or around mid-century will increase the peak warming by 0.2–0.3 °C relative to a CH_4 mitigation initiated at present-day…. In our model simulations, SAT changes are influenced by biogeochemical feedbacks in addition to the timing of CH_4 mitigation. In particular, we find that the feedback of SAT changes on the atmospheric CO_2 concentration (referred to as the carbon-climate feedback) contributes to increasing peak SAT differences between early and delayed CH_4 mitigation. While we prescribe the same anthropogenic CO_2 emissions in all our model simulations (See Methods), atmospheric CO_2 levels are projected to be higher for delayed CH_4 mitigation scenarios than for early CH_4 mitigation scenarios (Fig. 2c). In comparison to early CH_4 mitigation, delayed CH_4 mitigation results in high [CH_4] levels that lead to high SAT levels. Enhanced global warming results in high [CO_2] levels, which in turn contribute to increase the SAT differences between early and delayed CH_4 mitigation scenarios. Such feedbacks between SAT and [CO_2] involve the response of natural CO_2 sinks to global warming and climate change. For instance, increased SAT enhances the release of CO_2 through soil respiration and weakens the uptake of atmospheric CO_2 by oceans through the solubility pump, resulting in enhanced [CO_2] and an amplification of global warming14. Overall, we deduce that the carbon-climate feedback amplifies the SAT response in late versus early CH_4 mitigation scenarios (Fig. 2d and Fig. 3). To quantify the contribution of the carbon-climate feedback to additional peak warming from delayed CH_4 mitigation, we performed additional model simulations with prescribed CO_2 concentration from the early mitigation scenario (i.e. Early CH_4 Mitig SSP1-2.6). These model simulations suppress the warming signal from delayed CH_4 mitigation that is due to the carbon-climate feedback, and their difference with our standard model simulations allows to quantify the magnitude of the feedback. According to our results, the contribution of the carbon-climate feedback to the peak warming increases for every 10-year delay in CH_4 mitigation (Fig. 3). The peak warming attributable to the feedback ranges from ~0.03 °C for CH_4 mitigation initiated in 2020 to ~0.06 °C for CH_4 mitigation initiated in 2050 (Fig. 3).").

[194] Staniaszek Z., Griffiths P. T., Folberth G. A., O'Connor F. M., Abraham N. L., Archibald A. T. (2021) *The role of future anthropogenic methane emissions in air quality and climate*, NPJ CLIM. ATMOS. SCI. 5(21): 1–8, 3 ("Between 2015 to 2050 alone, SSP3-7.0 leads to almost 2° of warming in UKCA-CH_4 (see Fig. 3a)—the entirety of the temperature limit compared to pre-industrial levels set in the Paris agreement[1]. The total temperature increase (pre-industrial to 2050) in SSP3-7.0 is 2.82 ± 0.12 K. The ZAME experiment shows that 1° of this warming (or one-third

of the SSP3-7.0 total temperature increase to 2050) can be attributed to the effects of future anthropogenic methane emissions. This further highlights the potential of methane emissions reductions for climate mitigation[6–8,32] but shows that even the zero methane scenario breaches 1.5°, and underscores the necessity of CO_2 mitigation.").

[195] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 239 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."), 246 ("Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.").

[196] Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S. W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 1–11, 1 ("Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action).").

[197] Staniaszek Z., Griffiths P. T., Folberth G. A., O'Connor F. M., Abraham N. L., Archibald A. T. (2021) *The role of future anthropogenic methane emissions in air quality and climate*, NPJ CLIM. ATMOS. SCI. 5(21): 1–8, 2 ("In the ZAME scenario, (following the cessation of anthropogenic methane emissions, Fig. 1a), surface methane decreases globally with an e-folding timescale of 6.55 ± 0.06 years, and reaches below pre-industrial levels by 2030 (i.e. within 15 years; see Fig. 1b). The whole atmosphere methane burden declines to below pre-industrial levels within 12 years, stabilising at 1775 ± 15 Tg, 71% below the counterfactual in 2050.").

[198] Sun T., Ocko I. B., Hamburg S. P., (2022) *The value of early methane mitigation in preserving Arctic summer sea ice*, ENVIRON. RES. LETT. 17(4): 1–11, 1 ("While drastic cuts in carbon dioxide emissions will ultimately control the fate of Arctic summer sea ice, we show that simultaneous early deployment of feasible methane mitigation measures is essential to avoiding the loss of Arctic summer sea ice this century. In fact, the benefit of combined methane and carbon dioxide mitigation on reducing the likelihood of a seasonally ice-free Arctic can be greater than the simple sum of benefits from two independent greenhouse gas policies. The extent to which methane mitigation can help preserve Arctic summer sea ice depends on the implementation timeline. The benefit of methane mitigation is maximized when all technically feasible measures are implemented within this decade, and it decreases with each decade of delay in implementation due to its influence on end-of-century temperature. A key insight is that methane mitigation substantially lowers the risk of losing Arctic summer sea ice across varying levels of concomitant carbon dioxide mitigation.").

[199] Meier W. N., Petty A., Hendricks S., Kaleschke L., Divine D., Farrell S., Gerland S., Perovich D., Ricker R., Tian-Kunze X., Webster M. (2023) *Sea Ice, in* ARCTIC REPORT CARD 2023, Thoman R. L., Moon T. A., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 40 ("This satellite record tracks long-term trends, variability, and seasonal changes from the annual extent maximum in late February or March and the annual extent

minimum in September. Extents in recent years are ~50% lower than values in the 1980s. In 2023, March and September extents were lower than other recent years (Fig. 1), and though not a new record low, they continue the long-term downward trends (Table 1)."). *See also* Arctic Monitoring and Assessment Programme (2021) *ARCTIC CLIMATE CHANGE UPDATE 2021: KEY TRENDS AND IMPACTS*, Summary for Policymakers, 6 ("The extent of Arctic sea ice in September declined by 43% between 1979 and 2019, and—with the exception of the Bering Sea—sea-ice extent and area are declining throughout the Arctic in all months. Sea-ice cover also continues to be younger and thinner than during the 1980s, 1990s, and early 2000s."); *and* Druckenmiller M. L., *et al.* (2021) *The Arctic*, BULL. AM. MET. SOC. 102(8): S263–S316, S280 ("September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km^2 (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km^2 was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of −82,700 km^2 per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c).").

[200] International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 41 ("This former "ecosystem of ice" no longer exists. … The occurrence of the first sea ice-free Arctic summer is therefore unpredictable, but scientists now believe it is inevitable, and likely to occur at least once before 2050 even under a "very low" emissions scenario.[13,27,28,30] … In contrast, continuing on the current emissions trajectory may lead to the Arctic becoming ice free in the summer as soon as the 2030s.23 Even moderate emissions will lead to ice-free conditions most summers once global mean temperature rise reaches about 1.7°C. The length of this ice-free state would increase in lock-step with emissions and temperature,[10,28,29,39] eventually stretching from July–October at 2°C.[21,29]"). *See also* Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, COMMUN. EARTH ENVIRON. 2(144): 1–8, 4 ("In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)"), 6 ("This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035."); Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, CLIMATE 8(15): 1–24, 17 ("Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations."); *and* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYS. RES. LETT. 40(10): 2097–2101, 2097 ("Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.").

[201] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, GEOPHYS. RES. LETT. 48(18): 1–12, 1 ("Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the "likely" date occurs between 2040 and 2062 in September and much later in the 21st century from July to October.").

[202] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7474 ("Here we use satellite observations to estimate the amount of solar energy that would be added in the worst-case scenario of a complete disappearance of Arctic sea ice throughout the sunlit part of the year. Assuming constant cloudiness, we calculate a global radiative heating of 0.71 W/m^2 relative to the 1979 baseline state. This is equivalent to the effect of one trillion tons of CO_2 emissions. These results suggest that the additional heating due to complete Arctic sea ice loss would hasten global warming by an estimated 25 years.").

[203] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period."); *and* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 9–10 ("Given the smaller role of other non-CO_2 climate pollutants, methane emission cuts therefore provide the strongest leverage for near-term warming reduction (Figure 5)(13, 95). Achievement of methane reductions consistent with the average in 1.5°C scenarios could reduce warming by ~0.3°C by 2050 in comparison with baseline increases (4). A hypothetical complete elimination of anthropogenic methane emissions could avert up to 1°C of warming by 2050 relative to the high emissions Shared Socioeconomic Pathway [SSP; (96)] SSP3–7.0 scenario (97). This large near-term impact partly reflects methane's short lifetime; >90% of increased atmospheric methane would be removed within 30 years of an abrupt cessation of anthropogenic emissions compared with only ~25% of increased CO_2 following CO_2 emission cessation (98).").

[204] Saunois M., *et al.* (2020) *The Global Methane Budget 2000-2017*, EARTH SYST. SCI. DATA 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH_4 yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH_4 yr^{-1} or ~ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH_4 yr^{-1} or 50 %–65 %).").

[205] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 25 ("Anthropogenic methane emissions come primarily from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.").

[206] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 29 ("In comparison, biomass burning, which has a mixture of anthropogenic and natural causes, and the use of biofuels are relatively minor sources of methane. Agricultural waste burning, included in the biofuels category in the US EPA inventory and in the agricultural sector in CEDS. GAINS, EDGAR and FAO estimates for this category but not included in Figure 2.1, range from 1 to 3 Mt/yr. … Though some biomass burning is natural, current burning results largely from anthropogenic activities.

Large amounts of biomass are burned in the tropics in human induced fires related to shifting cultivation, deforestation, burning of agricultural wastes and the use of biofuels (Dlugokencky and Houweling 2015). Biomass burning remains a relatively small source of methane and it accounts for approximately 5 per cent of global methane emissions, an estimated 10–25 Mt/yr (Figure 2.1) (Saunois et al. 2020).").

[207] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 9–10 ("Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target... Roughly 60 per cent, around 75 Mt/yr, of available targeted measures have low mitigation costs2, and just over 50 per cent of those have negative costs – the measures pay for themselves quickly by saving money.").

[208] United Nations Environment Programme (2021) EMISSIONS GAP REPORT 2021: THE HEAT IS ON – A WORLD OF CLIMATE PROMISES NOT YET DELIVERED, 47 ("Over the last two decades, the main cause of increasing atmospheric methane is likely increasing anthropogenic emissions, with hotspot contributions from agriculture and waste in South and South-East Asia, South America and Africa, and from fossil fuels in China, the Russian Federation and the United States of America (Jackson *et al.* 2020). Emissions from natural sources may also be increasing, as wetlands warm, tropical rainfall increases and permafrost thaws."). *See also* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH4 observations and the way forward*, PHILOS. TRANS. R. SOC. A 379(2210): 1–14, 11 ("Explaining the renewed and accelerating increase in atmospheric CH_4 burden since 2007 remains challenging, and the exact causes are not yet clear. But, the observations we describe suggest that increased emissions from microbial sources are the strongest driver, with a relatively smaller contribution from other processes, e.g., fossil fuel exploitation. A more difficult question to answer is the one posed by this special issue: is warming feeding the warming? We cannot say for certain, but we cannot rule out the possibility that climate change is increasing CH_4 emissions. The strong signals from the tropics combined with the isotopic data are consistent with increased emissions from natural wetlands, but large [interannual variability (IAV)] and inter-decadal variability in wetland drivers like precipitation make it difficult to identify small trends. Observations are needed that will help process models capture this variability. The size of the IAV illustrates the potential scope of uncontrollable near-future change and emphasizes the urgency of reducing the global methane burden by mitigating the methane emissions that we can control, from the fossil fuel and agricultural sectors."). However, other studies suggest a more limited increase in recent emissions from natural wetlands compared to agriculture and waste and energy production sectors. *See* Zhang Z., *et al.* (2021) *Anthropogenic emissions are the main contribution to the rise of atmospheric methane (1993-2017)*, NAT'L SCI. REV. 9(5): 1–13, 1 ("Our emission scenarios that have the fewest biases with respect to isotopic composition suggest that the agriculture, landfill, and waste sectors were responsible for 53±13% of the renewed growth over the period 2007-2017 compared to 2000-2006; industrial fossil fuel sources explained an additional 34±24%, and wetland sources contributed the least at 13±9%. The hypothesis that a large increase in emissions from natural wetlands drove the decrease in atmospheric $\delta^{13}C\text{-}CH_4$ values cannot be reconciled with current process-based wetland CH_4 models. This finding suggests the need for increased wetland measurements to better constrain the contemporary and future role of wetlands in the rise of atmospheric methane and climate feedbacks. Our findings highlight the predominant role of anthropogenic activities in driving the growth of atmospheric CH_4 concentrations."); *and* Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 128 ("While the precise explanation for the stabilization and subsequent growth of atmospheric CH_4 over the past two decades has been a subject of debate within the scientific community (Nisbet et al., 2019; Kirschke et al., 2013; Rigby et al., 2017; Turner et al., 2019; Schaefer, 2019; Saunois et al., 2016, 2020), a new study concludes that the recent growth is due in roughly equal parts to emissions from fossil fuel sources and the combined emissions from agricultural and waste sources (Jackson et al., 2020)."), 129 ("Wetlands are currently the largest natural source of atmospheric CH_4 (Saunois et al., 2020), with emissions controlled by environmental factors including the soil temperature, water table depth, and vegetation cover and composition (Dean et al., 2018; Gedney et al., 2004); all of these variables are affected by climate change. Zhang et al. (2017) calculate that increased CH_4 emissions from wetlands under climate change scenarios could result in an increased radiative forcing ranging from 0.08 W m^{-2} for

RCP2.6 (strong climate mitigation with the possibility of reaching the 2◦ target) to 0.19 W m^{-2} for RCP8.5 (business-as-usual). Beyond 2100, climate change-induced CH_4 emissions from marine and freshwater systems and permafrost could also become important (Arneth et al., 2010; Dean et al., 2018; O'Connor et al., 2010)."). *Compare* Gauci V., Pangala S. R., Shenkin A., Barba J., Bastviken D., Figueiredo V., Gomez C., Enrich-Prast A., Sayer E., Stauffer T., Welch B., Elias D., McNamara N., Allen M., & Malhi Y. (2024) *Global atmospheric methane uptake by upland tree woody surfaces*, NATURE 631(8022): 796–800, 796 ("Stable carbon isotope measurement of methane in woody surface chamber air and process-level investigations on extracted wood cores are consistent with methanotrophy, suggesting a microbially mediated drawdown of methane on and in tree woody surfaces and tissues. By applying terrestrial laser scanning-derived allometry to quantify global forest tree woody surface area, a preliminary first estimate suggests that trees may contribute 24.6–49.9 Tg of atmospheric methane uptake globally. Our findings indicate that the climate benefits of tropical and temperate forest protection and reforestation may be greater than previously assumed.").

[209] Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 481 ("In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed $53 \pm 10\%$ of the MGR anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation."). *See also* Allen G. H. (2022) *Cause of the 2020 surge in atmospheric methane clarified*, NATURE 612(7940): 413–414; Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ENVIRON. RES. LETT. 17(9): 1–8; *and* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 5 ("A switch from La Niña to El Niño during 2023 appears to have reduced the observed growth rate (Figure 2), supporting a large role for wetland responses to La Niña in the very high 2020–2022 growth rates. However, emissions appear to have remained substantially higher in 2023 relative to pre-2020 values (Figure 1B), suggesting longer-term contributions from increasing anthropogenic sources along with a forced trend in natural sources. Recent work also suggests a potentially permanent shift to an altered state of enhanced wetland methane emissions (8).").

[210] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 28 ("Fossil fuels: release during oil and gas extraction, pumping and transport of fossil fuels accounts for roughly 23 per cent of all anthropogenic emissions, with emissions from coal mining contributing 12 per cent.").

[211] Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 7–8 (Table 2 and Supplementary material tab "World"). *See also* International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 4 ("We estimate that the global energy sector was responsible for around 135 million tonnes of methane emitted into the atmosphere in 2021. Following the Covid-induced decline in 2020, this represents a year-on-year increase in energy-related methane emissions of almost 5%, largely due to higher fossil fuel demand and production as economies recovered from the shock of the pandemic... Of the 135 million tonnes of energy-related emissions, an estimated 42 Mt are from coal operations, 41 Mt from oil, 39

Mt are from extracting, processing and transporting natural gas, 9 Mt from the incomplete combustion of bioenergy (largely when wood and other solid biomass is used as a traditional cooking fuel), and 4 Mt leaks from end-use equipment.").

[212] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 29 ("Within the fossil fuel sector, extraction, processing and distribution of the three main fuels have comparable impacts, with emissions from oil and gas each contributing 34 per cent followed by coal with 32 per cent of sectoral emissions in 2020 (Höglund-Isaksson 2020). Emissions from the coal subsector are entirely from mining-related activities, including both active and abandoned facilities. Within oil and gas, methane emissions associated with onshore conventional extraction along with downstream gas usage are the largest sources (Figure 2.3). Venting, the deliberate release of unwanted gas, is the primary cause of emissions during onshore conventional extraction, whereas fugitive emissions, the inadvertent release or escape of gas from fossil fuel systems, dominate downstream gas emissions. Within the fossil fuel sector, at the national level, emissions from the oil subsector in Russia and the coal subsector in China appear to be far larger than any other national level subsectors (Scarpelli *et al*. 2020). While these types of data based on national inventories are useful, it is important to note that many local measurements show large differences and often substantially higher emissions than conventional reporting, in many cases due to the presence of a small number of super-emitters, and imply these estimates may be too low (Zhang *et al*. 2020; Duren *et al*. 2019; Varon *et al*., 2019; Zavala-Araiza *et al*. 2018). These emissions give a sense of mitigation opportunities by region and sector, which is explored in Chapter 4.").

[213] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 30 (Figure 2.3, "Within the fossil fuel sector, extraction, processing and distribution of the three main fuels have comparable impacts, with emissions from oil and gas each contributing 34 per cent followed by coal with 32 per cent of sectoral emissions in 2020 (Höglund-Isaksson 2020). Emissions from the coal subsector are entirely from mining-related activities, including both active and abandoned facilities. Within oil and gas, methane emissions associated with onshore conventional extraction along with downstream gas usage are the largest sources (Figure 2.3). Venting, the deliberate release of unwanted gas, is the primary cause of emissions during onshore conventional extraction, whereas fugitive emissions, the inadvertent release or escape of gas from fossil fuel systems, dominate downstream gas emissions. Within the fossil fuel sector, at the national level, emissions from the oil subsector in Russia and the coal subsector in China appear to be far larger than any other national level subsectors (Scarpelli *et al*. 2020). While these types of data based on national inventories are useful, it is important to note that many local measurements show large differences and often substantially higher emissions than conventional reporting, in many cases due to the presence of a small number of super-emitters, and imply these estimates may be too low (Zhang *et al*. 2020; Duren *et al*. 2019; Varon *et al*., 2019; Zavala-Araiza *et al*. 2018). These emissions give a sense of mitigation opportunities by region and sector, which is explored in Chapter 4.").

[214] Hope M. (2014) *Explained: Fugitive methane emissions from natural gas production*, CARBONBRIEF ("Natural gas is mainly methane, some of which escapes during the drilling, extraction, and transportation process. Such outbreaks are known as fugitive emissions."). *See also* Picard D. (2000) *Fugitive emissions from oil and natural gas activities*, Background Paper in IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories ("In general, fugitive emissions from oil and gas activities may be attributed to the following primary types of sources: • fugitive equipment leaks; • process venting; • evaporation losses; • disposal of waste gas streams (e.g., by venting or flaring), and • accidents and equipment failures.").

[215] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 6 ("Globally, our analysis finds that methane emissions from the energy sector are about 70% greater than the sum of estimates submitted by national governments.").

[216] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 18 ("Emissions from abandoned coal mines and oil and gas wells are not included in the Global Methane Tracker: existing measurements cover a limited number of facilities and regions, and reliable data on abandoned mines and wells is not available for most countries. These sources could, nonetheless, represent significant levels of emissions. The U.S. Environmental Protection Agency indicates they are responsible for close to 5% of energy-related methane in the United States; and a recent study estimated that abandoned mines could account for almost one fifth of methane emissions from worldwide coal production."); *citing* Kholod N., Evans M., Pilcher R. C., Roshchanka V., Ruiz F., Coté M., & Collings R. (2020) *Global methane emissions from coal mining to continue growing even with declining coal production*, J. CLEAN. PROD. 256(120489): 1–12. *See also* Williams J. P., Regehr A., & Kang M. (2021) *Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States*, ENVIRON. SCI. TECHNOL. 55: 563–570, 563 ("We estimate the number of abandoned wells to be at least 4,000,000 wells for the U.S. and at least 370,000 for Canada. Methane emission factors range from 1.8×10^{-3} g/h to 48 g/h per well depending on the plugging status, well type, and region, with the overall average at 6.0 g/h. We find that annual methane emissions from abandoned wells are underestimated by 150% in Canada and by 20% in the U.S. Even with the inclusion of two to three times more measurement data than used in current inventory estimates, we find that abandoned wells remain the most uncertain methane source in the U.S. and become the most uncertain source in Canada.").

[217] United States Environmental Protection Agency, *About Coal Mine Methane* (*last visited* 5 February 2023) ("CMM is released by different types of mines: Active underground mines, which release methane through degasification systems (drainage system methane) and ventilation systems (ventilation air methane or VAM); Abandoned or closed mines release abandoned mine methane (AMM) from diffuse vents, ventilation pipes, boreholes, or fissures in the ground; Surface mines emit less methane than underground mines, but because surface mines produce large volumes of coal, some surface mines can also emit methane in large quantities.").

[218] Assan S. (2022) *Tackling Australia's Coal Mine Methane Problem*, EMBER, 5 ("The IEA estimated that Australian coal mines emitted 1.8 million tonnes of methane in 2021, double the officially reported figures. Independent satellite measurements have also uncovered underreporting of methane emissions from Australian coal mines. Open-pit mines show the greatest disparity between reported and measured emissions.").

[219] Coal production increased in 2021 and 2022 despite hopes that it had peaked in 2018, and is now forecast to peak in 2022 or 2023 before plateauing. *See* International Energy Agency (2022) *Coal 2022: Analysis and forecast to 2025* ("Coal markets have been shaken severely in 2022, with traditional trade flows disrupted, prices soaring and demand set to grow by 1.2%, reaching an all-time high and surpassing 8 billion tonnes for the first time. In last year's annual market report, Coal 2021, we said that global coal demand might well reach a new peak in 2022 or 2023 before plateauing thereafter. Despite the global energy crisis, our overall outlook remains unchanged this year, as various factors are offsetting each other. Russia's invasion of Ukraine has sharply altered the dynamics of coal trade, price levels, and supply and demand patterns in 2022."); International Energy Agency (2021) *Coal 2021: Analysis and forecast to 2024* ("The declines in global coal-fired power generation in 2019 and 2020 led to expectations that it might have peaked in 2018. But 2021 dashed those hopes."); *and* International Energy Agency (2023) NET ZERO ROADMAP, 15 ("Stringent and effective policies in the NZE Scenario spur clean energy deployment and cut fossil fuel demand by more than 25% by 2030 and 80% in 2050. Coal demand falls from around 5 800 million tonnes of coal equivalent (Mtce) in 2022 to 3 250 Mtce by 2030 and around 500 Mtce by 2050.").

[220] Kholod N., Evans M., Pilcher R. C., Roshchanka V., Ruiz F., Coté M., & Collings R. (2020) *Global methane emissions from coal mining to continue growing even with declining coal production*, J. CLEAN. PROD. 256(120489): 1–12, 9–10 ("The results show that regardless of future coal production scenario used by the model, [abandoned mine methane (AMM)] emissions will increase in the future. AMM emissions accounted for 17% of the total methane from coal mining in 2010. For comparison, data reported to the United Nations Framework Convention on Climate Change (UNFCCC) from key coal producing countries show that the share of AMM in total methane emissions from coal mining in the latest available year (2015) was 1% in Germany, 2% in each Australia and Poland, 11% in the United States and 34% in the United Kingdom (UNFCCC, 2017). AMM emissions can be difficult to inventory because of

ownership issues, measurement problems, the extent of mine flooding, and other factors. Because AMM emissions grow faster than [coal mine methane (CMM)], the share of AMM in total methane emissions may increase to 23% by 2050 and 27% in 2100 in the reference scenario.").

[221] International Energy Agency (2021) NET ZERO BY 2050: A ROADMAP FOR THE GLOBAL ENERGY SECTOR, 104 ("In the NZE, total methane emissions from fossil fuels fall by around 75% between 2020 and 2030, equivalent to a 2.5 gigatonne of carbon-dioxide equivalent ($GtCO_2$-eq) reduction in GHG emissions (Figure 3.5).").”). *See also* Smirnov A. (2 November 2021) *Why the world must act on coal mine methane*, EMBER ("The IEA estimates that 40.5 million tonnes (MT) of methane leaked from global operational coal mines in 2020. Using a multiplier of 86, as recommended by the IPCC to assess the short-term climate impact of methane, this means coal mines leak methane equivalent to 3,490 million tonnes of CO_2 each year. This is much bigger than the multiplier of 30 used by the IEA when they calculated coal mine methane's impact was already bigger than aviation and shipping combined. This means coal mine methane's short-term climate impact – at 3,490 million tonnes CO_2e – is greater than the EU-27's CO_2 emissions, which were 2,920 million tonnes in 2019. … The IEA's Net Zero by 2050 report shows that coal power generation needs to fall by two thirds this decade – a massive 67% fall from 2020 to 2030 – to keep warming to 1.5 degrees.").

[222] International Energy Agency (28 July 2022) *Global coal demand is set to return to its all-time high in 2022*, Press Release ("Based on current economic and market trends, global coal consumption is forecast to rise by 0.7% in 2022 to 8 billion tonnes, assuming the Chinese economy recovers as expected in the second half of the year, the IEA's July 2022 *Coal Market Update* says. This global total would match the annual record set in 2013, and coal demand is likely to increase further next year to a new all-time high."). *See also* International Energy Agency (2022) *Coal 2022: Analysis and forecast to 2025* ("Coal markets have been shaken severely in 2022, with traditional trade flows disrupted, prices soaring and demand set to grow by 1.2%, reaching an all-time high and surpassing 8 billion tonnes for the first time. In last year's annual market report, Coal 2021, we said that global coal demand might well reach a new peak in 2022 or 2023 before plateauing thereafter. Despite the global energy crisis, our overall outlook remains unchanged this year, as various factors are offsetting each other. Russia's invasion of Ukraine has sharply altered the dynamics of coal trade, price levels, and supply and demand patterns in 2022."). However, the rise in coal use in Europe in 2022 was lower than initially expected, *see* Jones D., *et al*. (31 January 2023) *European Electricity Review 2023*, EMBER, 5 ("It could have been much worse: wind, solar and a fall in electricity demand prevented a much larger return to coal. In context, the rise was not substantial: coal power increased by just 1.5 percentage points to generate 16% of EU electricity in 2022, remaining below 2018 levels. The 28 TWh rise in EU's coal generation added only 0.3% to global coal generation."). *See also* Hanock A. *Norway's Equinor and German state energy group sign €50bn long-term gas deal*, FINANCIAL TIMES ("Norway's Equinor signed its biggest long-term gas contract in nearly 40 years on Tuesday in a €50bn deal with German state energy group SEFE. It comes as EU countries seek stable supplies to compensate for the loss of piped gas from Russia.").

[223] Zhu R., Khanna N., Gordon J., Dai F., & Lin J. (2023) ABANDONED COAL MINE METHANE REDUCTION: LESSONS FROM THE UNITED STATES, California-China Climate Institute, 3 ("In 2021, U.S. abandoned coal mines produced an estimated 330,000 metric tons of methane – about 12.5% of the country's methane emissions from coal mining.").

[224] Zhu R., Khanna N., Gordon J., Dai F., & Lin J. (2023) ABANDONED COAL MINE METHANE REDUCTION: LESSONS FROM THE UNITED STATES, California-China Climate Institute, 11 ("To date, insufficient data makes it impossible to accurately estimate AMM emissions in the U.S. Abandoned mines do not report emission data to the GHGRP, for example. Further, the data for three important parameters used in predicting AMM emissions rates – the coal's adsorption isotherm, methane flow capacity as expressed by permeability, and gas pressure at abandonment – are not available for every abandoned coal mine. Therefore, these values must be estimated using ranges of values established in IPCC guidelines. … Although remote sensing data from satellite or aerial methane surveys is available in some regions, identifying AMM emissions from specific abandoned coal mines is difficult due to the detection threshold of these technologies. By contrast, ground-based technologies can measure AMM emissions more accurately. Vehicle-mounted methane detection systems (such as GasFinder3-VB, Remote Methane Leak Detector, and Portable Methane Leak Observatory system) should therefore be considered for road-accessible sites. Future R&D investment should

target lowering the methane detection threshold of aerial survey instruments and improving their precision for low-emissions sources.").

[225] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 28 ("Agriculture: emissions from enteric fermentation and manure management represent roughly 32 per cent of global anthropogenic emissions. Rice cultivation adds another 8 per cent to anthropogenic emissions. Agricultural waste burning contributes about 1 per cent or less.").

[226] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 29 ("The two largest sources are livestock and fossil fuels. Within the livestock subsector, enteric fermentation and manure management are the two processes generating emissions, with the former dominant and cattle the dominant animal (Figure 2.2). Within the manure category, pigs play the largest role though cattle are again important.").

[227] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 29 (*see* Figure 2.2 *showing* annual livestock methane emissions with cattle accounting for majority of enteric methane emissions). *See also* Food and Agriculture Organization of the United Nations (2016) *Reducing Enteric Methane for Improving Food Security and Livelihoods*, 3 ("Globally, ruminant livestock produce about 2.7 Gt CO_2 eq. of enteric methane annually, or about 5.5% of total global greenhouse gas emissions from human activities. Cattle account for 77% of these emissions (2.1 Gt), buffalo for 14% (0.37 Gt) and small ruminants (sheep and goats) for the remainder (0.26 Gt).").

[228] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 29 ("The two largest sources are livestock and fossil fuels. Within the livestock subsector, enteric fermentation and manure management are the two processes generating emissions, with the former dominant and cattle the dominant animal (Figure 2.2). Within the manure category, pigs play the largest role though cattle are again important.").

[229] Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 7–8 (Table 2) and Supplementary material tab "World."

[230] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: *2030 BASELINE REPORT*, SPM-7 ("Emissions in the agricultural sector are expected to increase over the decade to about 11 million tonnes per year by 2030 ranging between 6 and 23 million tonnes. This is equivalent to an 5-16 per cent increase from 2020 levels. This is almost entirely due to livestock, with minimal growth (or perhaps even a decrease) in the rice sector (Figure ES4).").

[231] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 29 ("While rice cultivation feeds up to a third of the world's population, rice fields are a significant source of methane (Mbow *et al*. 2019; Dlugokencky and Houweling 2015). Methane is produced through anaerobic decomposition of organic material in flooded rice fields which are responsible for approximately 8–11 per cent of global anthropogenic methane emissions (Saunois *et al*. 2020; Mbow *et al*. 2019).").

[232] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Figure 2.6 (Showing that rice cultivation accounted for an estimated 26.6 million tons of methane emissions in 2017, out of a total of 129 million tons of methane emissions in Asia and a total of 10.4 million tons ins Southeast Asia, Korea, and Japan.).

[233] Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 7–8 (Table 2) and Supplementary material tab "World."

[234] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 28 ("Waste: landfills and waste management represents the next largest component making up about 20 per cent of global anthropogenic emissions.").

[235] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Table 2.1 (showing estimated natural and anthropogenic source and sinks of methane in 2017, with landfill and waste accounting for 68 [64-71] $MtCH_4$). *See also* Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21.

[236] Maasakkers J. D., Varon D. J., Elfarsdóttir A., McKeever J., Jervis D., Mahapatra G., Pandey S., Lorente A., Borsdorff T., Foorthuis L. R., Schuit B. J., Tol P., van Kempen T. A., van Hees R., & Aben I. (2022) *Using satellites to uncover large methane emissions from landfills*, SCI. ADV. 8(32): 1–8, 1 ("We use the global surveying Tropospheric Monitoring Instrument (TROPOMI) to identify large emission hot spots and then zoom in with high-resolution target-mode observations from the GHGSat instrument suite to identify the responsible facilities and characterize their emissions. Using this approach, we detect and analyze strongly emitting landfills (3 to 29 t $hour^{-1}$) in Buenos Aires, Delhi, Lahore, and Mumbai. Using TROPOMI data in an inversion, we find that city-level emissions are 1.4 to 2.6 times larger than reported in commonly used emission inventories and that the landfills contribute 6 to 50% of those emissions.").

[237] Kaza S., Yao L. C., Bhada-Tata P., & Van Woerden F. (2018) WHAT A WASTE 2.0 : A GLOBAL SNAPSHOT OF SOLID WASTE MANAGEMENT TO 2050, World Bank Urban Development Series, 3 ("The world generates 2.01 billion tonnes of municipal solid waste annually, with at least 33 percent of that—extremely conservatively—not managed in an environmentally safe manner. … When looking forward, global waste is expected to grow to 3.40 billion tonnes by 2050."); *discussed in* World Bank (20 September 2018) *Global Waste to Grow by 70 Percent by 2050 Unless Urgent Action is Taken: World Bank Report*, Press Release ("Without urgent action, global waste will increase by 70 percent on current levels by 2050, according to the World Bank's new *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050* report. Driven by rapid urbanization and growing populations, global annual waste generation is expected to jump to 3.4 billion tonnes over the next 30 years, up from 2.01 billion tonnes in 2016, the report finds.").

[238] Miner K. R., Turetsky M. R., Malina E., Bartsch A., Tamminen J., McGuire A. D., Fix A., Sweeney C., Elder C. D., & Miller C. E. (2022) *Permafrost carbon emissions in a changing Arctic*, NAT. REV. EARTH ENVIRON. 3: 55–67, 55 ("Permafrost underlies ~25% of the Northern Hemisphere land surface and stores an estimated ~1,700Pg (1,700Gt) of carbon in frozen ground, the active layer and talik[1,2]. Rapid anthropogenic warming and resultant thaw threaten to mobilize permafrost carbon stores[3,4], potentially increasing atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4), and converting the Arctic from a carbon sink to a carbon source."). *See also* Schuur E. A. G., *et al.* (2015) *Climate Change and the Permafrost Carbon Feedback*, NATURE 520: 171–179, 171 ("The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (.1 m) in permafrost, below the traditional zone of soil carbon accounting.").

[239] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c;

Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC $^{\circ}C^{-1}$. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} $^{\circ}C^{-1}$ (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2)."). *See also* Lawrence D. M., Slater A. G., Tomas R. A., Holland M. M., & Deser C. (2008) *Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss*, GEOPHYS. RES. LETT. 35(L11506): 1–6, 5 ("We find that rapid sea ice loss forces a strong acceleration of Arctic land warming in CCSM3 (3.5-fold increase, peaking in autumn) which can trigger rapid degradation of currently warm permafrost and may increase the vulnerability of colder permafrost for subsequent degradation under continued warming. Our results also suggest that talik formation may be a harbinger of rapid subsequent terrestrial change. This sea ice loss – land warming relationship may be immediately relevant given the record low sea ice extent in 2007."); *and* Vaks A., Mason A., Breitenbach S., Kononov A., Osinzev A., Rosensaft M., Borshevsky A., Gutareva O., & Henderson G. (2020) *Palaeoclimate evidence of vulnerable permafrost during times of low sea ice*, NATURE 577(7789): 221–225, 221 ("The robustness of permafrost when sea ice is present, as well as the increased permafrost vulnerability when sea ice is absent, can be explained by changes in both heat and moisture transport. Reduced sea ice may contribute to warming of Arctic air, which can lead to warming far inland. Open Arctic waters also increase the source of moisture and increase autumn snowfall over Siberia, insulating the ground from low winter temperatures. These processes explain the relationship between an ice-free Arctic and permafrost thawing before 0.4 Ma. If these processes continue during modern climate change, future loss of summer Arctic sea ice will accelerate the thawing of Siberian permafrost."). For more on impacts of melting permafrost to climate and water supply, *see* Taillant J. D. (2021) *Chapter 5. A Thawing Earth*, *in* MELTDOWN: THE EARTH WITHOUT GLACIERS, Oxford University Press; *and* Taillant J. D. (2015) *Chapter 4. Invisible Glaciers*, *in* GLACIERS: THE POLITICS OF ICE, Oxford University Press.

[240] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 22 ("From a carbon emission perspective, both gradual and abrupt thaw will contribute to climate change slowly over a century or longer rather than being released all at once (Turetsky et al., 2019, 2020).").

[241] Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, ENVIRON. RES. LETT. 9(8): 1–9, 2 ("If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF is irreversible on human time scales because in a warming climate, the burial mechanisms described above slow down or stop, so there is no way to convert CO_2 into organic matter and freeze it back into the permafrost."). *See also* Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS B 63(2): 165–180, 166 ("The permafrost carbon feedback (PCF) is an amplification of surface warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric CO_2 and methane concentrations increase, surface air temperatures will increase, causing permafrost degradation and thawing some portion of the permafrost carbon. Once permafrost carbon thaws, microbial decay will resume, increasing respiration fluxes to the atmosphere and atmospheric concentrations of CO_2 and methane. This will in turn amplify the rate of atmospheric warming and accelerate permafrost degradation, resulting in a positive PCF feedback loop on climate (Zimov et al., 2006b)."); *and* Chen Y., Liu A., & Moore J.C. (2020) *Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering*, NAT. COMMUN. 11(2430): 1–35, 2 ("Between 2020 and 2069, PInc-Panther simulations of soil C change, driven by outputs of 7 ESMs for the RCP4.5 projection, varied from 19.4 Pg C gain to 52.7 Pg C loss (mean 25.6 Pg C loss), while under G4 the ensemble mean was 11.9 Pg C loss (range: 29.2 Pg C gain to 44.9 Pg C loss). Projected C losses are roughly linearly proportional to changes in soil temperature, and each 1 °C warming in the Arctic permafrost would result in ~13.7 Pg C loss; the yintercept indicates that the Arctic permafrost, if maintained in current state, would remain a weak carbon sink. MIROC-ESM and MIROC-ESM-CHEM, with simulations of warming above 3°C, produce severe soil C losses, while GISS-E2-R with minor soil temperature change produces net soil C gains under both scenarios before 2070."), 3 ("PIncPanTher simulations of

the anoxic respiration rates over the period 2006–2010 are 1.2–1.7 Pg C year^{-1}, and so the estimated range of CH_4 emissions is 28–39 Tg year^{-1}, which is very close to the 15–40 Tg CH_4 year^{-1} estimates of current permafrost wetland CH_4 emissions.").

[242] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 728 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC ºC^{-1}. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} ºC^{-1} (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2). … Beyond 2100, models suggest that the magnitude of the permafrost carbon feedback strengthens considerably over the period 2100–2300 under a high-emissions scenario (Schneider von Deimling et al., 2015; McGuire et al., 2018). Schneider von Deimling et al., (2015) estimated that thawing permafrost could release 20–40 PgC of CO_2 in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO_2 under a RCP8.5 scenario. The multi-model ensemble in (McGuire et al., 2018) project a much wider range of permafrost soil carbon losses of 81–642 PgC (mean 314 PgC) for an RCP8.5 scenario from 2100 to 2300, and of a gain of 14 PgC to a loss of 54 PgC (mean loss of 17 PgC) for an RCP4.5 scenario over the same period... Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020)."); 739 ("Other feedback contributions, such as the non-CO_2 biogeochemical feedback, can be converted into a carbon-equivalent feedback term (γ; Section 5.4.5.5, 7.6) by reverse application of the linear feedback approximation (Gregory et al., 2009). The contributions of non-CO_2 biogeochemical feedbacks combine to a linear feedback term of 30 ± 27 PgC_{eq} °C^{-1} (1 standard deviation range, 111 ± 98 Gt CO_2-eq °C^{-1}), including a feedback term of –11 [–18 to –5] PgC_{eq} °C^{-1} (5–95% range, –40 [–62 to –18] Gt CO_2-eq °C^{-1}) from natural CH_4 and N_2O sources. The biogeochemical feedback from permafrost thaw leads to a combined linear feedback term of –21 ± 12 PgC_{eq} °C^{-1} (1 standard deviation range – 77 ± 44 Gt CO_2-eq °C^{-1})."). Note that PgC_{eq} for the methane feedback is converted to $GtCO_2eq$ by multiplying by 44/12. *See also* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 737 ("Land biosphere models show high agreement that long-term warming will increase N_2O release from terrestrial ecosystems (XuRi et al., 2012; B.D. Stocker et al., 2013; Zaehle, 2013; Tian et al., 2019). A positive land N_2O climate feedback is consistent with paleoevidence based on reconstructed and modelled emissions during the last deglacial period (Schilt et al., 2014; H. Fischer et al., 2019; Joos et al., 2020). The response of terrestrial N_2O emissions to atmospheric CO_2 increase and associated warming is dependent on nitrogen availability (van Groenigen et al., 2011; Butterbach-Bahl et al., 2013; Tian et al., 2019). Model-based estimates do not account for the potentially strong emissions increases in boreal and arctic ecosystems associated with future warming and permafrost thaw (Elberling et al., 2010; Voigt et al., 2017). There is medium confidence that the land N_2O climate feedback is positive, but low confidence in the magnitude (0.02 ± 0.01 W m^{-2} °C^{-1}).").

[243] Armstrong McKay D. I., *et al.* (2023) *Section 1: Earth systems tipping points*, *in* GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., *et al.* (eds.), 26 ("Current-generation climate models suggest a net positive impact of the permafrost carbon-climate feedback on global climate with estimates of additional warming of 0.05-0.7°C by 2100 (Schaefer et al., 2014, Burke et al., 2018, Kleinen and Brovkin, 2018, Nitzbon et al., 2023) based on low- to high-emissions scenarios, respectively. Methane emissions from permafrost could temporarily contribute up to 50 per cent of the permafrost-induced radiative forcing due to its higher warming potential (Walter Anthony et al., 2016, Turetsky

et al., 2020, Miner et al., 2022). Overall, however, Canadell et al., (2021) summarise that "thawing terrestrial permafrost will lead to carbon release (high confidence), but there is low confidence in the timing, magnitude and relative roles of CO2 and CH4" of the permafrost carbon-climate feedback.").

[244] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC $^{\circ}C^{-1}$. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} $^{\circ}C^{-1}$ (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2). … Beyond 2100, models suggest that the magnitude of the permafrost carbon feedback strengthens considerably over the period 2100–2300 under a high-emissions scenario (Schneider von Deimling et al., 2015; McGuire et al., 2018). Schneider von Deimling et al., (2015) estimated that thawing permafrost could release 20–40 PgC of CO_2 in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO_2 under a RCP8.5 scenario. The multi-model ensemble in (McGuire et al., 2018) project a much wider range of permafrost soil carbon losses of 81–642 PgC (mean 314 PgC) for an RCP8.5 scenario from 2100 to 2300, and of a gain of 14 PgC to a loss of 54 PgC (mean loss of 17 PgC) for an RCP4.5 scenario over the same period... Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH4 from 2100–2300 (Turetsky et al., 2020).").

[245] Chadburn S. E., Burke E. J., Cox P. M., Friedlingstein P., Hugelius G., & Westermann S. (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NAT. CLIM. CHANGE 7(5): 340–344, 340 ("The estimated permafrost area is 15.5 million km^2 using this technique (12.0–18.2 million km^2 using minimum/maximum curves), which compares well to 15.0 million km^2 from observations (12.6–18.4 million km^2)."). *See also* Obu J., *et al.* (2019) *Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale*, EARTH-SCI. REV. 193: 299–316, 305 ("The best estimate of the permafrost area in the Northern Hemisphere is 13.9×10^6 km^2 (14.6% of the exposed land area), representing the total area with where MAGT <0 °C (Fig. 3). The borehole temperature comparison can be used to incorporate uncertainty into this estimate, giving a minimum permafrost extent of 10.1×10^6 km^2 (10.5% of exposed land area; the area within MAGT < −2 °C) and a maximum extent of 19.6×10^6 km^2 (20.6% of exposed land area; the area within MAGT < +2 °C). The extent of the permafrost region (i.e. all permafrost zones) inferred from permafrost occurrence probabilities is 20.8×10^6 km^2 (21.8% of exposed land area). The continuous permafrost zone occupies about half of this area, underlying 10.7×10^6 km^2 (11.2% of exposed land area), while the discontinuous (3.1×10^6 km^2; 3.3% of exposed land area), sporadic (3.5×10^6 km^2; 3.6% of exposed land area), and isolated patches zones (3.5×10^6 km^2; 3.6% of exposed land area) almost equally divide the remainder."); *and* Obu J. (2021) *How Much of the Earth's Surface is Underlain by Permafrost?*, J. GEOPHYS. RES. EARTH SURF. 126(5): 1–5, 5 ("Globally, permafrost underlies between 14 and 15.7 × 106 km^2 of the exposed land area (Gruber, 2012; Obu, Westermann, Bartsch, et al. (2019)), which equates to approximately 11% of the exposed land surface with around 2% uncertainty. No subglacial, relict, or subsea permafrost is included in the above estimates. Circum-Arctic subsea permafrost extent was estimated to be 2.5 × 106 km^2 (Overduin et al., 2019). Thus, the permafrost area including Circum-Arctic subsea permafrost can be estimated to be around 17 × 106 km^2.").

[246] Chadburn S. E., Burke E. J., Cox P. M., Friedlingstein P., Hugelius G., & Westermann S. (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NAT. CLIM. CHANGE 7(5): 340–344, 340 ("Under a 1.5 °C stabilization scenario, 4.8 (+2.0, -2.2) million km^2 of permafrost would be lost compared with the 1960–1990 baseline (corresponding to the IPA map, Fig. 1b), and under a 2 °C stabilization we would lose 6.6 (+2.0, -2.2) million

km^2, over 40% of the present-day permafrost area. Therefore, stabilizing at 1.5 ºC rather than 2 ºC could potentially prevent approximately 2 million km^2 of permafrost from thawing."). *See also* Burke E.J., Zhang Y., & Krinner G. (2020) *Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change*, THE CRYOSPHERE 14(9): 3155–3174, 3173 ("The CMIP6 models project a loss of permafrost under future climate change of between 1.7 and 2.7×10^6 km^2∘C^{-1}. A more impact-relevant statistic is the decrease in annual mean frozen volume (3.0 to 5.3×103 km3°C−1) or around 10 %–40 %∘C−1."); *and* Wang X., *et al.* (2022) *Contrasting characteristics, changes, and linkages of permafrost between the Arctic and the Third Pole*, EARTH SCI. REV. 230(104042): 1–21, 9 ("The future reduction in near-surface permafrost (permafrost in the topmost ground layers, < 10–15 m depth, (Hjort et al., 2022) area exhibits different magnitudes in the two regions. In the Arctic, the near-surface permafrost area is projected to gradually decline, from 22% (28%) in 2041–2060 to 29% (49%) in 2061–2080 under the RCP 4.5 (RCP 8.5) scenarios relative to the baseline (Table 3). This means that almost one-half of the near-surface permafrost would be lost by the end of the 21st century under the high emission scenario. In western Siberia, permafrost is projected by the CMIP6 models to disappear under SSP5–8.5 because of the MAAT 0 °C isocline moving toward the north (Alexandrov et al., 2021). On the TP, near-surface permafrost exhibits more rapid thaw than in the Arctic, especially under RCP 8.5: 58% in 2041–2060 and 84% in 2061–2080 (Table 3), indicating that near-surface permafrost on the TP is more susceptible to rising air temperatures than the Arctic near-surface permafrost. The near-surface permafrost area on the TP is projected to decrease to 0.54 × 106 km2 in 2099 under a future air temperature increase of 2.9 °C (warming magnitude under RCP 4.5) using an "altitude model" (Li and Cheng, 1999), which is close to the projection under RCP 4.5 (Table 3).").

[247] Hunt K. (14 March 2022) *Holes the size of city blocks are forming in the Arctic seafloor*, CNN ("Marine scientists have discovered deep sinkholes – one larger than a city block of six-story buildings – and ice-filled hills that have formed "extraordinarily" rapidly on a remote part of the Arctic seafloor.").

[248] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 50 ("Gradual permafrost thaw (Section 2.4) could contribute significant additional carbon emissions over the near-term (92 Gt C by 2100 under RCP8.5) (Meredith et al., 2019). Abrupt permafrost thaw processes acting over faster timescales could emit up to ∼18 Gt C by 2100 including considerable methane (Turetsky et al., 2019, 2020). Over this century, emissions from abrupt thaw could contribute approximately 6,771 Mt CH_4 (Mt C) and 10.95 Gt CO_2 (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020)."). *See also* Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, NAT. GEOSCI. 13(2): 138–143, 139 ("Gradual permafrost thaw (Section 2.4) could contribute significant additional carbon emissions over the near-term (92 Gt C by 2100 under RCP8.5) (Meredith et al., 2019). Abrupt permafrost thaw processes acting over faster timescales could emit up to ∼18 Gt C by 2100 including considerable methane (Turetsky et al., 2019, 2020). Over this century, emissions from abrupt thaw could contribute approximately 6,771 Mt CH_4 (Mt C) and 10.95 Gt CO2 (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020).").

[249] Abbott B. W., *et al.* (2016) *Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment*, ENVIRON. RES. LETT. 11(3): 1–13, 2 ("Precise empirical or model-based assessments of the critical factors driving carbon balance are unlikely in the near future, so to address this gap, we present estimates from 98 permafrost-region experts of the response of biomass, wildfire, and hydrologic carbon flux to climate change. Results suggest that contrary to model projections, total permafrost-region biomass could decrease due to water stress and disturbance, factors that are not adequately incorporated in current models. Assessments indicate that end-of-the-century organic carbon release from Arctic rivers and collapsing coastlines could increase by 75% while carbon loss via burning could increase four-fold. Experts identified water balance, shifts in vegetation community, and permafrost degradation as the key sources of uncertainty in predicting future system response. In combination with previous findings, results suggest the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario but that 65%–85% of permafrost carbon release can still be avoided if human emissions are actively reduced.").

[250] Schuur E. A. G., *et al*. (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47: 343–371, 362 ("The recent appearance of "craters" with high concentrations of CH_4 in some parts of Siberia have raised new questions (133). This phenomenon is a surprise to the permafrost community and appears to be connected with potential CH_4 emissions. Each crater does not contain exceptional levels of CH_4 but could represent new pathways from deep fossil methane that have previously been capped by permafrost. Sources of geologic methane have been observed where ice and permafrost are retreating (116), including subsea (25, 134), and could be new sources to the atmosphere at levels that are only poorly constrained by the projections synthesized in this review."). *See also* Froitzheim N., Majka J., & Zastrozhnov D. (2021) *Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave*, PROC. NAT'L. ACAD. SCI. 118(32): 1–3, 1 ("In the Taymyr Peninsula and surroundings in North Siberia, the area of the worldwide largest positive surface temperature anomaly for 2020, atmospheric methane concentrations have increased considerably during and after the 2020 heat wave. Two elongated areas of increased atmospheric methane concentration that appeared during summer coincide with two stripes of Paleozoic carbonates exposed at the southern and northern borders of the Yenisey-Khatanga Basin, a hydrocarbon-bearing sedimentary basin between the Siberian Craton to the south and the Taymyr Fold Belt to the north. Over the carbonates, soils are thin to nonexistent and wetlands are scarce. The maxima are thus unlikely to be caused by microbial methane from soils or wetlands. We suggest that gas hydrates in fractures and pockets of the carbonate rocks in the permafrost zone became unstable due to warming from the surface. This process may add unknown quantities of methane to the atmosphere in the near future."); *discussed in* Carrington D. (2 August 2021) *Climate crisis: Siberian heatwave led to new methane emissions, study says*, THE GUARDIAN ("The Siberian heatwave of 2020 led to new methane emissions from the permafrost, according to research. Emissions of the potent greenhouse gas are currently small, the scientists said, but further research is urgently needed. Analysis of satellite data indicated that fossil methane gas leaked from rock formations known to be large hydrocarbon reservoirs after the heatwave, which peaked at 6C above normal temperatures. Previous observations of leaks have been from permafrost soil or under shallow seas."); *and* Mufson S. (3 August 2021) *Scientists expected thawing wetlands in Siberia's permafrost. What they found is 'much more dangerous'*, THE WASHINGTON POST.

[251] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, PROC. NAT'L. ACAD. SCI. 118(21): 1–3, 1 ("This global climate feedback is being intensified by the increasing frequency and severity of Arctic and boreal wildfires (8, 9) that emit large amounts of carbon both directly from combustion and indirectly by accelerating permafrost thaw. Fire-induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of Arctic carbon emissions during the coming decades (9)."). *See also* Walker X. J., Baltzer J. L., Cumming S. G., Day N. J., Ebert C., Goetz S., Johnstone J. F., Potter S., Rogers B. M., Schuur E. A. G., Turetsky M. R., & Mack M. C. (2019) *Increasing wildfires threaten historic carbon sink of boreal forest soils*, NATURE 572(7770): 520–523, 523 ("The frequency of boreal forest fires is projected to increase even more with expected climate warming and drying28 and, as a result, the total burned area is expected to increase to 130%–350% by mid-century29. These changes will increase the proportion of young forests vulnerable to burning and increase both the loss of legacy C per unit area burned and the expanse of forests transitioning from net C uptake over consecutive fire intervals to net C loss."); *and* Genet H., McGuire A. D., Barrett K., Breen A., Euskirchen E. S., Johnstone J. F., Kasischke E. S., Melvin A. M., Bennett A., Mack M. C., Rupp T. S., Schuur A. E. G., Turetsky M. R., & Yuan F. (2013) *Modeling the effects of fire severity and climate warming on active layer thickness and soil carbon storage of black spruce forests across the landscape in interior Alaska*, ENVIRON. RES. LETT. 8(4): 1–13, 2 ("In simulations that included the effects of both warming and fire at the regional scale, fire was primarily responsible for a reduction in organic layer thickness of 0.06 m on average by 2100 that led to an increase in active layer thickness of 1.1 m on average by 2100. The combination of warming and fire led to a simulated cumulative loss of 9.6 kgC m^{-2} on average by 2100. Our analysis suggests that ecosystem carbon storage in boreal forests in interior Alaska is particularly vulnerable, primarily due to the combustion of organic layer thickness in fire and the related increase in active layer thickness that exposes previously protected permafrost soil carbon to decomposition.").

[252] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 13 ("Early estimates of high rates of methane emissions from hydrate dissociation on the East Siberian Arctic Shelf (Shakhova et al., 2014) have been revised substantially downwards by numerous subsequent studies (Berchet et al., 2016; Thornton et al., 2016, 2020; Tohjima et al., 2020). Present-day marine methane release from Arctic hydrate dissociation is probably primarily of natural origin, resulting from the pressure decrease associated with isostatic uplift following the last glacial maximum, rather than a response to anthropogenic forcing (Wallmann et al., 2018). And in the Beaufort Sea, fossil methane possibly from hydrate emissions was observed in deeper waters but was removed, likely via oxidation, prior to atmospheric emission (Sparrow et al., 2018).…As a result of being positioned at shallower depths and the significant warming currently experienced at high latitudes, Arctic methane hydrate deposits are thought to be the most vulnerable pool of marine methane hydrates to warming-induced thaw….. In conclusion, while levels of warming exist beyond which large quantities of methane in hydrate deposits may eventually become destabilized, numerous physical, thermodynamic, chemical, and biological factors combine to substantially limit the rate at which this methane might escape to the atmosphere. For more moderate warming of ~2°C, methane hydrates might well exert a negligible overall impact on atmospheric temperatures. Methane hydrate dissociation would additionally take place on extremely long timescales of millennia, rather than over abrupt or fast timescales that would produce an acute warming spike. … With all of this in mind, in relation to other candidate tipping elements covered within this review, marine methane hydrates represent a relatively lower-impact climate feedback especially for warming in the Anthropocene (Table 3)."). *See generally* Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press; *and* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, GEOSCI. 9(6): 251, 1–23.

[253] Weldeab S., Schneider R. R., Yu J., & Kylander-Clark A. (2022) *Evidence for massive methane hydrate destabilization during the penultimate interglacial warming*, PROC. NAT'L. ACAD. SCI. 119(35): 1–9, 7 ("While further studies are needed to determine the extent of methane hydrate destabilization during the weakened AMOC interval of the Eemian, the consequence of broad methane hydrate destabilization is increased atmospheric CH_4 and CO_2 concentrations. Taking age model uncertainties into consideration, during the peak in anomalously low carbon isotopes, the atmospheric CO_2 and CH_4 concentrations rose by 17 to 10 parts per million per volume and 20 parts per billion per volume, respectively (SI Appendix, Fig. S9) (49–51). Although the magnitude of this change varies between ice cores and analytical laboratories, the $\delta^{13}C$ values of atmospheric CO_2 declined by 0.3 to 0.4‰ coeval with the $\delta^{13}C$ anomaly recorded in the Gulf of Guinea sediment sequence (SI Appendix, Fig. S9) (50, 52), indicating that a source with a significantly negative $\delta^{13}C$ signature contributed to the increase of atmospheric CO_2. Methane release and methane oxidation due to massive methane hydrate destabilization is the likely source."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 10 ("A significant time lag separates atmospheric warming due to climate change and the much longer timescales required for transport and diffusion of heat anomalies into the ocean and sediment. As sediment warming is required for methane hydrate instability, dissociation may not be initiated until centuries to millennia after the requisite warming spike (Archer, 2015; Archer et al., 2009; K. Kretschmer et al., 2015; Ruppel, 2011). For deep ocean sediments, tens of millennia might be required for the methane hydrate zone to begin appreciably warming, let alone for hydrate to begin dissociating (Archer et al., 2009; Ruppel, 2011). This factor does not preclude eventual significant release of carbon from methane hydrate, bud does mean that this climate feedback occurs with a very substantial delay between commitment and realization.").

[254] Whiteman G., Hope C., & Wadhams P. (2013) *Vast costs of Arctic change*, NATURE 499(7459): 401–403, 401 ("We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of $60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about $70 trillion). The total cost of Arctic change will be much higher… The methane pulse will bring forward by 15–35 years the average date at which the

global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario and to 2040 for the low-emissions case (see 'Arctic methane'). This will lead to an extra $60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about $400 trillion). In the low-emissions case, the mean net present value of global climate-change impacts is $82 trillion without the methane release; with the pulse, an extra $37 trillion, or 45% is added. … These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse. The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. … The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone. To find out the actual cost, better models are needed to incorporate feedbacks that are not included ….''). *See generally* Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press; *and* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, GEOSCI. 9(6): 251, 1–23.

[255] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements,* REV. GEOPHYS. 61: 1–81, 13 ("Early estimates of high rates of methane emissions from hydrate dissociation on the East Siberian Arctic Shelf (Shakhova et al., 2014) have been revised substantially downwards by numerous subsequent studies (Berchet et al., 2016; Thornton et al., 2016, 2020; Tohjima et al., 2020). Present-day marine methane release from Arctic hydrate dissociation is probably primarily of natural origin, resulting from the pressure decrease associated with isostatic uplift following the last glacial maximum, rather than a response to anthropogenic forcing (Wallmann et al., 2018). And in the Beaufort Sea, fossil methane possibly from hydrate emissions was observed in deeper waters but was removed, likely via oxidation, prior to atmospheric emission (Sparrow et al., 2018). … In conclusion, while levels of warming exist beyond which large quantities of methane in hydrate deposits may eventually become destabilized, numerous physical, thermodynamic, chemical, and biological factors combine to substantially limit the rate at which this methane might escape to the atmosphere. For more moderate warming of ~2°C, methane hydrates might well exert a negligible overall impact on atmospheric temperatures. Methane hydrate dissociation would additionally take place on extremely long timescales of millennia, rather than over abrupt or fast timescales that would produce an acute warming spike. … With all of this in mind, in relation to other candidate tipping elements covered within this review, marine methane hydrates represent a relatively lower-impact climate feedback especially for warming in the Anthropocene (Table 3)."). *See also* Malakhova V. V. & Eliseev A. V. (2024) *Subsea permafrost and associated methane hydrate stability zone: how long can they survive in the future?*, THEOR. APPL. CLIMATOL.: 1–19, 1 ("This Earth System Model was forced by idealized scenarios of CO2 emissions and by changes of the parameters of the Earth's orbit … We found that at the other shelf, permafrost disappears either before the onset of the anthropogenic emissions or during a few centuries after it. In contrast, for the middle and shallow parts of the shelf, in the CO2-emission forced runs, the subsea permafrost survive, at least, for 5 kyr after the emission onset or even for much longer. At the same parts of the self, methane hydrate stability. Zone (MHSZ) disappears not earlier than at 3 kyr after the CO2 emission onset. … In general, the CO2-induced warming in our simulations is able to enhance the pan-Arctic subsea permafrost loss severalfold during 1 kyr after the emissions onset, but it is less important for the respective MHSZ loss. The dynamics of MHSZ is largely independent on the chosen climate projection, at least for the next several thousand years.").

[256] Ye W., Li Y., Wen J., Zhang J., Shakhova N., Liu J., Wu M., Semiletov I., & Zhan L. (2023) *Enhanced Transport of Dissolved Methane From the Chukchi Sea to the Central Arctic*, GLOB. BIOGEOCHEM. CYCLES 37(2): 1–21, 2 ("Here, based on our integrated data set (including 420 samples) and combined with previous studies (including 238 data points) (Fenwick et al., 2017; Kudo et al., 2018; Li et al., 2017; Lorenson et al., 2016), we find that CH4 was significantly enhanced in the Chukchi Sea and distributed northward with the shelf-break jet, providing clear evidence of increased CH4 transport from the Chukchi Sea shelf to the central Arctic in the 2010s compared with the 1990s.").

[257] Wadham J. L., Hawkings J. R., Tarasov L., Gregoire L. J., Spencer R. G. M., Gutjahr M., Ridgwell A., & Kohfeld K. E. (2019) *Ice sheets matter for the global carbon cycle*, NAT. COMMUN. 10(3567): 1–17, 8 ("There are substantial uncertainties regarding the magnitude of present day sub-ice sheet CH_4 hydrate reserves because of the difficulties of accessing sediments in subglacial sedimentary basins. Global subglacial methane hydrate stocks at the present day are likely to be dominated by those in Antarctic sedimentary basins (estimated at up to 300 Pg C as methane hydrate and free gas95). At the LGM, the global sub-ice sheet hydrate reserve could have been much larger (>500 Pg C, 20% of the present day marine hydrate stocks), with hydrate also present beneath former northern hemisphere ice sheets17,18,122 (see Fig. 4 for details and calculation methods). The vulnerability of Antarctic subglacial CH_4 hydrate reserves to destabilization is high because of their predicted location around the continent's periphery in sedimentary basins where ice thinning in a warming climate is probable."). *See also* Dessandier P.-A., Knies J., Plaza-Faverola A., Labrousse C., Renoult M., & Panieri G. (2021) *Ice-sheet melt drove methane emissions in the Arctic during the last two interglacials*, GEOLOGY 49(7): 799–803, 799 ("Here, we argue that based on foraminiferal isotope studies on drill holes from offshore Svalbard, methane leakage occurred upon the abrupt Eurasian ice-sheet wastage during terminations of the last (Weichselian) and penultimate (Saalian) glaciations. Progressive increase of methane emissions seems to be first recorded by depleted benthic foraminiferal $\delta^{13}C$. This is quickly followed by the precipitation of methane-derived authigenic carbonate as overgrowth inside and outside foraminiferal shells, characterized by heavy $\delta^{18}O$ and depleted $\delta^{13}C$ of both benthic and planktonic foraminifera. The similarities between the events observed over both terminations advocate a common driver for the episodic release of geological methane stocks. Our favored model is recurrent leakage of shallow gas reservoirs below the gas hydrate stability zone along the margin of western Svalbard that can be re-activated upon initial instability of the grounded, marine-based ice sheets. Analogous to this model, with the current acceleration of the Greenland ice melt, instabilities of existing methane reservoirs below and nearby the ice sheet are likely.").

[258] United Nations Environment Programme (2021) EMISSIONS GAP REPORT 2021: THE HEAT IS ON – A WORLD OF CLIMATE PROMISES NOT YET DELIVERED, 47 ("Over the last two decades, the main cause of increasing atmospheric methane is likely increasing anthropogenic emissions, with hotspot contributions from agriculture and waste in South and South-East Asia, South America and Africa, and from fossil fuels in China, the Russian Federation and the United States of America (Jackson *et al.* 2020). Emissions from natural sources may also be increasing, as wetlands warm, tropical rainfall increases and permafrost thaws."). *See also* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH4 observations and the way forward*, PHIL. TRANS. R. SOC. A 379(2210): 1–14, 11 ("Explaining the renewed and accelerating increase in atmospheric CH_4 burden since 2007 remains challenging, and the exact causes are not yet clear. But, the observations we describe suggest that increased emissions from microbial sources are the strongest driver, with a relatively smaller contribution from other processes, e.g., fossil fuel exploitation. A more difficult question to answer is the one posed by this special issue: is warming feeding the warming? We cannot say for certain, but we cannot rule out the possibility that climate change is increasing CH_4 emissions. The strong signals from the tropics combined with the isotopic data are consistent with increased emissions from natural wetlands, but large [interannual variability (IAV)] and inter-decadal variability in wetland drivers like precipitation make it difficult to identify small trends. Observations are needed that will help process models capture this variability. The size of the IAV illustrates the potential scope of uncontrollable near-future change and emphasizes the urgency of reducing the global methane burden by mitigating the methane emissions that we can control, from the fossil fuel and agricultural sectors."); Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 481 ("In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed $53 \pm 10\%$ of the MGR

anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation."); Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ENVIRON. RES. LETT. 17(9): 1–8, 6 ("The inversion shows an increase in the methane growth rate from 28 Tg a−1 in 2019 to 59 Tg a−1 in 2020, consistent with observations. This implies a forcing on the methane budget away from a steady state by 36 Tg a−1 from 2019 to 2020, 86% (82 ± 18% in the nine-member inversion ensemble) of which is from the increase in emissions between the two years and the rest is from the decrease in tropospheric OH. Changes in methane mass offset the forcing by 5 Tg a−1 . The global mean OH concentration decreases by 1.2% (1.6 ± 1.5%) from 2019 to 2020, which could be due to reduced NOx emissions from COVID-19 decreases in economic activity but accounts for only a small fraction of the methane surge. We find that half of the increase in methane emissions from 2019 to 2020 is due to Africa. High precipitation and flooding in East Africa leading to increased wetland methane emissions could explain the increase. We also find a large relative increase in Canadian emissions, also apparently driven by wetlands.."); Rehder Z., Kleinen T., Kutzbach L., Stepanenko V., Langer M., & Brovkin V. (2023) *Simulated methane emissions from Arctic ponds are highly sensitive to warming*, BIOGEOSCI. 20: 2837–2855, 2838 ("Most Arctic ponds emit predominantly contemporary, recently fixed, carbon (Negandhi et al., 2013; Bouchard et al., 2015; Dean et al., 2020). However, newly-formed ice-wedge ponds might emit older carbon than the average Arctic pond. When the permafrost adjacent to the thawing ice wedge degrades, old carbon can leech from the thawed sediments into the pond fueling methanogenesis (Langer et al., 2015; Preskienis et al., 2021) and exerting a positive climatic feedback. Furthermore, the composition of the ponds' methanogenic communities might change in response to the warming Arctic."), 2849 ("While ponds are not hotspots of methane emissions in our study area under the current climate, our model simulations indicate that they will become stronger methane sources under further warming. We project an increase of pond methane emissions of 1.33 g CH_4 m^{-2} $year^{-1}$ °C^{-1} ."); Kleinen T., Gromov S., Steil B., & Brovkin V. (2021) *Atmospheric methane underestimated in future climate projections*, ENVIRON. RES. LETT. 16(9): 1–14, 4 ("In the case of the low radiative forcing scenarios SSP1–1.9 and SSP1–2.6, the concentration maximum occurs at the end of the historical period and does not differ significantly between our experiments and the published scenarios. The concentration decline after that maximum, however, occurs much more slowly in our experiments, leading to higher atmospheric methane concentrations than in the published scenarios. For the moderate to high warming scenarios SSP2–4.5, SSP3–7.0 and SSP5–8.5, however, the evolution of atmospheric methane is much more dramatic. Here, maximum atmospheric concentrations become substantially higher than in the published scenarios and stay at a very high level until the end of the experiments in 3000 CE. For SSP2–4.5, the maximum in CH_4 is 50% higher than published previously, for SSP3–7.0 it is 131% higher and for SSP5–8.5 it is 130% higher."); (29 November 2023) *Do rising methane levels herald a climate feedback loop?*, THE ECONOMIST ("The evidence that wetlands might be to blame comes from the type of methane being emitted. Methane is made of four atoms of hydrogen atoms and one of carbon. That carbon atom can be either the "light" isotope, with six neutrons in its nucleus, or the heavy isotope, which has seven. Methane-making bacteria find the lighter sort easier to handle. The methane they produce is therefore lighter than methane from fossil fuels or forest fires, another major source of the gas. And over the past 15 years the methane in the atmosphere has indeed become lighter. … In 2021 a group of researchers analysed improved satellite and ground observations and concluded, in a paper published in Atmospheric Chemistry and Physics, that 35% of the post-2006 increase came from wetlands. A more recent estimate by Dr Nisbet and colleagues puts the contribution at 45%. Those may even be underestimates. One way that methane is taken out of the atmosphere is through reactions with chlorine ions over the ocean, a process that preferentially targets the lighter sort of methane. A paper published in June suggests that interactions between dust and sea spray over theAtlantic may mean there is more chlorine out there than modellers previously thought. If so, the shift towards microbial methane sources may be even more pronounced than the lightness of the methane in the atmosphere suggests."); *and* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 5 ("A switch from La Niña to El Niño during 2023 appears to have reduced the observed growth rate (Figure 2), supporting a large role for wetland responses to La Niña in the very high 2020–2022 growth rates. However, emissions appear to have remained substantially higher in 2023 relative to pre-2020 values (Figure 1B), suggesting longer-term contributions from increasing anthropogenic sources along with a forced trend in natural sources. Recent work also suggests a potentially permanent shift to an altered state of enhanced wetland methane emissions (8)."); *compare* Gauci V., Pangala S. R., Shenkin A., Barba J., Bastviken D., Figueiredo V., Gomez C., Enrich-Prast A., Sayer E., Stauffer T., Welch B., Elias D., McNamara N., Allen M., & Malhi Y. (2024) *Global atmospheric methane uptake by upland tree woody surfaces*, NATURE 631(8022): 796–800, 796 ("Stable carbon isotope measurement of methane in woody surface chamber air and process-level investigations on extracted wood cores are consistent with methanotrophy, suggesting a microbially mediated drawdown of methane on and in tree woody surfaces and tissues. By applying terrestrial laser scanning-derived allometry to quantify global forest tree woody surface area, a preliminary first estimate suggests that trees may contribute 24.6–49.9 Tg of atmospheric methane uptake globally. Our findings indicate that the climate benefits of tropical and temperate forest protection and reforestation may be greater than previously assumed.").

[259] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 9 ("Currently available measures could reduce emissions from [the fossil-fuel, waste, and agriculture] sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1)").

[260] United Nations Environment Programme and Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: *2030 BASELINE REPORT*, 10 ("The Global Methane Pledge targets at least a 30 per cent reduction in human-caused methane emissions below 2020 levels by 2030. Achieving the GMP target would require a decrease in annual emissions from approximately 380 million tonnes in 2020 to less than 270 million tonnes in 2030—a drop of at least 110 million tonnes. Compared to baseline methane emissions in 2030, this represents a 36% reduction in methane emissions, equivalent to at least 150 million tonne reduction, by 2030 from baseline levels.").

[261] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 10 ("The levels of methane mitigation needed to keep warming to 1.5°C will not be achieved by broader decarbonization strategies alone. The structural changes that support a transformation to a zero-carbon society found in broader strategies will only achieve about 30 per cent of the methane reductions needed over the next 30 years. Focused strategies specifically targeting methane need to be implemented to achieve sufficient methane mitigation. At the same time, without relying on future massive-scale deployment of unproven carbon removal technologies, expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5°C. (Sections 4.1, 4.2 and 4.3)"). For a general discussion and list of policy recommendations on how to pursue effective decarbonization, *see* National Academy of Sciences (2023) ACCELERATING DECARBONIZATION IN THE UNITED STATES.

[262] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 10 ("Roughly 60 per cent, around 75 Mt/yr, of available targeted measures have low mitigation costs2, and just over 50 per cent of those have negative costs – the measures pay for themselves quickly by saving money (Figure SDM2). Low-cost abatement potentials range from 60–80 per cent of the total for oil and gas, from 55–98 per cent for coal, and approximately 30–60 per cent in the waste sector. The greatest potential for negative cost abatement is in the oil and gas subsector where captured methane adds to revenue instead of being released to the atmosphere. (Section 4.2) … Less than US$ 600 per tonne of methane reduced, which would correspond to ~US$ 21 per tonne of carbon dioxide equivalent if converted using the IPCC Fifth Assessment Report's GWP_{100} value of 28 that excludes carbon-cycle feedbacks.").

[263] International Energy Agency (2023) CREDIBLE PATHWAYS TO 1.5 °C - FOUR PILLARS FOR ACTION IN THE 2020S, 1–15, 11 ("In the NZE Scenario, methane emissions from the energy sector fall by around 75% between 2020 and 2030

and total methane emissions from human activity fall by around 45%. The IEA's latest update of its Global Methane Tracker found that methane emissions from oil and gas alone could be reduced by 75% with existing technologies. Around $100 billion in total investment is needed over the period to 2030 to achieve this reduction—equivalent to less than 3% of oil and gas net income in 2022. To address methane emissions from fossil energy production and consumption, countries covering over half of global gas imports and over one-third of global gas exports released a Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels at COP27 calling for minimizing flaring, methane, and CO_2 emissions across the supply chain to the fullest extent practicable.").

[264] Lowe M. & Lowe-Skillern R. (2021) *Find, Measure, Fix: Jobs in the U.S. Methane Emissions Mitigation Industry*, Datu Research, 6 ("Methane emissions mitigation means jobs. A wide and steadily expanding range of skills are required, from field technicians to chemical engineers to data scientists. Interviews with firms indicate that these jobs offer upward mobility. Many firms expect to expand their workforce if new federal and/or state methane rules are put into place. Of the eight states that either have methane rules or are considering them, seven are among the top states for employee locations in the methane emissions mitigation industry, including California, Colorado, Pennsylvania, New York, Wyoming, New Mexico, and Ohio. This would suggest that employee locations are poised to grow if the federal government and/or states roll out new rules on methane emissions.").

[265] Example of methane mitigation technical potentials and costs include: Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21; International Energy Agency (2021) *Methane Tracker 2021*; United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010; *and* DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability.

[266] *See* Solar Impulse Foundation, *Solutions Explorer*.

[267] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr.").

[268] International Energy Agency (2021) *Curtailing Methane Emissions from Fossil Fuel Operations: Pathways to a 75% cut by 2030*, 11–13 ("Reducing methane from oil and gas operations is particularly promising because more than 70% of emissions can be abated with existing technologies. In addition, the cost of mitigation is often lower than the market value of the gas that is captured. Based on average natural gas prices from 2017-2021, we estimate that almost 45% of oil and gas methane emissions can be avoided with measures that would come at no net cost. While new investments to abate the remaining emissions would total about USD 13 billion, those costs would be more than offset by revenues from the sale of captured methane. … Under the Net Zero Scenario, total methane emissions from fossil fuels fall by around 75% from 2020 levels by 2030. About one-third of this drop results from overall reduction in fossil fuel consumption. Most of it depends on the accelerated deployment of mitigation measures and technologies leading to the elimination of all technically avoidable methane emissions by 2030."); *and* International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("In our Net Zero Emissions by 2050 (NZE) Scenario – which sees the global energy sector achieving net zero emissions by mid-century, limiting the temperature rise to 1.5 °C – methane emissions from fossil fuel operations fall by around 75% by 2030. By that year, all fossil fuel producers have an emissions intensity similar to the world's best operators today. Targeted measures to reduce methane emissions are necessary even as fossil fuel use begins to decline; cutting fossil fuel demand alone is not enough to achieve the deep and sustained reductions needed.").

[269] International Energy Agency (2024) Global Methane Tracker 2024 ("Methane abatement in the fossil fuel industry is one of the most pragmatic and lowest cost options to reduce greenhouse gas emissions. The technologies and measures to prevent emissions are well known and have already been deployed successfully around the world. Around 40% of the 120 Mt of methane emissions from fossil fuels could be avoided at no net cost, based on average energy prices in 2023. This is because the required outlays for abatement measures are less than the market value of the additional methane gas captured and sold or used."). *See also* International Energy Agency (2021) METHANE TRACKER 2021 ("We estimate that it is technically possible to avoid around three quarters of today's methane emissions from global oil and gas operations. Moreover, a significant share of these could be avoided at no net cost, as the cost of the abatement measure is less than the market value of the additional gas that is captured. Natural gas prices around the world affect the share of global emissions that can be abated at no net cost; this share is typically around 40-50%, although the plunge in natural gas prices in 2020 temporarily brought this down to around 10%.").

[270] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 4–5 ("Methane leaks in 2021 from fossil fuel operations, if captured and marketed, would have made an additional 180 billion cubic metres of gas available to the market, an amount similar to all the gas used in Europe's power sector. This would have been comfortably enough to ease today's price pressures.").

[271] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("The methane emissions intensity of oil and gas production varies widely. The best-performing countries score more than 100 times better than the worst. Norway and the Netherlands have the lowest emissions intensities. Countries in the Middle East, such as Saudi Arabia and the United Arab Emirates, also have relatively low emissions intensities. Turkmenistan and Venezuela have the highest. High emissions intensities are not inevitable; they can be addressed cost-effectively through a combination of high operational standards, policy action and technology deployment. On all these fronts, best practices are well established.").

[272] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 5 ("The best companies and countries are showing what can be done to reduce emissions from oil and gas operations, but the intensity of methane emissions (emissions per unit of production) ranges widely. The best performing countries are more than 100 times better than the worst. Norway and the Netherlands have the lowest emissions intensities in our updated Tracker, and countries in the Middle East such as Saudi Arabia and the United Arab Emirates also have relatively low emissions intensities; Turkmenistan and Venezuela have the highest. If all producing countries were to match Norway's emissions intensity, global methane emissions from oil and gas operations would fall by more than 90%."), 24 ("The methane emissions intensity of oil and gas operations varies greatly across countries, with the best performing countries having an emission intensity over 100 times lower than the worst performers. High emission intensities from oil and gas operations are not inevitable; they are an "above-ground issue" that can be addressed cost-effectively through a well-established combination of high operational standards, firm policy action and technology deployment."). *See also* Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S.W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 1–11, 5 ("For oil and gas, we supplement the IEA (2017) abatement potential of 75% below current levels with voluntary company commitments of capping upstream leakage. This results in an 83% below 2030 level abatement potential rather than 77% without industry targets.").

[273] International Energy Agency (2023) EMISSIONS FROM OIL AND GAS OPERATIONS IN NET ZERO TRANSITIONS: A WORLD ENERGY OUTLOOK SPECIAL REPORT ON THE OIL AND GAS INDUSTRY AND COP28, 16 ("We estimate that the oil and gas industry is responsible for 80 Mt of methane emissions, equivalent to 2.4 Gt CO2-eq. There is a wide variety of well-known technologies and measures available to reduce methane emissions from operations, and in the NZE Scenario emissions fall by over 60 Mt – a 75% reduction – to 2030. One-third of this drop occurs because of reductions in oil and gas use to 2030 in the NZE Scenario, with the remaining two-thirds stemming from widespread efforts across all parts of the supply chain to reduce the emissions intensity of oil and gas operations (the methane

emissions intensity of oil and gas production falls by more than 70% to 2030). By 2030, all oil and gas producers have an emissions intensity similar to the world's best operators today.").

[274] International Energy Agency (2023) EMISSIONS FROM OIL AND GAS OPERATIONS IN NET ZERO TRANSITIONS: A WORLD ENERGY OUTLOOK SPECIAL REPORT ON THE OIL AND GAS INDUSTRY AND COP28, 16 ("We estimate that the oil and gas industry is responsible for 80 Mt of methane emissions, equivalent to 2.4 Gt CO2-eq. There is a wide variety of well-known technologies and measures available to reduce methane emissions from operations, and in the NZE Scenario emissions fall by over 60 Mt – a 75% reduction – to 2030. One-third of this drop occurs because of reductions in oil and gas use to 2030 in the NZE Scenario, with the remaining two-thirds stemming from widespread efforts across all parts of the supply chain to reduce the emissions intensity of oil and gas operations (the methane emissions intensity of oil and gas production falls by more than 70% to 2030). By 2030, all oil and gas producers have an emissions intensity similar to the world's best operators today.").

[275] International Energy Agency (2023) EMISSIONS FROM OIL AND GAS OPERATIONS IN NET ZERO TRANSITIONS: A WORLD ENERGY OUTLOOK SPECIAL REPORT ON THE OIL AND GAS INDUSTRY AND COP28, 16 ("We estimate that the oil and gas industry is responsible for 80 Mt of methane emissions, equivalent to 2.4 Gt CO2-eq. There is a wide variety of well-known technologies and measures available to reduce methane emissions from operations, and in the NZE Scenario emissions fall by over 60 Mt – a 75% reduction – to 2030. One-third of this drop occurs because of reductions in oil and gas use to 2030 in the NZE Scenario, with the remaining two-thirds stemming from widespread efforts across all parts of the supply chain to reduce the emissions intensity of oil and gas operations (the methane emissions intensity of oil and gas production falls by more than 70% to 2030). By 2030, all oil and gas producers have an emissions intensity similar to the world's best operators today.").

[276] Global Climate and Health Alliance (2023) MITIGATING METHANE FROM THE ENERGY SECTOR, 7 ("Targeted technical solutions to reduce methane emissions from fossil fuels can deliver multiple human health benefits. First, they can limit tropospheric ozone, a harmful air pollutant created by methane emitted from sources such as oil and natural gas extraction, production, combustion, as well as coal mining. Methane-driven tropospheric ozone can lead to adverse health outcomes, such as cardiovascular diseases, asthma, respiratory illness, and premature death, resulting in roughly 1 million premature deaths yearly, as discussed in the Overview Report. Furthermore, reducing methane can avoid health impacts from exposure to air pollutants co-emitted with methane, including: NOx, which is linked to asthma incidences and hospitalization, respiratory illnesses, cardio- vascular disease mortality; PM2.5, which can lead to the same adverse health outcomes as NOx, as well as premature birth, lung cancer, and low birth weight; Hydrogen sulfide (H2S), which can cause eye and respiratory system irritations, as well as apnea, coma, convulsions, dizziness, headache, weakness, irritability, insomnia, and upset stomach. BTEX, which can increase cancer risks. Finally, reducing methane can avoid safety risks from explosions and fires caused by methane leaks in natural gas pipelines or high methane concentrations in coal mines.").

[277] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 5 February 2023) ("Fortunately, most leaks are straightforward to repair (and fixing leaks is paid for by the value of the gas that is saved by repairing them). Further, finding leaks has become efficient with modern technology. The standard approach today is to use special cameras that can detect infrared light (think of night-vision goggles) which are tuned to make methane, which is invisible to our eyes, visible. They allow inspectors to directly image leaking gas in real time, with the ability to inspect entire components (not just connections and other areas most likely to leak) and pinpoint the precise source, making repair more straightforward. And, technology promises to make this process even more efficient (and cheaper) over the coming years. These technologies can be utilized to reduce harmful leak emissions, by using regular inspections as the lynchpin of rigorous "leak detection and repair" (LDAR) programs. These programs require operators to regularly survey all of their facilities for leaks and improper emissions, and repair all the leaks they identify in a reasonable time. For example, California requires operators to survey all sites four times a year. Colorado has a different approach, requiring operators of the largest sites to survey them monthly, but requiring less frequent inspections for site with smaller potential emissions.").

[278] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 5 February 2023) (Listing pneumatic equipment venting, compressor seal venting, tank venting, well completion venting, oil well venting and flaring, and dehydrator venting as sources of the "biggest mitigation opportunities.").

[279] International Energy Agency (2021) *Methane Tracker 2021* ("Many pieces of equipment in the oil and natural gas value chains emit natural gas in their regular course of operation, including valves, and gas-driven pneumatic controllers and pumps. Retrofitting these devices or replacing them with lower-emitting versions can reduce emissions."). *See also* Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development, 29 ("Leak detection and repair (LDAR) is an essential component of monitoring and reducing methane emissions"); *and* United Nations Economic Commission for Europe (2019) BEST PRACTICE GUIDANCE FOR EFFECTIVE METHANE MANAGEMENT IN THE OIL AND GAS SECTOR, xiii ("Major gaps exist in information about emissions originating from the oil and gas sector. Reported estimates often diverge by 10% or more, and revisions of national inventory reports from some of the largest emitters highlight the lack of reliable data. Methane emissions cannot be quantified through continuous measurement alone. Emissions originate from a vast number of sources and monitoring each source would be prohibitively expensive. Emission detection and measurement must complement calculation-based approaches that quantify emissions by multiplying activity data by relevant emission factors. Estimates will be more reliable if they reflect field and country specific circumstances, so empirical studies of emissions and emission intensities are a key to improved quantification. Detection and measurement consist of top-down methods that measure concentrations of methane in the atmosphere and bottom-up methods involving on-site quantification of emissions from individual sources. The technology for both top-down and bottom-up approaches is improving and the choice of approach depends on the objective. Best practices for top-down or bottom-up detection and measurement and for calculation-based methods depend on the objectives and the manner of reporting.").

[280] International Energy Agency (2021) *Methane Tracker 2021* (Listing replacement of existing devices, installing new emissions control devices, leak detection and repair (LDAR), and alternative and innovative technologies as the four "main mitigation measures."). *See also* Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 5 February 2023) ("Fortunately, most leaks are straightforward to repair (and fixing leaks is paid for by the value of the gas that is saved by repairing them). Further, finding leaks has become efficient with modern technology. The standard approach today is to use special cameras that can detect infrared light (think of night-vision goggles) which are tuned to make methane, which is invisible to our eyes, visible. They allow inspectors to directly image leaking gas in real time, with the ability to inspect entire components (not just connections and other areas most likely to leak) and pinpoint the precise source, making repair more straightforward. And, technology promises to make this process even more efficient (and cheaper) over the coming years. These technologies can be utilized to reduce harmful leak emissions, by using regular inspections as the lynchpin of rigorous "leak detection and repair" (LDAR) programs. These programs require operators to regularly survey all of their facilities for leaks and improper emissions, and repair all the leaks they identify in a reasonable time. For example, California requires operators to survey all sites four times a year. Colorado has a different approach, requiring operators of the largest sites to survey them monthly, but requiring less frequent inspections for site with smaller potential emissions.").

[281] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 5 February 2023) ("Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous low-cost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%.").

[282] World Bank (5 May 2022) *Global Flaring and Venting Regulations* ("Flared and vented gas can replace more-polluting fuels in local communities, cutting emissions and expanding energy access for the poorest. In 2021, an

estimated 144 billion cubic meters of associated gas were wastefully flared around the world. If captured and put to productive purposes, this gas could power the entirety of sub-Saharan Africa.”).

[283] Curry T., Hellgren L., Russell P., & Fraioli S. (2022) BENCHMARKING METHANE AND OTHER GHG EMISSIONS OF OIL AND NATURAL GAS PRODUCTION IN THE UNITED STATES, Ceres & Clean Air Task Force, 3 (“Of 303 oil and natural gas producers with reported data, the top 100 oil and gas producers by total energy production were responsible for approximately 74% and 77%, respectively, of total reported methane and GHG emissions in 2020. While most top-100 producers are also among the top 100 emitters, production rank does not correspond to emissions rank. The methane emissions intensity of natural gas production and the GHG emissions intensity of oil and gas production varies dramatically across producers. Natural gas producers in the highest quartile of methane emissions intensity have an average emissions intensity that is nearly 24 times higher than natural gas producers in the lowest quartile of methane emissions intensity. Oil and gas producers in the highest quartile of GHG emissions intensity have an average emissions intensity that is more than 13 times higher than oil and gas producers in the lowest quartile.”); *discussed in* Clean Air Task Force (14 July 2022) *Greenhouse gas emissions vary dramatically across U.S. oil and gas companies, according to updated analysis*, News and Media; *and* Budryk Z. (14 July 2022) *Four companies are top sources of US greenhouse gas, methane emissions: report*, THE HILL.

[284] Curry T., Hellgren L., Russell P., & Fraioli S. (2022) BENCHMARKING METHANE AND OTHER GHG EMISSIONS OF OIL AND NATURAL GAS PRODUCTION IN THE UNITED STATES, Ceres & Clean Air Task Force, 3 (“Pneumatic controllers were the largest source of total reported production-segment methane emissions, making up 62% of total reported methane emissions. • Fuel combustion equipment, such as engines and heaters, were the largest source of total reported production-segment CO_2 emissions, responsible for 58% of total reported CO_2 emissions. In oil-heavy basins, associated gas venting and flaring can be a significant contributor to GHG emissions. In the Williston basin, for example, this source is responsible for 59% of total GHG emissions. In gas-heavy basins, associated gas is limited or non-existent; for example, there was no reported associated gas venting and flaring in the Appalachian basin. Across all basins, associated gas venting and flaring was responsible for 14% of total reported onshore production segment GHG emissions.”).

[285] United Nations Environment Programme (24 November 2020) *Oil and Gas Industry commits to new framework to monitor, report and reduce methane emissions*, Press Release (“Crucially, the OGMP 2.0 includes not only a company’s own operations, but also the many joint ventures responsible for a substantial share of their production. The OGMP 2.0 framework applies to the full oil and gas value chain, not only upstream production, but also midstream transportation and downstream processing and refining – areas with substantial emissions potential that are often left out of reporting today.... In order to support the realization of global climate targets, OGMP 2.0 aims to deliver a 45 per cent reduction in the industry’s methane emissions by 2025, and a 60-75 per cent reduction by 2030.”).

[286] World Bank (5 December 2023) *GGFR to evolve to the Global Flaring & Methane Reduction Partnership* (“GFMR will establish eligibility criteria so that support drives long term emissions reduction projects and initiatives. For example, access to project development and financing support through GFMR will be subject to a commitment to: measure and report emissions through the Oil and Gas Methane Partnership 2.0 framework, achieve near-zero absolute methane emissions by 2030 by reducing methane intensity to below 0.2%, and achieve zero routine flaring by 2030.”).

[287] Proville J., Roberts K. A., Peltz A., Watkins L., Trask E., & Wiersma D. (2022) *The demographic characteristics of populations living near oil and gas wells in the USA*, POPUL. ENVIRON. 44: 1–14, 10 (“These results underscore the degree to which the US population and oil and gas production are intertwined. Over 18 million people live within one mile of wells. Many of these consist of marginalized groups (Hispanic: 3.3 m; Black: 1.8 m; Asian: 0.7 m; Native American: 0.5 m; below the poverty line: 2.9 m; over 64 years old: 2.7 m; under 5 years old: 1.2 m). From a relative standpoint, at a national aggregated scale, most population groups are found to be less prevalent near wells than their county-level controls. The exceptions to this are Native Americans, Whites, people over 64 years old, and people with less than a high school degree. For these populations, we find a respective 25.0%, 9.5%, 6.6%, and 46.6% higher prevalence living within one mile of wells than controls.”), 11 (“Another important policy aspect for exploration in

subsequent research is the relationship between employment and populations living near wells. Our results highlight widespread clusters of high unemployment near wells 4–12 times the national average (Online Resource 3)."); *discussed in* Proville J. & Roberts K. (21 June 2022) *Creating data to support communities on the front lines of oil and gas production in the US*, ENVIRONMENTAL DEFENSE FUND.

[288] Raimi D., Nerurkar N., & Bordoff J. (2020) GREEN STIMULUS FOR OIL AND GAS WORKERS: *CONSIDERING A MAJOR FEDERAL EFFORT TO PLUG ORPHANED AND ABANDONED WELLS*, Columbia School of International and Public Affairs Center on Global Energy Policy & Resources for the Future, 20 ("A large federal effort to plug orphaned and abandoned oil and gas wells has the potential to provide tens of thousands of jobs—potentially up to 120,000. These efforts would reduce local air pollution, safety risks, and greenhouse gas emissions at a cost of $67 to $170 per ton of CO_2-equivalent, well within the range of other policy options. These costs are somewhat uncertain due to limited data on methane emissions from abandoned wells and potential changes to the future costs of carrying out such a program.").

[289] Alvarez R. A., *et al*. (2018) *Assessment of methane emissions from the U.S. oil and gas supply chain*, SCIENCE 361(6398): 186–188, 186 ("Methane emissions from the U.S. oil and natural gas supply chain were estimated by using ground-based, facility-scale measurements and validated with aircraft observations in areas accounting for ~30% of U.S. gas production. When scaled up nationally, our facility-based estimate of 2015 supply chain emissions is 13 ± 2 teragrams per year, equivalent to 2.3% of gross U.S. gas production. This value is ~60% higher than the U.S. Environmental Protection Agency inventory estimate, likely because existing inventory methods miss emissions released during abnormal operating conditions. Methane emissions of this magnitude, per unit of natural gas consumed, produce radiative forcing over a 20-year time horizon comparable to the CO_2 from natural gas combustion. Substantial emission reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems.").

[290] Chen Y., Sherwin E. D., Berman E. S. F., Jones B. B., Gordon M. P., Wetherley E. B., Kort E. A., & Brandt A. R. (2022) *Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey*, ENVIRON. SCI. TECHNOL. 56(7): 4317–4323, 4321 ("Importance of Large Sample Size and Direct Measurement. Compared to an EPA GHGI estimate aligned to our study area and time period (Figure 4a), this study suggests total methane emissions from upstream and midstream O&G activities in the New Mexico Permian to be 6.5 (+2.4/−2.3) times larger. It is important to explore further a key strength of our method compared to prior bottom-up studies: very large study sample size.").

[291] Sadavarte P., Pandey S., Maasakkers J. D., Lorente A., Borsdorff T., van der Gon H. D., Houweling S., & Aben I. (2021) *Methane Emissions from Super-emitting Coal Mines in Australia quantified using TROPOMI Satellite Observations*, ENVIRON. SCI. TECHNOL. 55(24): 16537–16580, 16537 ("Our results indicate that for two of the three locations, our satellite-based estimates are significantly higher than reported to the Australian government. Most remarkably, 40% of the quantified emission came from a single surface mine (Hail Creek) located in a methane-rich coal basin."); *discussed in* Clark A. (29 November 2021) *These Australian Coal Mines are Methane Super-Emitters*, BLOOMBERG GREEN.

[292] Lauvaux T., Giron C., Mazzolini M., d'Aspremont A., Duren R., Cusworth D., Shindell D., & Ciais P. (2022) *Global assessment of oil and gas methane ultra-emitters*, SCIENCE 375(6580): 557–561, 557 ("Ultra-emitters are primarily detected over the largest O&G basins throughout the world. With a total contribution equivalent to 8 to 12% (~8 million metric tons of methane per year) of the global O&G production methane emissions, mitigation of ultra-emitters is largely achievable at low costs and would lead to robust net benefits in billions of US dollars for the six major O&G-producing countries when considering societal costs of methane.").

[293] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 6 ("Globally, our analysis finds that methane emissions from the energy sector are about 70% greater than the sum of estimates submitted by national governments."), 16 ("Accounting for the level of satellite coverage, very large emitting events detected by satellite

are estimated to have been responsible for around 3.5 Mt of emissions from oil and gas operations in 2021 (6% of our estimate of oil and gas emissions in the 15 countries where events were detected).").

[294] Rocky Mountain Institute, *Profiling Supply Chain Emissions* (*last visited* 5 February 2023) ("Russian Federation Astrakhanskoye Total Emissions Intensity 1,060 kg CO_2 eq./barrel oil equivalent; Turkmenistan South Caspian Basin Total Emissions Intensity 1,010 kg CO_2 eq./barrel oil equivalent; United States Permian TX Total Emissions Intensity 908 kg CO_2 eq./barrel oil equivalent"). *See also* Malik N. S. (23 June 2022) *World's Dirtiest Oil and Gas Fields Are in Russia, Turkmenistan and Texas*, BLOOMBERG (Graph, "The Worst Offenders"); *and* Gordon D., Koomey J., Brandt A., & Bergerson J. (2022) KNOW YOUR OIL AND GAS: *GENERATING CLIMATE INTELLIGENCE TO CUT PETROLEUM INDUSTRY EMISSIONS*, Rocky Mountain Institute.

[295] Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development, 32 ("Direct measurement and verification are essential to accurate and credible emissions quantification. A key challenge in the methane monitoring space in the O&G sector is integrating different measurement and monitoring techniques and approaches to provide accurate, comprehensive, and timely quantification of emissions with source attribution. Multiple research efforts are underway to develop methodologies for integrating bottom-up and top-down approaches to address this challenge (e.g., Energy Emissions Modeling and Data Lab, Veritas). In June, MiQ-Highwood released an index for integrating inventory and direct measurement data for national-level emissions intensity quantification."). *See also* Tibrewal K., *et al.* (2024) *Assessment of methane emissions from oil, gas and coal sectors across inventories and atmospheric inversions*, COMMUN. EARTH ENVIRON. 5: 1–12, 1 ("Larger disagreement in emissions exists for the oil/gas sector across the inventories compared to coal, arising mostly from disparate data sources for emission factors. Moreover, emissions reported to the United Nations Framework Convention on Climate Change are lower than other bottom-up and inversion estimates, with many countries lacking reporting in the past decades."), 8 ("Overall, total fossil emissions averaged over 2011–2020 from bottom-up inventories is within the range estimated by atmospheric inversions for countries examined here. Disagreements largely arise from the oil and gas sector, in both emissions magnitudes averaged over the last decade (2011–2020) and trends from 2000 to 2020. Disagreements exist not only between estimates from bottom-up inventories and inversions but also among the various bottom-up inventories. For Russia, Kazakhstan, Iran and countries under Arabian Peninsula, the spread of the bottomup inventories is larger than that of atmospheric inversions. Given the large contribution from fossil sectors to global methane emissions, using a single inventory may overestimate or underestimate the evaluation of future emissions reductions under methane pledge.").

[296] Shen L., Jacob D. J., Gautam R., Omara M., Scarpelli T. R., Lorente A., Zavala-Araiza D., Lu X., Chen Z., & Lin J. (2023) *National quantifications of methane emissions from fuel exploitation using high resolution inversions of satellite observations*, NAT. COMMUN. 14(4948): 1–9, 1 ("We find global emissions of 62.7 ± 11.5 (2σ)Tga−1 for oil-gas and 32.7 ± 5.2 Tg a−1 for coal. Oil-gas emissions are 30% higher than the global total from UNFCCC reports, mainly due to under-reporting by the four largest emitters including the US, Russia, Venezuela, and Turkmenistan. Eight countries have methane emission intensities from the oil-gas sector exceeding 5% of their gas production (20% for Venezuela, Iraq, and Angola), and lowering these intensities to the global average level of 2.4% would reduce global oil-gas emissions by 11 Tg a−1 or 18%.").

[297] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr.").

[298] Gordon D., Reuland F., Jacob D. J., Worden J. R., Shindell D., & Dyson M. (2023) *Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates*, ENVIRON. RES. LETT. 18(8): 1–10, 2 ("Methane can be emitted from both coal and gas operations, including coal mines and conventional and

unconventional gas systems. Unconventional gas includes coalbed methane (CBM), a production method that taps coal seams. Coal mine methane (CMM) is attributed to coal production systems, while leakage from CBM is attributable to gas supply chains."). For best practice on managing and mitigating coal mine methane, *see* United Nations Economic Commission for Europe (2021) BEST PRACTICE GUIDANCE FOR EFFECTIVE MANAGEMENT OF COAL MINE METHANE AT NATIONAL LEVEL.

[299] Gordon D., Reuland F., Jacob D. J., Worden J. R., Shindell D., & Dyson M. (2023) *Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates*, ENVIRON. RES. LETT. 18(8): 1–10, 2 ("Methane can be emitted from both coal and gas operations, including coal mines and conventional and unconventional gas systems. Unconventional gas includes coalbed methane (CBM), a production method that taps coal seams. Coal mine methane (CMM) is attributed to coal production systems, while leakage from CBM is attributable to gas supply chains.").

[300] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 29–30 ("In the IEA's Net Zero Emissions by 2050 Scenario, coal use drops by 55% from 2020 to 2030, and by almost 90% by 2050. This decline would significantly cut methane emissions from coal mines as well as emissions of CO_2 and other air pollutants; emissions reductions would be even larger if concentrated on the worst-performing coal assets. For example, removing the worst-performing quartile of production would remove around 25 Mt of methane while removing the best performing quartile would only remove about 4 Mt.").

[301] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 107 ("Coal mining: pre-mining degasification; air methane oxidation with improved ventilation."). *See also* DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 22 ("Levers such as full ventilation and degasification of underground mines are standard coal mine methane (CMM) abatement technology but would likely see adoption rates of only 0.5 to 1.0 percent by 2030 and 2 to 4 percent by 2050. Other levers—such as ventilation air methane (VAM) capture and utilization, capture of abandoned mine gas, degasification of surface mines, and predrainage of surface mine—are less technically challenging but are expensive. They could see 2 to 16 percent adoption rates in 2030, growing to 20 to 30 percent adoption rates by 2050."); *and* United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010, 14 ("In 2030, VAM oxidation is the leading emission abatement measure, but using degasification for power generation presents the largest abatement potential at prices below \$0/tCO_2e. The two technologies combined contribute 90% of potential abatement in 2030.").

[302] DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 22 ("Levers such as full ventilation and degasification of underground mines are standard coal mine methane (CMM) abatement technology but would likely see adoption rates of only 0.5 to 1.0 percent by 2030 and 2 to 4 percent by 2050. Other levers—such as ventilation air methane (VAM) capture and utilization, capture of abandoned mine gas, degasification of surface mines, and predrainage of surface mine—are less technically challenging but are expensive. They could see 2 to 16 percent adoption rates in 2030, growing to 20 to 30 percent adoption rates by 2050."). *See also* United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010, 15 ("In 2030, the top 3 mitigation technologies globally are the use of stand-alone VAM, degasification for power generation, and degasification for pipeline injection. Using stand-alone VAM can abate up to 443 MtCO2e (76% of coal mining's total abatement potential), although it is one of the most expensive abatement options in coal mining because of three key factors: (1) the equipment itself is large and costly; (2) there is no revenue source; and (3) only a handful of technologies have been demonstrated at a commercial scale and, as such, economies of scale in production have not been realized. Technology improvements have the potential to reduce the costs of VAM oxidation technology, making more of the potential abatement economically feasible for mine operators.").

[303] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Table 4.1 ("Coal mining: flooding abandoned mines.").

[304] United Nations Economic Commission for Europe (2019) BEST PRACTICE GUIDANCE FOR EFFECTIVE METHANE RECOVERY AND USE FROM ABANDONED COAL MINES, ECE Energy Series No. 64, 3 ("Technologies and management practices allow methane from abandoned mines to be extracted, providing significant environmental, economic, social and public safety benefits. The methods for extracting gas from abandoned mines differ from those employed to capture and recover gas from working mines. Once a mine is sealed from the atmosphere, gas from all underground sources becomes potentially available for extraction at a single production location. Methane concentrations recovered from a well-sealed former gassy mine typically range from 15% to 90%, and with no oxygen. The other major gaseous components may be nitrogen, including de-oxygenated air, and carbon dioxide. Low concentrations of carbon monoxide and trace hydrocarbons such as ethane are sometimes present.").

[305] United Nations Economic Commission for Europe. (2019) BEST PRACTICE GUIDANCE FOR EFFECTIVE METHANE RECOVERY AND USE FROM ABANDONED COAL MINES, iii ("Closed mines can provide a small but significant opportunity to exploit a clean energy resource, known as Abandoned Mine Methane (AMM), that can be extracted and used. AMM capture and use offers many benefits, such as improved safety, air quality and health, energy supply and environmental performance. Technology exists that can recover methane from abandoned coal mines.").

[306] Zhu R., Khanna N., Gordon J., Dai F., & Lin J. (2023) ABANDONED COAL MINE METHANE REDUCTION: LESSONS FROM THE UNITED STATES, California-China Climate Institute, 18 ("AMM can explode, posing hazards to residential and commercial buildings. AMM is also a precursor of air pollutants including volatile organic compounds, benzene (a carcinogen), and ozone. Mitigating AMM is therefore an important component of addressing health and safety issues on lands around abandoned coal mines, known as "abandoned mine lands" (AML)."). Note that this report focuses on U.S. federal and state examples of Abandoned Coal Mine Methane Regulation. For the Biden Administration's announcement of $725 million to fund the reclaiming of abandoned coal mine lands, as part of a broader total of $11.3 billion in abandoned mine land (AML) funding being provided over 15 years, *see* United States Department of the Interior (1 June 2023) *Biden-Harris Administration Announces Availability of $725 Million from Investing in America Agenda to Clean Up Legacy Pollution*, Press Release ("The Department of the Interior today announced that nearly $725 million from President Biden's Bipartisan Infrastructure Law is available to 22 states and the Navajo Nation to create good-paying jobs and catalyze economic opportunity by reclaiming abandoned coal mine lands. The law provides a total of $11.3 billion in abandoned mine land (AML) funding over 15 years, which will help communities clean up dangerous environmental conditions and pollution caused by past coal mining. This funding is expected to enable reclamation of the majority of current inventoried abandoned mine lands in this country.").

[307] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 91 ("In addition, a transition away from fossil fuels could still leave abandoned infrastructure. There were more than 3.2 million abandoned oil and gas wells in the United States alone in 2018, which emit ~0.3 Mt/yr of methane according to the US EPA (US EPA report to UNFCCC; 2020). That agency acknowledges that this figure is likely a large underestimate due to incomplete data. Similarly, The International Institute for Applied Systems Analysis (IIASA) estimates that 2020 emissions of methane from abandoned coal mines around the world are just over 3.5 Mt/yr (Höglund-Isaksson 2020).").

[308] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 14 ("Additional measures, which reduce methane emissions but do not primarily target methane, could substantially contribute to methane mitigation over the next few decades. Examples include decarbonization measures – such as a transition to renewable energy and economy-wide energy efficiency improvements. Various implementation levers exist. Emissions pricing, for example, can be an effective policy which could incentivize substantial methane mitigation and support the broad application

of methane reduction measures. A rising global tax on methane emissions starting at around US$ 800 per tonne could, for instance, reduce methane emissions by as much as 75 per cent by 2050. (Section 4.3)").

[309] The higher boundary of the calculation comes from the following report's value of 1,419 $MtCO_2e$ using a 100 year GWP value of 27.9 for livestock. *See* Global Methane Hub & Climateworks Foundation (2023) THE GLOBAL INNOVATION NEEDS ASSESSMENTS*: FOOD SYSTEM METHANE*, 6 (Table on Methane abatement by food system sector). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr.").

[310] The Global Methane Pledge calls for at least a 30% reduction in global anthropogenic methane emissions compared to 2020 levels by 2030, which translates into an annual reduction of 150 Mt in 2030 to be consistent with scenarios limiting warming to 1.5 °C with limited overshoot. Using the mitigation potential for livestock and rice (4–50 $MtCH_4$/yr and 6–9 $MtCH_4$/yr, respectively) results in a 7–39% progression towards the GMP target. *See* United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: *2030 BASELINE REPORT*, 10 (Figure ES6: "Illustrative example of the GMP-consistent methane emissions reduction pathway to 2030. Mitigation in all three main anthropogenic sectors is required to achieve the GMP target in 2030 with slightly more than half of the mitigation expected to come from the fossil fuels sector.").

[311] Global Methane Hub & Climateworks Foundation (2023) THE GLOBAL INNOVATION NEEDS ASSESSMENTS*: FOOD SYSTEM METHANE*, 6 ("Food system innovations analyzed in this GINAs study can help meet climate targets by reducing food system methane in line with the Global Methane Pledge. This study analyzes abatement potential and benefits of innovations across the food system value chain, including low-cost or cost-saving productivity measures as well as direct mitigation and diet shift measures, and finds food system methane innovations could abate up to 2 $GtCO_2e$ in 2030 and 5.6 $GtCO_2e$ in 2050 (reducing methane emissions in food system sectors in 25% by 2030 and up to 75% by 2050).").

[312] Note that this analysis assumes dietary patterns will remain constant, however several other studies find that dietary patterns are expected to experience many changes as population grows and demand for protein increases along with GDP per capita: Ivanovich C. C., Sun T., Gordon D. R., & Ocko I. B. (2023) *Future warming from global food consumption*, NAT. CLIM. CHANGE 13(3): 297–302, 297 ("We find that global food consumption alone could add nearly 1 °C to warming by 2100."); 298 ("Methane is responsible for the majority of the projected increase, accounting for nearly 60% of the warming associated with food consumption by the end of the century.").

[313] Shroff J. (28 September 2022) *Why smallholder farmers are central to new food security interventions*, WORLD ECONOMIC FORUM ("The 600 million smallholder farmers around the world working on less than two hectares of land, are estimated to produce 28-31% of total crop production and 30-34% of food supply on 24% of gross agricultural area.").

[314] International Institute for Sustainable Development (21 June 2023) *FAO Guidelines Help ECA Countries Integrate LNOB in Development Planning* ("The report underscores that in agrifood systems, it is crucial to reach those furthest behind first. Citing the World Bank's estimates, it notes that 80% of people living below the international poverty line reside in rural areas. In the ECA region, the prevalence of severe food insecurity in 2020 was 2.4%, or 22.8 million people, according to the report. At the same time, the report emphasizes, 'smallholder farmers produce one-third of the world's food but bear a double vulnerability burden,' having to deal with vulnerabilities related to climate change as well as those 'associated with having limited access to productive resources such as land and water, public services and markets in food supply chains.'").

[315] *See* the annual average emissions for 2017 *in* Skea J., *et al.* (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-10 ("The annual average during the decade 2010–2019 was 56 ± 6.0 $GtCO_2$-eq, 9.1 $GtCO_2$-eq yr^{-1} higher than in 2000–2009."). *See* total food system emissions for 2017 *in* Zhu J., Luo Z., Sun T., Li W., Zhou W., Wang X., Fei X., Tong H., & Yin K. (2023) *Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems*, NAT. FOOD 4(3): 1–13, 2 ("The global food system generated 18.6 ± 12.6 (1σ) Gt of CO_2 equivalent ($GtCO_2$e) GHGs in 2017 (Fig. 1) in four food categories (cereals, pulses and others; roots and oil crops; vegetables and fruit; and meat and animal products).").

[316] Global Methane Hub & Climateworks Foundation (2023) THE GLOBAL INNOVATION NEEDS ASSESSMENTS*: FOOD SYSTEM METHANE*, 6 ("Methane represents approximately a fifth of global greenhouse gases, 60% of which arise from the food system. An estimated 10.3 $GtCO_2$e of methane are emitted per year. Food system methane accounts for an estimated 6-7 $GtCO_2$e, including emissions arising from the agriculture sector (40% share of total methane) as well as waste emissions associated with food waste.").

[317] Food and Agriculture Organization of the United Nations, International Fund for Agriculture Development, United Nations Children's Fund, World Food Programme, & World Health Organization (2023) THE STATE OF FOOD SECURITY AND NUTRITION IN THE WORLD 2023: *URBANIZATION, AGRIFOOD SYSTEMS TRANSFORMATION AND HEALTHY DIETS ACROSS THE RURAL–URBAN CONTINUUM*, xvi ("Global hunger, measured by the prevalence of undernourishment (Sustainable Development Goal [SDG] Indicator 2.1.1), remained relatively unchanged from 2021 to 2022 but is still far above pre-COVID-19-pandemic levels, affecting around 9.2 percent of the world population in 2022 compared with 7.9 percent in 2019."), 32 ("Conflict, climate change and the enduring secondary effects of the COVID-19 pandemic continue to affect malnutrition, birthweights and caring practices like exclusive breastfeeding.").

[318] Food and Agriculture Organization (2023) ACHIEVING SDG 2 WITHOUT BREACHING THE 1.5C THRESHOLD, 9 ("Methane emissions from the livestock sector have been reduced by 25 percent compared to 2020.").

[319] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: *2030 BASELINE REPORT SUMMARY FOR POLICYMAKERS*, 11 ("Using the results from the 2021 Global Methane Assessment, we calculate that Global Methane Pledge would provide additional benefits worldwide through 2050, beyond keeping the planet cool, including: - Prevention of roughly 200,000 premature deaths per year due to ozone exposure - Avoidance of ~580 million tonnes of yield losses to wheat, maize (corn), rice and soybeans per year - Avoidance of ~$500 billion (2018 US$) per year in losses per year due to non-mortality health impacts, forestry and agriculture - Avoidance of ~1,600 billion lost work hours per year due to heat exposure.").

[320] United Nations, *Population* (*last visited* 25 October 2023) ("The world's population is more than three times larger than it was in the mid-twentieth century. The global human population reached 8.0 billion in mid-November 2022 from an estimated 2.5 billion people in 1950, adding 1 billion people since 2010 and 2 billion since 1998. The world's population is expected to increase by nearly 2 billion persons in the next 30 years, from the current 8 billion to 9.7 billion in 2050 and could peak at nearly 10.4 billion in the mid-2080s.").

[321] Van Dijk M., Morley T., Rau M. L., & Saghai Y. (2021) *A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050*, NAT. FOOD 2(7): 494–501, 498 ("Our findings indicate that, under NOCC, per capita and total food demand are expected to change by +0% to +20% and +35% to +56% between 2010 and 2050, respectively, while population at risk of hunger is projected to change by −91% to +8%. Projections that account for climate change show a somewhat wider range of outcomes (−1% to +20% for per capita food demand, +30% to +62% for total food demand and −91% to +30% for population at risk of hunger).").

[322] Li Y., Zhong H., Shan Y., Hang Y., Wang D., Zhou Y., & Hubacek K. (2023) *Changes in global food consumption increase GHG emissions despite efficiency gains along global supply chains*, NAT. FOOD 4(6): 483–95, 483 ("In 2019, emissions throughout global food supply chains reached 30 ±9% of anthropogenic GHG emissions, largely triggered by beef and dairy consumption in rapidly developing countries—while per capita emissions in developed countries with a high percentage of animal-based food declined. Emissions outsourced through international food trade dominated by beef and oil crops increased by ~1 Gt CO_2 equivalent, mainly driven by increased imports by developing countries. Population growth and per capita demand increase were key drivers to the global emissions increase (+30% and +19%, respectively) while decreasing emissions intensity from land-use activities was the major factor to offset emissions growth (−39%).").

[323] Clark M. A., Domingo N. G. G., Colgan K., Thakrar S. K., Tilman D., Lynch J., Azevedo I. L., & Hill J. D. (2020) *Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets*, SCIENCE 370(6517): 705–708, 705 ("Our analysis suggests that reducing GHG emissions from the global food system will likely be essential to meeting the 1.5° or 2°C target. Our estimate of cumulative business-as-usual food system emissions from 2020 to 2100 is 1356 Gt CO_2-we (Fig. 1). As such, even if all non–food system GHG emissions were immediately stopped and were net zero from 2020 to 2100, emissions from the food system alone would likely exceed the 1.5°C emissions limit between 2051 and 2063 (date range reflects uncertainties in the 1.5°C emissions limit; see supplementary materials)."), 706 ("We show that meeting the 1.5° and 2°C targets will likely require extensive and unprecedented changes to the global food system. … The need for rapid reduction in GHG emissions from fossil fuels to meet the 1.5° or 2°C targets is widely acknowledged. We show that the same is true for food systems: Even if fossil fuel emissions were rapidly reduced, emissions from the global food system are on a trajectory that would prevent achievement of the 1.5° and 2°C targets before the end of the century. Our analyses also suggest there are many opportunities to meet the 1.5° or 2°C emission targets.").

[324] Clark M. A., Domingo N. G. G., Colgan K., Thakrar S. K., Tilman D., Lynch J., Azevedo I. L., & Hill J. D. (2020) *Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets*, SCIENCE 370(6517): 705–708, 707 (*See* Fig.2A for modeled food emission mitigation pathways that avoid crossing 1.5°C by 2050). Soil carbon sequestration strategies may additionally support temperature goals in avoiding 2 °C by 2050, *see* United Nations Environment Programme (2022) EMISSIONS GAP REPORT 2022: *THE CLOSING WINDOW — CLIMATE CRISIS CALLS FOR RAPID TRANSFORMATION OF SOCIETIES*, xxv (Figure ES.5 Food systems emissions trajectory and mitigation potentials by transformation domain); *discussed in* Harvey F. (4 July 2023) *Improving soil could keep world within 1.5C heating target, research suggests*, THE GUARDIAN.

[325] Zhu J., Luo Z., Sun T., Li W., Zhou W., Wang X., Fei X., Tong H., & Yin K. (2023) *Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems*, NAT. FOOD 4(3): 1–13, 2 ("The global food system generated 18.6 ± 12.6 (1σ) Gt of CO_2 equivalent (GtCO2e) GHGs in 2017 (Fig. 1) in four food categories (cereals, pulses and others; roots and oil crops; vegetables and fruit; and meat and animal products). Among these, meat and animal products led the GHG emissions (11.53 ± 8.12 $GtCO_2e$), followed by cereals, pulses and others (5.76 ± 3.49 $GtCO_2e$).").

[326] Ivanovich C. C., Sun T., Gordon D. R., & Ocko I. B. (2023) *Future warming from global food consumption*, NAT. CLIM. CHANGE 13(3): 297–302, 298–299 ("We found that the consumption of dairy and meat is responsible for more than half of the warming by the year 2030 and through to the year 2100 (Fig. 3).").

[327] Poore J. & Nemecek T. (2018) *Reducing food's environmental impacts through producers and consumers*, SCIENCE 360(6392): 987–992, 988 (*See* Fig. 1 for breakdown of emissions by product compared to land use.).

[328] Bonilla-Cedrez C., Steward P., Rosenstock T. S., Thornton P., Arango J., Kropff M., & Ramirez-Villegas J. (2023) *Priority areas for investment in more sustainable and climate-resilient livestock systems*, NAT. SUSTAIN. 6(10): 1279–1289, 1282–1283 ("From a global perspective, the weighting of adaptation and mitigation indicators highlights the geographies with the greatest problems, providing a regional focus. At local scales, however, these indicators emerge

from farmers' decisions on system management and, as such, are interconnected; any choice of adaptive or mitigating priorities needs understanding of the trade-offs that impact other goals. Adopting a livestock practice or technology nearly always involves trade-offs between adaptation and mitigation outcomes[19]. Thus, to avoid unintended consequences, actions need to be aligned with local demands and goals. The consideration that adaptation and mitigation need to be addressed jointly is especially important in areas where population growth and/or dietary change are most prominent[20]. Yet, a lack of alignment at the policy level potentially hinders this objective. Roughly 50% of the NDCs that mention livestock note just one of the priorities[21], and only 28 out of 184 countries' NDCs include soil-related targets[22]. This omittance suggests that, as a global community, we are creating institutions and narratives that disincentivize or preclude action on adaptation, mitigation or both.").

[329] Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, NAT. CLIM. CHANGE 6(5): 452–461, 453 ("We estimate that total emissions from livestock from 1995 to 2005 were between 5.6 and 7.5 $GtCO_2e\ yr^{-1}$ (Table 1). The most important sources of emissions were enteric CH_4 (E_{CH4}; 1.6–2.7 $GtCO_2e\ yr^{-1}$; refs 9–13,15), N_2O emissions associated with feed production (1.3–2.0 $GtCO_2e\ yr^{-1}$; ref. 15) and land use for animal feed and pastures, including change in land use (~1.6 $GtCO_2e\ yr^{-1}$; ref. 15). …Taking an aggregate view of the sector, and using all LCA sources of emissions, animal feed production accounts for about 45% of the sector's emissions, with about half of these emissions related to fertilization of feed crops and pastures (manure and fertilizer included)[15]. The remaining animal feed emissions are shared between energy use and land use. Enteric fermentation contributes about 40% of total emissions, followed by manure storage and processing (~10% of emissions)[17,18].").

[330] Lazenby R. (2022) *Rethinking manure biogas: Policy considerations to promote equity and protect the climate and environment*, Vermont Law and Center for Agriculture and Food Systems, 24–25 ("Because manure biogas systems capture rather than reduce emissions, these systems require the ongoing generation of GHG emissions to be financially viable. The digester's function is to capture the emissions, so the system breaks down if emissions are reduced at the source. Producers must continue to generate manure at scale for the facilities to remain financially sustainable. The large upfront investment in these systems then fixes the current numbers and concentration of livestock at facilities where they are installed, despite the range of harms generated by such concentrated operations. Simultaneously, the new subsidized revenue streams support the ongoing generation of manure at scale.").

[331] United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010, 56 ("Many of the currently available enteric fermentation abatement options work indirectly by increasing animal growth rates and reducing time to finish (or increasing milk production for dairy cows). These abatement measures achieve emission reductions because increased productivity means fewer animals are required to produce the same amount of meat or milk. Furthermore, several of the abatement measures are inexpensive to implement and are cost-effective at reducing emissions."). *See also* Herrero M., Henderson B., Havlik P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garbett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, NAT. CLIM. CHANGE 6(5): 452–461, 455 ("*Animal productivity and health.* Improving the genetic potential of animals for production, their reproductive performance, health and liveweight gain rates are among the most effective approaches for reducing GHG emissions per unit of product[32,58]. In subsistence agricultural systems, reduction of herd size by increased reproduction rates increases feed availability as well as the productivity of individual animals and the total herd, thus lowering E_{CH4} and overall GHG emissions per unit of product.").

[332] Bonilla-Cedrez C., Steward P., Rosenstock T. S., Thornton P., Arango J., Kropff M., & Ramirez-Villegas J. (2023) *Priority areas for investment in more sustainable and climate-resilient livestock systems*, NAT. SUSTAIN., 1279–1289, 1283 ("Adopting a livestock practice or technology nearly always involves trade-offs between adaptation and mitigation outcomes[19]. Thus, to avoid unintended consequences, actions need to be aligned with local demands and goals.").

[333] Balehegn M. (2021) *Livestock sustainability research in Africa with a focus on the environment*, ANIM. FRONT. 11(4): 47–56, 54 ("In Africa, sustainable livestock production must address food security and climate change concerns simultaneously in addition to social and economic aspects. The need for and principles of sustainable livestock production apply universally. Although many high-income countries focus on the environmental impacts of livestock production, low-income countries are concerned with increasing livestock productivity to improve income and food supply and reduce high rates of childhood undernutrition and stunting (Tricarico et al., 2020).").

[334] Balehegn M. (2021) *Livestock sustainability research in Africa with a focus on the environment*, ANIM. FRONT. 11(4): 47–56, 48 ("Such interventions include improving feed quality by upgrading crop residues, concentrate supplementation, that effectively reduce enteric CH_4 production and emission intensity while improving feed conversion efficiency and miscellaneous sustainable livestock intensification strategies that improve productivity while minimizing the negative environmental impact of livestock. Such strategies include manure management, animal breeding, grazing practices, and sustainable forage production or pastureland management practices such as intercropping, silvopastoral practices, etc. Perhaps more than the need for new research is that for awareness creation about best bet technologies and approaches for improving livestock production and sustainability and for sustained extension support to enhance the adoption and use of available technologies and approaches. Given that African countries are already critically affected by climate change as manifested by extreme weather variability and recurrent drought, strategies that provide synergetic opportunities for climate adaptation and mitigation are needed for resource-limited smallholder farmers. Implementation of successful adaptation and mitigation schemes, however, is costly to smallholder farmers, and therefore policy support towards providing financial and technical incentives is required."). *See also* Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 7 ("Better feed quality primarily means more digestible feed – feed ruminants can more thoroughly digest and use for energy – and feed with balanced nutrients, including sufficient protein. Although ruminants can break down the cellulosic material that makes up much of the hard cell walls of grasses, leaves and other forages, some fibrous material is easier to digest than other material. As a result, more digestible feeds provide more energy for cattle and less that is lost to methane, other gases, or manure. Because cattle also cannot digest lignin, which increases with the age of the grass, consuming fresher grasses and reducing reliance on most crop residues also helps to reduce methane and improve growth.").

[335] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 7–8 ("As importantly, the quantity of feed that ruminants can eat is limited by the speed with which the material is digested. Because cattle cannot digest lignin at all, and digest carbohydrates more rapidly than cellulose, they can eat more overall feed when it is more digestible. That has an important effect because the first use of feed by an animal is to support its own maintenance: the energy an animal needs to live. It is the surplus of energy in feed over maintenance requirements that can contribute to milk production, or to weight gain, which means the addition of meat. Although cattle need a balance of different types of feed, in general, cattle fed more digestible feeds can eat more, produce more milk and grow faster than cattle fed less digestible feeds. Although they produce more methane per animal, the methane per kilogram of milk or meat decreases.").

[336] Bengston O., Feng S., Ganesan V., Katz. J., Kitchel H., Mannion P., Prabhala P., Richter A., Roen W., & Vleck J. (2023) THE AGRICULTURAL TRANSITION: *BUILDING A SUSTAINABLE FUTURE*, McKinsey & Company, 49 (*See* (19) Heat stress management).

[337] Fox N. J., *et al*. (2018) *Ubiquitous parasites drive a 33% increase in methane yield from livestock*, INT. J. PARISITOL. 48(13): 1017–1021, 1017 ("This is to our knowledge the first study that empirically demonstrates disease-driven increases in methane (CH_4) yield in livestock (grams of CH_4 per kg of dry matter intake). We do this by measuring methane emissions (in respiration chambers), dry matter intake, and production parameters for parasitized and parasite-free lambs. This study shows that parasite infections in lambs can lead to a 33% increase in methane yield (g CH_4/kg DMI).").

[338] von Soosten D., Meyer U., Flachowsky G., & Dänicke S. (2020) *Dairy Cow Health and Greenhouse Gas Emission Intensity*, DAIRY: 20–29, 26 ("In the case of illness in a dairy cow (clinical or subclinical), feed intake and milk yield are usually reduced. For this reason, GHG emissions then increase per kilogram of product. An extended productive life is desirable to achieve a reduction in emission intensity. It remains difficult to consider animal losses in terms of GHG emissions. Apart from the dead animal, we also have to consider the GHG emissions for the production of feed the dead animal had consumed during its life. More data that consider animal health up to animal losses seem to be necessary for a better quantification of GHG emission intensity."). *See also* Özkan Gülzari Ş., Vosough Ahmadi B., Stott A. W. (2018) *Impact of subclinical mastitis on greenhouse gas emissions intensity and profitability of dairy cows in Norway*, PREV. VET. MED. 150: 19–29, 28 ("We concluded that there is a potential to reduce the total farm emissions intensity by 3.7% if the milk production was improved through reducing the level of [somatic cell count] SCC to 50,000 cells/mL in relation to SCC level 800,000 cells/mL. We, however, acknowledge that this may be an underestimation as [subclinical mastitis] SCM is usually accompanied by other diseases. Based on the presented results, it is concluded that preventing and/or controlling SCM consequently reduces the GHG emissions per unit of production on farm, which results in improved profits for the farmers through reductions in milk losses, optimum culling rate and reduced feed and other variable costs.").

[339] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 9 ("High quality feed and care can also make it possible to use breeds, particularly European breeds, that are more efficient at converting feed and produce more milk per animal and higher daily weight gains. The use of these breeds can be inefficient in warmer countries where these breeds can suffer from heat stress and are less resistant to local diseases or ticks. These breeds are also less efficient where feed has poor quality. Improvements in feed and health care, however, can often allow greater use of western breeds or, quite commonly, productive crossbreeds of western breeds and indigenous cattle breeds."). *See also* O'Brien A. (17 June 2023) *New breeding values for sheep aim to reduce emissions*, AGRILAND ("The initiative is part of the €3 million research project 'GREENBREED', funded by the DAFM. The key research findings were: - Large differences in daily methane emissions were found between ewes, with 17% of these differences being traced to genetics; - The genetically identified highest 20% of emitting animals are expected to emit 15% more methane per day compared to the lowest 20% emitting animals.").

[340] Palangi V., Taghizadeh A., Abachi S., & Lackner M. (2022) *Strategies to Mitigate Enteric Methane Emissions in Ruminants: A Review,* SUSTAINABILITY 14(20): 1–15, 6 ("Singh and Sharma [46] recorded higher body weight gain in concentrate-fed goat kids. Accordingly, animals were fed concentrate at the early growth stage, followed by green fodder after weaning.").

[341] Kauffman J. B., Beschta R. L., Lacy P. M., & Liverman M. (2022) *Livestock Use on Public Lands in the Western USA Exacerbates Climate Change: Implications for Climate Change Mitigation and Adaptation*, ENVIRON. MANAG. 69(6): 1137–1152, 1137 ("About 85% of public lands in the western USA are grazed by domestic livestock, and they influence climate change in three profound ways: (1) they are significant sources of greenhouse gases through enteric fermentation and manure deposition; (2) they defoliate native plants, trample vegetation and soils, and accelerate the spread of exotic species resulting in a shift in landscape function from carbon sinks to sources of greenhouse gases; and (3) they exacerbate the effects of climate change on ecosystems by creating warmer and drier conditions. On public lands one cow-calf pair grazing for one month (an "animal unit month" or "AUM") produces 875 kg CO_2e through enteric fermentation and manure deposition with a social carbon cost of nearly $36 per AUM. Over 14 million AUMs of cattle graze public lands of the western USA each year resulting in greenhouse gas emissions of 12.4 Tg CO_2e year^{-1}. The social costs of carbon are > $500 million year^{-1} or approximately 26 times greater than annual grazing fees collected by managing federal agencies. These emissions and social costs do not include the likely greater ecosystems costs from grazing impacts and associated livestock management activities that reduce biodiversity, carbon stocks and rates of carbon sequestration.").

[342] Castonguay A. C., Polasky S., Holden M. H., Herrero M., Mason-D'Croz D., Godde C., Chang J., Gerber J., Bradd Witt G., Game E. T., Bryan B. A., Wintle B., Lee K., Bal P., & McDonald-Madden E. (2023) *Navigating sustainability trade-offs in global beef production,* NAT. SUSTAIN. 6: 284–306, 284 ("Here we optimize global beef production at fine spatial resolution and identify trade-offs between economic and environmental objectives interpretable to global sustainability ambitions. We reveal that shifting production areas, compositions of current feeds and informed land restoration enable large emissions reductions of 34–85% annually (612–1,506 $MtCO_2e\ yr^{-1}$) without increasing costs. Even further reductions are possible but come at a trade-off with costs of production.").

[343] Herrero M., Henderson B., Havlík P., Thornton P. K., Conant R. T., Smith P., Wirsenius S., Hristov A. N., Gerber P., Gill M., Butterbach-Bahl K., Valin H., Garnett T., & Stehfest E. (2016) *Greenhouse gas mitigation potentials in the livestock sector*, NAT. CLIM. CHANGE 6(5): 452–461, 455 ("Improving the genetic potential of animals for production, their reproductive performance, health and liveweight gain rates are among the most effective approaches for reducing GHG emissions per unit of product32,58. In subsistence agricultural systems, reduction of herd size by increased reproduction rates increases feed availability as well as the productivity of individual animals and the total herd, thus lowering ECH4 and overall GHG emissions per unit of product. Reducing the age at slaughter by increasing liveweight gain rates significantly decreases GHG emissions per unit of product in beef and other meat production systems. Improved animal health and reduced mortality and morbidity can increase herd productivity and reduce emissions intensity in all livestock systems.").

[344] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: *A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT*, 13 ("Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure, utilizing pasture-based systems, or installing anaerobic digesters significantly reduces methane from manure management on dairy, swine, and other livestock operations. These practices may reduce methane from manure management by as much as 70 percent in U.S. Climate Alliance states (Appendix A) and can help improve soil quality and fertility, reduce water use and increase water quality, reduce odors, and decrease the need for synthetic fertilizers and associated greenhouse gas emissions. Promising technologies are also emerging that may cut methane emissions from enteric fermentation by 30 percent or more (se A). Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits."). *See also* Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 13–14 ("The technical abatement potential for agricultural sources is assessed at 21 percent below baseline emissions in year 2050. This includes relatively limited abatement potentials for livestock of 12 percent due to applicability limitations (see section S3.4. in the SI for details). Large farms with more than 100 LSU contribute about a third of global CH_4 emissions from livestock and for this group we find it technically feasible to reduce emissions by just over 30 percent below baseline emissions in year 2050 (see figures S6–2 in the SI). The available options include reduction of enteric fermentation emissions through animal feed changes (Gerberetal 2013, Hristov et al 2013) combined with implementation of breeding schemes that simultaneously target genetic traits for improved productivity and enhanced animal health/longevity and fertility. Increased productivity reduces system emissions by enabling the production of the same amount of milk using fewer animals. The dual objective in breeding schemes is important as a one-eyed focus on increased productivity leads to deteriorating animal health and fertility and a risk that system emissions increase due to a need to keep a larger fraction of unproductive replacement animals in the stock (Lovett et al 2006, Berglund 2008, Bell et al 2011). The enteric fermentation options are considered economically feasible for commercial/industrial farms with more than 100 LSU but not for smaller- and medium- sized farms. Breeding schemes are assumed to deliver impacts on emissions only after 20 years and feed changes are assumed applicable only while animals are housed indoor. Emissions from manure management can be reduced through treatment of manure in anaerobic digesters (Ads) with biogas recovery. To be efficient from both an economic and environmental point of view, a certain scale is needed to accommodate both the fixed investment of the AD plant and the time farmers spend carefully attending to and maintaining the process (for details see section 3.3.1.3 in Höglund-Isaksson et al 2018).").

[345] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 138 ("Feeding insect protein to animals has the potential to reduce overall global emissions from feed production (in comparison to conventional protein production e.g. soya grown overseas) and support a circular economy (e.g. if insects are raised on waste). There is ongoing research to determine the potential of these measures and the sector is at an early stage of development. This measure is unlikely to have significant UK GHG or land use impacts. It could, however, reduce supply chain emissions from feed supply occurring outside the scope of UK carbon budgets.").

[346] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 13 ("Despite these very promising signs, important issues remain to be resolved. Although studies have promising results so far, the world is unlikely to undertake a massive investment to incorporate these feed additives globally on the basis of a limited number of studies that have lasted each for only a few months for 3-NOP and three studies with live animals for algae. We believe a few steps are critical to widespread adoption although they could be undertaken with enough commitment in the next three years. … The first need is for studies that last at least two years for each of these products. Studies to date have at most lasted four months. . . Longer-term studies also provide the opportunity to evaluate effects on yields and feed conversion efficiency…safety tests…costs of production….").

[347] For example, in Europe, South America and California. *See* European Commission (23 February 2022) *Daily News 23/02/2022*, Press Release ("Today, Member States have approved the marketing in the EU of an innovative feed additive, as proposed by the Commission. The additive, consisting of 3-nitrooxypropanol, will help to reduce the emission of methane, a potent greenhouse gas, from cows. Commissioner for Health and Food Safety, Stella Kyriakides, said: "Innovation is key for a successful shift towards a more sustainable food system. The EU continues to lead the way in ensuring food safety while adapting to new technologies that can make food production more sustainable. Cutting farming-related methane emissions is key in our fight against climate change and today's approval is a very telling example of what we can achieve through new agricultural innovations." The product went through a stringent scientific assessment by the European Food Safety Authority which concluded that it is efficacious in reducing methane emissions by cows for milk production. Once the decision is adopted by the Commission, expected in the coming months, the feed additive will be the first of its kind available on the EU market."); Martin R. (20 April 2022) *Methane-reducing feed pilot to include 10,000 cows in three European countries*, IRISH EXAMINER ("The cooperative is set to pilot the use of Bovaer® with 10,000 dairy cows across more than 50 farms in Denmark, Sweden and Germany, ensuring a diverse group of farms participate in the pilot programme. . . If preliminary findings are as expected, Arla Foods plans to double the pilot project to include 20,000 cows in 2023. Bovaer® is currently commercially available in the EU, Brazil, Chile, and Australia."); Byrne J. (5 July 2023) *dsm-firmenich: Bovaer has saved 50,000 tons of CO2e to date*, FEED NAVIGATOR ("Authorities recently approved the sale of Bovaer in Paraguay, for use in dairy and beef cattle, making it the seventh country in Latin America to give the feed additives the green light, while Elance Animal Health, dsm-firmenich's strategic partner for developing, manufacturing, and commercializing Bovaer in the US, anticipates US approval and launch of the supplement in the first half of 2024."); de Sousa A. (9 September 2021) *World's Top Beef Supplier Approves Methane-Busting Cow Feed*, BLOOMBERG ("Latin America is the first region to grant approvals for the DSM product, which is also trying to get permission in the European Union, the U.S. and New Zealand. A trial on Brazilian beef showed Bovaer cut methane emissions from cows' stomachs by as much as 55%, the company said. Bovaer has undergone trials in 13 countries, with more than 48 peer-reviewed studies published."); *and* Duggan T. (6 May 2022) *To fight climate change, California approves seaweed that cuts methane emissions in cow burps*, SAN FRANCISCO CHRONICLE ("On Friday, Blue Ocean Barns, which produces the red seaweed at a farm on the Big Island of Hawaii, announced that the supplement had been approved for use on both conventional and organic dairy farms. Called Brominata, the red seaweed variety has been shown to cut methane emissions in dairy cows by 52% over 50 days but so far has been used only in trials."). For hurdles, *see generally* Steele M. (22 June 2023) *Methane-reducing supplement for cows still trapped in regulatory limbo*, RADIO NEW ZEALAND.

[348] McCullogh C. (1 July 2022) *Beef produced with 90% methane reducing feed hits shelves*, ALL ABOUT FEED ("The more environmentally friendly beef is available from June 30 in selected Coop supermarkets in Sweden. It is claimed 5% of the world's greenhouse gas emissions come from methane produced by cows' burps and farts."). *See also* Peters A. (30 June 2022) *The world's first 'methane-reduced' beef is now at grocery stores*, FAST COMPANY ("At the Swedish grocery chain, Coop, there's now a new product that isn't available anywhere else in the world: "low methane" beef. Selected stores are selling a limited-edition run of ground beef, sirloin steak, and beef fillets from cattle that have been fed red seaweed—a supplement that cuts emissions of methane, a potent greenhouse gas that cows and steers emit when they burp and fart.").

[349] Global Methane Hub (2 December 2023) *Enteric Fermentation Research & Development Accelerator, a $200M Agricultural Methane Mitigation Funding Initiative* ("The Enteric Fermentation R&D Accelerator, or Accelerator, is the largest-ever, globally coordinated investment of breakthrough research tackling livestock methane emissions. The Global Methane Hub announced the intention to establish the Accelerator at COP27 as an AIM for Climate Innovation Sprint. The Accelerator will unite funders, guided by a science oversight committee, to invest in a globally coordinated research plan. This strategy aims to address gaps in current research and enhance existing efforts. The strategy includes work on exploring new and alternate livestock feed additives, tools to breed low-methane livestock, immunological studies for a methane vaccine, understanding the organisms in the rumen and their functions, and lowering the costs of measurement, essential to generate evidence for regulatory approval and validation of mitigation technologies.").

[350] Kebreab E. & Feng X. (2021) *Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources*, California Air Resources Board, 69 ("In general, higher moisture contents in raw composting manure could enhance the CH_4 mitigation rates, however, the pH, and C/N content were not linearly related to CH_4 mitigation. Adding biochar, acids, and straw to manure could mitigate CH_4 emissions by 82.4%, 78.1%, and 47.7%, respectively. However, the data for straw is quite small so it should not be taken out of context as it may introduce a source of carbon into lagoons. The meta-analysis conducted with selected additives indicated manure additives were an effective method to reduce CH_4 emission, with biochar being the most effective. However, further studies of manure additives on CH_4 mitigation are required to support a more accurate quantitative analysis and potential impacts to water quality and crop yield after land application. Most of the research for biochar and straw is when used as additive to solid or semi solid manure so they should be interpreted in that context.").

[351] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 26 ("Another emerging option involves adding acid to manure stored in wet form, which can almost eliminate methane emissions. Some experiments with acidification have occurred for many years (Fangueiro, Hjorth, and Gioelli 2015) (Søren O. Petersen, Andersen, and Eriksen 2012), but experimental work has been increasing (Rodhe et al. 2019). Acidification can be done at different stages of manure management: in the barn, in storage tanks, prior to field application. Methane reductions require a regular, but modest, insertion of acid into storage tanks. Acidifying manure also reduces ammonia losses when methane is applied, and in some experiments increases yields (Loide 2019). Yield gains probably occur if farmers either do not apply or are not allowed to apply more nitrogen fertilizer to replace the nitrogen lost with the releases of ammonia. The amount of acid required for sufficient acidification to greatly reduce methane is still unclear."); ("There are also a variety of promising innovative methods to reduce methane. There is experimental evidence, for example, that some additives, such as sulfate, can be added in modest quantities and still reduce two-thirds of the methane emissions from storage even without significantly reducing pH (Petersen, Andersen & Eriksen 2012) (Petersen et al. 2014) (Sokolov et al. 2020).").

[352] Kebreab E. & Feng X. (2021) *Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources*, California Air Resources Board, 7 ("Effect size and meta-analyses were conducted to identify the additives with greatest potential for CH4 mitigation. For feed additives, 3-nitrooxypropanol (3NOP), bromochloromethane, chestnut, coconut, distillers dried grains and solubles, eugenol, grape pomace, linseed, monensin, nitrate, nitroethane, saifoin, fumaric acid, and tannins had significant impacts on enteric emissions. For manure additives, acidification, biochar, microbial digestion, physical agents, straw, and other chemicals significantly reduced CH4 emissions.").

[353] Chiodini M. E., Costantini M., Zoli M., Bacenetti J., Aspesi D., Poggianella L., & Acutis M. (2023) *Real-Scale Study on Methane and Carbon Dioxide Emission Reduction from Dairy Liquid Manure with the Commercial Additive SOP LAGOON*, SUSTAINABILITY 15(3): 1–13, 1 ("After 3 and 4 months from the first additive applications, the SL storage tank showed lower and statistically significantly different emissions concerning the UNT (up to −80% for CH_4 and −75% for CO_2, $p < 0.001$), confirming and showing improved results from those reported in the previous small-scale works. The pH of the UNT tank was lower than that of the SL on two dates, while the other chemical characteristics of the slurry were not affected."). *See also* Peterson C., El Mashad H. M., Zhao Y., Pan Y., & Mitloehner F. M. (2020) *Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure*, SUSTAINABILITY 12(4): 1–17, 1 ("A variety of additives have been applied to reduce emissions from manure. Although the composition and mechanism of the emission reduction of several additives are known, information on many other commercial additives is not available because of confidentiality and limits in the marketing literature. Calcium sulfate (gypsum) can be found abundantly in nature and has been used to improve soil properties. … Different forms of gypsum have been tested for the mitigation of GHG and ammonia emissions from livestock effluents. The results have had varying results: while some studies reported a decrease in ammonia emissions after the addition of gypsum, not all have demonstrated the efficacy of gypsum in reducing the release of GHGs. Many of the results were obtained using a considerable amount of material (3% to 10% of manure wet weight) making the application not practical in real-world conditions. Borgonovo et al. first published results on this specific commercial additive (SOP LAGOON), made of gypsum processed with proprietary technology, and found that the addition of the products to fresh liquid manure has a reduction potential of 21.5% of CH_4, 22.9% of CO_2, 100% of N_2O and 100% of NH_3 emissions on day 4, even at very low dosages. It should be mentioned that similar to other commercial additives, the exact manufacturing process of SOP Lagoon is unknown due to confidentiality."); *and* Borgonovo F., Conti C., Lovarelli D., Ferrante V., & Guarino M. (2019) *Improving the sustainability of dairy slurry with a commercial additive treatment*, SUSTAINABILITY 11(18): 1–14, 8 ("N_2O, CO_2, and CH_4 emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded.").

[354] Babiker M., Berndes G., Blok K., Cohen B., Cowie A., Geden O., Ginzburg V., Leip A., Smith P., Sugiyama M., & Yamba F. (2022) *Chapter 12: Cross Sectoral Perspectives* *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 12-102 ("Anaerobic digestion of organic wastes (e.g., food waste, manure) produces a nutrient-rich digestate and biogas that can be utilised for heating and cooking or upgraded for use in electricity generation, industrial processes, or as transportation fuel (See Chapter 6) (Parsaee et al. 2019; Hamelin et al. 2021).").

[355] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 25 ("Several alternative manure management options exist. One starts with more quickly removing manure from barns because barn temperatures tend to be high, and higher temperatures increase methane formation (Montes et al. 2013). Barn storage can lead to high methane losses even in a few days, particularly in pig barns where temperatures are often higher than outside (Petersen et al. 2016). In many systems, it is common for manure to remain in pig or dairy barns for a few weeks – and some for much longer -- but it is possible to construct systems and sometimes to operate existing barns to remove manure each day. One analysis of different studies found average reduction rates for methane at the level of 50%, although that will obviously depend on climate and alternative management systems (Mohankumar, et al. 2018). A second set of options focuses on separating the solid portion of manure from the liquid portion. Even without adding water for barn cleaning, manure in pork and cattle systems tends to be wet enough to create the oxygen-less conditions that create methane. A variety of techniques with increasing sophistication can separate solids from liquids."). *See also* Cameron K. C. & Di H. J. (2019) *A new method to treat farm dairy effluent to produce clarified water for recycling and to reduce environmental risks from the land application of effluent*, J. SOILS SEDIMENTS 19(5): 2290–2302, 2291 ("The basis of the new method for treating FDE is to use a coagulant to coagulate and flocculate colloidal particles in the FDE into flocs that have sufficient mass for gravity to cause them

to settle out of the liquid, thus producing: (i) clarified water and (ii) treated effluent. Coagulation involves the addition of a coagulant to neutralize the negative electrical charges on the surfaces of colloids (e.g. soil, dung, organic matter) that would normally prevent them from coagulating into flocs that have sufficient mass to settle out of the water under gravity. In addition, during mixing of the coagulant into the effluent, the coagulant can create a mechanism called 'sweep floc' which also causes the colloids to stick together producing flocs."); *discussed in* Mulhollem J. (11 July 2022) *Researcher gets grant to study biofilters to reduce livestock facility methane*, THE PENNSYLVANIA STATE UNIVERSITY.

[356] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, White Paper, 24 ("Much of the focus on manure management has been to encourage the use of digesters. Digesters turn even more of the [manure] into methane into biogas, but in a way that can be captured and burned for energy. Millions of small, low-technology digesters are in use in Asia for household energy use, and larger, modern digesters have also received significant investments in Western countries. For farms that now produce large quantities of methane – for example, that use large lagoons to store manure in warm parts of the world – digesters can be a cost-effective mechanism for reducing methane as well as overall greenhouse gas emissions (Searchinger et al. 2019). In other contexts, however, the climate benefits for methane are uncertain and probably unable to justify the expense. The purpose of a digester is to turn as much of the biomass in manure into methane as possible. As a result, digesters create more methane than normal storage systems. Although the intent is to capture and burn this methane for energy, if the digester has significant leakage rates the amount of methane released can exceed the methane released by present management, depending on the system in use. That seems particularly likely in informal, household systems studied so far (Bruun et al. 2014), although the leakage rates around the world have been little studied.").

[357] Lazenby R. (2022) *Rethinking manure biogas: Policy considerations to promote equity and protect the climate and environment*, Vermont Law and Center for Agriculture and Food Systems, 28 ("The massive quantities of manure produced at industrial scale livestock facilities can and do cause serious environmental, quality of life, and public health harms to neighboring communities. These harms do not cease to exist upon the addition of an anaerobic digester. In fact, while proponents of biogas systems sometimes argue that capping lagoons can address these issues, impacted environmental justice communities around the country have organized against the proliferation of biogas because it is viewed as maintaining and supporting a harmful system.[104]"); *citing* Gittelson P., Diamond D., Henning L., Payan M., Utesch L., & Utesch N. (2021) *The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue*, ENVIRONMENTAL JUSTICE. *See also* Hindenanch J. (27 October 2021) *Climate credits for factory farm gas violate civil rights, fail to achieve climate benefits, states petition submitted to CARB*, Leadership Counsel for Justice & Accountability ("The petition calls on [California Air Resources Board (CARB)] to exclude polluting factory farm-derived methane from the [Low Carbon Fuel Standard (LCFS)] or amend the credit system to better account for the actual climate impact of using factory farm-generated methane as a transportation fuel and exclude those projects that entrench and exacerbate local air and water pollution. As currently formulated, the credit system overstates the emission reduction benefits of factory farm gas by failing to account for the fuel's life-cycle emissions — from crop production, intestinal emissions and animal feed to the disposal of manure and pipeline leaks. In the petition, groups also emphasize that factory farms have been able to exploit the credit systems to "double dip" — using public dollars to subsidize the construction of dairy digesters, while also receiving millions for the credits sold through the LCFS."); Oglesby C. (28 March 2022) *'This plan is a lie': Biogas on hog farms could do more harm than good*, ENERGY NEWS NETWORK ("White-Williamson has been fighting the hog industry's waste management practices in Sampson County for decades. A year ago, she launched the Environmental Justice Community Action Network, a network of residents and organizations that educate and organize around hog farming and other local environmental hazards. She said widespread adoption of biogas systems will further cement the hog industry's poor waste management practices in low-income communities of color. Others say it could actually increase water pollution in certain areas. Small-scale farmers are concerned that this newest strategy allows an industry where they see little of the profit to make more money, without actually alleviating their waste problems."); *and* Sainato M. (4 February 2022) *California subsidies for dairy cows' biogas are lose-lose, campaigners say*, THE GUARDIAN ("But environmental advocates argue that the environmental benefits of biogas are exaggerated, and that the LCFS encourages the expansion of factory farms and

could end up increasing emissions and pollution. In a petition to the California Air Resources Board (Carb), the state government's clean air agency that runs the LCFS, six environmental groups called for dairy farms to be excluded from the policy. In January, Carb turned down the request but said it would continue to engage with the petitioners.").

[358] Merrigan K., Giraud E. G., Scialabba N. E., Brook L., Johnson A., & Aird S. (2022) GROW ORGANIC: *THE CLIMATE, HEALTH, AND ECONOMIC CASE FOR EXPANDING ORGANIC AGRICULTURE*, Swette Center for Sustainable Food Systems at Arizona State University, Natural Resource Defense Council, & Californians for Pesticide Reform, 9 ("The CAFO system produces excessively high levels of methane and other emissions. In conventional livestock production, animals live in CAFOs for a significant portion of their lives, subsisting primarily on conventionally grown corn and soy-based feed that brings them to market weight quickly.[114] This feed is produced with large amounts of synthetic fertilizers and pesticides that, as noted above, are GHG intensive.[115] CAFOs also pack together thousands of animals, which leads to vast amounts of waste. This waste is often stored in liquid-based systems, including manure lagoons that can be as large as several football fields.[116] In these liquid systems, the absence of oxygen leads manure to break down into methane. Due to a broad shift to the industrial CAFO model, with its waste management issues and reliance on manure lagoons and spray fields, methane emissions from manure increased by nearly 70 percent in the United States in recent decades.[117]"), 20 ("Methane emissions from pastured animals are also significantly lower due to dry manure management and the communities of microbial decomposers found on well- managed pastures.[122] For example, holistic or rotational grazing, where animals move to different sections of pasture on a regular basis to allow grazed areas to recover and grow, may help reduce methane and other emissions and offer soil carbon sequestration benefits. This type of grazing disperses manure throughout the landscape in balance with the needs of the ecosystem, instead of concentrating it in a massive lagoon or spray field. Using grazing best practices can reduce net GHG emissions per pound of meat or milk production.[123]").

[359] Ivanovich C. C., Sun T., Gordon D. R., & Ocko I. B. (2023) *Future warming from global food consumption*, NAT. CLIM. CHANG. 13(3): 297–302, 299 ("We used dietary recommendations provided by the Harvard Medical School, which focus on reduced meat intake, promoting a protein-rich diet with less saturated fat and cholesterol[27]. These recommendations specifically prescribe the sparing consumption of red meat (beef and pork; about one serving per week) and the limited consumption of fish, poultry and eggs (up to two servings each per day)[27]. We found that if these dietary changes were implemented globally, warming due to food consumption could be decreased by 0.19 °C by the end of the century, consistent with previous literature that has highlighted the potential for dietary recommendations to provide environmental as well as health benefits[42,45,48–50]. This amounts to ~21% of the anticipated warming due to sustained dietary consumption rates."). *See also* Laine J. E., *et al.* (2021) *Co-benefits from sustainable dietary shifts for population and environmental health: an assessment from a large European cohort study*, LANCET PLANET. HEALTH 5(11): 786–796, 794 ("Supporting the co-benefits of our findings, we also found that reductions in greenhouse gas emissions and land use could occur with higher adherence to the EAT–*Lancet* reference diet, whereby greenhouse gas emissions could be reduced by 50% and land use levels by 62%. Overall, adhering to the EAT–*Lancet* reference diet seems to be beneficial for reducing all-cause mortality and cancer while mutually reducing greenhouse gas emissions and land use; this is particularly concerning for Europe's local environmental impacts, where agricultural production is among the most intensive in the world.[28]"); *and* Springmann M., Mason-D'Croz D., Robinson S., Wiebe K., Godfray H. C. J., Rayner M., & Scarborough P. (2017) Mitigation potential and global health impacts from emissions pricing of food commodities, NAT. CLIM. CHANGE 7: 69–74, 69 ("Using a coupled agriculture and health modelling framework, we show that the global climate change mitigation potential of emissions pricing of food commodities could be substantial, and that levying greenhouse gas taxes on food commodities could, if appropriately designed, be a health-promoting climate policy in high-income countries, as well as in most low- and middle-income countries.").

[360] Swanson Z. Welsh C., & Majkut J. (2023) MITIGATING RISK AND CAPTURING OPPORTUNITY: *THE FUTURE OF ALTERNATIVE PROTEINS*, Center for Strategic & International Studies, 4 ("In response to these looming challenges, alternative proteins offer the opportunity for food production with fewer GHG emissions and lower environmental impact. While still a relatively young industry, the production of alternative proteins—particularly plant-based products—is already more efficient than traditional animal husbandry, producing fewer GHG emissions and requiring

fewer inputs."). *See also* Bengston O., Feng S., Ganesan V., Katz. J., Kitchel H., Mannion P., Prabhala P., Richter A., Roen W., & Vleck J. (2023) THE AGRICULTURAL TRANSITION: *BUILDING A SUSTAINABLE FUTURE*, McKinsey & Company, 16–17 ("In addition, alternative protein sources have smaller physical footprints and consequently limit future land conversion while creating opportunities for sequestration. For example, one kilogram of beef protein requires an estimated 326 square meters of land versus four for plant-based options, 12 for poultry, and only three for cell-based.[42] Dietary shifts away from animal proteins could save nearly 640 million hectares of land, which could in turn be reforested or provide a locus for other nature-based solutions.[43]"). For a discussion on climate concerns from traditional animal agriculture, *see* Xu X., Sharma P., Shu S., Lin T.-S., Ciais P., Tubiello F. N., Smith P., Campbell N., & Jain A. K. (2021) *Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods*, NAT. FOOD 2(9): 724–732, 724 ("Global GHG emissions from the production of food were found to be 17,318 ± 1,675 $TgCO_2eq\ yr^{-1}$, of which 57% corresponds to the production of animal-based food (including livestock feed), 29% to plant-based foods and 14% to other utilizations. Farmland management and land-use change represented major shares of total emissions (38% and 29%, respectively), whereas rice and beef were the largest contributing plant- and animal-based commodities (12% and 25%, respectively), and South and Southeast Asia and South America were the largest emitters of production-based GHGs.").

[361] Kozicka M., Havlík P., Valin H., Wollenberg E., Deppermann A., Leclère D., Lauri P., Moses R., Boere E., Frank S., Davis C., Park E., & Gurwick N. (2023) *Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives*, NAT. COMMUN. 14: 1–13, 6 ("We show that substituting 50% of [animal source food] ASF with novel alternatives can lead to profound system-wide impacts. Unlike previous studies that assessed dietary changes with novel foods, in this study we considered a more realistic composition of the plant ingredients that would be used to produce novel alternatives and analyzed them in a dynamic systemwide global framework. Instead of growing by 15% in the REF scenario, agriculture and land use emissions decline by 31%. A large part of this decline comes from CH_4 reduction, which could have significant near-term climate mitigation benefits[59]. The result is comparable in relative terms to a previous analysis of replacing 60% of beef consumption in the USA with plant-based alternatives, which found agricultural emissions reduction in the USA by 13.5%[40].").

[362] *See generally* Scarborough P., Clark M., Cobiac L., Papier K., Knuppel A., Lynch J., Harrington R., Key T., & Springmann M. (2023) *Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts*, NAT. FOOD 4(7): 565–74.

[363] Global Methane Hub & Climateworks Foundation (2023) THE GLOBAL INNOVATION NEEDS ASSESSMENTS*: FOOD SYSTEM METHANE, TECHNICAL REPORT*, 19 ("The impacts of diet shifts towards non-ruminant and plant based as well as alternative proteins could abate up to 0.65 $GtCO_2e$ per year by 2030, and even higher benefits between 2030 and 2050 (1.2 $GtCO_2e$).").

[364] As of 2022, plant-based foods accounted for 15% of the dollar share for milk options and 1.4% of total retail food and beverage dollar sales in the United States. *See* Ignaszewski E. & Piece B., *U.S. retail market insights for the plant-based industry*, Good Food Institute (*last visited* 14 February 2024) (*See* Table: Summarizing plant-based food market sales data).

[365] Swanson Z. Welsh C., & Majkut J. (2023) MITIGATING RISK AND CAPTURING OPPORTUNITY: *THE FUTURE OF ALTERNATIVE PROTEINS*, Center for Strategic & International Studies, 3 ("The consumption of these alternative protein products is ultimately driven by consumer preference— preference that is, in large part, determined by taste and price parity. With time, investment, and technological improvements, the parity gaps that currently exist between meat and alternative proteins will continue to diminish. Under specific economic circumstances, price parity has already been achieved. In mid-2022, for example, the Netherlands saw the price of plant-based alternative proteins drop below that of conventional meat, due in part to meat price increases caused by European drought and the Russian war in Ukraine, while the price of plant-based alternative proteins remained relatively unaffected. Shifting attitudes toward climate change and increased market exposure could additionally drive increased acceptance of alternative protein—particularly cultivated meat—in the future. Given existing and projected protein demand, even subtle dietary shifts

toward increased consumption of alternative proteins could have a profound effect on the rate of market growth. This growth will determine the magnitude of the impact that alternative proteins will have on the environment, human health, and the economy.").

[366] Good Food Institute (2022) STATE OF THE INDUSTRY REPORT: *CULTIVATED MEAT AND SEAFOOD*, 91 ("Cultivated meat is on the cusp. Products have the potential to offer consumers the same meat-eating experience as conventional meat, which could present a breakthrough opportunity for mass adoption of alternative proteins. Yet the vast majority of consumers globally have yet to taste cultivated meat. Before taste and price considerations enter the picture, industry participants must make continued investments in R&D, infrastructure buildout, and regulatory processes to ensure consumers are even able to try cultivated meat. Considering the investment and regulatory progress made in 2022, the coming years will prove critical for the development of this market. As more products receive regulatory approval from governments around the world—and companies continue to improve and scale their offerings—the potential of a "meat without the animal" future will draw closer to reality.").

[367] Global Methane Hub & Climateworks Foundation (2023) THE GLOBAL INNOVATION NEEDS ASSESSMENTS*: FOOD SYSTEM METHANE, TECHNICAL REPORT*, 6 ("Innovations could support 118 million jobs, $700 billion in gross value added (GVA) and multiple food security and nature goals. In the near term, job support is dominated by productivity innovations in cold chain technology and waste tracking and analytics, jointly generating roughly 30 million jobs globally by 2030. In the medium- to long-term, the scaling up of investment in alternative proteins required to facilitate a diet shift away from ruminant livestock products generates up to 83 million jobs by 2050. Total value generation follows a similar pattern to job support, scaling from roughly $160 billion in 2030 to over $700 billion by 2050. However, unlike job creation, value addition is dominated across the study period by alternative proteins, which represent close to 98% of total value generation across innovations, by 2050. GVA contributions are dominated by alternative protein investment throughout study period. This reflects the significant necessary investment in developing alternative protein production capacity to the scale required to contribute to a 1.5°C transition, while ensuring caloric requirements of a growing population are met Innovations can have synergies with sustainable development goals in low- and middle-income regions while driving sustainable value creation in developed countries."). *See also* Good Food Institute (2022) *State of Global Policy*, 3 ("Public funding for alternative proteins increased significantly, with governments worldwide more than doubling their investments in 2022 alone. GFI estimates that governments invested $635 million in the alternative protein ecosystem in 2022, including approximately $180 million on research and development, $290 million on commercialization, and $165 million on initiatives that mixed elements of both. As a result, all-time public support for the alternative protein ecosystem has likely surpassed $1 billion. The United States became the second country after Singapore to complete a premarket consultation for cultivated meat. Food Standards Australia New Zealand (FSANZ) became the third regulatory body to receive an application for cultivated meat, and Israel granted regulatory approval for the country's first precision fermentation-derived animal protein. Courts have largely rejected, overturned, or temporarily suspended efforts to constrain alternative protein sales through labeling restrictions, though a ban on plant-based cheese in Türkiye remains in effect. Governments increased their financial, political, and regulatory support for alternative proteins in 2022 but have yet to approach the annual support needed to realize alternative proteins' benefits to the economy, climate, and global food system. Policymakers should consider increasing funding for research and development and product commercialization, as well as for regulatory instruments to ensure the safe, fair, and reliable entry of alternative proteins to the market."); *and* Lee A., Hofmaier K., & Wright H. (1 November 2023) *Opinion: Why China's alternative protein market matters*, CHINA DIALOGUE ("The 2022 FAIRR Sustainable Protein Transformation in China Index ranked 10 out of the 12 Chinese companies analysed as "high risk" in terms of greenhouse gas emissions. However, whilst still ranking as high risk on average across all sustainability categories, the average scores improved from 12 out of 100 in 2021 to 15 in 2022. According to the index, the number of Chinese companies that have developed an alternative protein product portfolio increased from three to four out of the 12. With this increase, FAIRR expects further regulatory developments in China to support alternative protein production, as its potential in building a sustainable food system is increasingly recognized. … Similarly, other countries in Asia have announced plans to innovate in the agri-food space, including on alternative protein, which may spur regional competition. Japan has announced plans to develop a cultivated meat industry, while South Korea opened a new centre on cellular agriculture,

featuring the world's largest piece of cultivated meat. In 2021, Singapore famously became the first country to approve the sale of cell-based chicken.").

[368] United States Department of Agriculture, *Partnerships for Climate-Smart Commodities* (*last visited* 18 October 2023) (*See* Pilot Projects and Climate-Smart Production Practices section for strategies that have been shown to reduce methane, e.g., "Feed management to reduce enteric emissions.").

[369] California Department of Food and Agriculture (7 June 2023) *CDFA Awards $4.1 Million For Climate-Smart Dairy And Livestock Research Projects*, News Release ("The California Department of Food and Agriculture (CDFA) today announced the award of $4.1 million in grant funding to three research projects as part of the California Livestock Methane Measurement, Mitigation, and Thriving Environments Research Grant Program (CLIM³ATE-RP), funded by Budget Act of 2021 (SB 170, Chapter 240). The research projects' goals are threefold: 1 - Verify the greenhouse gas and environmental co-benefits of climate-smart practices on California dairies 2 - Evaluate alternative methane mitigation strategies, including those that address enteric methane 3 - Advance manure recycling and innovative products development. 'This funding will help ensure that California continues to see emissions benefits from ongoing projects and achieve additional reductions from new practices that address enteric methane and turn manure into useful products,' said CDFA Secretary Karen Ross. 'We are excited about these proposals from our grantees and look forward to seeing their innovative work.'").

[370] For a discussion on private sector efforts to reduce Scope 1–3 emissions, *see* Blue Ocean Barns (13 July 2022) *Blue Ocean Barns Completes $20 Million Series A Financing, Accelerating Solution to Agricultural Methane Emissions*, PR NEWSWIRE ("Blue Ocean Barns works directly with companies to reduce GHG emissions from livestock within their own milk and beef supply chains, known as Scope 3 reductions. Companies pay Blue Ocean Barns to deliver the seaweed to their farmers; in return, companies earn verified carbon certificates that substantiate the reductions. These certificates are more valuable than so-called carbon offsets, which allow companies to fund climate-remediation projects outside their industry, such as wetlands restoration."). For a discussion on differences between Scope 1, 2, and 3 emissions, *see generally* Rocky Mountain Institute (5 October 2023) *A Primer on Embodied Carbon in Climate Disclosure* ("Scopes 1 and 2 include direct and indirect emissions from sources controlled by the business, while Scope 3 emissions include a range of indirect impacts resulting from parts of the value chain the business does not control.").

[371] Note that awards that recognize corporations for their mitigation efforts should account for a corporation's total emissions. Some corporations, such as JBS, have pledged emissions reductions in part of their operations, despite efforts in other parts to increase herd sizes and shift production to countries with fewer restrictions on deforestation, which would increase absolute GHG emissions. For a review of JBS's negative climate and environmental impact despite their Net Zero by 2040 goal, *see* Wasley A. (2 June 2023) *More than 800m Amazon trees felled in six years to meet beef demand*, THE GUARDIAN ("Researchers at the AidEnvironment consultancy used satellite imagery, livestock movement records and other data to calculate estimated forest loss over six years, between 2017 and 2022 on thousands of ranches near more than 20 slaughterhouses. All the meat plants were owned by Brazil's big three beef operators and exporters – JBS, Marfrig and Minerva… More than 2,000 hectares of forest were apparently destroyed on a single ranch between 2018 and 2021 – São Pedro do Guaporé farm, in Pontes e Lacerda, Mato Grosso state – which sold nearly 500 cattle to JBS, though the company said the farm was 'blocked' when its due diligences identified irregularities with them. The JBS meat plant that processed these cattle sold beef to the UK and elsewhere in recent years. The farm was also connected to the indirect supply of more than 18,000 animals across the three meat packers between 2018 and 2019 according to Aidenvironment. All three companies said they were not currently being supplied by the ranch. More than 250 cases of deforestation were attributable to indirect suppliers – farms that rear or fatten cattle but send them to other ranches before slaughter. (Some farms act as both direct and indirect suppliers.)"). For a demonstration of a corporation's methane targets, *see generally* Lyubomirova T. (17 January 2023) *Danone to cut methane by 30% by 2030 through regenerative farming, feed innovation*, FEEDNAVIGATOR.

[372] Changing Markets Foundation & Institute for Agriculture & Trade Policy (2022) EMISSIONS IMPOSSIBLE: *HOW EMISSIONS FROM BIG MEAT AND DAIRY ARE HEATING UP THE PLANET, METHANE EDITION*, 7 ("IATP and Changing Markets' recommendations for governments:… - Require companies to consistently and comprehensively report their GHG emissions, including scope 3, and set emission-reduction targets in line with science, including a system of independent third-party verification. Methane, nitrous oxide and carbon dioxide emissions must be reported separately. - Enact a phased and bottom-up transition for farms to reduce animal numbers in line with a just transition policy for the transformation of the animal agriculture sector.").

[373] *See generally* Carter N. & Urbancic N. (2023) SEEING STARS: THE NEW METRIC THAT COULD ALLOW THE MEAT AND DAIRY INDUSTRY TO AVOID CLIMATE ACTION, Changing Markets.

[374] Rice cultivation constitutes 13% of food system methane emissions. Global Methane Hub & Climateworks Foundation (2023) *Technical Summary, in* THE GLOBAL INNOVATION NEEDS ASSESSMENTS*: FOOD SYSTEM METHANE*, 10 (Figure 2.1).

[375] Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 14 ("For CH_4 emissions from rice cultivation, a halving of global emissions is considered possible through improved water management that shorten the period of continuous flooding of fields, combined with a use of low-CH_4 generating hybrids and different soil amendments (see section S6.5 of the SI for details)."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 16 (In Table SDM1 Measures To Reduce Methane By 45 Per Cent By 2030: "Rice paddies: improved water management or alternate flooding/drainage wetland rice; direct; phosphogypsum and sulphate addition to inhibit methanogenesis; composting rice straw; use of alternative hybrids species."); Project Drawdown, *Technical Summary: Improved Rice Production* (*last visited* 25 October 2023) ("Improved rice production practices include: changes to water management (alternate wetting and drying); fertility management; use of aerobic cultivars; no-tillage; and direct seeding. Data was collected only from studies that used two or more of these practices."); *and* Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 18 ("One way to mitigate methane emissions from rice cultivation is simply to increase yields. Rice emissions are based on the number of hectares planted and harvested each year, and higher yields reduce the area planted for the same total production. Higher yielding crop varieties also appear to generate less methane per hectare (Jiang et al. 2017).").

[376] Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 14 ("For CH_4 emissions from rice cultivation, a halving of global emissions is considered possible through improved water management that shorten the period of continuous flooding of fields, combined with a use of low-CH_4 generating hybrids and different soil amendments (see section S6.5 of the SI for details).").

[377] Ahmed J., Almeida E., Aminetzah D., Denis N., Henderson K., Katz J., Kitchel H., & Mannion P. (2020) AGRICULTURE AND CLIMATE CHANGE: *REDUCING EMISSIONS THROUGH IMPROVED FARMING PRACTICES*, McKinsey & Company, 18 ("Several practices could reduce methane emissions in rice paddies, relative to what is observed in the continuous flooding systems used most widely across the world. Alternate wetting and drying, single season drainage, and other methods can increase in nitrous oxide emissions. However, this adverse impact is significantly outweighed in terms of tCO_2e by direct methane-emissions reduction.").

[378] Climate & Clean Air Coalition, *Paddy rice production* (*last visited* 25 October 2023) ("Alternate wetting and drying (AWD), the practice of allowing the water table to drop below the soil surface at one or multiple points during a growing season, is an effective alternative to continuous flooding, proven to reduce methane emissions by as much

as 48%. The practice is also cost-saving for farmers, as it requires a third less water than continuous flooding and does not compromise yield."). *See also* Project Drawdown, *Improved Rice Production* (*last visited* 25 October 2023) ("These techniques can make rice production efficient, dependable, and sustainable, helping to meet growing demand for this staple food while minimizing adverse climate impacts. We investigated two low-methane rice production solutions: Improved Rice Production (profiled here), with techniques suitable to both small- and large-scale operations, and System of Rice Intensification, currently limited to smallholders. This solution replaces conventional paddy rice production in mechanized (non-smallholder) regions. Given that many rice farming methods are long-entrenched customs, change requires helping farmers see what results are possible, cultivating necessary knowledge and skills, and implementing incentives that make new methods compelling.").

[379] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 17 ("Moreover, in addition to management, rice yield potential has continued to rise steadily through improved crop breeding (Kumar et al. 2021), and breeders for rice, as for other crops, have many ideas for potentially larger increases in yield potential (Qian et al. 2016)."), 20 ("Results of biochar in rice fields are promising for methane reduction, yields gains and other benefits. Many experiments have now been done, and global meta-analyses suggest that biochar amendment in rice fields can reduce methane emissions by 6-13% compared to not using biochar (Awad et al. 2018) (Liao et al. 2021). In theory, if all rice straws were charred and returned to the fields, the estimated global methane emission reductions along with our estimated changes in water management would increase to 12.55 million tons (Figure 6). In addition, accumulating evidence suggests that biochar amendment in rice fields can boost rice yield by about 9% (Liao et al. 2021). This level of yield benefits could significantly help defray the costs of using biochar.").

[380] Low J. (20 June 2022) *How Pakistan is navigating water scarcity in agriculture*, GovInsider ("Mechanical rice transplanters may provide some relief. This is a machine that creates equal distancing between seedlings to optimizee plant density in the field and maximise yield; 'The technology helps automate manual work and will be able to reach a degree of precision that cannot be achieved physically,' Shahrukh explains.").

[381] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs, 18 ("Each 1% increase in rice yields roughly reduces rice methane emissions by 1%. If global rise yields rise only to 5.3 tons per hectare by 2050, the Globagri model estimates that rice methane emissions would rise 13% from 2010 levels (T. Searchinger et al. 2019). But achieving a global average yield of 6.4 tons per hectare per year in 2050 would result in a 4% drop in emissions.").

[382] Kumar A., *et al.* (2021) *Genetic gain for rice yield in rainfed environments in India*, Field Crops Res. 260(107977): 1–12, 9 ("This study documents the significant genetic gain for grain yield of a breeding program targeting rainfed lowland rice in India that was based on direct selection for grain yield under both irrigated control and drought conditions. The study utilized extensive multi-season evaluation in target environments under irrigated control, moderate drought stress and severe drought stress between 2004–2014 with number of popular varieties as checks to enable accurate estimation of the genetic gain. The yield improvement of the newly developed stress-tolerant varieties over the best currently grown varieties was also demonstrated on farmers' fields. The developed STRVs have potential to protect farmers from crop losses against an increasing impact of extreme droughts under climate change.").

[383] Wang W., Wu X., Chen A., Xie X., Wang Y., & Yin C. (2016) *Mitigating effects of ex situ application of rice straw on CH4 and N2O emissions from paddy-upland coexisting system*, Sci. Rep. 6(37402): 1–8, 1 ("Year-round measurements of CH_4 and N_2O emissions were conducted to evaluate the system-scaled GWP. The results showed that CH_4 accounted for more than 98% of GWP in paddy. Straw removal from paddy decreased 44.7% (302.1 kg ha^{-1} yr^{-1}) of CH_4 emissions and 51.2% (0.31 kg ha^{-1} yr^{-1}) of N_2O emissions, thus decreased 44.8% (7693 kg CO_2-eqv ha^{-1} yr^{-1}) of annual GWP."). *See also* Bengston O., Feng S., Ganesan V., Katz. J., Kitchel H., Mannion P., Prabhala P., Richter A., Roen W., & Vleck J. (2023) The agricultural transition: *Building a sustainable future*, McKinsey & Company, 42 (*See* (4) Improved rice straw management).

[384] California Air Resources Board, *Rice Cultivation Projects* (*last visited* 18 October 2023) ("The eligible practices for California are: 1) replacing wet seeding with dry seeding and 2) early drainage at the end of growing season; and the eligible practices for the Mid-South: 1) intermittent flooding and 2) early drainage at the end of growing season.").

[385] United Nations Development Programme (20 December 2022) *Strengthening capacity to protect the environment* ("The United Nations Development Programme (UNDP) in partnership with the Ministry of Environment, Science, Technology and Innovation (MESTI), and the Environmental Protection Agency (EPA) is building the capacity of Agricultural and Environmental Officers including Irrigation Scheme Managers for the promotion and the adoption of the AWD technology by rice farmers to reduce methane emissions. The training is a key capacity building activity of the "Alternative Wetting and Drying for Sustainable Rice Production" project which was developed out of the cooperative agreement between the Governments of Ghana and Switzerland under Article 6.2 of the Paris Agreement. The agreement falls under a $42 million pay-for-results collaboration between the Swiss Federal Office for the Environment (FOEN) and UNDP."); *discussed in* Ghana Business News (22 May 2023) *UNDP leads sustainable rice production in Ghana while reducing greenhouse gas emission*.

[386] The World Bank (31 May 2023) *World Bank Loan Will Support Reducing Methane, Saving Water in Hunan's Rice Paddies*, Press Release ("The World Bank's Board of Executive Directors approved a US$255 million loan today to support a program that will reduce methane emissions, improve irrigation and drainage services, and provide agricultural support for climate-resilient rice production in Hunan province, China's largest rice production area."); *discussed in* Devdiscourse (1 June 2023) *World Bank approves US$255M loan to provide agricultural support for climate-resilient rice production in Hunan province*.

[387] Romero-Briones A. (19 April 2022) *The Future of Agriculture in a Warming World Panel*, Speech.

[388] Heller M. (4 November 2021) *It's not weird, it's nuts: Farmers graze cows in groves of trees*, E&E GREENWIRE ("It's part of a broader set of practices called agroforestry that combine food production with trees. Advocates say it could help in the fight against climate change by encouraging both the planting of trees and less-intensive livestock farming. 'Research suggests silvopasture far outpaces any grassland technique for counteracting the methane emissions of livestock and sequestering carbon under-hoof,' said Project Drawdown, a San Francisco group inspired by the 2017 best-selling book 'Drawdown' by Paul Hawken, on its website. 'Pastures strewn or crisscrossed with trees sequester five to ten times as much carbon as those of the same size that are treeless, storing it in both biomass and soil.'").

[389] Heller M. (3 January 2022) *Solar grazing: Sheep tidy up at solar farms*, E&E GREENWIRE ("Promoters say the benefits are far-reaching. Site managers are looking for ways to keep vegetation from overgrowing and shading the panels, and some research suggests grazing saves as much as $300 per acre each year over other methods. Land owners are looking for whatever value they can draw from their property. And farmers who need places for livestock to munch on grass or other ground cover can charge for the service. The practice has environmental benefits, too, supporters say, by keeping land in agricultural production, controlling runoff and improving soil quality through rotational grazing, in which animals are moved from pasture to pasture over a season.").

[390] Cui J., Liu H., Wang H., Wu S., Bashir M. A., Reis S., Sun Q., Xu J., & Gu B. (2023) *Rice-Animal Co-Culture Systems Benefit Global Sustainable Intensification*, EARTH'S FUTURE 11(2): 1–18, 1 ("Compared to traditional monoculture of rice or animal production, the RAC [rice-animal co-culture] can not only reduce the demand for agricultural land areas, but also increase rice yields (+4%) as well as nitrogen use efficiency of rice (+6%). At the same time, RAC reduces nitrogen losses (−16% runoff and −13% leaching) and methane emissions (−11%), except for rice-fish coculture systems, which are likely to increase methane emissions (+29%). Furthermore, RAC increases the net income of farmers through reducing cost of fertilizer and pesticide input and achieving higher outputs with more marketable products. According to the development stage of different countries, promotion of RAC will thus

realize multiple benefits and aid sustainable intensification."); *discussed in* SciTechDaily (15 April 2023) *A Rice Idea: Old Farming Techniques Unlock New Sustainable Solutions*.

[391] McGrath S. R., Thomas D. T., & Greer A. W. (2021) *Dual-purpose cropping: the opportunity for a step change in production in the temperate region of Australia*, ANIM. PROD. SCI. 61(11): i–iv, i ("Dual-purpose cropping refers to the establishment of annual crops such as cereals (e.g. wheat, barley, oats and triticale) and brassicas (mainly canola) with the intended purpose of grazing during the vegetative stage and harvesting grain after the crop matures. Twelve years ago, a special issue published in Animal Production Science reported key studies from Grain and Graze, a research and extension program which provided impetus for increased uptake of dual-purpose cropping and highlighted management of crops and livestock to optimise production.").

[392] Kebreab E. & Feng X. (2021) *Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources*, California Air Resources Board, 69 ("In general, higher moisture contents in raw composting manure could enhance the CH_4 mitigation rates, however, the pH, and C/N content were not linearly related to CH_4 mitigation. Adding biochar, acids, and straw to manure could mitigate CH_4 emissions by 82.4%, 78.1%, and 47.7%, respectively. However, the data for straw is quite small so it should not be taken out of context as it may introduce a source of carbon into lagoons. The meta-analysis conducted with selected additives indicated manure additives were an effective method to reduce CH_4 emission, with biochar being the most effective. However, further studies of manure additives on CH_4 mitigation are required to support a more accurate quantitative analysis and potential impacts to water quality and crop yield after land application. Most of the research for biochar and straw is when used as additive to solid or semi solid manure so they should be interpreted in that context."). *See also* Peskett M. (15 November 2021) *Reducing methane emissions from cattle and dairy farming*, FOOD AND FARMING TECHNOLOGY ("Nearly all dairy farms use effluent or slurry ponds and they are the second largest source of on-farm methane emissions. At New Zealand's Lincoln University, scientists Emeritus Professor Keith Cameron and Professor Hong Di have developed technology that reduces the methane emissions from dairy farm effluent ponds by up to 99%. Built in conjunction with New Zealand ag solutions firm Ravensdown, the 'EcoPond' virtually eliminates the methane emitted from effluent ponds. A computer-controlled pump and mixing system precisely administers iron sulphate – a safe additive used in the treatment of drinking water, to neutralise methane production.").

[393] Slade E. M., Riutta T., Roslin T., & Tuomisto H. L. (2016) *The role of dung beetles in reducing greenhouse gas emissions from cattle farming*, SCI. REP. 6: 1–8, 1 ("Several recent papers suggest that dung beetles may affect fluxes of GHGs from cattle farming. Here, we put these previous findings into context. Using Finland as an example, we assessed GHG emissions at three scales: the dung pat, pasture ecosystem and whole lifecycle of milk or beef production. At the first two levels, dung beetles reduced GHG emissions by up to 7% and 12% respectively, mainly through large reductions in methane (CH_4) emissions. However, at the lifecycle level, dung beetles accounted for only a 0.05–0.13% reduction of overall GHG emissions. This mismatch derives from the fact that in intensive production systems, only a limited fraction of all cow pats end up on pastures, offering limited scope for dung beetle mitigation of GHG fluxes. In contrast, we suggest that the effects of dung beetles may be accentuated in tropical countries, where more manure is left on pastures and dung beetles remove and aerate dung faster and that this is thus a key area for future research.").

[394] Dore S., Deverel S. J., & Christen N. (2022) *A vermifiltration system for low methane emissions and high nutrient removal at a California dairy*, BIORESOUR. TECHNOL. REP. 18(101044): 1–10, 1 ("Methane fluxes and wastewater removal rate of volatile solids, N species, salinity, major ions, and trace elements were monitored for 12 months. Vermifiltration reduced methane emissions relative to an anaerobic lagoon by 97–99% and removed 87% of the volatile solids, contaminants such as salts and trace elements, P (83%) and N (84%) from the wastewater. Vermifiltration of dairy wastewater demonstrated to be a useful tool to mitigate methane emissions, regulate excess nutrients and improve water quality at dairy farms."). *See also* Singh R., Ray C., Miller D. N., Durso L. M., Meneses Y., Bartelt-Hunt S., & D'Alessio M. (2022) *Effects of feeding mode on the performance, life span and greenhouse gas emissions of a vertical flow macrophyte assisted vermifilter*, NPJ CLEAN WATER 5(31): 1– 9, 1 ("This study was conducted to investigate the impact of intermittent feeding on performance, clogging, and gaseous emission on

macrophyte assisted vermifiltration (MAVF) based treatment system. Synthetic slaughterhouse wastewater was applied to two different integrated vertical flow based MAVFs. Triplicates were used throughout the study. Eisenia fetida earthworms were added to MAVFs, and Carex muskingmenis plants were planted. Wastewater was applied to the reactors on 1) intermittent (8 h/day) (IMAVF) and 2) continuous (24 h/day) (CMAVF) basis. The average chemical oxygen demand, total nitrogen, and total phosphorous removals achieved by the IMAVF were 80.2 ± 1.6%, 53.9 ± 1.3% and 66.5 ± 1% respectively, and 68.3 ± 1.3%, 61.2 ± 1.4%, and 60.5 ± 1.4% by the CMAVF, respectively. The diffusion of air to the bedding of IMAVFs during no-flow conditions facilitated higher organics oxidation, adsorption of phosphorous, nitrification, and ammonification.... Intermittent application of influent could be considered for improving the performance and lifespan of MAVFs, causing lower environmental footprints."), *discussed in* van Deelan G. (15 July 2022) *Manure-Eating Worms Could Be the Dairy Industry's Climate Solution*, INSIDE CLIMATE NEWS ("Some scientists even say that vermifiltration could reduce greenhouse gas emissions from dairy farms by preventing the production of methane, a powerful greenhouse gas. As such, vermifiltration could be a possible alternative to manure digesters, controversial technologies that capture methane produced by manure ponds, then sell that methane as a fuel source.").

[395] N2–Applied, *N2 Solution* (*last visited* 25 October 2023) ("N2 Applied has developed a technology that enables local production of fertiliser using only livestock slurry, air and electricity, – dramatically reducing harmful emissions and improving yield at the same time. The technology adds nitrogen from the air into slurry, which increases the nitrogen content. The reaction prevents the loss of ammonia and eliminates methane emissions, making it a real solution helping to achieve climate target commitments on an industrial scale. The end-product is a nitrogen enriched organic fertiliser (NEO), which has the same characteristics as normal slurry, but contains more nitrogen and significantly less emissions. It can still be spread using existing farm equipment, enabling farmers to improve their own food production, reduce the need for chemical fertiliser, and make farming more circular.").

[396] El Abbadi S. H., Sherwin E. D., Brandt A. R., Luby S. P., & Criddle C. S. (2022) *Displacing fishmeal with protein derived from stranded methane*, NAT. SUSTAIN. 5: 47–56, 47 ("Methane emitted and flared from industrial sources across the United States is a major contributor to global climate change. Methanotrophic bacteria can transform this methane into useful protein-rich biomass, already approved for inclusion into animal feed. In the rapidly growing aquaculture industry, methanotrophic additives have a favourable amino acid profile and can offset ocean-caught fishmeal, reducing demands on over-harvested fisheries. … Our results show that current technology can enable production, in the United States alone, equivalent to 14% of the global fishmeal market at prices at or below the current cost of fishmeal (roughly US$1,600 per metric ton).").

[397] Bryant R. W., Burns E. E. R., Feidler-Cree C., Carlton D., Flythe M. D., & Martin L. J. (2021) *Spent Craft Brewer's Yeast Reduces Production of Methane and Ammonia by Bovine Rumen Microbes*, FRONT. ANIM. SCI. 2: 1–10, 1 ("Our research suggests that adding spent craft brewer's yeast to rumen microbes by single time-point 24-h *in vitro* incubations suppresses production of methane and ammonia. This project examines the correlation between the quantities of hop acids in spent yeast and the production of methane and ammonia by bovine rumen microbes *in vitro*. We determined, by HPLC, the hop acid concentrations in spent yeast obtained from six beer styles produced at a local brewery. We performed anaerobic incubation studies on bovine rumen microbes, comparing the effects of these materials to a baker's yeast control and to the industry-standard antibiotic monensin. Results include promising decreases in both methane (measured by GC–FID) and ammonia (measured by colorimetric assay) in the presence of craft brewer's yeast, and a strong correlation between the quantities of hop acids in the spent yeast and the reduction of methane and ammonia. Notably, two of the yeast samples inhibited methane production to a greater degree than the industry-standard antibiotic monensin. Our results suggest that spent brewer's yeast has potential to improve ruminant growth while reducing anthropogenic methane emission.").

[398] *See* Number 8 Bio (*last visited* 25 October 2023).

[399] Searchinger T., Herrero M., Yan X., Wang J., Dumas P., Beauchemin K., & Kebreab E. (2021) *Opportunities to Reduce Methane Emissions from Global Agriculture*, Princeton University School of Public and International Affairs,

12 ("Vaccines have so far proved frustrating and only temporarily effective but merit continued research. Breeding is another option. Variation in methane production among different individual animals (Wallace et al. 2019), which appears to be heritable, suggests that breeding can over time reduce methane levels. One study estimated methane reductions might approach 15% (González-Recio et al. 2020). These efforts merit serious work but will only show results over several decades.").

[400] Roston E. (3 January 2022) *Inside the Project to Genetically Modify Rice to Emit Fewer Greenhouse Gases*, TIME ("Now, 15 years after their initial meeting, Banfield, Doudna and a large team of co-authors have published a paper that takes a major step toward solving the thorny problem of how to study and alter genomes of microbes living in complicated real-world environments, such as the gut microbiome or soil. The complexity of microbial communities has been a major obstacle to discovering technologies that can prevent diseases and improve agriculture. It's a critical step toward curbing methane, a harmful greenhouse gas that is emitted during rice production.... Rice fields are like smokestacks for soil methane, and to shut down those emissions, scientists first need to understand the microbes. The trouble has been that culturing microbial communities and tinkering with them in a lab with traditional tools 'could take years or might fail altogether,' IGI authors write. Their new paper demonstrates that using a Crispr-based system can 'accelerate this process to weeks.'"). *See also* Rubin B. E., *et al.* (2022) *Species- and site-specific genome editing in complex bacterial communities*, NAT. MICROBIOL. 7: 34–47.

[401] GHGSat (2 March 2022) *Cow burps seen from space*, Press Release ("On March 2nd 2022, high-resolution satellites owned and operated by GHGSat, the environmental data company, detected methane (CH_4) emissions coming from an agricultural area in California's Joaquin Valley. … This highlights the importance of tracking greenhouse gas emission from cattle farming, and the ability to do so even from space.").

[402] Liu L., *et al.* (2022) *KGML-ag: A Modeling Framework of Knowledge-Guided Machine Learning to Simulate Agroecosystems: A Case Study of Estimating N_2O Emission Using Data from Mesocosm Experiments*, GEOSCI. MODEL DEV. 15(7): 2839–2858, 2839 ("The development of KGML-ag in our study is suitable to predict not only N_2O but also other variables, such as CO_2, CH_4 and ET, with complicated generation processes relying on the historical states. To develop a capable KGML model, we need to carefully address three questions."); *discussed in* University of Minnesota (28 April 2022) *New study could help reduce agricultural greenhouse gas emissions*, Research Brief ("A team of researchers led by the University of Minnesota has significantly improved the performance of numerical predictions for agricultural nitrous oxide emissions. The first-of-its-kind knowledge-guided machine learning model is 1,000 times faster than current systems and could significantly reduce greenhouse gas emissions from agriculture... Accurate, scalable, and cost-effective monitoring and reporting of greenhouse gas emissions are needed to verify what are called "carbon credits" or permits that offset greenhouse gas emissions. Farmers can be reimbursed for practices that reduce greenhouse gas emissions. The KGML-ag framework opens tremendous opportunities for quantifying the agricultural nitrous oxide, carbon dioxide, and methane emissions, helping to verify carbon credits and optimize farming management practices and policy making.").

[403] Kang M., Cho S., Kim J., Sohn S., Ryu Y., & Kang N. (2023) *On securing continuity of eddy covariance flux time-series after changing the measurement height: Correction for flux differences due to the footprint difference*, AGRIC. FOR. METEOROL. 331(109339): 1–11, 1 ("In this study, before changing the flux measurement height of the CRK (Cheorwon Rice paddy, Korea) site from 10 m to 5 m, we installed another eddy covariance system at 5 m and compared the sensible and H_2O/CO_2/CH_4 fluxes at both heights from April 2020 to April 2021. Although random errors could explain substantial portions of the flux differences between the two heights, it was confirmed that systematic errors also existed because the means of the flux differences were not zero, and the distributions of the flux differences were also significantly skewed. Further analysis showed that the primary cause of these systematic errors was the footprint differences rather than the difference in turbulent transport between the two heights. Based on the results, we proposed a strategy for securing the continuity of the flux time- series, which is necessary to understand the long-term variability using all data before and after a measurement change, and discussed the necessity of such a comparative observation."); *discussed in* Syed N. (29 June 2023) *Cutting-Edge Tech Boosts Methane Measurement in Rice*, ASIANA TIMES.

[404] Cusworth D. H., Thorpec A. K., Ayassea A. K., Steppb D., Hecklerd J., Asnerd G. P., Millerc C. E., Yadavc V., Chapmanc J. W., Eastwood M. L., Greenc R. O., Hmiele B., Lyone D. R., & Duren R. M. (2022) *Strong methane point sources contribute a disproportionate fraction of total emissions across multiple basins in the United States*, PROC. NATL. ACAD. SCI. 119(38): 1–7, 6 ("We demonstrated an application of this system using remote sensing platforms across multiple basins in the United States during 2019 to 2021. The results from this multibasin tiered analysis show that point sources make up around 40% of the total CH_4 flux (13 to 67% range) and highlight the heavy-tailed nature of point sources across many regions and sectors. It is likely that if a basin is known to be made of up of any combination of emission sectors that are characteristically heavy tailed (e.g., O&G, coal, manure management, waste), there is a strong likelihood that point sources will make up a significant fraction of the entire region's emissions.").

[405] International Fund for Agricultural Development (8 May 2023) *New IFAD initiative will help reduce global warming by lowering methane emissions from small-scale farming*, Press Release ("IFAD will provide technical assistance to 15 countries to support integrating methane reductions in their updated NDC for submissions to the United Nations Framework Convention on Climate Change in 2025. The Fund will also assist these countries to design projects and blended finance solutions, to reduce methane emissions in agriculture and food systems."). *See also* Global Alliance for the Future of Food (2022) UNTAPPED OPPORTUNITIES FOR CLIMATE ACTION: *AN ASSESSMENT OF FOOD SYSTEMS IN NATIONALLY DETERMINED CONTRIBUTIONS*, 9–10 ("But for most of the countries assessed, there was little indication that studies addressing food systems in an integrated manner were used to support NDC development and implementation plans. For instance, in the United States, where animal-based foods account for 82% of diet-related GHG emissions,6 the NDC does not include any actions to make healthy and sustainable food more accessible and affordable. Where the NDCs assessed indicated alignment with existing and forthcoming food systems policies, certain inconsistencies persist. A case in point is the U.K.'s NDC, which makes important references to the National Food Strategy, the U.K.'s Agriculture Act, and the Sustainable Fisheries Policies yet lacks concrete measures that can catalyze a transition to more sustainable and diversified diets in the country. While the mentioning of food-related strategies and policies in the NDC are per se a very positive development, the absence of any specific actions and articulation on the food–climate nexus generates uncertainty over how consistency between these policies will actually be ensured. China's NDC, for instance, commits to comprehensively reform existing laws and regulations that are incompatible with carbon neutrality but does not provide further details as to how this will be accomplished.").

[406] Bonilla-Cedrez C., Steward P., Rosenstock T. S., Thornton P., Arango J., Kropff M., & Ramirez-Villegas J. (2023) *Priority areas for investment in more sustainable and climate-resilient livestock systems*, NAT. SUSTAIN. 6: 1279–1289, 1282–1283 ("From a global perspective, the weighting of adaptation and mitigation indicators highlights the geographies with the greatest problems, providing a regional focus. At local scales, however, these indicators emerge from farmers' decisions on system management and, as such, are interconnected; any choice of adaptive or mitigating priorities needs understanding of the trade-offs that impact other goals. Adopting a livestock practice or technology nearly always involves trade-offs between adaptation and mitigation outcomes[19]. Thus, to avoid unintended consequences, actions need to be aligned with local demands and goals. The consideration that adaptation and mitigation need to be addressed jointly is especially important in areas where population growth and/or dietary change are most prominent[20]. Yet, a lack of alignment at the policy level potentially hinders this objective. Roughly 50% of the NDCs that mention livestock note just one of the priorities[21], and only 28 out of 184 countries' NDCs include soil-related targets[22]. This omittance suggests that, as a global community, we are creating institutions and narratives that disincentivize or preclude action on adaptation, mitigation or both.").

[407] Zhu J., Luo Z., Sun T., Li W., Zhou W., Wang X., Fei X., Tong H., & Yin K. (2023) *Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems*, NAT. FOOD 4(3): 1–13, 6 ("Analysis of the interactions between the various interventions reveals potential trade-offs. When multiple interventions are combined, possible synergy or antagonism should be understood. For example, the shift to more plant-based diets is key to the sustainability of the food system[41]; however, this shift will increase waste-management-related emissions. This may be compensated via adopting more advanced waste management technologies such as

AD or COM. The outcomes of combined interventions are also region dependent and time sensitive; these complexities are not investigated here but need further case studies.").

[408] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Analysis of the technical potential to mitigate methane from four separate studies shows that for 2030, reductions of 29–57 Mt/yr could be made in the oil and gas subsector, 12–25 Mt/yr from coal mining, 29–36 Mt/yr in the waste sector and 6–9 Mt/yr from rice cultivation. Values for the livestock subsector are less consistent, ranging from 4–42 Mt/yr.").

[409] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: *A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT*, 102 ("Within the waste sector, all cost abatement potential is concentrated within the solid waste subsector which has three to six times the potential found in the wastewater (sewage) subsector (Figure 4.9). Totals in the three available analyses are very similar for the full waste sector, so that the full range is captured by 32 ± 4 Mt/ yr. Hence this sector has about half the potential of the fossil sector for all cost measures and a much narrower uncertainty range. Evaluating this mitigation potential as a share of projected 2030 waste sector emissions is complicated by a large divergence between them, which were ~70 Mt/yr in the Harmsen and US EPA analyses, whereas there was a much larger value of 114 Mt/yr in the IIASA analysis. Hence although all the studies find similar abatement potential, the share of 2030 emissions from waste estimated to be abatable ranges from just 25 per cent in the IIASA analysis to ~40-50 per cent in the US EPA and Harmsen analyses. For low-cost measures in the waste sector, the analyses are again fairly consistent with all falling within the range 16 ±5 Mt/yr.").

[410] United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010, 70 ("Collection of LFG is feasible at most engineered landfills. It prevents high concentrations of gas in the landfill, which addresses public health and facility safety concerns. After collecting LFG, the least capital-intensive way to reduce emissions is flaring, which burns off the gas. However, flaring does not deliver any economic benefits for landfill operators. Energy production represents a potential revenue stream for landfills. It includes electricity generation, anaerobic digestion, and direct use. A variety of engine types and waste-to-energy processes can achieve electricity generation. Anaerobic digestion provides CH_4 for on-site electricity or for selling to the market. Direct use implies that a landfill transports captured methane to a facility, which uses it for electricity generation, as process heat, or as an input into other processes.").

[411] United States Environmental Protection Agency, *Basic information about landfill gas* (*last visited* 5 February 2023).

[412] United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010, 70 ("Energy production represents a potential revenue stream for landfills. It includes electricity generation, anaerobic digestion, and direct use. A variety of engine types and waste-to-energy processes can achieve electricity generation. Anaerobic digestion provides CH4 for on-site electricity or for selling to the market. Direct use implies that a landfill transports captured methane to a facility, which uses it for electricity generation, as process heat, or as an input into other processes.").

[413] DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 55 (*See* Reference Path for modeling maximum technical opportunity by 2030 and 2050 (continued)).

[414] United States Environmental Protection Agency, *Basic information about landfill gas* (*last visited* 5 February 2023) ("About 69 percent of currently operational LFG energy projects in the United States generate electricity. A variety of technologies, including reciprocating internal combustion engines, turbines, microturbines and fuel cells, can be used to generate electricity for onsite use and/or sale to the grid. The reciprocating engine is the most commonly used

conversion technology for LFG electricity applications because of its relatively low cost, high efficiency and size ranges that complement the gas output of many landfills. Gas turbines are typically used in larger LFG energy projects while microturbines are generally used for smaller LFG volumes and in niche applications."). *See also* Fuel Cell & Hydrogen Energy Association (27 April 2020) *Reducing waste emissions by using fuel cells and hydrogen*.

[415] Winn Z. (2 February 2022) *Reducing methane emissions at landfills*, MIT NEWS ("Now a startup that began at MIT is aiming to significantly reduce methane emissions from landfills with a system that requires no extra land, roads, or electric lines to work. The company, Loci Controls, has developed a solar-powered system that optimizes the collection of methane from landfills so more of it can be converted into natural gas. At the center of Loci's (pronounced "low-sigh") system is a lunchbox-sized device that attaches to methane collection wells, which vacuum the methane up to the surface for processing. The optimal vacuum force changes with factors like atmospheric pressure and temperature. Loci's system monitors those factors and adjusts the vacuum force at each well far more frequently than is possible with field technicians making manual adjustments.").

[416] DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 45–46 ("Methane emissions from solid waste could be abated by about 40 percent by 2030 and 90 percent by 2050 (Exhibit 18). Almost all of the reduction would be through diversion of organic material to secondary purposes, such as composting or biogas extraction. Organic waste could be sorted and processed through anaerobic digestion facilities to generate feedstock, fertilizer, soil enhancer, and renewable natural gas—or incinerated for energy."). *See also* United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050, EPA-430-R-19-010, 70 ("Furthermore, enhanced waste diversion practices redirect biodegradable components of the waste stream from the landfill for reuse through recycling or conversion to a value-added product (e.g., energy or compost). Diverting organic waste components lowers the amount of CH4 generated at the landfill. Other benefits from the measures under this category include the sale of recyclables, electricity, and cost savings in avoided tipping fees."); *and* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 87 ("Solid waste management: (residential) source separation with recycling/reuse; no landfill of organic waste; treatment with energy recovery or collection and flaring of landfill gas; (industrial) recycling or treatment with energy recovery; no landfill of organic waste.").

[417] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 114 ("While more than 10 per cent of the global population lives in hunger (FAO 2017) roughly a third of all food produced for human consumption turns into lost or wasted at some point along the food supply chain (Porter *et al*. 2018; Gustavsson *et al*. 2011). Many studies highlight the mitigation benefits of reducing this large volume and indicate that the potential reductions of emissions can be substantial but also diverse (FAO 2019; Springmann *et al*. 2018; Wollenberg *et al*. 2015; Bajželi *et al*. 2014). Most of these provide both base case emissions and emissions reductions estimates only in terms of carbon dioxide equivalent rather than separating the various greenhouse gases. For example, an FAO report (2019) suggests that the global carbon footprint of food loss and waste, excluding emissions from land-use change, is 3.3 gigatonnes12 of carbon dioxide equivalent (Gt CO e). Similarly, an earlier report from the FAO estimated total emissions related to food loss and waste of 2.7 Gt CO2e (FAO, 2014). Based on the source data reported in Chapter 2, methane emissions from ruminants and rice cultivation are ~145 Mt/yr. Hence if it is assumed here that loss and waste in these two categories is similar to the total across all food types, methane emissions associated with food loss and waste would be nearly 50 Mt/yr."). *See also* DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 46 ("As the world accelerates its efforts to align with the 1.5°C pathway, a key lever would be to reduce the volume of organic municipal solid waste. This would mean reducing food and paper waste by changing individual behaviors (for example, broad adoption of composting) and improving efficiency in supply chains (for example, ensuring food does not rot in transit and reducing overstocking at supermarkets). Local volumes of organic waste are linked to population size, but there are actions society can take to control organic-waste

volumes. Recycling of organic materials, such as paper, cardboard, and leather, as well as reduction of food waste are two effective approaches.”).

[418] Zhu J., Luo Z., Sun T., Li W., Zhou W., Wang X., Fei X., Tong H., & Yin K. (2023) *Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems*, NAT. FOOD 4(3): 1–13, 5 (“Globally, halving FLW generation (acknowledged as one of the SDG targets by 203014) will achieve an annual reduction of 3.23 GtCO_2e in supply-embodied emissions (Fig. 3a). Through reducing the FLW input to waste management, it will further mitigate the annual GHG emissions from waste management by 1.42 GtCO_2e (Fig. 3a). The total intervention outcome is equivalent to approximately one-quarter of the GHG emissions from the global food system in 2017.”).

[419] For the links between extreme heat, crop harvest losses, and cooling, *see* Parajuli R., Thoma G., & Matlock M. D. (2019) *Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review*, SCI. TOTAL ENVIRON. 650(2): 2863–2879, 2875 (“The basic factors that can support sustainable supply of F&V products are climate, proximity to the producers and the growing seasons. Likewise, logistic management, including facility-locations in the overall supply of F&V products is also connected with the seasonality of production, cost of transportation and the refrigeration/preservation requirements. In the logistic management areas, understanding the relationship between storage and waste is also relevant. Only less than 12% of the reviewed study (Table 1) explicitly considered the wastage at some part of the supply chain. The significance of such considerations can be explained from a Brazilian study, which compared food stores, with and without refrigerated units (Garnett, 2006). The study revealed that waste generation in the un-refrigerated store was 28% higher than the refrigerated store. Furthermore, refrigeration can also assist to improve self-sufficiency of F&V product supplies, and undoubtly it is important aspect while addressing the consequences of climate change on the food security. However, it is important to evaluate the environmental and economic costs of whether storing indigenous products beyond their growing season would outweigh the energy use and other emissions resulting from the transport of imported foods.”); *and* Kibiti B. & Strubenhoff H. (16 October 2019) *How off-grid cold storage systems can help farmers reduce post-harvest losses*, BROOKINGS (“It is estimated that less than 10 percent of all perishable foods is currently being refrigerated, despite the fact that post-harvest losses add up to 30 percent of food production worldwide. The cold chain innovations around decentralized renewable energy (DRE) are paramount in Africa and Asia given that access and connection to electricity in rural areas, where food is produced, is still a luxury. In Kenya, an estimated 40 to 50 percent of food is lost or wasted throughout the entire food chain as it goes from farm to fork—twice the global average. In 2017, $1.5 billion worth of food went to waste—tossed out or left to rot—according to the National Bureau of Statistics (KNBS), resulting in lost earnings for farmers and others. In Nigeria, 45 percent of postharvest output spoils due to the unavailability of cold storage, resulting in a 25 percent loss of income for the country’s 93 million small farmers. Cold stores reduce waste, and also help to improve the negotiation power of smallholders in the market.”). *See also* Parker L. E., McElrone A. J., Ostoja S. M., & Forrestel E. J. (2020) *Extreme heat effects on perennial crops and strategies for sustaining future production*, PLANT SCI. 295: 1–8, 1, (“Extreme heat exposure can stress plants, stunt development, and cause plant mortality, which often results in reduced quality and lower yield in agricultural crops [1]. Diminished crop yields due to extreme heat can have cascading effects on global economies and heighten concerns around food availability [[2], [3], [4]]. Recent heatwaves in Europe [2,3], Russia [4], and the central United States [5] reduced yields for cereal crops, and in some instances led to significant commodity price increases and spikes in food insecurity. Warming anomalies have also caused significant losses in woody perennial cropping systems.”).

[420] *See generally* Fitzpatrick A. (18 January 2023) *A new startup wants to turn your food waste into chicken feed*, AXIOS.

[421] Zhu J., Luo Z., Sun T., Li W., Zhou W., Wang X., Fei X., Tong H., & Yin K. (2023) *Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems*, NAT. FOOD 4(3): 1–13, 4–5 (“The growing international food trade between developed and developing countries results in long food supply chains, which exacerbate FLW and associated GHG emissions due to long transport distances and multiple transactions[34]. The complicated relationship is evident in the positive correlation between the food logistic GHG

emissions and GDP, except for EA + SEA (Fig. 2c). Developed countries tend to generate more food logistic emissions from their food supply than developing countries (Fig. 2c), due in part to systematic management systems for the food supply[35] involving more complex requirements and standards for food handling.").

[422] Geyik Ö., Hadjikakou M., & Bryan B. A. (2022) *Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions*, NAT. FOOD. 4: 61–73, 61 ("Here, we estimate the non-CO_2 greenhouse gas emissions resulting from closing the world's dietary nutrient gap—that between country-level nutrient supply and population requirements—for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate under five climate-friendly intervention scenarios in 2030. We show that improving crop and livestock productivity and halving food loss and waste can close the nutrient gap with up to 42% lower emissions (3.03 Gt CO_2eq yr^{-1}) compared with business-as-usual supply patterns with a persistent nutrient gap (5.48 Gt CO_2eq yr^{-1}).").

[423] Global Climate and Health Alliance (2023) MITIGATING METHANE FROM THE WASTE SECTOR, 8–9 ("The health benefits include:

- Avoid physical injuries, avoid respiratory infections, heart disease, stroke, and lung cancer associated with air pollution, such as the toxic smoke created from waste burning and landfill fires, which contain black carbon, carbon dioxide, and particulate matter, improved lung health and quality of life, especially for vulnerable and marginalized populations and communities living near sites. Improved waste management would help reduce the 7 million premature deaths attributed to air pollution globally.
- Avoid odor exposure, infection and disease from insects, rodents, and scavenging animals, and reduced pollution pathways in surface and groundwater caused by open dumping and unsanitary landfills. Diverting organic waste from landfills, and managing landfills with landfill gas collection, daily cover for waste, and liners in place to prevent leachate migration into groundwater can both mitigate methane and improve the overall health and livelihoods of communities surrounding landfill sites.
- Avoid physical injuries from landfills that are not engineered and rehabilitated to be resilient to extreme weather events and sea-level rise caused by climate change. For example, landfills that are not tightly compacted increase the risks of landfill slides and cause injuries and even casualties. In 2017, a garbage landslide in Addis Ababa, Ethiopia killed 116 people and buried dozens of homes surrounding the landfill.
- Avoid waterborne and foodborne diseases from the ingestion of water contaminated with leachate.
- Reduce the health impacts from producing and consuming fossil fuels as a source of energy by using biogas created by processing of organic waste through anaerobic digestion or capturing waste from landfills [see the Energy Sector report and GCHA's From Cradle to Grave brief].
- Improve nutrition and food security by improving soil quality and availability of soil amendments via composting and anaerobic digestion.").

[424] United Nations Climate Technology Centre & Network, *Biocovers of landfills* (*last visited* 5 February 2023) ("Landfill top covers, which optimise environmental conditions for methanotrophic bacteria and enhance biotic methane consumption, are often called 'biocovers' and function as vast bio-filters. Biocovers are typically spread over an entire landfill area. They are often waste materials, such as diverse composts, mechanically-biologically treated waste, dewatered sewage sludge or yard waste. Methane oxidation in compost materials shows high oxidation capacity. Manipulation of landfill covers to maximise their oxidation capacity provides a promising complementary strategy for controlling methane emissions."). *See also* Yazdani R. & Imhoff P. (2010) BIOCOVERS AT LANDFILLS FOR METHANE EMISSIONS REDUCTION DEMONSTRATION, CalRecycle, 70 ("Results from laboratory and field tests indicated both fresh and aged green material could oxidize CH_4 at high rates, up to 100-200 g CH_4/m^2/day in field tests. These rates are on the high end of oxidation rates reported for composts in the literature. Thus, at least for the duration of the field tests pH, P, and NO_2-N conditions did not significantly affect biocover performance. However, the biocovers were installed in relatively thick layers (~ 90 cm), and after seven months of operation with a high loading of [landfill gas] LFG (500-700 g CH_4/m^2/day) thick anaerobic zones developed. The formation of these zones was undoubtedly linked to the high LFG loading and the cooler winter temperatures. In this state both materials generated significant CH_4 (> 100 g CH_4/m^2/day, aged green material) and were ineffective in oxidizing CH_4. However, for the aged green material the performance was improved considerably when the loading rate was decreased to 200-

250 g CH_4/m^2/day. In this case the green material oxidized 50-70 g CH_4/m^2/day. When both biocovers were operated at this smaller loading rate for several months, the aged green material performed reasonably well with measured CH_4 removal rates matching independent model predictions. The same was not true for the fresh green material, though, where it appeared that CH_4 continued to be generated and the biocover performance was always significantly less efficient at removing CH_4 than model predictions.").

[425] Franqueto R., Cabral A., Capanema M. A., & Schirmer W. N. (2019) *Fugitive Methane Emissions From Two Experimental Biocovers Constructed With Tropical Residual Soils: Field Study Using a Large Flux Chamber*, DETRITUS 7: 119–127, 126 ("The methane oxidation capacity was quite high for both subareas (control and enriched). Oxidation efficiencies (at a depth of 0.10 m) averaged 42% for the control subarea and 80% for the enriched area. CH4 and CO2 surface fluxes averaged 20 g.m-2.d-1 and 316 g.m-2.d-1 in the organic-matter-enriched subarea during the monitoring period, while those measured in the control subarea averaged 34 g.m- 2.d-1 and 251 g.m-2.d-1, respectively. It is noteworthy that the surface fluxes were obtained using a custom-made 4.5-m2 flux chamber, which allows for better representativeness of surface fluxes, because it allows inclusion of cracks and other imperfections that may affect measurements. The lower CH4 fluxes and higher oxidation efficiency in the enriched subarea can be associated with the greater organic matter content in the enriched subarea, which created more favourable conditions for the development of ubiquitous methanotrophic colonies (Humer and Lechner, 2001). Temperature conditions, which ranged from 20 to 42°C at the surface and within the first 10 cm of the cover, favoured methane oxidation.").

[426] Chavan D. & Kumar S. (2018) *Reduction of methane emission from landfill using biocover as a biomitigation system: A review*, INDIAN J. EXP. BIOL. 56(7): 451–459, 456 (Table 3, "Lee et al.[54] found that rate of CH_4 oxidation of sandy biocover improved by 60 % with the addition of 100 mg-N NH_4 per kg of soil. Vegetation on biocover might affect the growth and activities of methanatophic bacteria in different ways. Bohn andJager[55] observed that the rate of CH_4 oxidation could be increased by 50% through vegetation growth on landfill biocover. A vegetation root assists the process of transporting O_2 from the atmosphere into deeper soil layers.").

[427] Franqueto R., Cabral A., Capanema M. A., & Schirmer W. N. (2019) *Fugitive Methane Emissions From Two Experimental Biocovers Constructed With Tropical Residual Soils: Field Study Using a Large Flux Chamber* DETRITUS 7: 119–127, 119 ("This study aimed at assessing the response of two experimental passive methane oxidation biocovers (PMOB) installed in a Brazilian landfill located in Guarapuava, State of Paraná. The PMOBs covered an area of 18 m^2 each, and were 0.70-m-thick. The first PMOB (control subarea) was constructed using the same soil used to cover closed landfill cells, i.e. a typical residual soil. The second PMOB (enriched subarea) was constructed with a mixture of the residual soil and mature compost, with a resulting organic matter content equal to 4.5%. CH_4 and CO_2 surface fluxes were measured in a relatively large (4.5 m^2) static chamber. CH_4, CO_2 and O_2 concentrations were also measured at different depths (0.10, 0.20, 0.25 and 0.30 m) within PMOBs. The concentrations from the raw biogas were also measured. Methane oxidation efficiencies (Effox) were estimated based on the CO_2/CH_4 ratio. The average CH_4 and CO_2 concentrations in the raw biogas (42% and 32%, respectively) for the 16 campaigns corroborated those typically found in Brazilian landfills. Lower CH_4 fluxes were obtained within the enriched subarea (average of 20 $g.m^{-2}.d^{-1}$), while the fluxes in the control subarea averaged 34 $g.m^{-2}.d^{-1}$. Effox values averaged 42% for the control subarea and 80% for the enriched one. The results indicate that there is a great potential to reduce landfill gas (LFG) emissions by using passive methane oxidation bio-systems composed of enriched substrates (with a higher content of organic matter).").

[428] United Nations Climate Technology Centre & Network, *Biocovers of landfills* (*last visited* 5 February 2023) ("Optimised and well-adapted biocovers are relatively less expensive in terms of operation and installation compared to a conventional gas collection system, whose cost can be high compared to the value of the captured fuel.").

[429] Scheutz C., Olesen A. O. U., Fredenslund A. M., & Kjeldsen P. (2022) *Revisiting the passive biocover system at Klintholm landfill, six years after construction*, WASTE MANAGE. 145: 92–101, 92 ("In spite of an inhomogeneous distribution of landfill gas load to the methane oxidation layer, the performance of the biocover system had not

declined over the 6–7 years since its establishment, even though no maintenance had been carried out in the intervening years.").

[430] United Nations Climate Technology Centre & Network, *Biocovers of landfills* (*last visited* 5 February 2023) ("These biocovers have low maintenance requirements and they can be maintained by a relatively untrained person. Thus, they are suitable for both high and low income countries.").

[431] Duan Z., Kjeldsen P., & Scheutz C. (2022) *Efficiency of gas collection systems at Danish landfills and implications for regulations*, WASTE MANAGE. 139: 269–278, 277 *(*"This study evaluated gas collection efficiency at 23 Danish landfills with active gas collection systems, based on whole-site methane emission measurements and collection rates obtained from landfill operators. Methane emissions at Danish landfills are generally low (2.6–60.8 kg h− 1), which is probably due to the small amount of waste disposed, its low organic content and waste aging with declining gas generation. Gas collection efficiencies at the studied Danish sites ranged from 13 to 86%, and the average efficiency was 50% (assuming no oxidation in landfill covers). Compared to other landfills reported in the literature, gas collection efficiencies at Danish landfills are generally low, which might be attributed to gas leaks from installations, lack of or insufficient gas collection in some waste cells or incomplete coverage of landfill surfaces. Gas collection efficiency can be used as an index for judging the landfill operator's performance in terms of managing landfill gas. For example, if a minimum efficiency of 80% is set as the methane mitigation goal, any landfill not achieving this figure will need to take remedial actions. In this regard, gas collection system optimisation or the establishment of other mitigation measures (e.g. installing engineered biocover systems) must be initiated, and landfill operators can decide which technology to use by conducting a life cycle cost (LCC) analysis.").

[432] Berkeley (2022) *Fighting Climate Change Through Landfill Biocovers* ("Fighting Climate Change through Landfill Biocovers Project Climate at UC Berkeley's Center for Law, Energy, and the Environment").

[433] Tseng E., Hanson-Lugo D., Thompson D., & Lee M. (2020) *When Viewed from Space*, MSW MAGAZINE 30(7): 18–23, 22–23 ("From the above graph, the estimated reduction in methane flux based on the NASA flyovers is approximately 60%. This significant amount of methane flux reduction also directly corresponds to the reduction in odor complaints over the same time and corresponds inversely with the increase in the volume of landfill gas being collected by the landfill. The SCL LEA separately compiled and analyzed the landfill gas collection data. These data show that there is an estimated 55% to 60% increase in the collected volume of landfill gas because of the addition of the major odor mitigation measures implemented compared to the prior period.").

[434] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: *A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT*, 15 ("Significant opportunities for reducing methane emissions from landfills and capturing value can be seized by reducing food loss and waste, diverting organic waste to beneficial uses, and improving landfill management. These and other actions collectively could reduce methane emissions from waste by an estimated 40-50 percent by 2030 (Appendix A). Such efforts could add value in our states by reducing emissions of volatile organic compounds and toxic air contaminants from landfills, recovering healthy food for human consumption in food insecure communities, supporting healthy soils and agriculture, generating clean energy and displacing fossil fuel consumption, and providing economic opportunities across these diverse sectors. Many of these benefits will accrue in low-income and disadvantaged communities.").

[435] For example, Chile is employing airborne surveys to detect sources of methane emissions in waste management and other infrastructure. *See* Geospatial World, *Airborne Surveys Launched in Chile to Detect Sources of Methane* (*last visited* 4 February 2023).

[436] Cusworth D. H., Duren R. M., Thorpe A. K., Tseng E., Thompson D., Guha A., Newman S., Foster K. T., & Miller C. E. (2020) *Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations*, ENVIRON. RES. LETT. 15(5): 1–11, 1 ("Remote sensing is an avenue to quantify process-level emissions from waste management facilities. The California Methane Survey flew the Next Generation Airborne Visible/Infrared

Imaging Spectrometer (AVIRIS-NG) over 270 landfills and 166 organic waste facilities repeatedly during 2016–2018 to quantify their contribution to the statewide methane budget. We use representative methane retrievals from this campaign to present three specific findings where remote sensing enabled better landfill and composting methane monitoring: (1) Quantification of strong point source emissions from the active face landfills that are difficult to capture by *in situ* monitoring or landfill models, (2) emissions that result from changes in landfill infrastructure (design, construction, and operations), and (3) unexpected large emissions from two organic waste management methods (composting and digesting) that were originally intended to help mitigate solid waste emissions. Our results show that remotely-sensed emission estimates reveal processes that are difficult to capture in biogas generation models. Furthermore, we find that airborne remote sensing provides an effective avenue to study the temporally changing dynamics of landfills.").

[437] Maasakkers J. D., Varon D. J., Elfarsdóttir A., McKeever J., Jervis D., Mahapatra G., Pandey S. Lorente A., Borsdorff T., Foothuis L. R., Schuit B. J., Tol P., van Kempen T. A., van Hees R., & Aben I. (2022) *Using satellites to uncover large methane emissions from landfills*, SCI. ADV. 8(32): 1–8, 1 ("We use the global surveying Tropospheric Monitoring Instrument (TROPOMI) to identify large emission hot spots and then zoom in with high-resolution target-mode observations from the GHGSat instrument suite to identify the responsible facilities and characterize their emissions. Using this approach, we detect and analyze strongly emitting landfills (3 to 29 t hour^{-1}) in Buenos Aires, Delhi, Lahore, and Mumbai. Using TROPOMI data in an inversion, we find that city-level emissions are 1.4 to 2.6 times larger than reported in commonly used emission inventories and that the landfills contribute 6 to 50% of those emissions. Our work demonstrates how complementary satellites enable global detection, identification, and monitoring of methane superemitters at the facility level."); *discussed in* Dickie G. (11 August 2022) *Landfills around the world release a lot of methane - study*, REUTERS.

[438] Clean Air Task Force (16 November 2022) *Clean Air Task Force and partners announce $3 million in Global Methane Hub funding for work on waste sector methane*, News & Media ("With Global Methane Hub funding, CATF and RMI will launch **The Waste Methane Assessment Platform (Waste MAP)**, an open-source platform for information on waste methane to facilitate sharing of information and best practices for global policymakers, operators, and financiers. The platform will leverage inventory, modeled, and measured data from organizations like Carbon Mapper, UN Habitat, the Climate and Clean Air Coalition, and others, and combine this with in country support to develop improved site-specific information to deliver actionable insights that empower key decision makers and communities to deploy resources to priority intervention areas."). *See also* Waste Map, *Measure, map, and mitigate global waste methane emissions* (*last visited* 3 February 2024).

[439] Spokas K. A., Bogner J., & Corcoran M. (2021) *Modeling landfill CH_4 emissions: CALMIM international field validation, using CALMIM to simulate management strategies, current and future climate scenarios*, ELEM. SCI. ANTH. 9: 1–20, 1 ("We focus on site-specific field data comparisons to CALMIM-predicted annual and monthly CH_4 emissions both without and without methanotrophic oxidation. Overall, 74% of 168 individual surface CH_4 emission measurements across 34 international sites were consistent with CALMIM-modeled annual predictions with oxidation (+ or – *SD*). Notably, the model overpredicted 30 comparisons and underpredicted 13 comparisons."); ("In order to realistically address current and future climate scenarios, updated modeling is required to focus more directly on *emissions* inclusive of soil *oxidation*, as opposed to reliance on a CH_4 *generation* model applied to all global landfills. Moreover, considering the high temporal variability of oxidation rates in individual cover soil profiles, use of a single estimated '% oxidation' routinely applied to many sites is not recommended. Also, the routine use of actual CH_4 recovery data should replace the use of a hypothetical '% CH_4 collection efficiency.'").

[440] DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 49 ("By 2030, methane emissions from wastewater could be abated by 27 percent, and by 2050, they could be abated by 77 percent (Exhibit 19). The most effective solution would be to increase the volume of wastewater collected and treated centrally. There is also an opportunity to widen access to modern wastewater infrastructure, which is underdeveloped in many geographies.").

[441] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: *A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT*, 16 ("Wastewater treatment: (residential) upgrade to secondary/tertiary anaerobic treatment with biogas recovery and utilization; wastewater treatment plants instead of latrines and disposal; (industrial) upgrade to two-stage treatment, i.e., anaerobic treatment with biogas recovery followed by aerobic treatment."). *See also* DeFabrizio S., Glazener W., Hart C., Henderson K., Kar J., Katz J., Pratt M. P., Rogers M., Tryggestad C., & Ulanov A. (2021) CURBING METHANE EMISSIONS: *HOW FIVE INDUSTRIES CAN COUNTER A MAJOR CLIMATE THREAT*, McKinsey Sustainability, 49 ("By 2030, methane emissions from wastewater could be abated by 27 percent, and by 2050, they could be abated by 77 percent (Exhibit 19). The most effective solution would be to increase the volume of wastewater collected and treated centrally. There is also an opportunity to widen access to modern wastewater infrastructure, which is underdeveloped in many geographies."); *and* Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 16–17 ("An additional almost 10 percent of baseline emissions in 2050 could be removed at a marginal cost below 20 €/t CO_2eq by implementing proper waste and wastewater handling in China, India and the rest of South-East Asia. This would likely come with considerable co-benefits in the form of reduced air and water pollution.").

[442] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, EARTH SYST. SCI. DATA 12(3): 1561–1623 ("Natural methane sources include vegetated wetland emissions and inland water systems (lakes, small ponds, rivers), land geological sources (gas–oil seeps, mud volcanoes, microseepage, geothermal manifestations, and volcanoes), wild animals, termites, thawing terrestrial and marine permafrost, and oceanic sources (biogenic, geological, and hydrate)."). *See also* Barba J., Bradford M.A., Brewer P.E., Bruhn D., Covey K., van Haren J., Megonigal J.P., Mikkelsen T.N., Pangala S.R., Pihlatie M., Poulter B., Rivas-Ubach A., Schadt C.W., Terazawa K., Warner D.L., Zhang Z., & Vargas R. (2019) *Methane emissions from tree stems: a new frontier in the global carbon cycle*, NEW PHYTOLOGIST 222: 18–28, 18 ("Tree stems from wetland, floodplain and upland forests can produce and emit methane (CH_4). Tree CH_4 stem emissions have high spatial and temporal variability, but there is no consensus on the biophysical mechanisms that drive stem CH_4 production and emissions. Here, we summarize up to 30 opportunities and challenges for stem CH_4 emissions research, which, when addressed, will improve estimates of the magnitudes, patterns and drivers of CH_4 emissions and trace their potential origin."); *compare* Gauci V., Pangala S. R., Shenkin A., Barba J., Bastviken D., Figueiredo V., Gomez C., Enrich-Prast A., Sayer E., Stauffer T., Welch B., Elias D., McNamara N., Allen M., & Malhi Y. (2024) *Global atmospheric methane uptake by upland tree woody surfaces*, NATURE 631(8022): 796–800, 796 ("Stable carbon isotope measurement of methane in woody surface chamber air and process-level investigations on extracted wood cores are consistent with methanotrophy, suggesting a microbially mediated drawdown of methane on and in tree woody surfaces and tissues. By applying terrestrial laser scanning-derived allometry to quantify global forest tree woody surface area, a preliminary first estimate suggests that trees may contribute 24.6–49.9 Tg of atmospheric methane uptake globally. Our findings indicate that the climate benefits of tropical and temperate forest protection and reforestation may be greater than previously assumed.").

[443] United Nations Environment Programme (2021) EMISSIONS GAP REPORT 2021: THE HEAT IS ON – A WORLD OF CLIMATE PROMISES NOT YET DELIVERED, 47 ("Over the last two decades, the main cause of increasing atmospheric methane is likely increasing anthropogenic emissions, with hotspot contributions from agriculture and waste in South and South-East Asia, South America and Africa, and from fossil fuels in China, the Russian Federation and the United States of America (Jackson *et al.* 2020). Emissions from natural sources may also be increasing, as wetlands warm, tropical rainfall increases and permafrost thaws."). *See also* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH4 observations and the way forward*, PHILOS. TRANS. R. SOC. A 379(2210): 1–14, 11 ("Explaining the renewed and accelerating increase in atmospheric CH_4 burden since 2007 remains challenging, and the exact causes are not yet clear. But, the observations we describe suggest that increased emissions from microbial sources are the strongest driver, with a relatively smaller contribution from other processes, e.g., fossil fuel exploitation. A more difficult question to answer is the one posed by this special issue: is warming feeding the warming? We cannot say for certain,

but we cannot rule out the possibility that climate change is increasing CH_4 emissions. The strong signals from the tropics combined with the isotopic data are consistent with increased emissions from natural wetlands, but large [interannual variability (IAV)] and inter-decadal variability in wetland drivers like precipitation make it difficult to identify small trends. Observations are needed that will help process models capture this variability. The size of the IAV illustrates the potential scope of uncontrollable near-future change and emphasizes the urgency of reducing the global methane burden by mitigating the methane emissions that we can control, from the fossil fuel and agricultural sectors.").

[444] Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 5 ("A switch from La Niña to El Niño during 2023 appears to have reduced the observed growth rate (Figure 2), supporting a large role for wetland responses to La Niña in the very high 2020–2022 growth rates. However, emissions appear to have remained substantially higher in 2023 relative to pre-2020 values (Figure 1B), suggesting longer-term contributions from increasing anthropogenic sources along with a forced trend in natural sources. Recent work also suggests a potentially permanent shift to an altered state of enhanced wetland methane emissions (8)."). *See also* Allen G. H. (2022) *Cause of the 2020 surge in atmospheric methane clarified*, NATURE 612(7940): 413–414, 413 ("Its atmospheric concentration has nearly tripled since pre-industrial times, from 700 parts per billion (p.p.b.) to more than 1,900 p.p.b. today[3] (see also go.nature.com/3xm1dx4). During 2007–19, the concentration rose at a rate of 7.3 ± 2.4 p.p.b. per year. Then, in 2020, the methane growth rate increased dramatically to 15.1 ± 0.4 p.p.b. per year. … The concentration of atmospheric methane surged again (see go.nature.com/3xm1dx4) to 18.2 ± 0.5 p.p.b. per year in 2021 — another mysterious acceleration without a clear cause, and the fastest rate of increase ever recorded."); *citing data from* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 2 February 2023); *and* Lan X., Thoning K. W., & Dlugokencky E. J., *Trends in globally-averaged CH_4, N_2O, and SF_6 determined from NOAA Global Monitoring Laboratory measurements*, Version 2023-01 (*last visited* 2 February 2023).

[445] Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 479 ("Warmer and wetter wetlands over the Northern Hemisphere in 2020 (Supplementary Table 1) increased emissions by 6.0 ± 2.5 Tg CH_4 yr^{-1} relative to 2019, dominating the net increase in global wetland emissions (6.0 ± 2.3 Tg CH_4 yr^{-1}) in 2020 (Extended Data Fig. 5)."), 481 ("In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed 53 ± 10% of the MGR anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation.").

[446] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al.,

2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020).”). Where RCP4.5 is generally consistent with current climate commitments. *See also* Secretariat of the United Nations Framework Convention on Climate Change (25 October 2021) *Nationally determined contributions under the Paris Agreement: Revised synthesis report*, FCCC/PA/CMA/2021/ 8/Rev.1, 29 (Figure 9, “Note: The assessed global emission ranges (including LULUCF) for the IPCC scenarios provided in the SR1.5 (table 2.4) are shown with interquartile ranges. The illustrative SSP scenarios considered in the contribution of Working Group I to the AR6 are indicated (SSP2-4.5 by a yellow solid line, with an estimated end-of-century temperature of 2.7 (2.1–3.5) °C). The total GHG emission level resulting from implementation of the latest NDCs is compared with the emission levels for three of the scenario groups in the SR1.5 scenario database: a group of scenarios in which global mean temperature rise is kept at all times below 1.5 °C relative to the 1850–1900 (“below 1.5 °C”); a group of scenarios in which warming is kept at around 1.5 °C with a potential limited overshoot and then decrease of global mean temperature rise below 1.5 °C by the end of the century (“1.5 °C with limited overshoot”); and a third group that implies warming of well below 2 °C, that is above 1.5 °C by 2100 but with a likely chance of it being below 2 °C at all times (“lower 2 °C”). The latter group features scenarios with strong emission reductions in the 2020s or only after 2030.”).

[447] Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, NAT. GEOSCI. 13(2): 138–143, 138–139 (“The permafrost zone is expected to be a substantial carbon source to the atmosphere, yet large-scale models currently only simulate gradual changes in seasonally thawed soil. Abrupt thaw will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon through collapsing ground, rapid erosion and landslides. Here, we synthesize the best available information and develop inventory models to simulate abrupt thaw impacts on permafrost carbon balance. Emissions across 2.5 million km^2 of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km^2 permafrost region under the warming projection of Representative Concentration Pathway 8.5. While models forecast that gradual thaw may lead to net ecosystem carbon uptake under projections of Representative Concentration Pathway 4.5, abrupt thaw emissions are likely to offset this potential carbon sink. Active hillslope erosional features will occupy 3% of abrupt thaw terrain by 2300 but emit one-third of abrupt thaw carbon losses. Thaw lakes and wetlands are methane hot spots but their carbon release is partially offset by slowly regrowing vegetation. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, we conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost.. Our simulations suggest net cumulative abrupt thaw carbon emissions on the order of 80±19PgC by 2300 (Fig. 2a). For context, a recent modelling study found that gradual vertical thaw could result in permafrost carbon losses of 208PgC by 2300 under RCP8.5 (multimodel mean), although model projections ranged from a net carbon gain of 167PgC to a net loss of 641PgC (ref. 2). Thus, our results suggest that abrupt thaw carbon losses are equivalent to approximately 40% of the mean net emissions attributed to gradual thaw. Most of this carbon release stems from newly formed features that cover <5% of the permafrost region”). *See also* Schuur E. A. G., *et al*. (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47: 343–71, 351 (“Research at the global scale that links these effects across both lowlands and uplands showed that 20% of the northern permafrost region was considered susceptible to past and future abrupt thaw (47). Importantly, this area also stores 50% of the near-surface soil carbon showing the correlation between carbon and ice accumulation that heightens the risk of abrupt thaw to climate change. Since ESMs do not simulate abrupt thaw, dynamics of ecosystem change including carbon cycling have been represented by a different class of regional models that track soil carbon losses as well as carbon gains from plant growth through ecological succession following abrupt thaw. The most comprehensive of these succession models that included the response of abrupt thaw across uplands and lowlands found that an additional 40% more net ecosystem carbon (80 ± 19 Pg C) would be released by 2300 (48) as compared to the ensemble estimate of net ecosystem carbon release from the PCN-MIP (30), which as described previously, only tracked the effect of gradual top-down permafrost thaw as the climate warms. Most of this additional 40% carbon release is attributed to new abrupt thaw features that cover <5% of the permafrost region. Moreover, plant growth in the succession model offset approximately 20% of the permafrost carbon release, a much lower proportion as compared to the estimate from ESMs in the PCN-MIP. Furthermore, the abrupt thaw succession model could track CH_4, in contrast to the PCN-MIP, which did not, and showed that approximately 20% of the net carbon loss from

abrupt thaw could be emitted as CH_4, which contributed 50% of the radiative forcing due to its higher global warming potential. These findings are consistent with other abrupt thaw models that considered subsets of the Arctic permafrost landscape such as lake expansion in lowlands (26, 27).").

[448] Rehder Z., Kleinen T., Kutzbach L., Stepanenko V., Langer M., & Brovkin V. (2023) *Simulated methane emissions from Arctic ponds are highly sensitive to warming*, BIOGEOSCI. 20(14): 2837–2855, 2838 ("Most Arctic ponds emit predominantly contemporary, recently fixed, carbon (Negandhi et al., 2013; Bouchard et al., 2015; Dean et al., 2020). However, newly-formed ice-wedge ponds might emit older carbon than the average Arctic pond. When the permafrost adjacent to the thawing ice wedge degrades, old carbon can leech from the thawed sediments into the pond fueling methanogenesis (Langer et al., 2015; Preskienis et al., 2021) and exerting a positive climatic feedback. Furthermore, the composition of the ponds' methanogenic communities might change in response to the warming Arctic."), 2849 ("While ponds are not hotspots of methane emissions in our study area under the current climate, our model simulations indicate that they will become stronger methane sources under further warming. We project an increase of pond methane emissions of 1.33 g CH_4 m^{-2} $year^{-1}$ $°C^{-1}$."). *See also* Kleinen T., Gromov S., Steil B., & Brovkin V. (2021) *Atmospheric methane underestimated in future climate projections*, ENVIRON. RES. LETT. 16(9): 1–14, 4 ("In the case of the low radiative forcing scenarios SSP1–1.9 and SSP1–2.6, the concentration maximum occurs at the end of the historical period and does not differ significantly between our experiments and the published scenarios. The concentration decline after that maximum, however, occurs much more slowly in our experiments, leading to higher atmospheric methane concentrations than in the published scenarios. For the moderate to high warming scenarios SSP2–4.5, SSP3–7.0 and SSP5–8.5, however, the evolution of atmospheric methane is much more dramatic. Here, maximum atmospheric concentrations become substantially higher than in the published scenarios and stay at a very high level until the end of the experiments in 3000 CE. For SSP2–4.5, the maximum in CH_4 is 50% higher than published previously, for SSP3–7.0 it is 131% higher and for SSP5–8.5 it is 130% higher.").

[449] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020)."). *See also* Permafrost Pathways, *Course of Action: Mitigation Policy* (*last visited* 5 February 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement. … Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish.... 82% [o]f IPCC models do not include carbon emissions from permafrost thaw."); *and* Froitzheim N., Majka J., & Zastrozhnov D. (2021) *Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave*, PROC. NAT'L. ACAD. SCI. 118(32): 1–3, 1 ("In the Taymyr Peninsula and surroundings in North Siberia, the area of the worldwide largest positive surface temperature anomaly for 2020, atmospheric methane concentrations have increased considerably during and after the 2020 heat wave. Two elongated areas of increased atmospheric methane concentration that appeared during summer coincide with two stripes of Paleozoic carbonates exposed at the southern and northern borders of the Yenisey-Khatanga Basin, a hydrocarbon-bearing sedimentary basin between the Siberian Craton to the south and the Taymyr Fold Belt to the north. Over the carbonates, soils are thin to nonexistent and wetlands are scarce. The maxima are thus unlikely to be caused by microbial methane from soils or wetlands. We

suggest that gas hydrates in fractures and pockets of the carbonate rocks in the permafrost zone became unstable due to warming from the surface. This process may add unknown quantities of methane to the atmosphere in the near future."); *discussed in* Carrington D. (2 August 2021) *Climate crisis: Siberian heatwave led to new methane emissions, study says*, THE GUARDIAN ("The Siberian heatwave of 2020 led to new methane emissions from the permafrost, according to research. Emissions of the potent greenhouse gas are currently small, the scientists said, but further research is urgently needed. Analysis of satellite data indicated that fossil methane gas leaked from rock formations known to be large hydrocarbon reservoirs after the heatwave, which peaked at 6C above normal temperatures. Previous observations of leaks have been from permafrost soil or under shallow seas."), *and* Mufson S. (3 August 2021) *Scientists expected thawing wetlands in Siberia's permafrost. What they found is 'much more dangerous'*, THE WASHINGTON POST.

[450] Cheng C. & Redfern S. A. T. (2022) *Impact of interannual and multidecadal trends on methane-climate feedbacks and sensitivity*, NAT. COMMUN. 13(3592): 1–11, 1 ("We identify oscillations between positive and negative feedbacks, showing that both contribute to increasing C_{CH4}. Interannually, increased emissions via positive feedbacks (e.g. wetland emissions and wildfires) with higher land surface air temperature (LSAT) are often followed by increasing C_{CH4} due to weakened methane sink via atmospheric •OH, via negative feedbacks with lowered sea surface temperatures (SST), especially in the tropics. Over decadal time scales, we find alternating rate-limiting factors for methane oxidation: when C_{CH4} is limiting, positive methane-climate feedback via direct oceanic emissions dominates; when •OH is limiting, negative feedback is favoured. Incorporating the interannually increasing C_{CH4} via negative feedbacks gives historical methane-climate feedback sensitivity ≈ 0.08 W m^{-2} $°C^{-1}$, much higher than the IPCC AR6 estimate.").

[451] Feng L., Palmer P. I., Zhu S., Parker R. J., & Liu Y. (2022) *Tropical methane emissions explain large fraction of recent changes in global atmospheric methane growth rate*, NAT. COMMUN. 13(1378): 1–8, 2 ("Our analysis of GOSAT CH_4 column data from 2010 to 2019 shows large-scale changes in tropical CH_4 emissions that explain more than 80% of the observed global atmospheric growth rate. Over this decadal period, we find that tropical Africa plays the largest role in determining the variation of tropical emissions, followed by tropical South America and India. We find that emissions from mainland and maritime (island nations) of Southeast Asia have reduced over our study period, driven by reduced rainfall. Contrary to a previous study we find no evidence of an upward trend in Indian emissions early in the study period, instead our analysis shows large year-to-year variations that peak during the 2014–2016 El Niño and again during 2017 and 2019. We find that we can explain a significant fraction of changes in CH_4 emissions over tropical South America and tropical Africa by large-scale changes in tropical SSTs characterized by indices that describe El Niño and the Indian Ocean Dipole, respectively."), 5 ("Our analysis over tropical Africa, in particular, represents a first step towards understanding a new positive climate feedback in the Earth system. Previous studies have reported relationships between a warming climate due to rising levels of atmospheric greenhouse gases and increases in the magnitude and variations of the IOD(28), and between the strength of the IOD and rainfall over East Africa(29) and, by extension via this study, wetland emissions of CH_4. Future changes in the IOD will also impact the large-scale fires over maritime Southeast Asia, where there is a large reservoir of carbon-rich peat, and over Australia. The situation over tropical South America is more complicated with future Atlantic–Pacific SST patterns resulting in regional patterns of anomalous positive and negative rainfall trends over the Amazon basin(30) so that the net regional effect on wetland emissions of CH_4 is uncertain."). *See also* Feng L., Palmer P. I., Parker R. J., Lunt M. F., & Bösch H. (2023) *Methane emissions are predominantly responsible for record-breaking atmospheric methane growth rates in 2020 and 2021*, ATMOS. CHEM. PHYS. 23(8): 4863–4880, 4867 ("Particularly, we find statistically significant large-scale positive correlations (typically 0.5- 0.6; p<0.001) for all seasons between methane and groundwater anomalies over Eastern Africa, tropical South America, and tropical Asia, but there is no significant correlation between methane and surface temperature anomalies. This is consistent with recent studies that have highlighted the increasing role for microbial sources in the tropical methane budget (Lunt et al. 2019; Fen et al. 2022; Wilson et al. 2020)."); *and* Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ENVIRON. RES. LETT. 17(9): 1–9, 5 ("Africa shows an increase of 15 Tg a^{-1} in methane emissions from 2019 to 2020, consistent with the 13 Tg a^{-1} increase reported in another inverse analysis of GOSAT observations (Feng et al 2022). We attribute most of the

increase to wetland emissions in East Africa (30◦ E–50◦ E, 15◦ S–10◦ N) due to the increases in rainfall by 20% (46 mm) in the first three seasons from 2019 to 2020 according to the tropical applications of meteorology using SATellite and ground based observations (TAMSAT) (www.tamsat.org.uk/index.php/data). Consistent with the increase in rainfall, the water flows of the Congo-Oubangui River, which goes through wetlands in the Congo Basin, were much higher in 2020 than in previous years (World Meteorological Organization 2021). Flooding in 2020 was widespread, affecting 50% more East Africans than in 2019 (BBC 2020).").

[452] Gulev S. K., *et al*. (2021) *Chapter 2: Changing State of the Climate System*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 2-100 ("The role of decadal to multi-decadal variability has recently emerged as an important aspect of the IOD with many indications of the effects of Pacific Ocean processes on IOD variability through atmospheric and oceanic mechanisms (Dong et al., 2016; Jin et al., 2018; Krishnamurthy & Krishnamurthy, 2016; Zhou et al.,2017) … Positive IOD events may have increased in frequency during the second half of the 20th century (Abram et al., 2020a,b). Earlier observations of apparent changes in the frequency and / or magnitude of the IOD events are considered unreliable, particularly prior to the 1960s (Hernández et al., 2020). … To summarize, there is *low confidence* in any multi-decadal IOD variability trend in the instrumental period due to data uncertainty especially before the 1960s. … Neither the IOD nor the IOB have exhibited behaviour outside the range implied by proxy records (*low confidence*)."). *Compare with* Cheng C. & Redfern S. A. T. (2022) *Impact of interannual and multidecadal trends on methane-climate feedbacks and sensitivity*, NAT. COMMUN. 13(3592): 1–11, 7 ("The feedback sensitivity, in ppb °C^{-1}, before 1994 initially rises under positive feedback dominance, but declines subsequently and appears to stabilize around 200 ppb °C^{-1} (Fig. 6a, b). This approximates ~0.08 W m^{-2} °C^{-1} (ref. 70) which is about four times greater than the mean net feedback estimate given in IPCC AR6 (~0.05 positive feedback including permafrost and −0.03 negative feedback, giving ~0.02 W m^{-2} °C^{-1}) but agrees within uncertainty[7]. The difference could be largely due to the positive $\partial C_{CH4}(T\&Pr)/\partial t$ from negative feedbacks following the years or decades of positive feedback. In fact, several interannual peaks of sensitivity are due to the positive contributions of lowering GMST (i.e., negative feedbacks). If we breakdown our estimated sensitivity into positive and negative feedbacks, we estimate 0.05 + 0.03 W m^{-2} °C^{-1} rather than 0.05 – 0.03 W m^{-2} °C^{-1}. Since the 200 ppb °C$_{-1}$ long-term sensitivity is even larger than the estimated absolute maximal instantaneous sensitivity in Eq. 5 (i.e., the calibration factor α in Eqs. 3–4) at 125 (ppb yr^{-1})/(°C yr^{-1}), the positive contributions from negative feedbacks should be viewed as lagged responses from earlier positive feedbacks due to nonlinearity. We note that the sensitivity is strongest in boreal and tropical regions (Fig. 6a) due to the positive feedbacks with wetland emissions.").

[453] Weldeab S., Schneider R. R., Yu J., & Kylander-Clark A. (2022) *Evidence for massive methane hydrate destabilization during the penultimate interglacial warming*, PROC. NAT'L. ACAD. SCI. 119(35): 1–9, 7 ("While further studies are needed to determine the extent of methane hydrate destabilization during the weakened AMOC interval of the Eemian, the consequence of broad methane hydrate destabilization is increased atmospheric CH_4 and CO_2 concentrations. Taking age model uncertainties into consideration, during the peak in anomalously low carbon isotopes, the atmospheric CO_2 and CH_4 concentrations rose by 17 to 10 parts per million per volume and 20 parts per billion per volume, respectively (SI Appendix, Fig. S9) (49–51). Although the magnitude of this change varies between ice cores and analytical laboratories, the $\delta^{13}C$ values of atmospheric CO_2 declined by 0.3 to 0.4‰ coeval with the $\delta^{13}C$ anomaly recorded in the Gulf of Guinea sediment sequence (SI Appendix, Fig. S9) (50, 52), indicating that a source with a significantly negative $\delta^{13}C$ signature contributed to the increase of atmospheric CO_2. Methane release and methane oxidation due to massive methane hydrate destabilization is the likely source.").

[454] Whiteman G., Hope C., & Wadhams P. (2013) *Vast costs of Arctic change*, NATURE 499(7459): 401–403, 401 ("We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of $60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about $70 trillion). The total cost of Arctic change will be much higher. … The methane pulse will bring forward by 15–35 years the average date at which the global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario

and to 2040 for the low-emissions case (see 'Arctic methane'). This will lead to an extra $60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about $400 trillion). In the low-emissions case, the mean net present value of global climate-change impacts is $82 trillion without the methane release; with the pulse, an extra $37 trillion, or 45% is added. … These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse. The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. … The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone. To find out the actual cost, better models are needed to incorporate feedbacks that are not included ….."). *See also* Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press; *and* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, GEOSCI. 9(6): 1–23.

[455] Wadham J. L., Hawkings J. R., Tarasov L., Gregoire L. J., Spencer R. G. M., Gutjahr M., Ridgwell A., & Kohfeld K. E. (2019) *Ice sheets matter for the global carbon cycle*, NAT. COMMUN. 10(1): 3567, 1–17, 8–9 ("There are substantial uncertainties regarding the magnitude of present day sub-ice sheet CH_4 hydrate reserves because of the difficulties of accessing sediments in subglacial sedimentary basins. Global subglacial methane hydrate stocks at the present day are likely to be dominated by those in Antarctic sedimentary basins (estimated at up to 300 Pg C as methane hydrate and free gas). At the LGM, the global sub-ice sheet hydrate reserve could have been much larger (>500 Pg C, 20% of the present day marine hydrate stocks), with hydrate also present beneath former northern hemisphere ice sheets (see Fig. 4 for details and calculation methods). The vulnerability of Antarctic subglacial CH_4 hydrate reserves to destabilization is high because of their predicted location around the continent's periphery in sedimentary basins where ice thinning in a warming climate is probable."). *See also* Dessandier P.-A., Knies J., Plaza-Faverola A., Labrousse C., Renoult M., & Panieri G. (2021) *Ice-sheet melt drove methane emissions in the Arctic during the last two interglacials*, GEOLOGY 49(7): 799–803, 799 ("Here, we argue that based on foraminiferal isotope studies on drill holes from offshore Svalbard, methane leakage occurred upon the abrupt Eurasian ice-sheet wastage during terminations of the last (Weichselian) and penultimate (Saalian) glaciations. Progressive increase of methane emissions seems to be first recorded by depleted benthic foraminiferal $\delta^{13}C$. This is quickly followed by the precipitation of methane-derived authigenic carbonate as overgrowth inside and outside foraminiferal shells, characterized by heavy $\delta^{18}O$ and depleted $\delta^{13}C$ of both benthic and planktonic foraminifera. The similarities between the events observed over both terminations advocate a common driver for the episodic release of geological methane stocks. Our favored model is recurrent leakage of shallow gas reservoirs below the gas hydrate stability zone along the margin of western Svalbard that can be re-activated upon initial instability of the grounded, marine-based ice sheets. Analogous to this model, with the current acceleration of the Greenland ice melt, instabilities of existing methane reservoirs below and nearby the ice sheet are likely.").

[456] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, Introductory Summary ("This report identifies priority research that should be addressed within 3-5 years so that a second-phase assessment could more robustly assess the technical, economic, and social viability of technologies to remove atmospheric methane at climate-relevant scales. The research agenda presented in this report includes foundational research that would help us better understand atmospheric methane removal while also filling knowledge gaps in related fields, and systems research that seek[s] to address what developing and/or deploying atmospheric methane removal at scale would entail. A Research Agenda Toward Admospheric Methane Removal also assesses five atmospheric methane removal technologies that would accelerate the conversion of methane to a less radiatively potent form or physically remove methane from the atmosphere and store it elsewhere."); *see also* Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 1 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely

this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."). *See also* Oeste F. D., de Richter R., Ming T., & Caillol S. (2017) *Climate engineering by mimicking natural dust climate control: the iron salt aerosol method*, EARTH SYSTEM DYNAMICS 8: 1–54; Ming T., Richter R. de, Dietrich Oeste F., Tulip R., & Caillol S. (2021) *A nature-based negative emissions technology able to remove atmospheric methane and other greenhouse gases*, ATMOSPHERIC POLLUTION RESEARCH 12(5): 101035; *and* Jackson R. (25 July 2024) *The Best Quick Fix for Climate Change? Curbing Methane*, THE WASHINGTON POST.

[457] Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., & Field C. B. (2019) *Methane removal and atmospheric restoration*, NAT. SUSTAIN. 2(6): 436–438, 437 ("Sustained efforts in methane removal, even after atmospheric restoration, could provide additional advantages for offsetting CH_4 emissions from agriculture and industry. A recent marginal cost-abatement curve for methane in the oil and gas sector estimated that almost half of methane emissions could be mitigated at no net cost; however, abatement costs rose steeply beyond that point. Sustained methane removal could offset the most expensive emissions effectively permanently, with research needed to determine the extent to which removal efficiency decreases and cost increases as methane concentrations decrease. Similarly in agriculture, some methane emissions from rice and meat production seem inevitable, even after substantial efforts to reduce them. Here, too, methane removal might counterbalance the most intractable emissions."). *See also* Brazzola N., Wohland J., & Patt A. (2021) *Offsetting unabated agricultural emissions with CO_2 removal to achieve ambitious climate targets*, PLOS ONE 16(3): 1–19, 1 ("Failing to mitigate agricultural methane and nitrous oxide emissions could contribute to an overshoot of the RCP2.6 warming by about 0.4℃. We explore using additional CDR to offset alternative agricultural non-CO_2 emission pathways in which emissions either remain constant or rise. We assess the effects on the climate of calculating CDR rates to offset agricultural emission under two different approaches: relying on the 100-year global warming potential conversion metric (GWP100) and maintaining effective radiative forcing levels at exactly those of RCP2.6. Using a reduced-complexity climate model, we find that the conversion metric leads to a systematic underestimation of needed CDR, reaching only around 50% of the temperature mitigation needed to remain on the RCP2.6 track. This is mostly because the metric underestimates, in the near term, forcing from short-lived climate pollutants such as methane.").

[458] The atmospheric concentration of CO_2 in 2022 is about 420 parts CO_2 per million parts air (ppm) compared with about 1.9 parts CH_4 per million parts air; 420/1.9 = 221. On a mass basis, CH_4 (molar mass 16) is 600 times more dilute than CO_2 (molar mass 44); 221x44/16 = 607. *See also* Lackner K. S. (2020) *Practical constraints on atmospheric methane removal*, NAT. SUSTAIN. 3(5): 357 ("Methane removal poses two challenges: extreme dilution and competition from natural processes. This raises the question of whether methane is really the best target for removal from the air. First, the dilute concentration of methane in the atmosphere challenges economical removal. On a mass basis, methane is currently 600 times more dilute in Earth's atmosphere than carbon dioxide; in pre-industrial times it was 1,000 times more dilute.").

[459] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 4 ("We first compare and contrast aspects of CH_4 and CO_2 removal. In contrast to CO_2, CH_4 can be oxidized catalytically, without the need for capture, in a thermodynamically favourable reaction: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ ($\Delta Hr = -803$ kJ mol^{-1}), although such a reaction is difficult at typical conditions of atmospheric temperature and pressure [29]. Because of methane's potency as a greenhouse gas (34 times higher Global Warming Potential (GWP) than CO_2 on a century timescale and 86 times higher on a 20-year timescale), considerably less methane removal is needed to realize the same climate impact.").

[460] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 1 ("Methane removal has at least two key benefits: reducing temperature more rapidly than carbon dioxide removal and improving air quality by reducing surface ozone concentration.").

[461] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 1 ("Methane removal has at least two key benefits: reducing temperature more rapidly than carbon dioxide removal and improving air quality by reducing surface ozone concentration.").

[462] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 8 ("One consideration is the potential unintended atmospheric chemistry effects of methane removal. For example, removal technologies that oxidize methane to carbon dioxide may inadvertently oxidize partially to carbon monoxide (CO) or methanol (CH_3OH) [24]. Furthermore, removal technologies must be compared in terms of costs, energy, land and water usage, and social implications of implementation.").

[463] For additional information, *see* Spark Climate Solutions *Atmospheric Methane Removal Primer* (*last visited* 8 March 2024). *See also* Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 4 ("Here, we describe broad classes of technologies for methane removal, including photocatalysts, metal catalysts associated with zeolites and porous polymer networks, biological methane removal, including industrial approaches and approaches for managing soils in agricultural or other ecosystems, and iron-salt aerosol formation (table 2). For each of these technologies, research is needed on its cost, technological efficiency, scaling and energy requirements, social barriers to deployment, co-benefits and potential negative by-products. Research is also needed broadly on methane sorption to concentrate methane from low concentration background air; having better sorbents would make methane removal technologies more efficient generally.").

[464] de Richter R., *et al.* (11 September 2019) *Iron Salt Aerosol a natural method to remove methane & other greenhouse gases*, Institution of Mechanical Engineers Presentation, 8 ("Iron Salt Aerosol can enhance both natural sinks: the hydroxyl radical sink and the chlorine sink"). *See also* Van Herpen M. M. J. W., Li Q., Saiz-Lopez A., Liisberg J. B., Röckmann T., Cuevas C. A., Fernandez R. P., Mak J. E., Mahowald N. M., Hess P., Meidan D., Stuut J.-B. W., & Johnson M. S. (2023) *Photocatalytic chlorine atom production on mineral dust–sea spray aerosols over the North Atlantic*, PROC. NATL. ACAD. SCI. U.S.A. 120(31): e2303974120, 1–8, 2 ("Here, we present field and modeling evidence of the mechanism of the production of atomic Cl via the photocatalytic oxidation of chloride in aerosols containing Sahara mineral dust. By this mechanism, Cl_2 and Cl are generated when lofted iron-bearing mineral dust aerosol from North Africa descends into the marine boundary layer (MBL) over the Atlantic and mixes with sea spray aerosol to form Mineral Dust-Sea spray Aerosols (MDSA). We combine data from field with global atmospheric modeling and predict extremely low δ^{13}C-CO values that match those seen in CO in air samples from Barbados (25); these results remained unexplained for 20 y. Finally, we discuss the global significance of this mechanism that is not yet included in global models."); Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-34 ("About 90% of the loss of atmospheric CH_4 occurs in the troposphere by reaction with hydroxyl (OH) radical, 5% by bacterial soil oxidation, and the rest 5% by chemical reactions with OH, excited state oxygen (O^1D), and atomic chlorine (Cl) in the stratosphere (Saunois et al., 2020)."); *and* Lan X., *et al.* (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH_4 observations and the way forward*, PHILOS. TRANS. R. SOC. A 379(2210): 1–14, 8 ("The largest atmospheric loss process in the global CH_4 budget is mostly initiated by reaction with OH, especially in the tropical mid-troposphere, but also by Cl and $O(^1D)$ (stratosphere only). Oxidation by microbes in soils is likely a small sink, but uncertainty in its magnitude and trend remain large [37].").

[465] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 7–8 ("Enhanced microbial oxidation of methane in agricultural and other soils or in artificial substrates (e.g., biotrickling filters) is a microbially based approach for methane mitigation or atmospheric removal (e.g., [44,45]). Han et al. [61] showed that amendments of biochar derived from rice straw reduced methane emissions from paddy soils by 40% in microcosm experiments, a case of methane mitigation from a known source (i.e. with elevated methane concentrations in air). The decrease was attributable to both decreased activity of methanogens and increased methane oxidation activity of methanotrophs. Sulfate additions have also been shown to reduce methane emissions from rice paddies [62]. Miller et al. [63] demonstrated that iron and humic acid amendments significantly suppressed in situ net methane fluxes by 26% in Arctic Alaska peatland soils, likely by enhancing alternative electron acceptor availability. This example is more analogous to methane removal from the bulk air because it was not associated with a known methane source."). *See also* He L., Groom J. D., Wilson E. H., Fernandez J., Konopka M. C., Beck D. A. C., & Lidstrom M. E. (2023) *A methanotrophic bacterium to enable methane removal for climate mitigation*, PROC. NATL. ACAD. SCI. U.S.A.120(35): e2310046120, 1–8, 1 ("We report here that some existing methanotrophic strains grow well at 500 ppm methane, and one of them, *Methylotuvimicrobium buryatense* 5GB1C, consumes such low methane at enhanced rates compared to previously published values. Analyses of bioreactor-based performance and RNAseq-based transcriptomics suggest that this ability to utilize low methane is based at least in part on extremely low non-growth-associated maintenance energy and on high methane specific affinity. This bacterium is a candidate to develop technology for methane removal at emission sites. If appropriately scaled, such technology has the potential to slow global warming by 2050.").

[466] Yoon S., Carey J. N., & Semrau J. D. (2009) *Feasibility of atmospheric methane removal using methanotrophic biotrickling filters*, APPL. MICROBIOL. BIOTECHNOL. 83(5): 949–956, 949 ("Here, we describe the modeling of a biotrickling filtration system composed of methane-consuming bacteria, i.e., methanotrophs, to assess the utility of these systems in removing methane from the atmosphere. Model results indicate that assuming the global average atmospheric concentration of methane, 1.7 ppmv, methane removal is ineffective using these methanotrophic biofilters as the methane concentration is too low to enable cell survival. If the concentration is increased to 500–6,000 ppmv, however, similar to that found above landfills and in concentrated animal feeding operations (factory farms), 4.98–35.7 tons of methane can be removed per biofilter per year assuming biotrickling filters of typical size (3.66 m in diameter and 11.5 m in height).... The use of methanotrophic biofilters for controlling methane emissions is technically feasible and, provided that either the costs of biofilter construction and operation are reduced or the value of CO_2 credits is increased, can also be economically attractive."). *See also* Sly L. I., Bryant L. J., Cox J. M., & Anderson J. M. (1993) *Development of a biofilter for the removal of methane from coal mine ventilation atmospheres*, APPL. MICROBIOL. BIOTECHNOL. 39(3): 400–404, 400 ("The experimental biofilter utilizing a biofilm of M. fodinarum was shown to reduce methane levels substantially provided the residence times were sufficiently long. In the range 0.25–1.0% methane in air, commonly experienced in coal mine atmospheres, more than 70% of the methane was removed with a residence time of 15 min, with a 90% reduction at 20 min. Even at a residence time of 5 min approximately 20% of the methane in air was removed. Equal quantities of O_2 are consumed during the bacterial oxidation of methane and 1% methane is converted to 0.7% CO_2. Scale-up and alternative biofilter packings are likely to reduce the residence times in the biofilter.").

[467] Krogsbøll M., Russell H. S., & Johnson M. S. (2023) *A high efficiency gas phase photoreactor for eradication of methane from low-concentration sources*, ENVIRON. RES. LETT. 19(014017): 1–8 ("A laboratory prototype of the methane eradication photochemical system (MEPS) technology achieves 58% removal efficiency with a flow capacity of 30 l min^{-1}; a reactor volume of 90 l; UV power input at 368 nm of 110 W; chlorine concentration of 99 ppm; and a methane concentration of 55 ppm; under these conditions the apparent quantum yield (AQY) ranged from 0.48% to 0.56% and the volumetric energy consumption ranged from 36 to 244 kJ m^{-3}. The maximum achieved AQY with this system was 0.83%. A series of steps that can be taken to further improve performance are described. These metrics show that MEPS has the potential to be a viable method for eliminating low-concentration methane from waste air.").

[468] Brenneis R. J., Johnson E. P., Shi W., & Plata D. L. (2021) *Atmospheric- and Low-Level Methane Abatement via an Earth-Abundant Catalyst*, ACS ENVIRON. AU 2(3): 223–231, 223 ("Here, we describe the use of a biomimetic copper zeolite capable of converting atmospheric- and low-level methane at relatively low temperatures (e.g., 200−300 °C) in simulated air."); *discussed in* Chandler D. L. (10 January 2022) *A dirt-cheap solution? Common clay materials may help curb methane emissions*, MIT NEWS.

[469] Alicat Scientific, *Frost Methane mitigates methane gas emissions from Arctic Circle permafrost* (*last visited* 26 January 2023) ("Frost Methane and collaborators from University of Alaska Fairbanks tested their methane-capture technology for the first time on August 13, 2021. The team deployed their equipment at a lake in the Arctic Circle, about 67.25 degrees north. Laughlin Barker, Frost Methane's Senior Embedded Systems Engineer, described the lake as, 'basically a Jacuzzi, there's so much natural gas.'"). *See also* Yin J., Su S., Yu X., Bae J.-S., Jin Y., Villella A., Jara M., Ashby M., Cunnington M., & Loney M. (2020) *Site Trials and Demonstration of a Novel Pilot Ventilation Air Methane Mitigator*, ENERGY FUELS 34(8): 9885–9893, 9885–9886 ("Principal uses of [ventilation air methane] involve combustion of the methane in ventilation air as the primary fuel, which offers the greatest mitigation potential. Currently, technologies for principal use of VAM can be grouped into the following categories: • Flow reversal reactors, including the thermal flow reversal reactors (TFRR) and catalytic flow reversal reactors (CFRR). • Flow through reactors, including the catalytic monolith combustor (CMR), porous burner, and rotary recuperative thermal oxidizer (RTO). • Chemical/stone dust looping (SDL) for VAM abatement. • Biologic reactors. • Lean-burn gas turbines, including the catalytic lean-burn gas turbine, and recuperative gas turbine. • Enrichment by adsorbents, solvents (e.g., ion liquids), membrane, metal−organic frameworks (MOFs), hydration, centrifugal separation, and buoyancy separation. • Negative emissions reduction pathway and emerging technologies, such as photocatalytic oxidation of methane in the atmosphere."); *and* Prabhu Energy Labs, *Oxiperator* (*last visited* 26 January 2023).

[470] Shayegan Z., Lee C.-S., & Haghighat F. (2018) *TiO_2 photocatalyst for removal of volatile organic compounds in gas phase – A review*, CHEM. ENG. J. 334: 2408–2439, 2408 ("Heterogeneous photocatalytic oxidation process (PCO) is a promising technology for removing indoor volatile organic compounds (VOCs) contaminants. Titanium dioxide (TiO_2) has been regarded as the most suitable photocatalyst for its cost effectiveness, high stability and great capability to degrade various VOCs.").

[471] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 8 ("In this first-phase report, the Committee has identified priority research questions that should be addressed within 3–5 years. With the results from this research, a second-phase assessment could more robustly assess the viability of technologies to remove atmospheric methane at 2 ppm—from the perspective of technical, economic, and broader social viability, and the potential for climate-scale impacts. Advances in the recommended research areas and a second-phase assessment would inform any decision to move from knowledge discovery into more targeted investment in additional research, development, and/or deployment.").

[472] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03 Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of *E*."); *discussed in* Jordan R. (26 September 2021) *Stanford-led research reveals potential of an overlooked climate change solution*, STANFORD WOODS INSTITUTE FOR THE ENVIRONMENT ("The

analyses, published Sept. 27 in Philosophical Transactions of the Royal Society A, reveal that removing about three years-worth of human caused emissions of the potent greenhouse gas would reduce global surface temperatures by approximately 0.21 degrees Celsius while reducing ozone levels enough to prevent roughly 50,000 premature deaths annually. The findings open the door to direct comparisons with carbon dioxide removal – an approach that has received significantly more research and investment – and could help shape national and international climate policy in the future. … Under a high emissions scenario, the analysis showed that a 40 percent reduction in global methane emissions by 2050 would lead to a temperature reduction of approximately 0.4 degrees Celsius by 2050. Under a low emissions scenario where temperature peaks during the 21st century, methane removal of the same magnitude could reduce the peak temperature by up to 1 degree Celsius.").

[473] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 6 (*see* Table S-1 "Summary of the State of Atmospheric Methane Removal Technology Research Relative to 2 Parts Per Million (ppm) Atmospheric Methane Concentrations").

[474] The UCLA Emmett Institute has published a global survey of existing, and imminent, methane regulations as part of the Advancing Methane Regulation Project to help guide policymakers to develop effective methane regulations: UCLA Law, *Advancing Methane Regulation* (*last visited* 11 April 2024) ("The UCLA Emmett Institute launched the Advancing Methane Regulation Project to help guide policymakers as they develop regulations to hunt and halt super-polluting methane. In October 2023, the Emmett Institute convened a meeting on the UCLA campus of more than two-dozen experts in science, technology, law, and policy to inform the goals of the project. To inform the project's launch, we produced a global survey of existing, and imminent, methane regulations.") *See* UCLA Emmett Institute on Climate Change & the Environment, *The State of Methane Regulation: A Global Survey* (*last visited* 11 April 2024).

[475] Rogelj J. & Lamboll R. D. (2024) *Substantial reductions in non-CO_2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget*, COMMUN. EARTH ENVIRON. 5: 1–5, 2 ("RCB estimates in line with limiting warming to 1.5 °C assume 1.5 °C-compatible CH_4 reductions from 2020 to 2050 of 51% (47–60%, range between 25th and 75th quantile regressions at 1.5 °C of global warming across scenarios, see Fig. 1, panel a)."), 4 ("Assuming global CH_4 emissions do not decline but instead are kept constant at 2020 levels would reduce the RCB by 431, 370, and 280 $GtCO_2$-we for RCBs compatible with 1.5 °C, 1.7 °C, and 2 °C, respectively. In other words, choosing not to reduce CH_4 emissions and correctly adjusting for this decision in RCB estimates would cause 1.5 °C-compatible RCBs to be exhausted as of today (Fig. 1b, Table 1, Supplementary Tables S2, S5), in effect putting the 1.5 °C ambition of the Paris Agreement out of reach. Even a global 40% reduction between 2020 and 2040 would cause a 1.5 °C-compatible RCB reduction of about 60 $GtCO_2$-we, highlighting the importance of deep reductions in CH_4.").

[476] Olczak M., Piebalgs A., & Balcombe P. (2023) *A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness*, ONE EARTH 6(5): 519–535, 520 ("Only ~13% (minimum [min.] 10%, maximum [max.] 17%) of global methane emissions are covered by direct methane mitigation policies, while limited policy stringency and reliance on inaccurate emission estimates remain barriers to effective policy. These findings suggest that a consistent approach for accurate identification, quantification, and verification of methane emission sources alongside greater pol- icy coverage and stringency (e.g. measurable objectives and enforcement) must be put into place to realize significant methane emission reduction opportunities").

[477] International Energy Agency (2021) DRIVING DOWN METHANE LEAKS FROM THE OIL AND GAS INDUSTRY: A REGULATORY ROADMAP AND TOOLKIT.

[478] Colombia Ministry of Mines and Energy (11 February 2022) Resolución Número 40066 de 11 Feb 2022; *discussed in* Miranda-González A. & Banks J. (16 February 2022) *A Methane Champion: Colombia becomes first South American country to regulate methane from oil and gas*, Clean Air Task Force.

[479] XV BRICS Summit (23 August 2023) *Johannesburg II Declaration,* 19 ("We oppose trade barriers including those under the pretext of tackling climate change imposed by certain developed countries and reiterate our commitment to enhancing coordination on these issues. We underline that measures taken to tackle climate change and biodiversity loss must be WTO-consistent and must not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade and should not create unnecessary obstacles to international trade. Any such measure must be guided by the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), in the light of different national circumstances. We express our concern at any WTO inconsistent discriminatory measure that will distort international trade, risk new trade barriers and shift burden of addressing climate change and biodiversity loss to BRICS members and developing countries.").

[480] International Energy Agency, *Methane Tracker Database Australia* (*last visited* 2 July 2023). For a summary overview of Australian national and subnational methane policies and regulations and proposed pledges, *see* Government of Australia (2023) DISCUSSION Paper on Agriculture and Land Emissions.

[481] Climate Watch, *Australia Greenhouse Gas Emissions* (*last visited* 2 July 2023).

[482] *See generally* Denis-Ryan A. (2023) *Gross under-reporting of fugitive methane missions has big implications for industry*, Institute for Energy Economics and Financial Analysis. *See also* (8 August 2023*) Methane camera reveals widespread potent gas leaks*, THE MIRAGE ("The field trip - a joint initiative of the global non-profit Clean Air Task Force and the Australian Conservation Foundation - visited coal mines and gas facilities in June and found: Methane leaking or being deliberately vented from more than 100 individual sources. At least 25 leaks/vents along Jemena's JGN and Darling Downs pipelines. At least 10 leaks/vents from Origin's coal seam gas wells and Shell/QGC gas-gathering pipelines in Queensland. Methane being released from four of the seven Santos' coal seam gas wells surveyed in the Pilliga/Bibblewindi forest in NSW. Multiple cases of continuous venting at the APA-operated compressor station at the Wallumbilla Gas Hub.").

[483] Denis-Ryan, A. (2023) *Gross under-reporting of fugitive methane missions has big implications for industry*, Institute for Energy Economics and Financial Analysis, 3 ("Our analysis indicates that fugitive methane emissions from coal mining and oil and gas supply have likely been grossly underestimated to date – by about 80% for coal and 90% for oil and gas. Correcting this under-reporting would have big implications for industrial facilities covered by the Safeguard Mechanism. In order to stay within the newly introduced emissions caps, facilities would have to double their rate of decarbonisation and halve their emissions between 2023 and 2030. This highlights the need for urgent action to improve methane emissions monitoring in Australia and to develop a plan to address domestic methane emissions.").

[484] Australian Government Department of Climate Change, Energy, the Environment and Water (23 October 2022) *Australia joins Global Methane Pledge*, Press Release ("The Australian Government is prioritising long-term competitiveness and joining the over 120 countries committed to collectively reduce global methane emissions across energy and resources, agriculture and waste sectors.").

[485] Climate Change Act 2022 S10 ("Australia's greenhouse gas emissions reduction targets are as follows: (a) reducing Australia's net greenhouse gas emissions to 43% below 2005 levels by 2030: (i) implemented as a point target; and (ii) implemented as an emissions budget covering the period 2021-2030; (b) reducing Australia's net greenhouse gas emissions to zero by 2050.").

[486] Denis-Ryan A. (2023) *Gross under-reporting of fugitive methane missions has big implications for industry*, Institute for Energy Economics and Financial Analysis, 5 ("Australia joined the Global Methane Pledge, which aims

to reduce global methane emissions by at least 30% below 2020 levels by 2030, but did not specify a domestic methane reduction target or a plan for how it will address them.").

[487] Government of Australia (2023) *Safeguard Mechanism (Crediting) Amendment Bill 2023* ("Amends the: National Greenhouse and Energy Reporting Act 2007 to create safeguard mechanism credit units (SMCs) and provide for related registration, transfer and compliance arrangements consistent with the treatment of Australian Carbon Credit Units (ACCUs); Income Tax Assessment Act 1997 to provide that SMCs receive the same tax treatment as other specified units; Australian National Registry of Emissions Units Act 2011 to: provide ownership and transfer arrangements for SMCs; require the publication of information about holdings and cancellations of SMCs; and provide for the making of legislative rules to increase transparency of information on unit holdings or allow for the voluntary surrender of units; Clean Energy (Consequential Amendments) Act 2011, Clean Energy Regulator Act 2011 and National Greenhouse and Energy Reporting Act 2007 to: provide that protected information includes all information held by the Clean Energy Regulator regardless of when it was obtained; and make consequential amendments; and Carbon Credits (Carbon Farming Initiative) Act 2011 to: enable legislative rules to prevent the regulator from entering into carbon abatement contracts that reduce covered emissions of facilities covered by the safeguard mechanism; require the regulator to consider the safeguard mechanism when assessing the regulatory additionality of proposed offsets projects; and make a consequential amendment."). *See also* Morton A. & Hannam P. (9 January 2023) *Australia's big polluters must cut emissions by nearly 5% a year, but can use offsets to get there*, THE GUARDIAN ("Starting from 1 July, big polluters would be expected to cut their emissions intensity – how much they emit per unit of production – by 4.9% a year until 2030. That was forecast to cut industrial emissions by at least 30% between 2021 and 2030, from 143m tonnes a year to no more than 100m tonnes.").

[488] Government of New South Wales (2023) *Climate Change (Net Zero Future) Bill 2023* ("The targets for reducing net greenhouse gas emissions in New South Wales are—
(a) by 30 June 2030—to reduce net greenhouse gas emissions in New South Wales by at least 50% from the net greenhouse gas emissions in 2005, and
(b) by 30 June 2035—to reduce net greenhouse gas emissions in New South Wales by at least 70% from the net greenhouse gas emissions in 2005, and
(c) by 30 June 2050—to reduce net greenhouse gas emissions in New South Wales to zero."). *See also* Vorrath S. (30 November 2023) *NSW passes climate bill to write 70 pct by 2035 emissions reduction target into law*, RENEW ECONOMY. ("NSW parliament has voted unanimously to enshrine the state's emissions reduction task in law, legislating a new 70 per cent by 2035 target as well as the Paris aligned goal net zero by 2050.").

[489] Thompson Reuters Practical Law, *Oil and gas regulation in Australia: overview* (*last visited* 15 November 2023) ("Flaring is typically covered by the relevant petroleum and environmental regulations in each State and Territory. The legislation that regulates flaring differs between each jurisdiction. For example, in Queensland petroleum should be commercially used wherever possible, and flared if not. In addition, venting will only be allowed if it is not technically possible or unsafe to flare.").

[490] Queensland Petroleum and Gas (Production and Safety) Act 2004 S 151 ("Flaring the gas is authorised if it is not commercially or technically feasible to use it— (a) commercially under the lease; or (b) for an authorised activity for the lease. (3) Venting the gas is authorised if— (a) it is not safe to use the gas for a purpose mentioned in subsection (2)(a) or (b) or to flare it; or (b) flaring it is not technically practicable.").

[491] Northern Territory of Australia Department of Environment and Natural Resources & Department of Primary Industry and Resources (2019) CODE OF PRACTICE: ONSHORE PETROLEUM ACTIVITIES IN THE NORTHERN TERRITORY, 108 ("Venting and flaring of natural gas should be eliminated or minimised where practicable.").

[492] Government of Western Australia Department of Mines, Industry Regulation and Safety, *A Look at Western Australia* (*last visited* 15 November 2023) ("Western Australia remains the nation's premier petroleum producer, accounting for 50 per cent of gas production (including natural gas, coal seam methane and LNG feedstock), 61 per

cent of crude oil production and 76 per cent of condensate production. In total, Western Australian produced just over half (52 per cent) of the nation's total petroleum output in energy equivalence terms in 2016.").

[493] Government of Western Australia (2016) SHALE AND TIGHT GAS IN WESTERN AUSTRALIA, 19 ("There are several possible sources of emissions into the air from shale or tight gas operations, and these sources change over time as the operation progresses from exploration to decommissioning. The environment plan submitted to DMP must detail the anticipated emissions and how the risk of these emissions will be managed to as low as reasonably practicable and within acceptable standards and monitoring of bulk emissions, such as venting or flaring.").

[494] Australian Government Department of Climate Change, Energy, the Environment and Water, *Reducing methane from livestock* (*last visited* 15 November 2023) ("The Australian Government is funding the $6 million Methane Emissions Reduction in Livestock (MERiL) Stage 1 program to support research and development of methane-reducing livestock feed technologies.").

[495]Australian Government Department of Climate Change, Energy, the Environment and Water, *Reducing methane from livestock* (*last visited* 15 November 2023) ("Stage 2 is providing $5 million in grants to develop and determine the feasibility of delivery technologies.").

[496] Australian Government Department of Climate Change, Energy, the Environment and Water, *Reducing methane from livestock* (*last visited* 15 November 2023) ("Stage 3 will provide $15 million in grants to undertake trials to validate the delivery technology and demonstrate its emissions reduction and productivity impacts.").

[497] Australian Government Department of Climate Change, Energy, the Environment and Water, *Reducing methane from livestock* (*last visited* 15 November 2023) ("The Government is providing $8.1 million to support the commercialisation of seaweed as a low emissions feed technology and lower barriers to market entry.").

[498] Australian Government Department of Climate Change, Energy, the Environment and Water, *Reducing methane from livestock* (*last visited* 15 November 2023) ("A further $9.3 million is being directed to scale-up production of the red seaweed, Asparagopsis, including: a $3.82 million funding contribution through the Securing Raw Materials Program, which will enable Sea Forest, in collaboration with the University of Tasmania, to develop a commercial-scale, land-based Asparagopsis production model. This is in addition to previous funding for Sea Forest including $1 million through the Entrepreneurs' Programme and $675,000 from the Commercialisation Fund. … a $3.76 million funding contribution through the Securing Raw Materials Program for CH4 South Australia's seaweed production project in regional South Australia.").

[499] Australia Department of Agriculture Fisheries and Forestry (2018) NATIONAL WASTE POLICY, 15 ("Reduce organic waste, including garden and food waste, by avoiding their generation and supporting diversion away from landfill into soils and other uses, supported by appropriate infrastructure.").

[500] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("Australia's governments have set the goal to halve Australia's food waste, and halve the amount of organic waste sent to landfill, by 2030. This means redirecting 2.7 million tonnes of organic waste to productive re-use every year instead of sending it to landfill. Reusing our organic waste contributes to a circular economy, in which waste is turned into valuable products like compost, soil conditioners and mulches.").

[501] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("Governments expanded Garden Organic (GO) and Food Organics and Garden Organics (FOGO) kerbside collection services to households and businesses in Australia. Many jurisdictions have targets in place for these roll-outs. The Australian Government published an interactive map showing where GO and FOGO collection is available.").

[502] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("Stop Food Waste Australia began working to drive industry change and deliver a voluntary commitment program, the Australian Food Pact. It will work with organisations across the food supply chain to develop tailored plans to help them achieve their food waste goal.").

[503] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("The national Food Waste for Healthy Soils Fund was announced, to support recycling infrastructure that will create consistent, safe and high-quality recycled organic products for use on our soils.").

[504] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("NSW ran a pilot 'Scrap Together' campaign, drawing on results of bin audits and social research, to improve the rate of food waste recycling in 3 council areas. The pilot campaign increased food waste recycling by an average of 10% and the campaign has since been expanded to other council areas.").

[505] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("South Australia released a State Food Waste Strategy 2020–2025 to reduce and divert household and business food waste, outlining 38 actions including policy measures, behavioural change actions and continued support for industry across 3 program areas to capture material and return to productive use.").

[506] Australia Department of Energy and Climate Change (2021) NATIONAL WASTE POLICY PROGRESS SUMMARY REPORT, 12 ("The SA Government's Kerbside Performance Plus Food Organics Incentives Program provided financial support for local government to roll out area-wide high performing food waste diversion systems. All 19 metropolitan councils and 14 regional councils, representing over 80% of South Australia's population, have FOGO systems in place.").

[507] International Energy Agency, *Methane Tracker Data Explorer* (*last visited* 5 February 2023).

[508] de Oliveira-Junior, M. (4 April 2022) *The Impact of the Global Methane Pledge on the Brazilian Beef Industry*, WEB ADVOCACY ("Due to its large bovine herd (220 million cattle, equivalent to 14% of the bovine global herd), Brazil is the fifth largest methane emitter in the world[3]. In 2020, it emitted almost 402,000 million metric tons of CO_2 equivalent (MMTCO_2E – around 2% of total world emissions). The heaviest methane emitter in Brazil is agriculture, which accounts for 78% of total emissions. Livestock, on its own, is responsible for 75% (300,000 MMTCO_2E) of the country's methane emissions (primarily from enteric fermentation and manure management). Therefore, to achieve a 30% reduction below the 2020 levels, livestock emissions must fall sharply.").

[509] Global Methane Initiative, *Methane Emissions Data* (*last visited* 5 February 2023).

[510] Government of Brazil (2022) DECRETO Nº 11.003, DE 21 DE MARÇO DE 2022; *discussed in* Bezerra L. G., Trevizan V. P., Gomes G., Negro R., & Rodrigues V. (28 March 2022) *Brazil Launches Federal Strategy to Incentivize the Sustainable Use of Biogas and Biomethane and Methane Zero Program*, Tauil, Chequer, Mayer, Brown ("On March 21, 2022, the Brazilian government enacted Decree No. 10,003/2022, creating the Federal Strategy to Incentivize the Sustainable Use of Biogas and Biomethane. The strategy is a new package of incentives and programs to reduce methane emissions, promote usage of biogas and biomethane as renewable sources of energy and fuel, and help meet the commitments Brazil made under the United Nations Framework-Convention on Climate Change, the Glasgow Climate Pact and the Global Methane Commitment.").

[511] Bezerra L. G., Trevizan V. P., Gomes G., Negro R., & Rodrigues V. (28 March 2022) *Brazil Launches Federal Strategy to Incentivize the Sustainable Use of Biogas and Biomethane and Methane Zero Program*, Tauil, Chequer, Mayer, & Brown ("To enable the implementation of the Federal Strategy to Incentivize to the Sustainable Use of Biogas and Biomethane, the decree established comprehensive guidelines to encourage, among other things, the development of carbon markets and sector plans, the use of biomethane as a source of sustainable energy and fuel,

and scientific-technological research. It is worth noting that the decree provides a non-exhaustive list of urban and rural waste that shall be considered as sources of biogas and biomethane, including waste disposed of in landfills, generated in sewage treatment plants and derived from the sugar-energy chain. This provision is in line with Federal Law No. 12,305/2010, which created the National Policy on Waste Management and established that incentivizing environmental management systems was one of its objectives, particularly through waste-to-energy initiatives.").

[512] Government of Brazil (2022) DECRETO Nº 11.003, DE 21 DE MARÇO DE 2022, Art. 7 ("As principais fontes de biogás e biometano consideradas no âmbito da Estratégia Federal de Incentivo ao Uso Sustentável de Biogás e Biometano são os resíduos de origem urbana e rural, incluídos, entre outros: I - os resíduos dispostos em aterros sanitários; II - os resíduos gerados em estações de tratamento de esgoto; III - os resíduos da cadeia sucroenergética; e IV - os resíduos de suinocultura, avicultura e outros.").

[513] Government of Brazil (2022) PORTARIA MMA No 71, DE 21 DE MARÇO DE 2022; *discussed in* Bezerra L. G., Gomes G., & Costa L. (26 March 2022) *Brazil launches Methane Zero National Program with a package of incentive measures to biogas and biomethane*, Mayer & Brown ("The new package – called Federal Strategy of Incentive to the Sustainable Use of Biogas and Biomethane – includes the Methane Zero National Program. … One of the main targets of the incentive package – in addition to promoting research and development of new technologies allowing the reduction of methane emissions and the use of biogas and biomethane as sources of sustainable energy and fuel – is to promote the development of carbon markets, particularly introducing the methane credit. Although the package does not provide further details on such methane credits, they are supposed to represent a ton of methane that has not been emitted and are expected to be aligned with existing carbon credits markets, in the sense that the marketing of such methane credits should generate additional income to biogas and biomethane projects.").

[514] Bezerra L. G., Gomes G., & Costa L. (26 March 2022) *Brazil launches Methane Zero National Program with a package of incentive measures to biogas and biomethane*, Mayer & Brown ("Considering RenovaBio created a regulated market in which fossil fuel distribution companies have yearly decarbonization targets they must meet by acquiring decarbonization credits, which in turn are generated by producers of biofuels, such as ethanol, biodiesel and biomethane, it is expected that in fact the newly created methane credit will be a part of the RenovaBio market, not only reinforcing its already significant role, but also further developing such a market.").

[515] United States Department of Energy Office of International Affairs (22 August 2022) *United States and Brazil Strengthen Bilateral Cooperation on Energy and Launch a New Public Private Cooperation to Promote Clean Energy*, Press Release ("Secretary Granholm and Minister Sachsida endorsed a bilateral cooperation plan for technical, regulatory, and policy cooperation in three areas: Carbon and Methane Management, Civil Nuclear Power, and Renewables, Energy Efficiency, and Grid Modernization: The two governments agreed to exchange expertise in carbon and methane management, and carbon sequestration and storage.").

[516] Vasconcellos R. B. (4 August 2022) *Energy Is Up on U.S.-Brazil Relations*, United States Chamber of Commerce ("Offshore wind energy is a common priority for these two continental countries, and there is fertile ground for a productive dialogue on this topic. Wind (albeit onshore) already plays an important role as a source of energy in diversifying Brazil's energy grid, ranking second (13.4%) behind only hydropower (56.7%). Meanwhile, the U.S. contribution will come from the U.S. administration's vision of wind as a key pillar of the U.S. clean energy agenda and its work towards the deployment of 30 GW of offshore wind by 2030. Collaboration on sustainable fuels is also important for the dialogue. Brazil is known for having vehicles running on ethanol derived from sugarcane since the 1970s. On the other hand, U.S. industry, inspired by the U.S. administration's ambitious goal to rapidly increase the production of sustainable aviation fuels by 2030, has a lot of knowledge to offer to Brazil and the Latin America region.").

[517] Climate and Clean Air Coalition (4 December 2023) *Highlights from the 2023 Global Methane Pledge Ministerial*, ("Brazil announced that its National Council of Energy Policy will establish guidelines on methane reduction in the

oil and gas sector by the end of 2024, and the National Agency for Petroleum, Natural Gas and Biofuels (ANP) aims to finalize regulations by the end of 2025 based on these guidelines.").

[518] Government of Canada. (2021) *Canada's 2021 Nationally Determined Contribution under the Paris Agreement*, 1 ("Through this submission, the Government of Canada is pleased to update its nationally determined contribution (NDC) under the Paris Agreement. Canada's updated NDC is to reduce emissions by 40-45% below 2005 levels by 2030, a substantial increase of ambition beyond Canada's original NDC, as previously communicated upon ratifying the Paris Agreement in 2016. Additionally, Canada is committed to reducing its emissions to net-zero by 2050. Canada's enhanced NDC, and accompanying information for clarity, transparency, and understanding, are further outlined in Annex 1 to this submission. Annex 2 outlines provincial and territorial climate action and Annex 3 outlines Indigenous climate action."); 26 ("Alberta: Climate Goals: Through regulatory measures, Alberta will reduce methane emissions from upstream oil and gas production by 45%, from 2014 levels, by 2025."). *See also* Government of Canada (2017) *Canada's 2017 Nationally Determined Contribution Submission to the United Nations Framework Convention on Climate Change*, 3 ("To reduce emissions from industrial sectors, Canada is developing regulations to achieve a reduction of methane emissions from the oil and gas sector, including offshore activities, by 40–45 percent by 2025.").

[519] Environment and Climate Change Canada (11 October 2021) *Canada confirms its support for the Global Methane Pledge and announces ambitious domestic actions to slash methane emissions*, News Release ("The International Energy Agency has made it clear that curbing methane emissions from oil and gas operations represents one of the best near-term opportunities for limiting the worst impacts of climate change and has called on countries and companies to reduce methane emissions from the sector by 75% below 2012 levels by 2030. At the Meeting, the Minister noted the importance of the 75% goal and called on other oil-producing nations to join Canada in adopting it."). *See generally* Environmental Defense Fund (2023) *How to meet Canada's methane reduction goals*.

[520] Environment and Climate Change Canada (2019) *Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)* ("Companies must register their facilities before April 30th, 2020, or within 120 days of when the facility begins to be covered by any of the requirements. There are also provisions in the regulations to retain information for record-keeping, inspection purposes, and for on-demand reporting to Environment and Climate Change Canada. Regulatory requirements for fugitive equipment leaks, venting from well completions, and compressors, come into force on January 1, 2020. Regulatory requirements for facility production venting restrictions and venting limits for pneumatic equipment come into force on January 1, 2023.").

[521] Environment and Climate Change Canada (10 November 2022) *Canada and the United States to take further actions to address emissions from North American oil and gas sector*, Press Release ("In Canada, earlier this year, Minister Guilbeault committed to working with the Canadian oil and gas industry to identify pathways to achieving net-zero emissions by 2050 and reaffirmed Canada's commitment to reduce methane emissions by at least seventy-five percent by 2030. Today, Environment and Climate Change Canada published a proposed framework outlining the main elements of the new regulations. The draft regulations will be published early next year.").

[522] Government of Canada (*last updated* 20 September 2023) *Proposed regulatory framework for reducing oil and gas methane emissions to achieve 2030 target* ("Hydrocarbon Gas Conservation and Destruction Equipment**:** ● Destruction equipment would be required to operate at a 99%+ control efficiency; ● Conservation equipment would be required to operate at 98%+ efficiency; and ●Fuel combustion would be required to meet a 95% control efficiency.").

[523] Government of Canada (*last updated* 20 September 2023) *Proposed regulatory framework for reducing oil and gas methane emissions to achieve 2030 target* ("Flaring**:** ● Would be prohibited at oil sites; ● Enclosed combustion methods and equipment would be required to have an auto-igniter; and ●Operators would be required to ensure that equipment is working as intended.").

[524] Government of Canada (*last updated* 20 September 2023) *Proposed regulatory framework for reducing oil and gas methane emissions to achieve 2030 target* ("Fugitive Emissions ● Would no longer be bound by conditional requirements. All facilities would be required to have a fugitive emission management plan with monthly inspections; single wellhead sites included; ● Once a suspected leak is detected, the operator would be required to confirm and fix the leaking component immediately or if not feasible, within 30 days; and ● An extension repair request in extreme circumstances could be granted by the Minister.").

[525] Helmore K. (26 November 2023) *Ottawa poised to announce new methane regulations, heading into COP28*, THE GLOBE AND MAIL ("The federal government is poised to announce new regulations and funding around methane – a greenhouse gas that's 85 times more potent than carbon dioxide – heading into COP28 on Thursday. These regulations will be the cornerstone of Canada's COP28 climate plan. They follow the 2021 Global Methane Pledge, a joint agreement in which more than 100 countries promised to cut methane emissions by at least 30 per cent below 2020 levels by 2030.").

[526] Government of Canada (4 December 2023) *Proposed Amendments to the Federal Methane Regulations for the Oil and Gas Sector - Technical backgrounder* ("The proposed Regulatory amendments are intended to ensure a reduction of methane emissions in the upstream oil and gas sector by at least 75 per cent below 2012 levels by 2030."). A draft version of the proposed amendments is available here *see* Government of Canada (2023) *Regulations Amending the Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)*.

[527] Government of Canada (4 December 2023*) Proposed Amendments to the Federal Methane Regulations for the Oil and Gas Sector - Technical backgrounder* ("The proposed Regulatory amendments are intended to ensure a reduction of methane emissions in the upstream oil and gas sector by at least 75 per cent below 2012 levels by 2030. This would be achieved by expanding the scope of the existing Regulations, introducing a focus on maximizing emission reductions, removing some exclusions, and ensuring all practical actions to lower emissions that are considered both achievable and cost effective are in place by 2030.").

[528] Government of Canada (2020) *Agreement on the equivalency of federal and Alberta regulations respecting the release of methane from the oil and gas sector in Alberta*. *See also* Government of Canada (2020) *Agreement on the Equivalency of Federal and British Columbia Regulations Respecting the Release of Methane from the Oil and Gas Sector in British Columbia*; *and* Government of Canada (2020) *Saskatchewan equivalency with federal methane regulations: emissions reduction estimation*.

[529] Canada Energy Regulator (*last updated* 24 January 2024) *Provincial and Territorial Energy Profiles – Canada* ("Canadian production is centered in western Canada, which accounted for about 95% of total production in 2020. The remaining 5% was produced mostly in Newfoundland and Labrador. Alberta, Saskatchewan, and Newfoundland produce 96% of Canada's oil. These three are also the only provinces that produce heavy oil…. Alberta and B.C. accounted for almost 98% of Canadian production in 2020. Smaller amounts of natural gas are produced in Saskatchewan, New Brunswick, Ontario, and the Northwest Territories (NWT).").

[530] Canada Energy Regulator (*last updated* 24 January 2024) *Provincial and Territorial Energy Profiles – Canada* ("Alberta's gas production represented 63% of total Canadian natural gas production in 2020."); *contrasting* Canada Energy Regulator (*last updated* 2 February 2024) *Provincial and Territorial Energy Profiles – British Columbia* ("In 2020, natural gas production in B.C. averaged 5.38 billion cubic feet per day (Bcf/d) (Figure 1), accounting for 35% of total Canadian natural gas production."); *and* Canada Energy Regulator (*last updated* 2 February 2024) *Provincial and Territorial Energy Profiles – Saskatchewan* ("Saskatchewan's gas production represented approximately 2% of total Canadian natural gas production in 2020.").

[531] Government of Alberta, *Reducing methane emissions* (*last visited* 16 November 2023) ("Alberta was the first regional government in North America to commit to a methane emissions reduction target for the oil and gas sector.

Alberta will use a combination of policy tools to achieve the province's 45% methane reduction target by 2025 including regulatory requirements, market-based programs, and investments in technology and innovation."). *See also* Government of Alberta (2023) *Alberta emissions reduction and energy development plan*, 28 ("Alberta Environment and Protected Areas will engage stakeholders, Albertans, and Indigenous organizations to assess potential pathways to achieve a provincial 75 to 80 percent methane emission reduction target from the conventional oil and gas sector by 2030 (from 2014 levels). The pathways will use combination of regulations, market-based incentives and programs, complemented by continuous improvement in measurement and reporting. It will focus on cost-effective, outcome-based approaches.").

[532] Government of Alberta (2023) *Alberta emissions reduction and energy development plan*, 27 ("Alberta achieved a 44 percent reduction in methane emissions from the oil and gas sector between 2014 and 2021, and we are on track to meet or surpass our goal for a 45 percent reduction by 2025.").

[533] Government of Alberta (2023) *Alberta emissions reduction and energy development plan*, 27 ("To support the methane emissions policy, Alberta established a working group in 2022 with experts from academia, industry and associations, Indigenous businesses, ENGOs and technology service providers. The working group assessed the effectiveness of the policy to achieve the 2025 target and provided recommendations for government").

[534] Government of Alberta, *Reducing methane emissions* (*last visited* 16 November 2023) ("Examples of current and previously implemented programs to support technology and innovation related to methane emissions reductions include: Current programs: Alberta Methane Emissions Program (AMEP): $17-million to support investigating and testing alternative approaches to detection and quantification of fugitive and vented emissions.")

[535] Government of Alberta (2023) *Alberta emissions reduction and energy development plan*, 27 ("The Methane Technology Implementation Program has supported projects at oil and gas sites that are anticipated to reduce methane emissions by 17 Mt over the lifetime of the technologies. This program is supported by $25 million from Alberta's TIER fund").

[536] Government of Alberta, *Reducing methane emissions* (*last visited* 16 November 2023) ("Using funds from the industry-supported TIER system, the Government of Alberta is to providing continued support for methane technology and innovation approaches across the oil and gas sector."). *See also* Alberta Methane Emissions Program (2023) *Supporting innovation to reduce methane emissions*, Government of Alberta.

[537] Government of Alberta (2023) *Alberta emissions reduction and energy development plan*, 28 ("Alberta Environment and Protected Areas will engage stakeholders, Albertans, and Indigenous organizations to assess potential pathways to achieve a provincial 75 to 80 percent methane emission reduction target from the conventional oil and gas sector by 2030 (from 2014 levels). The pathways will use combination of regulations, market-based incentives and programs, complemented by continuous improvement in measurement and reporting. It will focus on cost-effective, outcome-based approaches."). *See also* Conrad B. M., Tyner D. R., Li H. Z., Xie D., & Johnson M. (2023) *A measurement-based upstream oil and gas methane inventory for Alberta, Canada reveals higher emissions and different sources than official estimates*, COMMUN. EARTH ENVIRON. 4: 416 ("Mitigation actions and regulations to meet critical 2030 methane reduction targets under the Global Methane Pledge are hampered by uncertainty in true levels of emissions and source breakdowns. Here we present a measurement-based, source-resolved, hybrid top-down/bottom-up methane inventory for conventional upstream oil and gas operations in Canada's largest oil and gas-producing province, Alberta. The derived 2021 inventory of 1337 kt/y is approximately 1.5× the official federal inventory and matches independent top-down aerial mass-balance and satellite estimates within uncertainties. Major sources are starkly different from official estimates, with venting (e.g., uncontrolled tanks, pneumatics, unlit flares) comprising almost two-thirds of emissions implying important mitigation opportunities. Derived methane intensities, while similar to U.S. basins, are approximately 4× those in neighbouring British Columbia and further reveal order-of-magnitude differences among individual anonymized companies at directly comparable facility types. This

highlights the importance of independent monitoring, reporting, and verification to ensure collective success in reducing emissions.").

[538] Government of Saskatchewan (2019) *Methane Action Plan*, 2 ("[I]ntroduce new made-in-Saskatchewan results-based regulations to reduce methane-based GHG emissions by 40 to 45 percent of 2015 levels or between 4 and 4.5 million tonnes of carbon dioxide equivalent (CO2e)[.]").

[539] Government of Saskatchewan (18 May 2022) *Saskatchewan Releases Latest Oil and Gas Emissions Report*, News and Media ("Provincial Oil And Gas Sector Has Reduced Greenhouse Gas Emissions By 60 Per Cent Since 2015 Today, the Ministry of Energy and Resources published its second Oil and Gas Emissions Management Regulations (OGEMR) Annual Emissions Report. In 2021, greenhouse gas (GHG) emissions from vented and flared gas at upstream oil facilities in Saskatchewan totalled 4.4 million tonnes (Mt) of carbon dioxide equivalent (CO2e). This represents a 6.5 Mt CO2e, or 60 per cent, reduction from 2015 levels and a 0.8 Mt or 15 per cent reduction from 2020 levels.").

[540] Chan E., Worthy D. E. J., Chan D., Ishizawa M., Moran M. D., Delcloo A., & Vogel F. (2020) *Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada Are Nearly Twice Those Reported in Inventories*, ENVIRON. SCI. TECHNOL. 54(23): 14899–14909, 14899 ("Total anthropogenic (oil and gas, agriculture, and waste) emission rates of methane from 2010 to 2017 in Alberta and Saskatchewan were derived using hourly atmospheric methane measurements over a six-month winter period from October to March. Scaling up the winter estimate to annual indicated an anthropogenic emission rate of 3.7 ± 0.7 $MtCH_4$/year, about 60% greater than that reported in Canada's National Inventory Report (2.3 $MtCH_4$). This discrepancy is tied primarily to the oil and gas sector emissions as the reported emissions from livestock operations (0.6 $MtCH_4$) are well substantiated in both top-down and bottom-up estimates and waste management (0.1 $MtCH_4$) emissions are small. The resulting estimate of 3.0 $MtCH_4$ from the oil and gas sector is nearly twice that reported in Canada's National Inventory (1.6 $MtCH_4$)."), 14905–14906 ("This result suggests that systematic inconsistencies found using the smaller-scale, shorter-term studies in Lloydminster (20) may indeed affect the overall energy-related methane emissions in Alberta and Saskatchewan. Individual regions in Alberta and Saskatchewan were also previously reported to suffer from unreported venting emissions in that actual venting emissions were 2.5 ± 0.5 times higher than the values in the inventory. (20) Furthermore, our findings are generally consistent with the results from a larger-scale (hemispheric) methane inversion study that focused on the high northern latitudes (north of 50°N) and which estimated 4.3 ± 1.3 $MtCH_4$/year of anthropogenic emissions for Alberta.").

[541] Environment and Climate Change Canada (11 October 2021) *Canada confirms its support for the Global Methane Pledge and announces ambitious domestic actions to slash methane emissions*, News Release ("Globally, agriculture and landfills are among the largest sources of methane emissions. The 2030 objective in the Pledge is expected to help prevent over 20 million tonnes of crop losses a year by 2030 by reducing ground-level ozone pollution, caused in part by methane. The Government of Canada is committed to supporting Canadian farmers and industry partners who are taking action to reduce emissions, sequester carbon and make their operations more sustainable, productive and competitive. This includes through investments in new programs, such as the Agricultural Climate Solutions initiative and the Agricultural Clean Technology Program, which aim to help farmers adopt new, beneficial management practices and clean technologies to boost productivity and lower emissions—including from methane. The Government is also committed to developing an approach to increase the number of landfills that collect and treat methane, and ensure existing systems capture as many methane emissions as possible."). *See also* Environment and Climate Change Canada (11 September 2023) *The Government of Canada invests in cleaning up Canada's landfill emissions*, News Release ("Today, the Honourable Steven Guilbeault, Minister of Environment and Climate Change, announced more than $575,000 to support a total of five projects. These projects are for pilot-scale implementation of innovative monitoring and automation systems to reduce methane emissions at Canadian landfills. Municipal solid waste landfills are responsible for almost one quarter of Canada's methane emissions, which are generated when biodegradable waste decomposes.").

[542] Environment and Climate Change Canada (2019) *Taking Stock: Reducing Food Loss and Waste in Canada*, 24 ("The Canadian Council of Ministers of the Environment (CCME) has traditionally played a role in promoting a coordinated approach for provincial and territorial authorities on waste issues through the Waste Reduction and Recovery Committee. Organic waste has been one area of focus in recent years.").

[543] Environment and Climate Change Canada (2019) *Taking Stock: Reducing Food Loss and Waste in Canada*, 24 ("British Columbia's Climate Leadership Plan which set a food waste prevention target of 30% by 2050. Guidance prepared to support the development of Municipal Waste Management Plans required under the Environmental Management Act encourages regional districts to plan for food waste reduction as part of their waste management plans.").

[544] Environment and Climate Change Canada (2019) *Taking Stock: Reducing Food Loss and Waste in Canada*, 24 ("Ontario's Food and Organic Waste Policy Statement includes proposed activities such as: developing awareness and education tools; directing food retailers and businesses to reduce food waste in their own operations; and working with schools to educate children on preventing and reducing food waste. Quebec's Politique bioalimentaire 2018-2025 commits to reducing waste and food losses, and promoting food donations. Recyc-Quebec included the reduction of food loss and waste in its 2016 action plan on source reduction (with actions targeting both household waste and industry waste) to contribute to the objectives of the Quebec Residual Materials Management Policy. Recyc-Quebec has also partnered with the National Zero Waste Council (NZWC) on the Love Food Hate Waste (LFHW) campaign and works with municipalities to reduce both food and organic waste going to landfill.").

[545] Environment and Climate Change Canada (2019) *Taking Stock: Reducing Food Loss and Waste in Canada*, 6 ("Tax credits that support agricultural food donation activities are offered in British Columbia, Ontario, Quebec and Nova Scotia to help offset the cost to harvest, package, and store surplus harvest for donation.").

[546] Agriculture and Agri-Food Canada, *Agricultural Climate Solutions* (*last visited* 5 February 2023) ("Agricultural Climate Solutions (ACS) is a multi-stream program that will help to develop and implement farming practices to tackle climate change. Through agricultural practices, such as shelterbelts or cover crops, farmland can store carbon and reduce greenhouse gas emissions. ACS is a program under the more than $4 billion Natural Climate Solutions Fund. Agriculture and Agri-Food Canada (AAFC) is partnering with Natural Resources Canada (NRCan) and Environment and Climate Change Canada (ECCC) to develop projects that invest in natural climate solutions, including NRCan's 2 Billion Trees program and ECCC's Nature Smart Climate Solutions Fund. These solutions will contribute to meeting Canada's greenhouse gas reduction targets and provide benefits towards the well-being of all Canadians.").

[547] Agriculture and Agri-Food Canada, *Agricultural Clean Technology Program: Adoption Stream: Applicant Guide* (*last visited* 5 February 2023) ("bioeconomy solutions that use agricultural waste and by-products to generate energy or create bio-products, including: • purchase and installation of technologies and equipment to support improved manure management and processing waste into bioenergy products and other useful outputs, including: • Anaerobic digesters for processing agricultural waste into bioenergy • Bio-product boiler systems for heating greenhouses and nurseries").

[548] Babu J. (11 December 2023) *Canada to offer incentives to cattle farms to reduce methane emissions*, REUTERS ("The new draft protocol, Reducing Enteric Methane Emissions from Beef Cattle (REME protocol), will incentivize farmers to implement changes that would cut enteric methane emissions from their beef cattle operations with an opportunity to generate offset credits that they can sell…Each credit represents one tonne of emission reductions and the REME protocol is expected to encourage cattle farms to reduce emissions by improving animal diets, management, and other strategies that support more efficient animal growth. The implementation of project activities will reduce the quantity of greenhouse gases (GHGs) emitted per unit mass of beef produced, by improving animal performance or directly reducing enteric methane emissions."). *See generally* Government of Canada (December 2023) *Draft Federal Offset Protocol: Reducing Enteric Methane Emissions from Beef Cattle*.

[549] Beef Magazine (5 February 2024) *Canada approves Bovaer to reduce methane emissions from cattle* ("Canadian authorities have granted market authorization for Bovaer, a methane reducing feed ingredient for cattle, which enables dairy and beef farmers to substantially lower their carbon footprint. The feed ingredient is an important tool for the nearly 10,000 dairy farmers in Canada and will enable them to make a substantial step forward towards their net zero ambitions. Bovaer reduces methane emissions by 30% on average for dairy cows, and thereby lowers the overall greenhouse gas footprint per liter of milk by 10-15%.").

[550] Canada Office of the Prime Minister (23 February 2021) *Roadmap for a Renewed U.S.-Canada Partnership* ("The leaders reaffirmed the shared commitment to reducing oil and gas methane emissions to protect public health and the environment, as guided by the best science.").

[551] Executive Body Working Group on Strategies and Review (30 September 2020) *Preparations for the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012*, ECE/EB.AIR/2020/3 – EBE/EB.AIR/WG.5/2020/3 at ¶ 20, ("As per the long-term strategy for the Convention for 2020–2030 and beyond (paragraph 50), the review should look at appropriate steps towards reducing emissions of black carbon, ozone precursors not yet addressed such as methane, and emissions from shipping with due consideration for International Maritime Organization (IMO) policies and measures... In line with the priorities identified in the long-term strategy for the Convention for 2020–2030 and beyond, the following should specifically be considered in answering the questions in annex I:(b) Hemispheric transport of ozone and particulate matter and their precursors and advancing efforts to address air pollution on a broader scale per paragraphs 63 and 78 of the long-term strategy for the Convention for 2020–2030 and beyond; health and ecosystem impacts from outside the ECE region; (c) Methane and its relationship to the hemispheric transport of ozone and its contribution to ozone in the ECE region[.]").

[552] China Ministry of Foreign Affairs (22 September 2020) *Statement by H.E. Xi Jinping, President of the People's Republic of China, At the General Debate of the 75th Session of The United Nations General Assembly*, Speech ("China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. We aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060."). *See also* China Ministry of Foreign Affairs (1 November 2021) *Written Statement by H.E. Xi Jinping, President of the People's Republic of China, Unite for Action, To Protect the Planet, Our Shared Home, At the World Leaders Summit*, 5 ("Recently, China released two directives: Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, and the Action Plan for Carbon Dioxide Peaking Before 2030. Specific implementation plans for key areas such as energy, industry, construction and transport, and for key sectors such as coal, electricity, iron and steel, and cement will be rolled out, coupled with supporting measures in terms of science and technology, carbon sink[s], fiscal and taxation [measures], and financial incentives. Taken together, these measures will forma. '1+N' policy framework for delivering carbon peak and carbon neutrality, with clearly defined timetable, roadmap and blueprint."); *and* Institute for Governance & Sustainable Development (25 October 2021) *Briefing: China Details Plans for Achieving Carbon-Peaking and Carbon-Neutrality Goals* ("On October 22 and 24, 2021, China issued two policy documents detailing its plans for achieving its carbon-peaking and carbon-neutrality goals: (1) the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, and (2) the Action Plan for Achieving Carbon Peaking Before 2030.").

[553] *Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035* [国民经济和社会发展第十四个五年规划和 2035 年远景目标纲要] (China) (2021) (hyperlink to original Chinese).

[554] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*.

[555] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*.

[556] China Ministry of Ecology and Environment et al. (7 November 2023) *Methane Emissions Control Action Plan* [甲烷排放控制行动方案] (hyperlink to original Chinese) (IGSD's annotated, English reference translation of the China Methane Emissions Control Action Plan is available here.).

[557] China Ministry of Ecology and Environment et al. (7 November 2023) *Methane Emissions Control Action Plan* [甲烷排放控制行动方案] (hyperlink to original Chinese) (IGSD's annotated, English reference translation of the China Methane Emissions Control Action Plan is available here.). *See also*, China Ministry of Ecology and Environment (7 July 2023) *Measures for the Administration of Greenhouse Gas Voluntary Emission Reduction Trading (Trial) (Draft for Comment)* [《温室气体自愿减排交易管理办法（试行）》（征求意见稿）] (hyperlink to original Chinese).

[558] China Ministry of Ecology and Environment et al. (7 November 2023) *Methane Emissions Control Action Plan* [甲烷排放控制行动方案] (hyperlink to original Chinese) (IGSD's annotated, English reference translation of the China Methane Emissions Control Action Plan is available here.).

[559] China National Energy Administration (24 November 2016) *13th Five-Year Plan for the Development and Utilization of Coalbed Methane (Coal Mine Gas)* [煤层气（煤矿瓦斯）开发利用"十三五"规划], 12 (hyperlink to original Chinese).

[560] Institute for Governance & Sustainable Development (28 April 2021) *China Announces Further Steps Toward Reduction of Non-CO_2 Super Climate Pollutant Emissions* (MEE issued the Emissions Standard for Coal-bed Methane / Coal Mine Gas (Trial) in 2008). *See also* China Ministry of Environmental Protection (now "Ministry of Ecology and Environment") and the General Administration of Quality Supervision, Inspection and Quarantine (2 April 2008) *Emission Standard of Coal-bed Methane / Coal Mine Gas (Trial)* [煤层气（煤矿瓦斯）排放标准（暂行）] (hyperlink to original Chinese).

[561] China National Development and Reform Commission, National Energy Administration, Ministry of Emergency Management and National Mine Safety Administration (17 January 2023) *Administrative Measures on Specialized Investment within the Central Government Budget for Coal Mine Safety Retrofit* [煤矿安全改造中央预算内投资专项管理办法] (hyperlink to original Chinese).

[562] Xinhua News Agency (3 October 2023) *Shanxi extracts record amount of coalbed methane* ("China's coal-rich province of Shanxi extracted 7.16 billion cubic meters of coalbed methane in the first eight months of 2023, a record high for the January-August period, according to the provincial statistics bureau. Shanxi's coalbed methane output accounted for about 81.8 percent of the country's total in the first eight months this year.").

[563] Central Committee of the Chinese Communist Party and the State Council (22 September 2021) *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy* [关于完整准确全面贯彻新发展理念做好碳达峰碳中和工作的意见] (hyperlink to original Chinese).

[564] The Central Committee of the Chinese Communist Party and the State Council (2 November 2021) *Opinions on Strengthening the Battle for Pollution Prevention and Control* [关于深入打好污染防治攻坚战的意见] (hyperlink to original Chinese).

[565] People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, submission to the Secretariat of UNFCCC, 2, 40.

[566] People's Republic of China (28 October 2021) *China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy*, submission to the Secretariat of UNFCCC, 8–9 ("By 2060, China will fully establish a clean, low-carbon, safe and efficient energy system, reach energy efficiency at international advanced levels, and improve the proportion of non-fossil fuels in energy consumption up to over 80%.") (Unofficial translation.).

[567] People's Republic of China (28 October 2021) *China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy*, submission to the Secretariat of UNFCCC, 13. *See also* Central Committee of the Chinese Communist Party and China State Council (22 October 2021) Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy [关于完整准确全面贯彻新发展理念做好碳达峰碳中和工作的意见] (hyperlink to original Chinese); *and* Institute for Governance & Sustainable Development (25 October 2021) *Briefing: China Details Plans for Achieving Carbon-Peaking and Carbon-Neutrality Goals* ("On October 22 and 24, 2021, China issued two policy documents detailing its plans for achieving its carbon-peaking and carbon-neutrality goals: (1) the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, and (2) the Action Plan for Achieving Carbon Peaking Before 2030.").

[568] (28 October 2021) *China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy*, submission to the Secretariat of UNFCCC, 9. *See also* China State Council (24 October 2021) *Action Plan for Achieving Carbon Peaking Before 2030* [2030 年前碳达峰行动方案] (hyperlink to original Chinese).

[569] China Ministry of Ecology and Environment et al. (7 November 2023) *Methane Emissions Control Action Plan* [甲烷排放控制行动方案] (hyperlink to original Chinese) (IGSD's annotated, English reference translation of the China Methane Emissions Control Action Plan is available here.).

[570] People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, submission to the Secretariat of UNFCCC, 52.

[571] China National Petroleum Corporation (19 May 2021) *China Oil and Gas Methane Alliance was inaugurated* ("It has seven members: CNPC, SINOPEC, CNOOC, PipeChina, Beijing Gas, CR Gas and ENN Energy, with CNPC serving as its first president. At the conference, the founding members jointly announced their pledge to control methane emissions across the entire industry chain and take practical measures to push for the clean and low-carbon transformation of energy. The China Oil and Gas Methane Alliance is committed to building a high-quality and open platform for technical experience sharing and cooperation, improving methane emissions control, and actively engaging in global climate governance. It will join the global efforts to ensure systematic, regular, standardized and international methane monitoring and measurement, promote and adopt leak detection and repair (LDAR) and other effective emissions control measures throughout the industry chain, from oil and gas production, storage and transportation to sales, increase the recovery and utilization of vented gas during exploration and development, actively develop new energy sources, and reduce dependence on fossil fuels during oil and gas production. … Through the China Oil and Gas Methane Alliance, member companies will incorporate methane emissions control into their carbon emissions reduction plan, comprehensively improve methane emissions control, strive to reduce the average methane intensity in natural gas production to below 0.25% by 2025.").

[572] China State Council (24 October 2021) *Action Plan for Achieving Carbon Peaking Before 2030* [2030 年前碳达峰行动方案] (link to original Chinese).

[573] The Central Committee of the Chinese Communist Party and the State Council (2 November 2021) *Opinions on Strengthening the Battle for Pollution Prevention and Control* [关于深入打好污染防治攻坚战的意见] (hyperlink to original Chinese).

[574] China Ministry of Ecology and Environment et al. (7 November 2023) *Methane Emissions Control Action Plan* [甲烷排放控制行动方案] (hyperlink to original Chinese) (IGSD's annotated, English reference translation of the China Methane Emissions Control Action Plan is available here.).

[575] The Central Committee of the Chinese Communist Party and the State Council (2 November 2021) *Opinions on Strengthening the Battle for Pollution Prevention and Control* [关于深入打好污染防治攻坚战的意见] (hyperlink to original Chinese).

[576] General Office of the Central Committee of the Communist Party of China and General Office of the State Council (2021) *Opinions on Innovative Institutional Mechanisms to Promote the Green Development of Agriculture* [关于创新体制机制推进农业绿色发展的意见] (hyperlink to original Chinese).

[577] China Ministry of Agriculture and Rural Affairs and National Development and Reform Commission (30 June 2022) *Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture Sector and Rural Area* [农业农村减排固碳实施方案] (hyperlink to original Chinese).

[578] General Office of China Ministry of Agriculture and Rural Affairs (9 November 2022) *Guiding Opinions for Promoting the Construction of Ecological Farms* [推进生态农场建设的指导意见] (hyperlink to original Chinese).

[579] Climate & Clean Air Coalition (1 November 2021) *Methane Mitigation Through Manure Management is Key to Successfully Transforming China's Agricultural Sector* ("Research developed in partnership with the CCAC on the most effective methane mitigation strategies was presented to the group drafting the work plan and the majority of the suggestions were included. These strategies include improved manure management systems such as carefully controlling the water, fertilizer, antibiotics, and type of feed, which can not only reduce emissions but can also increase agricultural production. A key contribution of the CCAC was developing baseline emissions scenarios and projections of emissions reductions based on different policy implementations, which helped to determine the most effective methane mitigation strategies.").

[580] *Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035* [国民经济和社会发展第十四个五年规划和 2035 年远景目标纲要] (China) (2021) (hyperlink to original Chinese).

[581] *Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035* [国民经济和社会发展第十四个五年规划和 2035 年远景目标纲要] (China) (2021) (hyperlink to original Chinese).

[582] The Central Committee of the Chinese Communist Party and the State Council (2 November 2021) *Opinions on Strengthening the Battle for Pollution Prevention and Control* [关于深入打好污染防治攻坚战的意见] (hyperlink to original Chinese).

[583] China National Development and Reform Commission and Ministry of Housing and Urban-Rural Development (6 June 2021) *14th Five-Year Urban Sewage Treatment and Resource Utilization Development Plan* ["十四五"城镇污水处理及资源化利用发展规划] (hyperlink to original Chinese).

[584] China Ministry of Housing and Urban-Rural Development and National Development and Reform Commission (30 June 2022) *Implementation Plan for Carbon Peaking in Urban and Rural Development* [城乡建设领域碳达峰实施方案], 5 (hyperlink to original Chinese).

[585] China National Development and Reform Commission and Ministry of Housing and Urban-Rural Development (6 June 2021) *14th Five-Year Urban Sewage Treatment and Resource Utilization Development Plan* [“十四五”城镇污水处理及资源化利用发展规划] (hyperlink to original Chinese).

[586] China State Council (24 October 2021) *Action Plan for Achieving Carbon Peaking Before 2030* [2030 年前碳达峰行动方案] (hyperlink to original Chinese).

[587] China National Development and Reform Commission and Ministry of Housing and Urban-Rural Development (6 May 2021) *14th Five-Year Urban Domestic Waste Classification and Treatment Facility Development Plan* [“十四五”城镇生活垃圾分类和处理设施发展规划], 7 (hyperlink to original Chinese).

[588] China Ministry of Industry and Information Technology (15 November 2021) *14th Five-Year Plan on Industry Green Development* [“十四五”工业绿色发展规划], 4 (hyperlink to original Chinese).

[589] China Ministry of Ecology and Environment, National Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Natural Resources, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture and Rural Affairs, Ministry of Commerce, Ministry of Culture and Tourism, National Health Commission, People’s Bank of China, State Administration of Taxation, State Administration for Market Regulation, National Bureau of Statistics, National Government Offices Administration, China Banking and Insurance Regulatory Commission, State Post Bureau, and the All-China Federation of Supply and Marketing Cooperatives (15 December 2021) *14th Five-Year Work Plan on the Construction of Zero-Waste Cities* [“十四五“ 时期“无废城市” 建设工作方案] (hyperlink to original Chinese).

[590] China Ministry of Ecology and Environment, National Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Natural Resources, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture and Rural Affairs, Ministry of Commerce, Ministry of Culture and Tourism, National Health Commission, People’s Bank of China, State Administration of Taxation, State Administration for Market Regulation, National Bureau of Statistics, National Government Offices Administration, China Banking and Insurance Regulatory Commission, State Post Bureau, and the All-China Federation of Supply and Marketing Cooperatives (15 December 2021) *14th Five-Year Work Plan on the Construction of Zero-Waste Cities* [“十四五“ 时期“无废城市” 建设工作方案] (hyperlink to original Chinese).

[591] China Ministry of Ecology and Environment et al. (7 November 2023) *Methane Emissions Control Action Plan* [甲烷排放控制行动方案] (hyperlink to original Chinese) (IGSD’s annotated, English reference translation of the China Methane Emissions Control Action Plan is available here.).

[592] China Ministry of Ecology and Environment (2022) *Mid - and Long - term Development Plan for Eco-Satellites (2021-2035)* [生态环境卫星中长期发展规划 （2021-2035 年）] (hyperlink to original Chinese).

[593] China Ministry of Ecology and Environment (12 September 2021) *Carbon Monitoring and Assessment Pilot Work Plan* [碳监测评估试点工作方案] (hyperlink to original Chinese).

[594] Institute for Governance & Sustainable Development (17 January 2023) *Briefing: China Announces Progress in Methane Monitoring and Evaluation in Preparation for the Release of Its National Action Plan on Methane* (“China’s Ministry of Ecology and Environment (MEE) highlighted progress on carbon dioxide and other greenhouse gas monitoring and evaluation pilot projects aimed at answering critical questions on ‘what to measure,’ ‘where to measure,’ and ‘how to measure.’ This includes pilot projects exploring preliminary technical methodologies for methane leakage detection. In particular, MEE noted that the oil and gas industry pilots have established a methane leakage detection mechanism by implementing an integrated “satellite + unmanned aerial vehicle + cruise” monitoring

system for tracking methane leakage in production processes. For the coal mining industry pilots, MEE observed that a collaborative methane emissions monitoring technology has been developed using existing coal mine safety monitoring systems. Last but not least, MEE commented that it has established a preliminary understanding of the concentrations and the spatial and temporal distributions of global methane emissions through analysis of satellite remote sensing data.").

595 *See* Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development.

596 China State Council (21 September 2021) *Full Text of Xi's Statement at the General Debate of the 76th Session of the United Nations General Assembly* ("China will step up support for other developing countries in developing green and low-carbon energy, and will not build new coal-fired power projects abroad.").

597 China Ministry of Ecology and Environment and Ministry of Commerce (5 January 2022*) Guidelines on Ecological and Environmental Protection of Foreign Investment and Construction Projects* [对外投资合作建设项目生态环境保护指南], Art. 3 (hyperlink to original Chinese). *See also* *Opinions on Promoting the Green Development of the "Belt and Road Initiative"* [关于推进共建"一带一路"绿色发展的意见] (Promulgated by China National Development and Reform Commission, Ministry of Foreign Affairs, Ministry of Ecology and Environment, and Ministry of Commerce, March 16, 2022) (hyperlink to original Chinese).

598 Commission Regulation 2021/1119, 2021 O.J.L. 243, Art. 4(1) ("In order to reach the climate-neutrality objective set out in Article 2(1), the binding Union 2030 climate target shall be a domestic reduction of net greenhouse gas emissions (emissions after deduction of removals) by at least 55 % compared to 1990 levels by 2030.").

599 European Commission (14 October 2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, 1 ("Nevertheless, the 2030 climate target plan's impact assessment 6 found methane will continue to be the EU's dominant non-CO_2 greenhouse. It concluded that stepping up the level of ambition for reductions in greenhouse gas emissions to at least 55% by 2030 compared to 1990 would also require an accelerated effort to tackle methane emissions, with projections indicating a step up needed to 35% to 37% methane emission reductions by 2030 compared to 2005.").

600 European Commission (14 October 2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, 4 ("A priority objective of the strategy is to ensure that companies apply considerably more accurate measurement and reporting methodologies for methane emissions, across sectors, than is currently the case. This will contribute to a better understanding of the problem and better inform subsequent mitigation measures.").

601 European Commission (14 July 2021) *European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions*, Press Release ("Today, the European Commission adopted a package of proposals to make the EU's climate, energy, land use, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Achieving these emission reductions in the next decade is crucial to Europe becoming the world's first climate-neutral continent by 2050 and making the European Green Deal a reality. With today's proposals, the Commission is presenting the legislative tools to deliver on the targets agreed in the European Climate Law and fundamentally transform our economy and society for a fair, green and prosperous future.").

[602] European Commission (14 July 2021) *Proposal for amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030*, 17 ("Regulation (EC) 2018/842 is amended as follows: (1) In Article 1, '30%' is replaced by '40%'").

[603] European Commission (14 July 2021) *Proposal for amending Regulations (EU) 2018/841 and (EU) 2018/1999*, 10 ("From 2031 onwards, the LULUCF sector will include the non-CO_2 emissions from agriculture sector and the amended Regulation will aim towards the objective to achieve climate neutrality in the Union-wide greenhouse gas emissions and removals in the combined sectors at the latest by 2035; reducing emissions to net zero by that date and generating negative emissions thereafter.").

[604] European Environment Agency, *EEA greenhouse gases – data viewer* (*last visited* 5 February 2023) (Data through 2020).

[605] van der Veen R., de Vries M., van de Pol J., van Santen W., Sinke P., de Vries J., Kampman B., & Bergsma G. (2022) METHANE REDUCTION POTENTIAL IN THE EU BETWEEN 2020 AND 2030, CE Delft for Changing Markets Foundation, 4 ("Because most of the fossil fuels consumed in the EU are imported from other world regions, the vast majority of emissions related to EU energy use (86%) are not emitted within the EU borders. As a result, the methane emissions share of the energy sector within the EU is limited to 13%.").

[606] van der Veen R., de Vries M., van de Pol J., van Santen W., Sinke P., de Vries J., Kampman B., & Bergsma G. (2022) METHANE REDUCTION POTENTIAL IN THE EU BETWEEN 2020 AND 2030, CE Delft for Changing Markets Foundation, 6–7 ("Our results show that the EU methane reduction targets between 2020 and 2030 cannot be realised without implementing policies that drive the uptake of behavioural and technical measures in the livestock agriculture sector. The adoption of healthier consumer diets alone could reduce EU methane emissions by 15 to 19%, if new policy initiatives would influence all EU citizens to switch to an advised diet based on national dietary health guidelines with lower meat and dairy consumption. This makes clear that the livestock agriculture sector has an important role to play in the reduction of EU methane emissions.").

[607] European Commission (15 December 2021) *Proposal for a Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (recast)*, 1 ("Despite their minor contribution to the current EU energy mix, biogas, biomethane, renewable and low carbon hydrogen as well as synthetic methane (all together renewable and low carbon gases) would represent some 2/3 of the gaseous fuels in the 2050 energy mix, with fossil gas with CCS/U (carbon capture, storage and utilisation) representing the remainder."). *See also* European Commission (15 December 2021) *Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen*.

[608] European Commission (15 December 2021) *Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen*, § 125 ("Long-term contracts are an important part of the gas supply of Member States. However, they should not constitute a barrier to the entry of renewable and low carbon gases, which is why the duration of contracts for the supply of fossil gas will not be able to run beyond 2049. Such contracts shall always be in line with the objective of this Directive and are compatible with the TFEU, including the competition rules. It is necessary to take into account long-term contracts in the planning of supply and transport capacity of undertakings.").

[609] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 12 ("1. By ... [*18~~2~~ months from the date of entry into force of this Regulation)*], operators shall submit a report to the competent authorities containing **the quantification of** source-level methane emissions estimated using **at least generic** ~~but source-specific~~ emission factors for all sources. **Operators may choose to submit at that stage a report according to the requirements in paragraph 2**. 3. By ... [*36 months from the date of entry into force of this Regulation*] and by ~~*30 March*~~ 31 May every year thereafter, operators shall submit a report to the competent authorities containing ~~*direct*~~

~~*measurements*~~ **quantification** of source-level methane emissions for operated assets referred to in paragraph 2, complemented by measurements of site-level methane emissions, thereby ~~*allowing*~~ **improving the** assessment ~~and verification~~ of the source-level estimates aggregated by site…. 4. By ... [*36 months from the date of entry into force of this Regulation*] undertakings established in the Union shall submit a report to the competent authorities **of the Member State where the asset is located** containing ~~*direct measurements*~~ **quantification** of source-level methane emissions for non-operated assets **provided these have not already been reported by an operator in response to the obligation under paragraph 2.** Reporting at such level may involve the use of source-level measurement and sampling as the basis for establishing specific emission factors used for emissions estimation.… 11. The competent authorities shall make the reports set out in this Article available to the public and the Commission, within three months from submission by operators and in accordance with Article 5(4).") (emphasis in original).

[610] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 14 ("[O]perators shall submit a leak detection and repair programme to the competent authorities which shall detail the ~~*contents of the surveys*~~ **contents of the surveys and activities, including specific timelines,** to be carried out in accordance with the requirements in this Article, **Parts 1 and 2 of Annex I and the relevant** ~~*standards*~~ **specifications established pursuant to Article 29a(1). If any changes to the leak detection and repair programme are made, the operators shall re-submit the programme to the competent authorities as soon as possible.**"), Art. 15 ("Venting shall be prohibited except in the circumstances provided for this Article. Routine flaring shall be prohibited.") (emphasis in original).

[611] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 6 ("1. The competent authorities shall carry out periodic inspections ~~*based on a risk assessment*~~ to check the compliance of operators or mine operators with the requirements set out in this Regulation. **Subject to paragraphs 2 and 3,** ~~*T*~~ **the competent authorities may decide on the scope and frequency of the periodic inspections, based on an assessment of risks associated with each site, such as environmental, human safety and public health risks, as well as any identified breaches of this Regulation.**... 2. Inspections shall include, where relevant, site checks or field audits examination of documentation and records that demonstrate compliance...."), Art. 10 ("~~*Provided the interest of the Union is protected*~~, **In performing their obligations and exercising their powers under this Regulation, verifiers, the competent authorities and the Commission shall consider relevant internationally available** ~~**the**~~ **information** ~~*made available by the International Methane Emissions Observatory shall be attributed a verification role with respect to methane emissions data*~~....") (emphasis in original).

[612] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 18 ("1. By [*12 months from the date of entry into force of this Regulation*], Member States shall establish and make publicly available an inventory of all **recorded** inactive wells, **temporarily plugged wells and permanently plugged and abandoned wells** on their territory or under their jurisdiction**, where information on location exists or where location can be identified with all reasonable efforts**.... 2. **Without prejudice to paragraph 3,** ~~**R**~~ **reports containing** ~~*the*~~ **information o**n ~~*measurements or*~~ **quantification of methane emissions and, where such monitoring equipment exists on wellheads, pressure monitoring,** ~~*of methane emissions*~~ **from all inactive wells,** ~~and~~**and temporarily plugged wells** ~~*and wells that do not meet the requirements set out in paragraph 3, referred to in paragraph 2*~~ shall be submitted to the competent authorities.... 6. The competent authorities shall make the reports set out in this Article available to the public and the Commission.... 7. ~~*Member States shall be responsible for fulfilling the obligations laid down in paragraphs 2 and 3, except where a responsible party can be identified, in which case that party shall bear responsibility*~~. **Member States shall ensure fulfilling the obligations laid down in paragraphs 2 to 4 by the operators. Where a responsible party provides reliable evidence that it does not have adequate financial assurance to fulfil those obligations or where the responsible party cannot be identified, the Member State shall bear responsibility.**... 8. **By** … [**284 months from the date of entry into force of this Regulation], Member States or the responsible party, in accordance with paragraph 7**, shall develop ~~*and implement*~~ a

mitigation plan to remediate, reclaim and permanently plug inactive wells and **temporarily plugged wells** ~~*located in their territory*~~ **including at least the elements set out in Part 2 of Annex IV and setting out an implementation period starting no later than 12 months after the first reports referred to in paragraph 2.** Mitigation plans shall use the inventories referred to in paragraph 1 **and the reports referred to in paragraph 2** to determine priority for activities including: (a) remediating, reclaiming and permanently plugging wells; (b) reclaiming related access roads **or the surrounding soil under water, as applicable**; (c) restoring land, water, **seabed** and habitat impacted by wells and the prior operations; (d) ~~*yearly*~~ **regular** checks to ensure ~~*plugged wells*~~ **temporarily plugged wells and, where deemed applicable, permanently plugged and abandoned wells** are not ~~*longer*~~ a source of methane emissions.") (emphasis in original).

[613] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 25 ("1. Member States shall set up and make publicly available an inventory of all closed coal mines and abandoned **underground** coal mines in their territory or under their jurisdiction **where operations have ceased since … [50 years prior to the date of entry into force of this Regulation]**... 2. From … [***~~18~~ 24 months from the date of entry into force of this Regulation***], **methane emissions shall be measured in all closed and abandoned underground coal mines where operations have ceased since** … **[50 years prior to the date of entry into force of this Regulation].** ~~m~~**Measurement equipment shall be installed on all elements listed in point (v) of Part 1(v) of Annex VII which were found to emit above 0,5 tonnes of methane per year based on the inventory in Paragraph 1**~~. *for closed coal mines and abandoned coal mines where operations have ceased since … [50 years prior to the date of entry into force of this Regulation]*~~. **The equipment shall perform** ~~*Methane concentration*~~ **source level direct** measurements **or quantifications** ~~*shall be*~~ taken in accordance with **the specifications established in accordance with Article 29a** ~~*appropriate scientific publicly available European and international standards*~~ and at least on an hourly basis **and of sufficient quality to allow for a representative estimation of yearly methane emissions** from all elements listed in part 1(v~~i~~) of Annex VII which were found to emit methane. **Until such methodologies are established, publicly available European and international standards may be used.** ~~*The measurement equipment mustshall operate for more than 90% of the period for which it is used to monitor the emissions, excluding downtime taken for re-calibration and repairs*~~ **2a. If the observed annual methane release of an element listed in part 1(v) of Annex VII is below 1 tonne of methane for six consecutive years in the case of flooded mines or twelve consecutive years in the case of dry mines, no further monitoring and reporting shall be taken for that specific element.** 3. Reports containing estimates of yearly source-level methane emissions data shall be submitted to the competent authorities....") (emphasis in original).

[614] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 20 ("1. For underground coal mines, mine operators shall perform continuous ~~*ventilation air methane emissions*~~ ***source*** **level direct** measurement ~~or~~ ~~*and*~~ **and** quantification on all exhaust ventilation shafts ~~*used by the*~~. ~~*mine*~~ **Mine** operator**s shall report to the competent authorities methane releases per ventilation shaft per year in kt of methane**.... 2. Drainage stations operators shall perform continuous **source level direct** measurements ~~*or*~~ **and quantifications** of ~~*volumes*~~ **total releases** vented and flared methane.... 3. As regards surface coal mines, mine operators shall use deposit-specific coal mine methane emission factors to quantify emissions resulting from mining operations.... 5. **Where relevant**, ~~*M*~~**m**ine operators shall estimate coal post-mining emissions using coal postmining emission factors....") (emphasis in original).

[615] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 20 ("1. For underground coal mines, mine operators shall perform continuous ~~*ventilation air methane emissions*~~ ***source*** **level direct** measurement ~~or~~ ~~*and*~~ **and** quantification on all exhaust ventilation shafts ~~*used by the*~~. ~~*mine*~~ **Mine** operator**s shall report to the competent authorities methane releases per ventilation shaft per year in kt of methane**.... 2. Drainage stations operators shall perform continuous **source level direct** measurements ~~*or*~~ **and quantifications** of ~~*volumes*~~ **total releases** vented and flared methane.... 3. As regards surface coal mines, mine operators shall use deposit-

specific coal mine methane emission factors to quantify emissions resulting from mining operations.... 5. **Where relevant**, ~~M~~**m**ine operators shall estimate coal post-mining emissions using coal postmining emission factors....") (emphasis in original).

[616] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 22 ("~~Venting and f~~ **F**laring **with a destruction and removal efficiency below 98% and venting** of methane from drainage stations shall be prohibited from ~~[~~1 January 2025~~]~~, except in the case of an emergency, a malfunction or where unavoidable and strictly necessary for maintenance **and venting in accordance with paragraph 2**."); Art. 23 ("From ~~[~~1 January 2025~~]~~, drainage station operators shall notify the competent authorities of all venting **events** and flaring events **with a destruction and removal efficiency below 98%**: (a) caused by an emergency or a malfunction, (b) occurring unavoidably due to maintenance of the drainage system.") (emphasis in original).

[617] Assan S. (2 March 2023) *Major loopholes for coal mines in EU methane regulation*, Ember ('The originally proposed regulation covered mitigation at active and abandoned underground mine operations which together represent 76% of EU coal mine methane (CMM) emissions. However recent amendments have increased the venting thresholds for thermal coal, whilst action on coking coal is expected to be delayed for at least five more years. Our analysis shows the latest revisions to the regulation will only cut methane emissions from coal mines by around 47%, well below its stated climate goal of a 58% reduction.").

[618] European Commission (15 December 2021) *Questions and Answers on reducing methane emissions in the energy sector*, 2 ("The proposal does not contain specific binding target reductions. However, according to the Impact Assessment for the Climate Target Plan 2030, the EU should reduce its methane emissions from energy by 58% by 2030.").

[619] European Commission (15 December 2021) *Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen*, §§121–122 ("(121) Natural gas is mainly, and increasingly, imported into the Union from third countries. Union law should take account of the characteristics of natural gas, such as certain structural rigidities arising from the concentration of suppliers, the long-term contracts or the lack of downstream liquidity. Therefore, more transparency is needed, including in regard to the formation of prices. (122) Prior to the adoption by the Commission of Guidelines defining further the record-keeping requirements, ACER and the Committee of European Securities Regulators (the 'CESR'), established by Commission Decision 2009/77/EC 20, should confer and advise the Commission in regard to their content. ACER and the CESR should also cooperate to investigate further and advise on whether transactions in gas supply contracts and gas derivatives should be subject to pre- and/or post-trade transparency requirements and, if so, what the content of those requirements should be.").

[620] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 27–29 ("Article 27. Importer Requirements. 1. By … [*9 months from the date of entry into force of the Regulation*] and by **30 June**~~1 December~~ every year thereafter, importers shall provide the information set out in Annex VIII to the competent authorities of the importing Member State. **Where importers fail to provide the information set out in Annex VIII, in whole or in part, they shall demonstrate to the competent authorities of the importing Member State that all reasonable efforts have been undertaken to acquire the information.** 2. By ... [*12 months from the date of entry into force of the Regulation*] and by **31 December** ~~*0June*~~ every year thereafter, Member States shall submit to the Commission the information provided to them by importers. The Commission shall make the information available in accordance with Article 28. … Article 28. Methane transparency database. (1) By ... [*18 months after the date of entry into force of the Regulation*] the Commission shall establish and maintain a methane transparency database containing the information submitted to it pursuant to Article 27 and Articles 12(11), 16(~~3~~**2**), 18(~~4~~**6**), 20(7), 23(2) and 25(5). … Article 29. Methane emitters global monitoring tool (1) By ... [*two years after the date of entry into force of the Regulation*], the Commission shall establish a global methane monitoring tool based on satellite data

and input from several certified data providers and services, including the Copernicus component of the EU Space Programme.") (emphasis in original).

[621] European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, ¶ 66a ("In order to fulfil the objectives of this Regulation and to contribute to the goal set out in the Global Methane Pledge to reduce global methane emissions by 30% until 2030, the European Union should consider extending the requirements set out in this Regulation to imports from third countries. By [12 months after the date of entry into force of this Regulation], the European Commission should submit to the European Parliament and the Council a report on the implications of a possible extension of the requirements under this Regulation to the energy supply chain and production of fossil fuels imported into the Union. When preparing the report, the European Commission should put particular focus on the methane mitigation potential, consequences for energy prices, security of energy supply and availability of energy resources on the EU market. Depending on the outcome of that report and as part of the review of this Regulation, the Commission should consider submitting appropriate legislative proposals to extend the scope of this Regulation and its requirements and standards accordingly to importers of the relevant products to the Union.").

[622] Council of Europe (15 November 2023) *Climate action: Council and Parliament reach deal on new rules to cut methane emissions in the energy sector* ("The Council and the Parliament agreed on three implementation phases. The first phase will focus on data collection and the creation of a methane emitters global monitoring tool and a super emitter rapid reaction mechanism. In the second and third phases, equivalent monitoring, reporting and verification measures should be applied by exporters to the EU by 1 January 2027, and maximum methane intensity values by 2030. The competent authorities of each member state will have the power to impose administrative penalties if these provisions are not respected.").

[623] Abnett K. (15 November 2023) *EU agrees law to hit fossil fuel imports with methane emissions limit*, Reuters (""Finally, the EU tackles the second most important greenhouse gas with ambitious measures," said Jutta Paulus, the EU Parliament's co-lead negotiator, adding that the law "will have repercussions worldwide". Paulus told reporters importers will face financial penalties if they buy from foreign suppliers that don't comply with the limit - effectively imposing a fee on non-compliant fuels. The methane standard would be mandatory for supply contracts signed after the law enters into force, likely later this year, after the European Parliament and EU countries give it final approval.").

[624] European Parliament (9 May 2023) *Amendments adopted by the European Parliament on 9 May 2023 on the proposal for a regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942 (COM(2021)0805 – C9-04,* 129 ("[O]nce every two months for all aboveground components using detection devices with the minimum detection limit referred to in paragraph 3, point (a)")

[625] European Parliament (9 May 2023) *Amendments adopted by the European Parliament on 9 May 2023 on the proposal for a regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942 (COM(2021)0805 – C9-04,* 9 ("given that upstream exploration and production, oil and fossil gas gathering and processing also yield naphtha and natural gas liquids for use in the petrochemical sector and result in methane emissions. The petrochemical sector should be subject to the measures on monitoring and reporting, leak detection and repair, and limits to venting and flaring similar to those in the energy sector.").

[626] European Parliament (9 May 2023) *Amendments adopted by the European Parliament on 9 May 2023 on the proposal for a regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942 (COM(2021)0805 – C9-04,* 202 ("As of 1 January 2026, importers of coal, oil and gas, shall demonstrate that exporters of coal, oil and gas into the Union comply with the requirements for the measurement, monitoring, reporting and verification, leak detection and repair, and venting and flaring

established in Chapters 3 and 4 of this Regulation or otherwise meet the requirements for derogations set out in paragraph 2b of this Article.”).

[627] European Commission (15 November 2023) *Climate action: Council and Parliament reach deal on new rules to cut methane emissions in the energy sector* (“The Council and the Parliament today reached a provisional political agreement on a regulation on tracking and reducing methane emissions in the energy sector.”).

[628] European Parliament (11 April 2024) *Methane: Parliament adopts new law to reduce emissions from energy sector* (“Parliament on Wednesday adopted a provisional political agreement with EU countries on a new law to reduce methane emissions from the energy sector, with 530 votes in favour, 63 against and 28 abstentions. … The law now also has to be adopted by Council, before being published in the EU Official Journal and entering into force 20 days later.”). *See also* European Parliament (17 May 2025) *Draft Regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942 (first reading) – Adoption of the legislative act*, 2 (“On 10 April 2024, the European Parliament adopted its position at first reading of the Commission proposal. The outcome of voting in the European Parliament reflects the compromise agreement reached between the institutions and should, therefore, be acceptable to the Council… If the Council approves the European Parliament's position, the legislative act will be adopted.”); Council of Europe (27-28 May 2024) *Voting Result: Regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942*, 2 (passed).

[629] European Parliament and the Council (7 May 2024), Regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942, Art. 28(1) (“From 1 January 2027, importers shall demonstrate, and report in accordance with Article 27(1), to the competent authorities of the Member State in which they are established that the contracts concluded or renewed on or after [June 2025] for the supply of crude oil, natural gas or coal produced outsidethe Union cover only crude oil, natural gas or coal that is subject to monitoring, reportingand verification measures applied at the level of the producer that are equivalent to those set out in this Regulation”); Art. 29(2) (“By [June 2030] and every year thereafter, Union producers and importers placing crude oil, natural gas and coal on the Union market under supply contracts concluded or renewed after [June 2030] shall demonstrate to the competent authorities of the Member State in which they are established that the methane intensity of the production of crude oil, natural gas and coal placed by them on the Union market, calculated in accordance with the methodology set out pursuant to paragraph 4, is below the maximum methane intensity values established in accordance with paragraph 6 to promote the global methane emissions reductions for those products”).

[630] European Commission (14 October 2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, 11 (“The Commission will deliver legislative proposals in 2021 on: • Compulsory measurement, reporting, and verification (MRV) for all energy related methane emissions, building on the Oil and Gas Methane Partnership (OGMP 2.0) methodology. • Obligation to improve leak detection and repair (LDAR) of leaks on all fossil gas infrastructure, as well as any other infrastructure that produces, transports or uses fossil gas, including as a feedstock. (7) The Commission will consider legislation on eliminating routine venting and flaring in the energy sector covering the full supply chain, up to the point of production. (8) The Commission will work to extend the OGMP framework to more companies in the gas and oil upstream, midstream and downstream as well as to the coal sector and closed as well as abandoned sites. (9) The Commission will promote remedial work under the initiative for Coal Regions in Transition. Best-practice recommendations and/or enabling legislation will be brought forward if necessary.”).

[631] European Commission (14 October 2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, 3–4 (“In the waste sector, the main identified sources of methane are uncontrolled emissions of landfill gas in landfill sites, the treatment of sewage sludge and leaks from biogas plants due to poor

design or maintenance. Emissions from the landfilling of waste fell by 47% between 1990 and 2017 (24), following better compliance with EU waste legislation on emissions from landfill. This was achieved primarily by diverting biodegradable waste to other waste treatment options higher in the waste hierarchy (25) such as composting and anaerobic digestion, as well as ensuring the stabilisation of biodegradable waste before disposal. However, more stringent compliance practices are needed to further reduce methane emissions from waste. … A priority objective of the strategy is to ensure that companies apply considerably more accurate measurement and reporting methodologies for methane emissions, across sectors, than is currently the case. This will contribute to a better understanding of the problem and better inform subsequent mitigation measures (26).”).

[632] European Commission, *The new common agricultural policy: 2023-27* (*last visited* 1 February 2023) (“40% of the CAP budget will have to be climate-relevant and strongly support the general commitment to dedicate 10% of the EU budget to biodiversity objectives by the end of the EU's multiannual financial framework (MFF) period.”).

[633] European Commission (23 November 2023) REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL Summary of CAP Strategic Plans for 2023-2027: joint effort and collective ambition, 6 (“CSPs’ support for extensive livestock systems helps to maintain not only carbon stocks but also traditional landscapes, while improving feed autonomy and economic activities on marginal land. Many CSPs recognise explicitly the need to reduce livestock-related emissions (notably methane from ruminants). In particular, CSPs include support for investments in: improving manure storage and management; equipment for low-emission slurry spreading; and anaerobic digesters. This will be supplemented by support for genetic improvements. Less than half of the CSPs include other relevant support (e.g. for outdoor grazing, improvement of feeding plans and feed additives) and set (widely differing) targets (2.4% of EU livestock units) to reduce methane or ammonia emissions. Maximum livestock densities feature in several land-based interventions, including also for coupled support in some environmental hotspots.”). *See also* European Commission (23 November 2023) REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL: *SUMMARY OF CAP STRATEGIC PLANS FOR 2023-2027*, 11 (“Some CSPs give attention to reducing food waste, at times combined with efforts at preserving the value of resources - through investments, sectoral programmes and cooperation. Some plans also identify needs related to consumers’ awareness regarding sustainable, healthy, and balanced diets. However, these issues are mainly considered as to be tackled outside the Plans.”).

[634] European Parliament (13 December 2022) *Deal reached on new carbon leakage instrument to raise global climate ambition*, Press Release (“According to the deal reached, an EU Carbon Border Adjustment Mechanism (CBAM) will be set up to equalise the price of carbon paid for EU products operating under the EU Emissions Trading System (ETS) and the one for imported goods. This will be achieved by obliging companies that import into the EU to purchase so-called CBAM certificates to pay the difference between the carbon price paid in the country of production and the price of carbon allowances in the EU ETS. The law will incentivise non-EU countries to increase their climate ambition and ensure that EU and global climate efforts are not undermined by production being relocated from the EU to countries with less ambitious policies.”).

[635] Smirnov A. (6 September 2021) *Coal mine methane: a missed opportunity for EU’s CBAM*, EURACTIV (“One of the many included proposals is the carbon border adjustment mechanism (CBAM), which seeks to prevent greenhouse gas emissions ‘leaking’ over the border by taxing carbon-intensive imports from regions with less stringent emissions policies. However, the CBAM applies mostly to carbon dioxide (CO2) emissions, excluding other climate-warming gases such as methane — a missed opportunity in the fight to address climate change.”).

[636] European Commission (29 September 2023) *Carbon Border Adjustment Mechanism (CBAM) starts to apply in its transitional phase* (“This Sunday, 1 October, the Carbon Border Adjustment Mechanism (CBAM) will enter into application in its transitional phase. CBAM is the EU's landmark tool to fight carbon leakage and one of the central pillars of the EU's ambitious Fit for 55 Agenda. It will equalise the price of carbon between domestic products and imports. This will ensure that the EU's climate policies are not undermined by production relocating to countries with less ambitious green standards or by the replacement of EU products by more carbon-intensive imports. CBAM is a

WTO-compatible measure that encourages global industry to embrace greener and more sustainable technologies. In its transitional phase, CBAM will only apply to imports of **cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. EU importers of these goods** will have to report on the volume of their imports and the greenhouse gas (GHG) emissions embedded during their production, but without paying any financial adjustment at this stage.") (emphasis in original). *See also* Sholli S. (2 October 2023) *EU carbon border tax enters transitional phase*, International Tax Review, KPMG.

[637] XV BRICS Summit (23 August 2023) *Johannesburg II Declaration,* 19 ("We oppose trade barriers including those under the pretext of tackling climate change imposed by certain developed countries and reiterate our commitment to enhancing coordination on these issues. We underline that measures taken to tackle climate change and biodiversity loss must be WTO-consistent and must not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade and should not create unnecessary obstacles to international trade. Any such measure must be guided by the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), in the light of different national circumstances. We express our concern at any WTO inconsistent discriminatory measure that will distort international trade, risk new trade barriers and shift burden of addressing climate change and biodiversity loss to BRICS members and developing countries."). *See also* Overland I. (2022) *Know your opponent: Which countries might fight the European carbon border adjustment mechanism?*, SCIENCE DIRECT ("The analysis indicates that the following countries are most likely to mount opposition to CBAM: Iran, Ukraine, the USA, the United Arab Emirates, Egypt, China, India, Kazakhstan, Russia, and Belarus. How the EU handles opposition from these countries will be decisive for the fate of CBAM. The index can serve as a tool for policymakers inside and outside the EU who need to negotiate over CBAM and want to anticipate the stances of other countries and understand their drivers.").

[638] See generally Clausing K., Garicano L., & Wolfram C (2023) *HOW AN INTERNATIONAL AGREEMENT ON METHANE EMISSIONS CAN PAVE THE WAY FOR ENHANCED GLOBAL COOPERATION ON CLIMATE CHANGE*, Peterson Institute for International Economics. *See also* Salata Institute for Climate and Sustainability (2023) METHANE AND TRADE: *PAVING THE WAY FOR ENHANCED GLOBAL COOPERATION ON CLIMATE CHANGE*, Research Brief, 3 ("As a first step, the United States, the European Union, and partner countries can work to coordinate their methane reduction policies, with an eye toward the eventual imposition of border adjustments on imports from countries that fail to raise their standards. The Biden administration could work with Congress on next steps for implementing a US methane border adjustment, while simultaneously leading efforts with the European Union, the G7, and other potential coalition members to develop a framework for a multilateral agreement. Ideally, a proposed framework could be presented at the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP28) in Dubai in late 2023.").

[639] International Energy Agency (3 March 2022) *A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas*, 4 ("Europe's reliance on imported natural gas from Russia has again been thrown into sharp relief by Russia's invasion of Ukraine on 24 February. In 2021, the European Union imported an average of over 380 million cubic metres (mcm) per day of gas by pipeline from Russia, or around 140 billion cubic metres (bcm) for the year as a whole. As well as that, around 15 bcm was delivered in the form of liquefied natural gas (LNG). The total 155 bcm imported from Russia accounted for around 45% of the EU's gas imports in 2021 and almost 40% of its total gas consumption.").

[640] Yanatma S. (24 February 2023*) Europe's 'energy war' in data: How have EU imports changed since Russia's invasion of Ukraine?*, EURONEWS GREEN ("The most striking change in EU energy imports since the Russia-Ukraine war began has been seen in 'natural' (fossil) gas. In 2021, the EU imported 83 per cent of its natural gas. Before the war, EU natural gas imports from Russia made up almost 50 per cent of the total. This fell significantly in 2022, down to 12 per cent in October.").

[641] In 2020, the EU established "criteria for determining whether an economic activity qualifies as environmentally sustainable" for the purposes of establishing the sustainability of investments. *See* European Commission (22 June

2020) *Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088*, 2020 O.J. (L 198) 13, Art. 1 ("This Regulation establishes the criteria for determining whether an economic activity qualifies as environmentally sustainable for the purposes of establishing the degree to which an investment is environmentally sustainable."). *See also* European Commission (2022) *Delegated regulation (EU) 2022/1214 of 9 March 2022 amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities (Text with EEA relevance),* Annex I, § 4.29 ("Construction or operation of electricity generation facilities that produce electricity using fossil gaseous fuels. This activity does not include electricity generation from the exclusive use of renewable non-fossil gaseous and liquid fuels as referred to in Section 4.7 of this Annex and biogas and bio-liquid fuels as referred to in Section 4.8 of this Annex.... An economic activity in this category is a transitional activity as referred to in Article 10(2) of Regulation (EU) 2020/852 where it complies with the technical screening criteria set out in this Section.."); *discussed in* Alderman L. & Pronczuk M. (2 January 2022) *Europe Plans to Say Nuclear Power and Natural Gas Are Green Investments*, THE NEW YORK TIMES ("France led a coalition this year that included nations in Eastern Europe—the continent's most coal-dependent region—to get nuclear energy and natural gas classified as sustainable investments. Poland, Hungary, Bulgaria and Romania are among the countries that want to attract more investment for nuclear power as they move away from fossil fuels. Germany, on the other side, along with Austria, Luxembourg, Portugal and Denmark have expressed concerns about a buildup of nuclear power plants and the radioactive waste they produce.... Tsvetelina Kuzmanova, an expert on sustainable finance and a policy adviser at E3G, a Brussels think tank, said including nuclear and natural gas in the taxonomy amounted to 'calling something that isn't green, green.'").

[642] European Commission (8 March 2022) *REPowerEU: Joint European Action for more affordable, secure and sustainable energy*, 1 ("The EU needs to be ready for any scenario. It can reach independence from Russian gas well before the end of the decade. The sooner and more decisively we diversify our supply, accelerate the roll out of green energy technologies and reduce our demand of energy, the earlier we can substitute Russian gas. This communication sets out new actions to ramp up the production of green energy, diversify supplies and reduce demand, focusing primarily on gas, which significantly influences the electricity market and where the global market is less liquid. The focus can be extended to phasing out dependence on Russian oil and coal, for which the EU has a broader diversity of potential suppliers. Accelerating the green transition will reduce emissions, reduce dependency on imported fossil fuels, and protect against price hikes."). *See also* Ravikumar A., *et al.* (2023) *Measurement-based differentiation of low-emission global natural gas supply chains*, NAT. ENERGY 8: 1174–1176, 1174 ("Energy and commodities markets globally have been transformed as a result of the Russian invasion of Ukraine. Europe's sudden shift away from Russian natural gas supplies has resulted in a race for alternative sources and increased demand for liquefied natural gas (LNG). Concerns over security and affordability have led to a rapid buildup of infrastructure in Europe and Asia that can receive LNG.").

[643] European Commission (23 March 2022) *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2017/1938 of the European Parliament and of the Council concerning measures to safeguard the security of gas supply and Regulation (EC) n°715/2009 of the European Parliament and of the Council on conditions for access to natural gas transmission networks*, Art. 6a ("(2) For 2022, the filling target shall be set at 80% of the capacity of all storage facilities on the territory of the respective Member States. Unless the Commission decides otherwise pursuant to paragraph 4, the filling target shall be set at 90% for the following years.").

[644] European Commission (23 March 2022) *Security of supply and affordable energy prices: Options for immediate measures and preparing for next winter*, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions, 4–5 ("The Commission stands ready to create a Task Force on common gas purchases at EU level. By pooling demand, the Task Force would facilitate and strengthen EU's international outreach to suppliers of LNG and of gas, with the view to secure well-priced LNG and gas imports ahead of next winter. The EU can better ensure LNG, gas and hydrogen at affordable prices from third countries in the short term, if it engages with those countries on the long term,

setting up long-term renewable gas partnerships which would also lay the basis for future hydrogen imports Thus, the Task Force will prepare the ground for energy partnerships with key suppliers of LNG, gas and hydrogen.").

[645] White House (25 March 2022) *Joint Statement between the United States and the European Commission on European Energy Security*, Statements and Releases ("The United States and European Commission will undertake efforts to reduce the greenhouse gas intensity of all new LNG infrastructure and associated pipelines, including through the use of clean energy to power onsite operations, the reduction of methane leakage, and the construction of clean and renewable hydrogen ready infrastructure. The United States commits to maintaining an enabling regulatory environment with procedures to review and expeditiously act upon applications to permit any additional export LNG capacities that would be needed to meet this emergency energy security objective and support the RePowerEU goals, affirming the joint resolve to terminate EU dependence on Russian fossil fuels by 2027. The European Commission will work with the governments of EU Member States to accelerate their regulatory procedures to review and determine approvals for LNG import infrastructure, to include onshore facilities and related pipelines to support imports using floating storage regasification unit vessels, and fixed LNG import terminals.").

[646] White House (8 May 2022) *G7 Leaders' Statement*, Statements and Releases ("First, we commit to phase out our dependency on Russian energy, including by phasing out or banning the import of Russian oil. We will ensure that we do so in a timely and orderly fashion, and in ways that provide time for the world to secure alternative supplies. As we do so, we will work together and with our partners to ensure stable and sustainable global energy supplies and affordable prices for consumers, including by accelerating reduction of our overall reliance on fossil fuels and our transition to clean energy in accordance with our climate objectives.").

[647] Executive Body Working Group on Strategies and Review (30 September 2020) *Preparations for the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012*, ECE/EB.AIR/2020/3 – EBE/EB.AIR/WG.5/2020/3 at ¶ 20, ("As per the long-term strategy for the Convention for 2020–2030 and beyond (paragraph 50), the review should look at appropriate steps towards reducing emissions of black carbon, ozone precursors not yet addressed such as methane, and emissions from shipping with due consideration for International Maritime Organization (IMO) policies and measures. … In line with the priorities identified in the long-term strategy for the Convention for 2020–2030 and beyond, the following should specifically be considered in answering the questions in annex I:(b) Hemispheric transport of ozone and particulate matter and their precursors and advancing efforts to address air pollution on a broader scale per paragraphs 63 and 78 of the long-term strategy for the Convention for 2020–2030 and beyond; health and ecosystem impacts from outside the ECE region; (c) Methane and its relationship to the hemispheric transport of ozone and its contribution to ozone in the ECE region[.]").

[648] European Commission (18 May 2022) *Joint Communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions in EU external energy engagement in a changing world*, 3 ("Before this summer, the EU aims to conclude a trilateral agreement with Egypt and Israel on supplying Europe with LNG. Japan and Korea have already redirected a number of LNG cargoes to Europe and work continues to use this option in the future. Qatar stands ready to facilitate swaps with Asian countries. In terms of pipeline gas, Norway has already increased its deliveries to Europe and both Algeria and Azerbaijan have expressed their willingness to do so as well. The EU will aim to restart the energy dialogue with Algeria and will intensify cooperation with Azerbaijan in the light of the strategic importance of the Southern Gas Corridor. Scaling up the Trans Adriatic Pipeline (TAP) capacity would increase the gas supply to the EU and the Western Balkan countries.").

[649] European Commission (18 May 2022) *Joint Communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions in EU external energy engagement in a changing world*, 4 ("The EU will aim to ensure that additional gas supplies from existing and new gas suppliers are coupled with targeted actions to tackle methane leaks and to address venting and flaring, creating additional liquidity on global markets, while ensuring significant climate benefits. To that end, the EU will cooperate with its fossil fuel supply partners to reduce methane emissions. At least 46 bcm of natural gas is lost4 a year to venting and flaring in the countries that could be supplying this to the EU. The technology exists to capture most of this methane (the main

component of natural gas) in a sustainable and economical way. The EU stands ready to provide technical assistance to partners to set up such mutually beneficial "You collect/we buy" schemes. The EU will also convene partners such as the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD) and the World Bank to create incentives for the rapid collection of wasted fossil gases, including methane, bundling those losses into meaningful products that can be sold to international buyers.").

[650] European Commission (15 June 2022) *Memorandum of Understanding on Cooperation Related to Trade, Transport, and Export of Natural Gas to the European Union*, 2 ("The Sides [European Union, Arab Republic of Egypt, and the State of Israel] will endeavour to work collectively towards enabling a stable delivery of natural gas to the EU that is consistent with long-term decarbonisation objectives and is based on the principle of market-oriented pricing, to the extent that it coincides with each Side's domestic laws, regulations, policies and procedures."). *See also* European Commission (18 July 2022) *EU and Azerbaijan enhance bilateral relations, including energy cooperation*, Press Release ("The new Memorandum of Understanding on a Strategic Partnership in the Field of Energy signed by the two Presidents today includes a commitment to double the capacity of the Southern Gas Corridor to deliver at least 20 billion cubic metres to the EU annually by 2027. This will contribute to the diversification objectives in the REPowerEU Plan and help Europe to end its dependency on Russian gas. Based on the strengthened energy cooperation, Azerbaijan is already now increasing deliveries of natural gas to the EU, from 8.1 billion cubic metres in 2021 to an expected 12 bcm in 2022.").

[651] European Commission (18 May 2022) *Joint Communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions in EU external energy engagement in a changing world*, 5 ("In order to facilitate imports of 10 million tonnes of hydrogen into the EU, the European Commission aims to conclude hydrogen partnerships with reliable partner countries to ensure open and undistorted trade and investment relations for renewable and low carbon fuels.").

[652] European Commission (18 May 2022) *Joint Communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions in EU external energy engagement in a changing world*, 8 ("As the EU moves away from Russian energy supply, it will prioritise energy savings and efficiency, aiming to achieve a 5% reduction in oil and gas demand in the short term. This will decrease the price and demand pressure on the global markets. The EU will also work with international partners to make energy savings and efficiency a global priority. Together with other developed economies, the EU will in particular focus on reducing energy consumption, among other things building on the IEA Playing My Part campaign.").

[653] European Commission (15 June 2022) 2 ("The Sides will endeavour to promote the reduction of methane leakages, and in particular examine new technologies for reducing venting and flaring and explore possibilities for the utilisation of captured methane throughout the entire supply chain.").

[654] European Commission (4 April 2023) *Joint Statement by the EU and the US following the 10th EU-US Energy Council*, Press Release ("The Council intends to continue advancing the reduction of global methane emissions in line with the Global Methane Pledge and the Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels. The Council intends to promote domestic and international measures for reinforced monitoring, reporting, and verification, as well as transparency, for methane emissions data in the fossil energy sector, such as through the Oil and Gas Methane Partnership 2.0 (OGMP 2.0) standard and the development of a common tool for life cycle analysis (LCA) of methane emissions for hydrocarbon suppliers and purchasers. Building upon the Joint Declaration, the Council intends to work with Joint Declaration members and other countries to develop an internationally aligned approach for transparent measurement, monitoring, reporting, and verification for methane and carbon dioxide emissions across the fossil energy value chain to improve the accuracy, availability, and transparency of emissions data at cargo, portfolio, operator, jurisdiction and basin-level. The Council recognised the International Methane Emissions Observatory as a key independent methane emissions data collector and verifier, and the Council recognised the need to develop effective global schemes to limit leakage, venting, and flaring, such as the mutually beneficial You Collect We Buy. The Council acknowledged the joint progress made on developing

international standards for leak detection and quantification of methane emissions. In this respect, the Council welcomes the agreement for cooperation between the two first-of-a-kind centres of excellence, the TotalEnergies Anomaly Detection Initiatives (TADI) of the Pôle d'Etudes et de Recherche de Lacq and the Colorado State University Methane Emission Technology Evaluation Center (METEC). The Council noted its support of other centres of expertise that may wish to join TADI and METEC in their initiative.”).

[655] European Commission (4 April 2023) *Joint Statement by the EU and the US following the 10th EU-US Energy Council*, Press Release (“The Council intends to continue advancing the reduction of global methane emissions in line with the Global Methane Pledge and the Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels. The Council intends to promote domestic and international measures for reinforced monitoring, reporting, and verification, as well as transparency, for methane emissions data in the fossil energy sector, such as through the Oil and Gas Methane Partnership 2.0 (OGMP 2.0) standard and the development of a common tool for life cycle analysis (LCA) of methane emissions for hydrocarbon suppliers and purchasers. Building upon the Joint Declaration, the Council intends to work with Joint Declaration members and other countries to develop an internationally aligned approach for transparent measurement, monitoring, reporting, and verification for methane and carbon dioxide emissions across the fossil energy value chain to improve the accuracy, availability, and transparency of emissions data at cargo, portfolio, operator, jurisdiction and basin-level. The Council recognised the International Methane Emissions Observatory as a key independent methane emissions data collector and verifier, and the Council recognised the need to develop effective global schemes to limit leakage, venting, and flaring, such as the mutually beneficial You Collect We Buy. The Council acknowledged the joint progress made on developing international standards for leak detection and quantification of methane emissions. In this respect, the Council welcomes the agreement for cooperation between the two first-of-a-kind centres of excellence, the TotalEnergies Anomaly Detection Initiatives (TADI) of the Pôle d'Etudes et de Recherche de Lacq and the Colorado State University Methane Emission Technology Evaluation Center (METEC). The Council noted its support of other centres of expertise that may wish to join TADI and METEC in their initiative.”).

[656] Bertagni M. B., Pacala S. W., Paulot F., & Porporato A. (2022) *Risk of the hydrogen economy for atmospheric methane*, NAT. COMMUN. 13(7706): 1–10, 1 (“We find that CH_4 concentration may increase or decrease depending on the amount of hydrogen lost to the atmosphereandthemethaneemissions associated with hydrogen production. Green H_2 can mitigate atmospheric methane if hydrogen losses throughout the value chain are below 9 ± 3%. Blue H_2 can reduce methane emissions only if methane losses are below 1%.”), 4 (“The [critical Hydrogen Emission Intensity (HEI_{cr})] is much lower for blue H_2 than for green H_2 because of the methane emissions associated with blue H_2 production. For the current tropospheric conditions, we find that HEI_{cr} is around 9% for green H_2, around 7% for blue H_2 with 0.2% methane leak rates, and 4.5% for blue H_2 with 0.5% methane leak rates. Blue H_2 with 1% methane leak rate has a HEI_{cr} that is close to zero, as displacement of fossil fuel with this hydrogen does not reduce methane emissions (Fig. 3b). For even higher methane leak rates, the methane burden would increase regardless of the H_2 emissions, so that the HEI_{cr} is negative.”). *See also* Howarth R. W. & Jacobson M. Z. (2021) *How green is blue hydrogen?*, ENERGY SCI. ENG. 9(10): 1676–1687, 1676 (“For our default assumptions (3.5% emission rate of methane from natural gas and a 20-year global warming potential), total carbon dioxide equivalent emissions for blue hydrogen are only 9%-12% less than for gray hydrogen. While carbon dioxide emissions are lower, fugitive methane emissions for blue hydrogen are higher than for gray hydrogen because of an increased use of natural gas to power the carbon capture. Perhaps surprisingly, the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat and some 60% greater than burning diesel oil for heat, again with our default assumptions. In a sensitivity analysis in which the methane emission rate from natural gas is reduced to a low value of 1.54%, greenhouse gas emissions from blue hydrogen are still greater than from simply burning natural gas, and are only 18%-25% less than for gray hydrogen. Our analysis assumes that captured carbon dioxide can be stored indefinitely, an optimistic and unproven assumption. Even if true though, the use of blue hydrogen appears difficult to justify on climate grounds.”).

[657] Sun T., Shrestha E., Hamburg S. P., Kupers R., & Ocko I. B. (2024) *Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales*,

ENVIRON. SCI. TECHNOL.: 1–11, 1 ("This study reanalyzes apreviously published lifecycle assessment as an illustrative example to show how the climate impacts of hydrogen deployment can be far greater than expected when including the warming effects of hydrogen emissions, observed methane emission intensities, and near-term time scales; this reduces the perceived climate benefits upon replacement of fossil fuel technologies. For example, for blue (natural gas with carbon capture) hydrogen pathways, the inclusion of upper-end hydrogen and methane emissions can yield an increase in warming in the near term by up to 50%, whereas lower-end emissions decrease warming impacts by at least 70%. For green (renewable-based electrolysis) hydrogen pathways, upper-end hydrogen emissions can reduce climate benefits in the near term by up to 25%. We also consider renewable electricity availability for green hydrogen and show that if it is not additional to what is needed to decarbonize the electric grid, there may be more warming than that seen with fossil fuel alternatives over all time scales."), 1 ("Hydrogen's indirect warming effects have been documented over the past several decades,[14–23] with a consensus emerging that hydrogen's global warming potential (GWP) is approximately 12 over a 100-year period and approximately 35−40 over a 20year period.[10−13] The largest uncertainties in hydrogen's GWP are associated with the removal of atmospheric hydrogen by soil and potential future changes in the atmospheric concentrations of other GHGs such as methane.[10−13]"). *See also* Sand M., Skeie R. B., Sandstad M., Krishnan S., Myhre G., Bryant H., Derwent R., Hauglustaine D., Paulot F., Prather M., & Stevenson D. (2023) *A multi-model assessment of the Global Warming Potential of hydrogen*, COMMUN. EARTH ENVIRON. 4: 1–12, 1 ("Hydrogen is not directly a greenhouse gas, but its chemical reactions change the abundances of the greenhouse gases methane, ozone, and stratospheric water vapor, as well as aerosols. Here, we use a model ensemble of five global atmospheric chemistry models to estimate the 100-year time-horizon Global Warming Potential (GWP100) of hydrogen. We estimate a hydrogen GWP100 of 11.6 ± 2.8 (one standard deviation).").

[658] Proponents of e-methane are making investments despite "green" e-methane having been shown to be uneconomical compared with electrification and no studies to our knowledge on the net climate benefits when accounting for methane and hydrogen leakage and additional renewable power demand. *See generally* Ueckerdt F., Bauer C., Dirnaichner A., Everall J., Sacchi R., & Luderer G. (2021) *Potential and risks of hydrogen-based e-fuels in climate change mitigation*, NAT. CLIM. CHANG. 11(5): 384–93; *and* Weber M. (30 November 2023) *Japan's embrace of e-methane*, Gas Pathways.

[659] Ocko I. B. & Hamburg S. P. (2022) *Climate consequences of hydrogen leakage*, ATMOS. CHEM. PHYS. 22(14): 9349–9368, 9362 ("We found that hydrogen's warming potency strongly depends on the time horizon and (similar to methane) can be at least 3 times more potent in the near term than in the long term relative to carbon dioxide when using the traditional GWP framework with pulses of equal emissions. If a constant emission rate is used in the calculations instead, hydrogen's warming potency may be 50 % higher for time horizons of several decades or longer. When assessing the relative climate impacts of replacing fossil fuel technologies with their hydrogen alternatives (based on a unit of clean H_2 deployed relative to the avoided CO_2 emissions for a generic case), we found that there are vastly different climate outcomes depending on emission rates, time horizons, and production method. For example, blue hydrogen with high hydrogen and methane emissions (a 10 % and 3 % emission rate, respectively) can be worse for the climate for decades compared with fossil fuel technologies, but green hydrogen with low hydrogen emissions (1 %) can nearly eliminate climate impacts from its fossil fuel counterparts over all timescales. On the other hand, the best-case blue hydrogen alternative (1 % for both hydrogen and methane) can show roughly the same climate benefits as the worst-case green hydrogen alternative (10 % emissions) – far from climate neutral but still halving the impacts of its fossil fuel counterparts within a decade. However, the perceived benefits of clean hydrogen alternatives compared with fossil fuel technologies will depend on how much carbon dioxide and methane are avoided, which needs to be assessed on a case-by-case basis with reliable emission data. Finally, we found that a level of hydrogen demand around 800 Tg or above (which could account for around a quarter of the final energy demand in 2050) could contribute at least 0.1 °C of warming with high hydrogen leakage (10 %) and upper-bound uncertainties in hydrogen's radiative properties."); 9367 ("If hydrogen applications supply around half of final energy demand globally in 2050 (an upper estimate by BloombergNEF (2020)), hydrogen applications could cause at least a tenth of a degree (C) of warming for 10% leakage. For context, this amount of warming could offset the avoided warming in 2050 from deploying all cost-effective options to mitigate methane emissions globally over the next decade – which otherwise could have slowed down global-mean warming rates by up to 15% (Ocko et al., 2021), or the avoided warming

anticipated from the phasing out of hydrofluorocarbons (HFCs) (Xu et al., 2013). This amount of warming (~0.1 °C) is also equal to the amount of warming projected in 2100 from carbon dioxide emissions from international shipping and aviation combined in the absence of climate action (Ivanovich et al., 2019). However, if leakage does not exceed 1% the temperature response could be an order of magnitude smaller."). *See also* Hamburg S. & Ocko I. (7 March 2022) *For hydrogen to be a climate solution, leaks must be tackled*, ENVIRONMENTAL DEFENSE FUND.

[660] Warwick N., Griffiths P., Archibald A., & Pyle J. (2022) *Atmospheric implications of increased hydrogen use*, United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy, 9 ("When only hydrogen increases in our model experiments, we calculate an effective radiative forcing of 0.148 W m^{-2} for an increase in hydrogen of 1.5 ppm; when the methane lower boundary is increased by 340 ppb, consistent with the decrease in hydroxyl radicals, the radiative forcing approaches 0.5 W m^{-2} (a warming tendency). In contrast, if there is no leakage of hydrogen into the atmosphere, and methane and other co-emissions are reduced, the change in radiative forcing is -0.29 W m^{-2} (a cooling tendency). Assuming an equilibrium climate sensitivity of 0.86 K W^{-1} m^2, this level of radiative forcing if sustained would lead to global-mean temperature changes of 0.12, 0.43 and -0.26 ℃ (without accounting for the reduced emissions of carbon dioxide that would result).").

[661] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 11 ("In 2016 India's total GHG emissions, excluding Land Use Land-Use Change and Forestry (LULUCF) were 2,838.89 million tonnes CO_2e and 2,531.07 million tonnes CO_2e with the inclusion of LULUCF. Carbon dioxide emissions accounted for 2,231 million tonnes (78.59 per cent), methane emissions for 409 million tonnes CO_2e (14.43 per cent) and nitrous oxide emissions for 145 million tonnes CO_2e (5.12 per cent)"). *Note* for reporting purposes, India uses a GWP_{100} for CH_4 of 21, per Table 2.2 ("All calculations in the present report use the Global Warming Potential (GWP) of GHGs for 100 years, IPCC AR2 (IPCC, 1995).").

[662] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 147 (Table 2.4: Sector-wise National GHG emission in Gg for 2016.).

[663] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 247 ("SRI is a promising and resource-saving method of rice cultivation. Studies have shown a significant increase in rice yield, with substantial savings of seeds (80-90 per cent), water (25-50 per cent), and cost (10-20 per cent) compared to conventional methods (Uphoff, 2011), and reduction in CH_4 emissions. As part of the National Food Security Mission (NFSM), SRI is being implemented in 193 districts of 24 States.").

[664] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 279 ("Area covered under DSR in 2017-18 and 2018-19 is 99,964 ha. It has led to reduction of 0.099 MtCO_2e in 2017- 18 and 2018-19.").

[665] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 247 ("Given the high water requirement of paddy crop and consequent decline in groundwater and high energy requirement in the traditional green revolution states such as Punjab, Haryana, and Uttar Pradesh, diversification from paddy to other crops was envisaged. The main objectives of the programme are to demonstrate and promote the improved production technologies of alternate crops and to restore soil fertility through the cultivation of leguminous crops. Due to the stagnancy in crop yields, the decline in soil quality, the incidence of pests and diseases due to continuous paddy cultivation in the three States, Punjab, Haryana, and Uttar Pradesh, diversion of paddy cultivation to other crops has become essential. This enables the reduction of the CH_4 emissions associated with paddy production. The budgetary allocation for this programme during 2018-19 was INR 1.328 million. A total area of 81,816 ha has been diversified from paddy to other crops in 2017-18 and 2018-19 (DAC&FW, 2020).").

[666] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 250–251 ("The horticulture sector consists of a wide range of crops such as fruits, vegetables, flowers, spices, and nuts of which the fruit crops produce relatively higher biomass and are retained in the field for a relatively long period. This helps in sequestering carbon both above and below the ground. The area brought under the mission from 2016-17 to 2018-19 has been reported in Table 3.25. The quantum of carbon sequestered is estimated to be 108.96 MtCO2 from 2017-18 to 2018-19. … The main objective of the Ration Balancing Programme (RBP) is to educate milk producers on feeding balanced ration to their animals so that the nutrients required by their milch animals are fulfilled in an optimum manner, thereby improving milk production efficiency and the economic return. The achievement under the scheme in 2018-19 has been reported in Table 3.26. The emission reduction as a result of the RBP initiatives was 0.061 $MtCO_2$ from 2017-18 to 2018-19") ; ("In India, crop residues that form the bulk of feed resources are of inferior quality with more degradable protein which results in lower production and higher GHG emissions. High yielding milch animals like crossbreds and graded buffaloes specially require more undegradable protein in the form of bypass protein for enhancing milk production potential of the animal. As such protein supplements are more expensive and optimizing the use of protein supplements within the ruminant system can improve milk productivity, income to the farmers, and lower greenhouse gas emissions. Commercial bypass protein technology was available with different seed meals and these bypass proteins reduce the degradability in the rumen. The main purpose of the establishment of the bypass protein units is to improve the availability of the protein and essential amino acids from feed to cattle. … The mitigation envisaged due to various initiatives of the GoI [Government of India] as well as the private initiatives are presented below in Table 3.27.").

[667] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 289–292 (Table 3.44, listing policies and programs that reduce methane emissions).

[668] United States Department of Energy (7 October 2022) *U.S.-India Strategic Clean Energy Partnership Ministerial Joint Statement,* Statements & Releases ("The Ministers welcomed collaboration between Indian and U.S. companies through a Memorandum of Understanding to deploy methane abatement technologies in India's city gas distribution sector under the Low Emissions Gas Task Force to help reduce emissions in the oil and gas sector. Agencies from across the U.S. and Indian governments demonstrated a number of accomplishments across the five technical pillars of cooperation on: *1) Power & Energy Efficiency*, *2) Renewable Energy*, *3) Responsible Oil & Gas*, *4) Sustainable Growth*, and *5) Emerging Fuels and Technologies*. The Ministers welcomed expanded efforts under the U.S.-India Strategic Clean Energy Partnership to support a just energy transition to meet today's unprecedented energy security and climate and energy challenges.").

[669] United States Department of Energy (2023) *International Cooperation: Office of Fossil Energy and Carbon Management* ("The U.S.-India Low Emission Gas Task Force (LEGTF) is an industry-focused forum which identifies innovative policy reforms to support India's ambitions to reduce consumption of high-polluting fuels by increasing the use of natural gas for transportation, industrial, and residential purposes. The LEGTF's focus on India's natural gas policy, technology, and addressing regulatory barriers promotes efficient and market-driven solutions aimed at meeting India's growing energy demand and emissions reduction targets. The LEGTF is a component of the Responsible Oil and Gas Pillar of the U.S.-India Strategic Clean Energy Partnership (SCEP). The Office of Resource Sustainability and India's Ministry of Petroleum and Natural Gas are the government leads for the LEGTF, and the U.S. Energy Association and India's Gas Authority of India Ltd. serve as the LEGTF co-secretariats. The LEGTF has three subcommittees of volunteer industry and regulatory experts which identify challenges to and opportunities for natural gas development in India: Markets and Regulation, Gas Grid Strengthening, and Cleaner Transport Fuels.").

[670] Government of India Ministry of Petroleum & Natural Gas (17 April 2023) *Government has set target to increase share of gas in energy mix up to 15 per cent by 2030 : Union Minister of Petroleum & Natural Gas and Housing &*

Urban Affairs Shri Hardeep Singh Puri, Press Release ("The Minister said that the production of CBG [compressed biogas] would have multiple benefits viz. reduction of natural gas imports, reduction of GHG emission, reduction in burning of agriculture residues, providing remunerative income to farmers, employment generation, effective waste management etc adding, "Government of India has set a target to increase the share of gas in the energy mix up to 15% in 2030 to make India a Gas-based economy. Presently we are importing around 50% of our requirement of Natural gas. Speedy expansion of CBG will help in meeting our additional requirement from domestic resources.").

[671] Government of India Ministry of New and Renewable Energy, Government of India, *New National Biogas and Organic Manure Programme (NNBOMP)* (*last visited* 5 February 2023) ("The Ministry of New and Renewable Energy promotes installation of biogas plants by implementing Central Sector Schemes under Off-Grid/distributed and decentralized Renewable Power. The two on going schemes are: New National Biogas and Organic Manure Programme (NNBOMP), for Biogas Plant size ranging from 1 cu.m. to 25 cu.m. per day. Biogas Power Generation (Off-grid) and Thermal energy application Programme (BPGTP), for setting up biogas plants in the size range of 30 m3 to 2500 m3 per day, for corresponding power generation capacity range of 3 kW to 250 kW from biogas or raw biogas for thermal energy / cooling applications."); *See also* Government of India Ministry of Drinking Water & Sanitation (30 April 2018) *Swachh Bharat Mission launches GOBAR-DHAN to promote wealth and energy from waste,* Press Release ("Union Minister for Drinking Water and Sanitation, Sushri Uma Bharti, today launched the GOBAR (Galvanizing Organic Bio-Agro Resources - DHAN scheme at the National Dairy Research Institute (NDRI) Auditorium, Karnal in the presence of the Chief Minister of Haryana, Shri Manohar Lal Khattar. The scheme aims to positively impact village cleanliness and generate wealth and energy from cattle and organic waste. The scheme also aims at creating new rural livelihood opportunities and enhancing income for farmers and other rural people.").

[672] Ahtasham (10 September 2023) *Global Biofuels Alliance Announced by PM Modi at G20 Summit:10 Facts*, NDTV.

[673] Ginni G., Kavitha S., Yukesh Kannah R., Shashi Kant B., Adish Kumar S., Rajkumar M., Gopalakrishnan K., Arivalagan P., Nguyen Thuy L., & Rajesh Banu J. (2021) *Valorization of agricultural residues: Different biorefinery routes*, J. ENVIRON. CHEM. ENG. 9(4): 1–18, 13 ("Anaerobic digestion being the most extensive technology among the various processes provides an integrated path to transform various agricultural wastes into biogas and fertilizer for energetic valorization [141]."); ("There should be establishment of policies, regulations, subsidies and benefits for not burning agri-wastes, improved supply and leasing of agriculture implements such as tools, machineries and equipments; technology development, upgrading and demonstration programs and promotion of agri-waste for biogas generation and utilization. The New National Biogas and Organic Manure Programme of the Ministry of New and Renewable Energy in India, permits the utilization of biogas as a hygienic cooking fuel for households, power requirements for farmers, and the usage of slurry produced from biogas plant as bio fertilizer substituting chemical fertilizers Kapoor et al. [29]. In order to promote the valorization of biomass, the farmers are pro- vided with support and motivation for the efficient use of resources, the Common Agricultural Policy (CAP) has been improved for the adoption of bioeconomy Duque-Acevedo et al. [7].").

[674] Government of India Ministry of Petroleum and Natural Gas, *Unconventional Hydrocarbons* (*last visited* 5 February 2023) ("The estimated CBM resources are of the order of 2,600 Billion Cubic Metres (BCM) or 91.8 Trillion Cubic Feet (TCF) spread over in 11 States in the country.").

[675] Government of India Ministry of Petroleum and Natural Gas (2021) ANNUAL REPORT 2020–21.

[676] Government of India National Data Repository, Directorate General of Hydrocarbons, Ministry of Petroleum and Natural Gas, *Coal Bed Methane* (*last visited* 5 February 2023) ("In order to harness CBM potential in the country, the Government of India formulated CBM policy in July 1997 wherein CBM being Natural Gas is explored and exploited under the provisions of Oil Fields (Regulation & Development) Act 1948 (ORD Act 1948) and Petroleum & Natural Gas Rules 1959 (P&NG Rules 1959) administered by Ministry of Petroleum & Natural Gas (MOP&NG).").

[677] National Data Repository, Directorate General of Hydrocarbons, Ministry of Petroleum and Natural Gas, Government of India, *Coal Bed Methane* (*last visited* 5 February 2023) ("Awarded CBM blocks.").

[678] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 22 ("The total fugitive emissions in the year 2016 were 37,179 Gg CO_2e, of which 46 per cent was from coal mining and post mining operations, and 54 per cent from oil and natural gas production and handling systems.").

[679] *See* United States Environmental Protection Agency, *Non-CO_2 Greenhouse Gas Data Tool* (*last visited* 16 November 2023). The US EPA estimates that total methane emissions in 2020 from coal mining in India are 22 MtCO_2e, representing 3.7% of the country's methane emissions, and will reach 48 MtCO_2e by 2050, representing 6.5% of the country's overall methane emissions. These estimates are derived from data compiled in EPA Non-CO2 Greenhouse Emission Projections & Mitigation Potential Reports (2019 & 2020).

[680] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 22 ("Fugitive methane emissions have registered a decrease of 2 per cent between 2014 and 2016, mainly due to a relative reduction in underground mining activities.").

[681] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 157 ("Emissions from surface mining increased by 7 per cent and underground mining decreased by 3 per cent over the period 2014 – 2016… these emissions factors (EFs) from coal mining and handling activities have been incorporated in the IPCC Emission Factor Database after due vetting of the Editorial Board with designated EF IDs 122973 – 122975 for underground mining and 124920 – 124921 for surface mining (IPCC, 2020).").

[682] Government of India Ministry of Environment, Forest and Climate Change (2021) INDIA: THIRD BIENNIAL UPDATE REPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 214 ("The upcoming projects of Coal Bed Methane (CBM) extraction will also reduce the liberation of CH4 into the atmosphere during coal mining, which will be taken up in the future (MoC, 2020).").

[683] Coal India Limited (2021) COAL INDIA REPORT: FY 2020 - 2021, 12 ("Our ESG Commitments: 1) Low-Carbon Coal… Adopting clean coal technologies such as: coal gasification; coal-to liquid; coal mine methane; coal bed methane; and coal washeries[.]").

[684] *See generally* India Coal Mine Methane / Coal Bed Methane Clearinghouse.

[685] Global Methane Initiative (2020) *India*, *in* COAL MINE METHANE COUNTRY PROFILES, 16-5 ("A pre-drainage project for CMM at BCCL's Moonidih underground mine with an envisaged project life of 10 years is currently under development. The Moonidih Mine is a highly gassy mine and the project has been planned to keep coal miners safe from methane outbursts, enhance coal production, and lower the cost of coking coal production. It will also reduce greenhouse gas (GHG) emissions. This will represent the first CMM production and utilization project in India.").

[686] Global Methane Initiative (2020) *India*, *in* COAL MINE METHANE COUNTRY PROFILES, 16-5 ("The Global Environment Facility, the United Nations Development Programme, and the Government of India funded a demonstration project on CBM recovery and its commercial utilization was successfully completed in 2008, proving the efficacy of the technology in Indian geo-mining conditions (Singh, 2010) … Under the auspices of the Global Methane Initiative (GMI), the U.S. Environmental Protection Agency conducted three pre-feasibility studies for the Chinakuri, Sawang, and Pootkee-Bulliary Collieries in the Damodar Valley coalfields. Through these studies, US EPA evaluated site-specific conditions for an initial assessment of potential technical and economic viability for coal mine methane project recovery and use (US EPA 2015, US EPA 2016, US EPA 2019c).").

[687] India Ministry of Coal (4 August 2021) *Domestic Coal Production*, Press Release ("Auction of commercial mining on revenue sharing mechanism from 5 coal bearing states (Jharkhand, Madhya Pradesh, Maharashtra, Odisha, and Chhattisgarh) was launched on 18.06.2020. During this round of auction, 20 coal mines with aggregate peak capacity of 59 MTPA were successfully auctioned. Second Tranche of auction for commercial mining was launched by Ministry of Coal on 25.03.2021. In the second Tranche, a total of 67 coal mine blocks were offered."). *See also* (25 March 2021) *Government offers 67 blocks in second tranche of commercial coal mine auction*, THE HINDU ("The government on Thursday offered 67 coal mines for sale, launching the second tranche of commercial coal mining auction and termed it a step towards 'Aatmanirbhar Bharat'. This is the highest number of mines on offer in a particular tranche after commencement of the auction regime in 2014.").

[688] India Ministry of Coal (15 December 2021) *Commercial Mining of Coal*, Press Release ("The auction process for 67 coal mines was launched on March 25, 2021 and is currently under progress. This is the largest tranche of mines ever being put up for auction by the Government of India. Total resources of about 36 billion tonnes of coal are on offer in this tranche.").

[689] Government of India Ministry of Environment, Forest and Climate Change (2008) NATIONAL ACTION PLAN ON CLIMATE CHANGE.

[690] Government of India Ministry of Housing and Urban Affairs (2017) SWACHH BHARAT MISSION – URBAN.

[691] Government of India Ministry of Environment, Forest and Climate Change (2016) SOLID WASTE MANAGEMENT RULES, 2016.

[692] Government of India Ministry of Environment, Forest and Climate Change (2019) NATIONAL CLEAN AIR PROGRAMME.

[693] Press Bureau of India (29 April 2022), *Swacch Bharat Mission-Urban 2.0 launches National Behavior Change Communication Framework for Garbage Free Cities*, Press Release ("Swachh Bharat Mission-Urban 2.0, under the aegis of the Ministry of Housing and Urban Affairs, has launched the '**National Behaviour Change Communication Framework for Garbage Free Cities'** to strengthen the ongoing jan andolan for 'Garbage Free Cities'.") (emphasis in original).

[694] Press Bureau of India (2016) *Solid Waste Management Rules, 2016 – major changes and likely implications*, 1 ("The SWM rules, 2016 emphasises source segregation of waste, a basic need for channelizing the waste to wealth by recovery, reuse and recycle.").

[695] Government of India Ministry of Environment, Forest and Climate Change (2019) NCAP: NATIONAL CLEAN AIR PROGRAMME, 42 ("An integrated solid waste management strategy, including targeting waste prevention, recycling, composting, energy recovery, treatment, and disposal, can have a significant impact on reducing greenhouse gas emissions. For instance, landfill gas, which is composed of about 50% methane and 50% carbon dioxide, can be captured and used as a source of clean energy and a substitute for fossil fuel. Methane not only contributes to warming the atmosphere, it has also been linked to the concentration of surface ozone, which is known to cause air quality and public health issues.").

[696] Centre for Science and Environment, (2023) METHANE EMISSIONS FROM OPEN DUMPSITES IN INDIA: ESTIMATION AND MITIGATION STRATEGIES, 54 ("At the same time, Swachh Bharat Mission 2.0 has been instrumental in promoting scientific treatment of all the fractions of municipal solid waste and remediation of existing dumpsites.").

[697] Centre for Science and Environment, (2023) METHANE EMISSIONS FROM OPEN DUMPSITES IN INDIA: ESTIMATION AND MITIGATION STRATEGIES, 39 ("More than 87 million tonnes of waste has been remediated all over the country, reclaiming 3,440 acres of land.").

[698] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-36 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}").

[699] Fernandes S. (2 May 2022) *Three ministries to form consortium for climate-related policies*, THE HINDUSTAN TIMES ("On Monday, M Ravichandran, secretary, MoES, said that the idea of the inter-ministerial consortium is to avoid duplication of climate-related policy formulation and research, and work cohesively towards climate action and towards realising India's Nationally Determined Contributions (NDC) under the Paris Agreement.").

[700] Government of India (2022) THE CONSTITUTION OF INDIA, 2 ("Name and territory of the Union.—(1) India, that is Bharat, shall be a Union of States. 1 [(2) The States and the territories thereof shall be as specified in the First Schedule.] (3) The territory of India shall comprise— (a) the territories of the States; 2 [(b) the Union territories specified in the First Schedule; and] (c) such other territories as may be acquired.").

[701] Centre for Policy Research, *State Action Plans on Climate Change in India* (*last visited* 24 October 2023) ("In 2009 the Government of India directed all state governments and union territories to prepare State Action Plans on Climate Change (SAPCC), consistent with the strategy outlined in the National Action Plan on Climate Change (NAPCC). Twenty two states in India have since initiated the process of drafting SAPCCs, putting in motion a dynamic process involving tie-ups with multiple stakeholders, formation of new committees, cross sectoral deliberations, workshops, and significantly, the marriage of new research and plans with existing policy programmes.").

[702] The International Maize and Wheat Improvement Center & Climate Change, Agriculture and Food Security (2014) CLIMATE-SMART VILLAGES IN HARYANA, INDIA, 5 ("In alternate wetting and drying, rice fields are alternately flooded and drained. The use of a monitoring instrument like a tensiometer can help farmers decide when to irrigate their fields. Alternate wet and drying reduces methane emissions by an average of 48 percent compared to continuous flooding. Combining this with precision fertilizer tools can further reduce greenhouse gas emissions.").

[703] Goa State Climate Change Cell (2023) STATE ACTION PLAN FOR CLIMATE CHANGE FOR THE STATE OF GOA, 21 ("Agriculture and allied sectors contribute to GHG emissions due to the use of machinery, water, fertilizers, etc. Inadequate, utilization of resources increases emissions. Methane is one of the main GHG's emitted in agriculture and cattle rearing activities. Some of the mitigation measures ongoing and proposed are as under: 1. Focus initiatives to increase vermicomposting at the community level Water Sector 3. Sensitize farmers on optimal utilization of water to reduce pump usage and reduce water wastage 8. Promoting Biomass residue from agriculture to be used for power generation where it does not have an alternate use[.]").

[704] Government of Odisha Forest and Environment Department, (2015) PROGRESS REPORT ON IMPLEMENTATION OF ODISHA CLIMATE CHANGE ACTION PLAN, 48 ("There are many ways in which methane management from livestock is possible (a) either using the cow dung etc. in bio-gas plants (b) recovering methane in modern abattoirs from

carcasses. There is also possibility of composting and digestion of methane. But the last one is from a whole range of wastes and the off sets have been estimated in Urban Development Context. The bio-gas related emission off set is estimated to be 4,04,681 units of tCO2 eqv.")

[705] Government of Jammu & Kashmir Department of Ecology, Environment & Remote Sensing (2014) STATE ACTION PLAN ON CLIMATE CHANGE: JAMMU & KASHMIR, xxv ("Application of methane capture technology and preparation of fertilizer from weeds generated in Dal lake"), 110 ("Thus state government is planning to implement several sewage treatment plants which would treat the sewage wastes produced from the city and hotels situated near Dal lake before discharging it into the water body. This would reduce the pollution load as well as methane generation resulting from anaerobic degradation of the high organic load of the city sewage. Also the potent GHG emission would be reduced along with restoration of the Dal lake."), 113 ("However the weeds harvested from the lake can be utilized for the extraction of methane through controlled anaerobic digestion system which can be utilized for power generation or any other energy sources. The digested sludge will be rich in nutrients and can be utilized as organic manure. Thus the process would restore the oxygenation characteristics of the Dal Lake, promoting healthy aquatic habitat while reducing undesirable weed growth, snails and blood suckers like leech etc along with the associated scum and algae population.").

[706] Government of Kerala Department of Environment and Climate Change (2022) KERALA STATE ACTION PLAN ON CLIMATE CHANGE 2023-2030, 119 ("With a high probability of occurrence of hazards such as heat stress, floods, and drought, high exposure of livestock in the districts of Kerala to these hazards, coupled with high to moderate vulnerability of the livestock sectors in the majority of the districts, the sector needs to be prioritized for adaptation and be climate proofed. Adaptation strategies that are aimed at improving livestock productivity through improved feed could also provide mitigation co-benefits by helping to lower methane emissions from enteric fermentation."), 141 ("The project, titled 'Climate Resilient Livestock Production' has components that can co-benefit in mitigating methane emissions from enteric fermentation with dietary changes, as well as sequester carbon in fodder trees planted by livestock far."), 140 ("Strategies to sustainably improve the productivity of milch animals include providing extra concentrate minerals supplementation and feed additives; making changes to micro-climate in cattle shed/ stall by the installation of shade, sprinklers, or evaporative cooling systems; plantation of fodder tree lines around animal shed/house to lower heat stress; ensuring livestock are both stall-fed and grazed in pastures; change feeding schedules to late afternoon and early morning; reducing livestock numbers in some cases, or changing herd composition; and improving water resources (availability, access, and use). Strategies that are focused on improving animal feed also have the added benefit of mitigating methane emissions from enteric fermentation.").

[707] Government of Karnataka Environmental Management and Policy Research Institute (2021) KARNATAKA STATE ACTION PLAN ON CLIMATE CHANGE, 178 ("Projections of climate change at the district level are available now. But agriculture planning may require block level projections. The same has also been prepared by Indian Institute of Science. This however will have to be incorporated into programmes and policies. Also, the information on spread of pests in agro climatic zones is to be gathered to protect crops. Protecting indigenous climate change resistant varieties by finding suitable market mechanisms are also to be researched. Dry land farming and agroforestry are under research and implementation using biotechnology. Department of Agriculture, Department of Horticulture and Agriculture universities are the agencies that will have to continue implementing and monitoring the programmes."); 207 ("In the agriculture sector, the three key levers for emission mitigation are increased adoption of energy-efficient (EE) pumps and solar pumps; and a solar-powered dedicated feeder connected to EE pumps. The total number of irrigation pump sets are assumed to be growing at a CAGR of 5.2% annually, resulting in nearly 50 lakh irrigation pumps by 2030. The total number is the same in all three cases. So both in BAU and Policy scenarios, the rate of uptake of solar pumps determines the number of EE pumps. We assume that a small fraction (0.4%) of the total pumps will continue to be diesel powered in 2030, to factor in possible remote areas with no electricity.") (internal citations omitted).

[708] Climate Studies IIT Bombay & Government of Rajasthan Department of Environment and Climate Change (2022) RAJASTHAN STATE ACTION PLAN ON CLIMATE CHANGE 2022, 253 ("Methane is one the major GHG released from waste, particularly from landfills. Reduction in methane emission can be achieved in two ways: i. Landfill gas recovery

systems. The technology is already in place, and many cities in various countries have already adopted the technology. ii. Reduction in the quantity of biodegradable waste to be landfilled.”).

[709] Government of Punjab Institute for Development and Communication (2023) PUNJAB VISION DOCUMENT 2047, 305 (“Climate change presents two challenges that shall be addressed simultaneously. The first is to stabilize the climate. Secondly, to slow the rate of warming to reduce the risk of climate extremes. This dual approach that tackles emissions of CO2 in the longer term and nonCO2 super pollutants in the near term is necessary to limit and reduce the impacts of climate change (Gabrielle Dreyfus et al, 2022). Cutting short-lived super climate pollutants, including black carbon, methane, tropospheric ozone, and hydrofluorocarbons can avoid four times more warming by 2050 than CO2 cuts alone. Such strategy should be adopted in Punjab to effectively reduce the impacts of climate change on Punjab and build a climate-resilient economy through an integrated multi-sectoral and multi-governance approach. Such an approach will ensure long-term food security, agricultural yields and income security for the marginalized.”).

[710] United Nations Environment Programme (28 February 2022) *In face of climate crisis, Iraq takes on methane pollution* (“The International Energy Agency estimated that in 2019 Iraq contributed 9 per cent of all global methane emissions originating from the oil and gas sector.”).

[711] Global Gas Flaring Reduction Partnership (2023) 2023 GLOBAL GAS FLARING TRACKER REPORT, 6 (“Consistent with previous years, flaring during 2022 was dominated by a relatively small number of countries, with the top nine flaring countries responsible for 74% of flare volumes and 45% of global oil production. These are, in order, Russia, Iraq, Iran, Algeria, Venezuela, the United States, Mexico, Libya, and Nigeria.”).

[712] United Nations (30 September 2022) *Iraq mulls tackling its methane problem and reaping major benefits along the way*, Press Release (“Following a high-level virtual seminar co-hosted by the Iraq Ministry of Health and Environment and the United Nations Environment Programme (UNEP), Iraq’s Deputy Environment Minister, Dr. Jassim Humadi, announced that the Ministries of Health and Environment and Oil have agreed to establish an inter-ministerial technical task force to better understand the nature and scale of methane emissions from the country’s oil and gas sector.”).

[713] Republic of Iraq (2021) *Nationally Determined Contributions of Iraq*, submission to the Secretariat of UNFCCC, 11–13, 15 (“يكتسب الدعم الدولي ونقل التكنولوجيا اهمية استثنائية في منع هدر الغاز المصاحب الذي يعتبر ثروة اقتصادية مهمة في حال استثماره اضافة الى انه يحقق خفضا كبيرا في انبعاثات غازات الاحتباس الحراري. وتقدر وكالة الطاقة الدولية أن تسربات غاز الميثان (المكون الأساسي للغاز الطبيعي) في العراق يمكن خفضها بنسبة تزيد عن 80٪ بإستخدام التكنولوجيا الموجودة حاليًا. وتقدر القيمة المالية لإنبعاثات الميثان في العراق بأكثر من 600 مليون دولار والتي تمثل خسارة إقتصادية كبيرة. بالإضافة إلى الفوائد الإقتصادية التي ستجلبها للعراق عملية استثمار هذا الغاز فإن تقليل إنبعاثات الميثان يحمي صحة الإنسان من خلال تحسين جودة الهواء على المستوي المحلي. ... “- قطاع الطاقة (النفط والغاز والكهرباء والنقل): ... - الإستثمار في الصناعات البترولية وتطويرها لتقليل إستنزاف الموارد وخفض الإنبعاثات في آنٍ واحد، وبالأخص تحسين تكنولوجيا حرق الغاز المصاحب ومراقبتها عن طريق التصميم الجيد، بما في ذلك عن طريق إسترجاع الغاز وإعادة تدويره. - إجراء برامج(venting) لتقليل إنبعاثات الميثان وتجنب "تنفيس" الغاز بالتعاون مع الشركاء الدوليين (التحالف العالمي (LDAR) للكشف الدوري لتسربات غاز الميثان في منشآت النفط والغاز لغرض القيام بإصلاحها وشركات النفط والغاز العاملة في العراق. - استخدام الدورات المركبة في زيادة انتاج الطاقة الكهربائية -تغيير نوع الوقود السائل الى (GMA-للميثان الوقود الغازي في محطات انتاج الطاقة الكهربائية (الغازية) وتحسين نوعية الوقود المستخدم بما يساهم في خفض الانبعاثات الكاربونية. -تقليل الانبعاثات باعتماد اليات تحسين كفاءة الطاقة وترشيد استهلاكها . -تحويل محطات الطاقة الكهربائية التي تعمل بالوقود الثقيل إلى إستخدام وقود الغاز البترولي المسال LPGالـ والغاز الجاف والذي بالإمكان توفيرهما عن طريق اصطياد الغاز المصاحب وتخفيف إنبعاثات غاز الميثان.... السيطرة على زراعة المحاصيل التي تنتج كمية كبيرة من غاز الميثان مثل زراعة الرز وكذلك الحد من إستهلاكه كمية كبيرة من المياه و محاربة إنجراف التربة وإعادة تأهيل أراضيها المتدهورة.... قطاع النفايات : إستثمار الميثان الناجم عن مواقع طمر النفايات في إنتاج الطاقة الكهربائية.... الرصد والإبلاغ والتحقق: تحفيز شركات النفط والغاز العاملة في العراق على الإبلاغ عن إنبعاثات غاز الميثان ضمن أطر شفافة معروفة، مثل إطار شراكة النفط والغاز والميثان OGMP)). - التعاون في حملات للقياس المباشر لكميات الميثان المنبعثة من مُنشئات النفط والغاز وإستخدام بيانات الأقمار الصناعية لتحديد خط أساس مرجعي للإنبعاثات.”) (“International support and technology transfer are of exceptional importance in preventing the waste of associated gas, which is an important economic wealth if invested, in addition to achieving a significant reduction in greenhouse gas emissions. The International Energy Agency estimates that leaks of methane (the main component of natural gas) in Iraq could be reduced by more than 80% using existing technology. The financial value of methane emissions in Iraq is estimated at more than 600 million dollars, which represents a great economic loss. In addition to

the economic benefits that the investment of this gas will bring to Iraq, reducing methane emissions protects human health by improving air quality at the local level. … *Energy Sector (oil, gas, electricity, and transport):* … - Investing in using methane from landfill sites in the production of electric power to reduce resource depletion and reduce emissions at the same time, in particular improving and monitoring associated gas flaring technology to reduce methane emissions and avoiding gas "venting" by using good designs, including through gas recovery and recycling. - Conducting periodic detection programs for methane gas leaks in oil and gas facilities for the purpose of repair (LDAR) in cooperation with international partners (Global Methane Alliance-GMA) and oil and gas companies operating in Iraq. - Converting heavy fuel power plants to using LPG and dry gas fuels, which can be provided by catching associated gas and reducing methane emissions. … *Agriculture sector:* - Controlling the cultivation of crops that produce a large amount of methane gas, such as rice cultivation, as well as reducing its consumption of a large amount of water as well as combating soil erosion and rehabilitating its degraded lands. *Waste sector:* - Investing methane from landfill sites in the production of electric power." "*Monitoring, reporting and verification:* - Incentivizing oil and gas companies operating in Iraq to report methane emissions within well-known transparent frameworks, such as the Oil, Gas and Methane Partnership Framework (OGMP). - Collaborate on campaigns to directly measure methane from oil and gas facilities and use satellite data to establish a baseline for emissions.") (in Arabic). *See also* Climate & Clean Air Coalition (10 January 2022) *Iraq Includes Methane in its Nationally Determined Contributions, Citing Health and Development Benefits*, News and Announcements ("Iraq aims to leverage international support to reduce its greenhouse gas emissions by 15 per cent by 2030, including by reducing methane emissions from its oil and gas, agriculture, and waste sectors. Iraq demonstrated its commitment for action by signing the Global Methane Pledge, a global effort to reduce methane emissions by at least 30 per cent from 2020 levels by 2030. … In 2020, Iraq developed a National Adaptation Plan (NAP) in partnership with the United Nations Environment Programme (UNEP) to help build the country's resilience to climate change, and did work under the CCAC's Oil & Gas Methane Partnership. It also established the Permanent National Committee on Climate Change and establishing the National Climate Change Center.").

[714] Ghaith B. (11 June 2022) *Iraq announces roadmap to eliminate gas flaring by 2030*, THE JORDAN TIMES ("Iraq has developed a roadmap to reduce gas flaring for the upcoming years, with the target of zero flaring by 2030, the minister told The Jordan Times, noting that it is the first time Iraq has made action plan for gas flaring.... Iraq is working with the World Bank through its Global Gas Flaring Reduction Partnership (GGFR), which is a public-private initiative to achieve zero flaring by 2030, Hammadi said.").

[715] (21 October 2022) *Iraq prepares law to support waste-to-energy projects*, MIDDLE EAST MONITOR ("The government of Iraq has introduced a new law to support the use of solid waste for the production of electricity and methane gas, *Iraq News Agency* (INA) reports. According to the report, the law will aim to create simple rules for investors, encouraging investments in the production of electricity and methane gas from solid waste.").

[716] (18 February 2023) *US, Canada ready to work with Iraq to tackle gas flare, say top diplomats*, KURDISTAN 24 ("To tackle its environmentally-polluting gas flare, the United States and Canada are willing to help Iraq by investing in gas capture technology in order to boost power production and reduce the adverse health implications of the emissions, the two countries' ambassadors said on Saturday.").

[717] (18 February 2023) *US, Canada ready to work with Iraq to tackle gas flare, say top diplomats*, KURDISTAN 24 ("To tackle its environmentally-polluting gas flare, the United States and Canada are willing to help Iraq by investing in gas capture technology in order to boost power production and reduce the adverse health implications of the emissions, the two countries' ambassadors said on Saturday.").

[718] Carpenter C (11 December 2023) *COP28: Iraq rejects fossil fuels phasedown, phaseout*, S & P GLOBAL ("Iraq is focused on eliminating gas flaring by 2028 and reducing methane output by 30% by 2030 to achieve its decarbonization goals, Alsalait said. It is "impossible" for Iraq to eliminate methane output by 2030 as other oil and gas companies pledged early in the COP28 negotiations, he said."We are talking about methane abatement, as you know it's very important especially for this COP" as methane accounts for 30% of emissions in the world, he said.

"It's a very important factor to abate methane. "We agree to phaseout emissions, phasedown emissions, not the fuel," Abdulbaqi Alsalait, energy adviser to the Iraq Ministry of Oil, said. When Iraq agreed to the Paris Agreement in 2015, it signed up for a 2% reduction in emissions from 2020 to 2030 and is already down 4%, he said. ").

[719] Carpenter C. (11 December 2023) *COP28: Iraq rejects fossil fuels phasedown, phaseout*, S & P GLOBAL ("Iraq, OPEC's second-biggest oil producer, will not agree to a phasedown or phaseout of fossil fuels, while it has already begun with steps to reduce emissions, the adviser to Iraq's oil ministry told S&P Global Commodity Insights at the UN Climate Change Conference in Dubai on Dec. 11, one day before talks are supposed to end. Iraq is focused on eliminating gas flaring by 2028 and reducing methane output by 30% by 2030 to achieve its decarbonization goals, Alsalait said. It is "impossible" for Iraq to eliminate methane output by 2030 as other oil and gas companies pledged early in the COP28 negotiations, he said.".").

[720]Government of Mexico, Agency for Safety, Energy and Environment (6 November 2018) *DISPOSICIONES Administrativas de carácter general que establecen los Lineamientos para la prevención y el control integral de las emisiones de metano del Sector Hidrocarburos* ("Que la información disponible a nivel internacional y nacional ha demostrado que, implementando mejoras operativas y tecnológicas disponibles, es factible reducir las emisiones de metano en el Sector Hidrocarburos. En ese sentido, la Agencia Internacional de Energía en la publicación Perspectiva Mundial de la Energía 2017, concretamente en lo relativo al caso ambiental del gas natural, reconoce que, aplicando las mejores prácticas internacionales, tales como las que este instrumento regulatorio integra, es factible y posible que a nivel mundial el sector reduzca las emisiones de metano hasta en un 75%."); *discussed in* Clean Air Task Force (13 November 2018) *Mexico Takes a Giant Leap Forward in Regulating Methane Emissions*, Press Release; *and* Del Rio D., Evangelista R., & Arrieta Maza M. (21 November 2018) *Mexico: Program For The Prevention And Comprehensive Management Of Methane Emissions Within The Hydrocarbon Sector ("PPCIEM")*, MONDAQ.

[721] United States Department of State (17 November 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Release ("Mexico and PEMEX will advance, with an investment of close to $2 billion of its own resources and international credits at special rates, a comprehensive assessment and implementation of projects and actions translating into a reduction of between 86 percent and 100 percent of methane gas emissions in gas exploration, production and processing processes by 2024. Mexico joins the United States and the rest of the countries adhering to the proposals for energy implementation of the Global Methane Pledge Energy Pathway to eradicate flaring and methane emissions in the oil and gas sector.").

[722] White House (12 July 2022) *President Biden and President Lopez Obrador Joint Statement*, Statements and Releases ("In support of the Global Methane Pledge and Global Methane Pledge Energy Pathway, Mexico and Pemex, in cooperation with the U.S., will develop an implementation plan to eliminate routine flaring and venting across onshore and offshore oil and gas operations and identify priority projects for investment.").

[723] Eschenbacher S. (25 January 2023) *Mexican energy companies lag methane emission rules, investigators say*, REUTERS ("Mexican oil and gas companies, including state giant Pemex, are lagging behind on their obligations to identify, report and mitigate methane emissions from their installations, an investigation by a group of non-profits found.").

[724] Government of Mexico (2022) *Contribución Determinada a Nivel Nacional Actualización 2022*, 14–15 ("Así, se tienen previstas medidas para fomentar las prácticas agroecológicas y la agricultura de conservación- entre ellas la sustitución de fertilizantes, la aplicación de bioinsumos, y disminución de quemas agrícolas – e impulsar sistemas agrosilvopastoriles, así como medidas para la captura y manejo del biogás de residuos pecuarios, tales como sistemas de composta, de biodigestión y de tratamiento diario para evitar la generación de gas metano… Las medidas en este sector consideran la mejora en la gestión integral de los residuos sólidos municipales, así como el tratamiento de aguas residuales tanto municipales como industriales, y otras actividades relacionadas a su disposición final, reaprovechamiento, reciclaje, compostaje y biodigestión. Se considera también avanzar en la captura y aprovechamiento del biogás, tanto de los rellenos sanitarios como de las plantas de tratamiento de aguas residuales.")

("Measures are planned to promote agroecological practices and conservation agriculture - including the substitution of fertilizers, the application of bio-inputs, and a reduction in agricultural burning - and to promote agrosilvopastoral systems, as well as measures for capturing and managing biogas from livestock waste, such as compost, biodigestion, and daily treatment systems to avoid the generation of methane gas… The measures in [the waste] sector consider improving integral management of municipal solid waste, as well as treating both municipal and industrial wastewater, and other activities related to its final disposal, reuse, recycling, composting and biodigestion. Programs are also being considered in the capture and use of biogas, both from sanitary landfills and from wastewater treatment plants.") (in Spanish).

[725] Government of Mexico (2022) *Contribución Determinada a Nivel Nacional Actualización 2022*, 14 ("El sector petróleo y gas tiene una meta de 14% de reducción de emisiones y contempla medidas para su cumplimiento que se agrupan en tres ejes de actuación: a) el incremento de la cogeneración, tanto en centros procesadores de gas como en la refinación del petróleo; b) reducción de las emisiones fugitivas del subsector gas y del subsector petróleo, y c) el Programa de Eficiencia Energética en Petróleos Mexicanos y sus empresas productivas. Petróleos Mexicanos ha establecido una meta de aprovechamiento de gas metano del 98%, considerando la producción de campos existentes y nuevos, para lo cual se desarrollará una Estrategia de aprovechamiento de gas en pozos existentes, y se realizarán obras prioritarias en los nuevos desarrollos, con inversiones estimadas en más de 2000 mil millones de dólares. … The oil and gas sector has a goal of 14% emissions reduction and contemplates measures to fulfill it that are grouped into three axes of action: a) increased cogeneration, both in gas processing centers and in oil refining; b) reducing fugitive emissions from the gas subsector and the oil subsector, and c) an Energy Efficiency Program for Petróleos Mexicanos and its productive companies. Petróleos Mexicanos has established a methane gas utilization goal of 98%, considering the production of existing and new fields, for which a Gas Exploitation Strategy will be developed in existing wells, and priority works will be carried out in new developments, with investments estimated at more than 2000 billion dollars.") (in Spanish).

[726] Government of Mexico (2022) *Contribución Determinada a Nivel Nacional Actualización 2022*, 9 ("Componente de mitigación Nuestra Contribución Determinada a Nivel Nacional en materia de mitigación con un mayor nivel de ambición establece las siguientes metas: México aumenta su meta de reducción de gases de efecto invernadero de 22% a 35% en 2030, con respecto a su línea base, con recursos nacionales que aportarán al menos un 30% y 5% con cooperación y financiamiento internacional previsto para energías limpias. De forma condicionada, México puede aumentar su meta al 2030 hasta 40%, con respecto a su línea base en 2030, si se escala el financiamiento internacional, la innovación y transferencia tecnológica, y si otros países, principalmente los mayores emisores, realizan esfuerzos conmensurados a los objetivos más ambiciosos del Acuerdo de París. Finalmente, se ratifica la meta de reducción de las emisiones de carbono negro de 51% de forma no condicionada en 2030, y 70% de forma condicionada.") ("Our Nationally Determined Contribution for mitigation with an increased level of ambition establishes the following goals: Mexico increases its goal of reducing greenhouse gases from 22% to 35% in 2030, with respect to its baseline, with national resources that will contribute at least 30% and 5% with cooperation and international financing planned for clean energy. Conditionally, Mexico can increase its goal for 2030 up to 40%, with respect to its baseline in 2030, if international financing, innovation and technology transfer are scaled up, and if other countries, mainly the largest emitters, make commensurate efforts toward the most ambitious objectives of the Paris Agreement. Finally, the goal of reducing black carbon emissions by 51% unconditionally by 2030, and 70% conditionally, is ratified.") (in Spanish).

[727] Shen L., Zavala-Araiza D., Gautam R., Omara M., Scarpelli T., Sheng J., Sulprizio M. P., Zhuang J., Zhang Y., Qu Z., Lu X., Hamburg S. P., & Jacob D. J. (2021) *Unravelling a large methane emission discrepancy in Mexico using satellite observations*, REMOTE SENS. ENVIRON. 260: 1–9, 1 ("Using TROPOMI measurements from May 2018 to December 2019, our methane emission estimates for eastern Mexico are 5.0 ± 0.2 Tg a^{-1} for anthropogenic sources and 1.5 ± 0.1 Tg a^{-1} for natural sources, representing 45% and 34% higher annual methane fluxes respectively compared to the most recent estimates based on the Mexican national greenhouse gas inventory. Our results show that Mexico's oil and gas sector has the largest discrepancy, with oil and gas emissions (1.3 ± 0.2 Tg a^{-1}) higher by a factor of two relative to bottom-up estimates—accounting for a quarter of total anthropogenic emissions.").

[728] Zavala-Araiza D., *et al.* (2021) *A tale of two regions: methane emissions from oil and gas production in offshore/onshore Mexico*, ENVIRON. RES. LETT. 16(2): 1–11, 1 ("We use atmospheric observations to quantify methane (CH_4) emissions from Mexico's most important onshore and offshore oil and gas production regions which account for 95% of oil production and 78% of gas production. We use aircraft-based top-down measurements at the regional and facility-levels to determine emissions. Satellite data (TROPOMI CH_4 data and VIIRS night-time flare data) provide independent estimates of emissions over 2 years. Our airborne estimate of the offshore region's emissions is 2800 kg CH_4 h^{-1} (95% confidence interval (CI): 1700–3900 kg CH_4 h^{-1}), more than an order of magnitude lower than the Mexican national greenhouse gas inventory estimate. In contrast, emissions from the onshore study region are 29 000 kg CH_4 h^{-1} (95% CI: 19 000–39 000 kg CH_4 h^{-1}), more than an order of magnitude higher than the inventory. One single facility—a gas processing complex that receives offshore associated gas—emits 5700 kg CH_4 h^{-1} (CI: 3500–7900 kg CH_4 h^{-1}), with the majority of those emissions related to inefficient flaring and representing as much as half of Mexico's residential gas consumption. This facility was responsible for greater emissions than the entirety of the largest offshore production region, suggesting that offshore-produced associated gas is being transported onshore where it is burned and in the process some released to the atmosphere. The satellite-based data suggest even higher emissions for the onshore region than did the temporally constrained aircraft data (>20 times higher than the inventory). If the onshore production region examined is representative of Mexican production generally, then total CH_4 emissions from Mexico's oil and gas production would be similar to, or higher than, the official inventory, despite the large overestimate of offshore emissions."); *discussed in* Glover A. (25 January 2021) *Climate Scientists Record Extremely High Methane Emissions Across the Gulf states of Mexico*, Environmental Defense Fund.

[729] United States Embassy & Consulates in Mexico (9 February 2022) *Special Presidential Envoy for Climate John Kerry Visits Mexico City*, Press Release ("The two sides agreed that they would expeditiously implement high-level dialogue on the implementation of these goals through the formation of a U.S.-Mexico Climate and Clean Energy Working Group, including key agencies on both sides. The policy focus areas will include, as listed in the October Joint Statement, accelerating renewable energy development including solar supply chains, tackling methane emissions from oil and gas, waste, and agriculture, reducing transportation emissions through electrification and other strategies, eliminating deforestation and supporting nature-based solutions, and Nationally Determined Contributions.").

[730] Madry K. & Graham D. (18 June 2022) *Pemex to cut methane emissions*, REUTERS ("Mexican President Andres Manuel Lopez Obrador said on Friday that state oil and gas company Petroleos Mexicanos (Pemex) would spend some $2 billion to lower its methane emissions by up to 98%. Speaking at the Major Economies Forum, a virtual event hosted by U.S. President Joe Biden, Lopez Obrador said the investment would apply to the company's exploration and production unit and would come from Pemex's own funds as well as international credit lines.").

[731] White House (12 July 2022) *President Biden and President Lopez Obrador Joint Statement*, Statements and Releases ("We commit to tackle methane emissions from oil and gas and other sectors, accelerate the transition to zero-emission vehicles, and deepen our efforts to seek nature-based solutions, enabling our two countries to become global leaders in clean energies and actions to combat climate change. In support of the Global Methane Pledge and Global Methane Pledge Energy Pathway, Mexico and Pemex, in cooperation with the U.S., will develop an implementation plan to eliminate routine flaring and venting across onshore and offshore oil and gas operations and identify priority projects for investment.").

[732] Irakulis-Loitxate I., Gorroño J., Zavala-Araiza D., & Guanter L. (2022) *Satellites Detect a Methane Ultra-emission Event from an Offshore Platform in the Gulf of Mexico*, ENVIRON. SCI. TECHNOL. LETT. 9(6): 520–25, 520 ("The study site is an offshore oil and gas production platform in the Gulf of Mexico, near the coast of Campeche, in one of Mexico's major oil producing fields. Our data suggest that the platform vented high volumes of methane during a 17-day ultra-emission event, amounting to 0.04 ± 0.01 Tg of methane (equivalent to 3.36 million tons of carbon dioxide) released to the atmosphere if integrated over time."). Additional emissions from the same platform were detected in

August. *See* Eschenbacher S. (2 September 2022) *Exclusive-Scientists detect second 'vast' methane leak at Pemex oil field in Mexico*, REUTERS.

[733] Durodola A. & Idunnu A. (10 November 2022) *Nigeria's cities are at severe risk from climate change. Time to build resilience, and fast*, UNFCCC Race to Resilience Campaign ("Vulnerability to extreme climatic change in Nigeria is becoming more intense as accelerated urbanization continues to push more people into the capital cities in different regions of the country. In many of the states in the country, urbanization pressure across different urban areas is gradually expanding towns and cities to flood plains and coastal strips where they are exposed to more coastal flood risks. It is therefore important to curb further occurrences and build resilience to climate change by promoting planned human settlements and intensive urban infrastructural development. More importantly, the government must ensure that properties and lives in susceptible areas are protected through policy interventions and increased funding of climate-related projects.").

[734] Federal Ministry of Agriculture and Food Security, *National Livestock Transformation Plan Summit* (*last visited* 14 February 2024).

[735] Climate & Clean Air Coalition (12 January 2023) *Nigeria Cements Methane Guidelines, and its Role as an African Climate and Clean Air Leader*, News and Announcements ("Nigeria is the first country in Africa to regulate methane emissions in the energy sector.").

[736] Gbonegun V. (29 January 2024) *Nigeria, 18 others responsible for 80 per cent of methane emissions*, THE GUARDIAN NIGERIA ("According to the report, 19 African countries are responsible for 80 per cent of the continent's methane emissions, with Nigeria, Sudan, the Democratic Republic of Congo, and Egypt contributing half of the total. The report reveals that methane emissions in Africa have risen at a yearly rate of two per cent from 1990 to 2022, contributing a staggering 14 per cent to the total global methane emissions. These emissions predominantly emanate from the agricultural sector (51per cent), energy production (35per cent), and waste management (14per cent).").

[737] Government of the Federal Republic of Nigeria (2021) Climate Change Act, 2021, 5–7 ("PART II – ESTABLISHMENT OF THE NATIONAL COUNCIL ON CLIMATE CHANGE: 3.(1) There is established the National Council on Climate Change (in this Act referred to as "the Council"), which shall be vested with powers to make policies and decisions on all matters concerning climate change in Nigeria… 5.(1) The Council shall consist of – (a) the President of the Federal Republic of Nigeria, who shall Head the Council, as Chairman; (b) the Vice-President of the Federal Republic of Nigeria, who shall be the Vice Chairman[.]"). For a discussion of the Act, *see* Tawfiq Ladan M. (28 March 2022) *A Review of Nigeria's 2021 Climate Change Act: Potential for Increased Climate Litigation*, International Union for Conservation of Nature.

[738] Government of the Federal Republic of Nigeria (2021) Climate Change Act, 2021, 4 ("This Act provides a framework for achieving low greenhouse gas emission (GHG), inclusive green growth and sustainable economic development by [among other actions,] setting a target for year 2050-2070 for the attainment of a net-zero GHG emission, in line with Nigeria's international climate change obligations[.]"); 25–26 ("In this Act - … "greenhouse gases" or "GHG" means the constituents of the atmosphere that contribute to the Greenhouse effect and includes – (a) carbon dioxide; (b) methane; (c) nitrous oxide; (d) hydro fluorocarbons; (e) per fluorocarbons; (f) sulphur hexafluoride; and (g) indirect greenhouse gases[.]").

[739] Government of the Federal Republic of Nigeria, Federal Ministry of Petroleum Resources (2017) NATIONAL GAS POLICY: NIGERIAN GOVERNMENT POLICY AND ACTIONS, 13 ("The Policy articulates the vision of the Federal Government of Nigeria, sets goals, strategies and an implementation plan for the introduction of an appropriate institutional, legal, regulatory and commercial framework for the gas sector. It is intended to remove the barriers affecting investment and development of the sector. The policy will be reviewed and updated periodically to ensure consistency in Government policy objectives at all times.").

[740] Government of the Federal Republic of Nigeria (2018) NATIONAL ACTION PLAN TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS (SLCPS), i ("The Plan consolidates all sectoral efforts on SLCP emission reductions (specifically, Black Carbon, Methane and hydrofluorocarbons (HFC)) in the country, and we are committed to ensuring that the measures and their implementation are comprehensively mainstreamed into the various sectoral policies of government.").

[741] Government of the Federal Republic of Nigeria, Federal Ministry of Environment, Department of Climate Change (2021) NATIONAL CLIMATE CHANGE POLICY FOR NIGERIA 2021-2030, 7 ("Thus, the purpose of this National Policy on Climate Change is to define a new holistic framework to guide the country's response to the development challenge of climate change. As a framework document, it prescribes sectoral and cross-sectoral strategic policy statements and actions
for the management of climate change within the country's pursuit for climate resilient sustainable development.").

[742] Government of the Federal Republic of Nigeria, Federal Ministry of Environment, Department of Climate Change (2021) 2050 LONG-TERM VISION FOR NIGERIA (LTV-2050): TOWARDS THE DEVELOPMENT OF NIGERIA'S LONG-TERM LOW EMISSIONS DEVELOPMENT STRATEGY, ii ("This Long-Term Vision, intended as a first contribution towards the invitation in Article 4.19 of the Paris Agreement to communicate long-term low greenhouse gas emissions development strategies (LT-LEDS), was elaborated in 2020-2021, to collect a broad set of views and prepare for the construction of a full long-term strategy to explore how Nigeria can achieve its new climate ambition.").

[743] Formerly No.99 of 1979. Now Cap A25 Laws of the Federation of Nigeria 2004 See Government of the Federal Republic of Nigeria (2004) *"Associated Gas Re-injection Act 2004" (AGRA)*.

[744] Government of the Federal Republic of Nigeria (2016) *Nigerian Gas Flare Commercialisation Programme (NGFCP)*. ("The Nigerian Gas Flare Commercialisation Programme (NGFCP) is an opportunity for Government, industry, State Government, ethnic nationalities, and local communities to work together to resolve an oil field unacceptable practice.").

[745] The 2018 Flare Gas regulations have been revoked by the *Gas Flaring, Venting and Methane Emissions (Prevention of Waste and Pollution) Regulations 2023* recently issued by the Nigerian Upstream Petroleum Regulatory Commission (NUPRC). *See also* Nigerian Upstream Petroleum Regulatory Commission (2023) *Gas Flaring, Venting and Methane Emissions (Prevention of Waste and Pollution) Regulations 2023*.

[746] Nigerian Midstream and Downstream Petroleum Regulatory Authority (2023) *Midstream Gas Flare Regulations 2023*.

[747] Government of the Federal Republic of Nigeria (17 August 2021) *Petroleum Industry Act, 2021*. Cap 10 Laws of the Federation of Nigeria (LFN) 2004. The PIA which was enacted in 2021, essentially repeals the Petroleum Act. It was enacted to provide governance, regulatory and fiscal framework for the Nigerian Petroleum industry and the development of host communities.

[748] Government of the Federal Republic of Nigeria (2020) *Draft Gas Flaring (Prohibition and Punishment) Bill, 2020*.

[749] Government of the Federal Republic of Nigeria, Upstream Petroleum Regulatory Commission (2022) *Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria*.

[750] Global Gas Flaring Reduction Partnership (2022) 2022 GLOBAL GAS FLARING TRACKER REPORT, 6–7 ("Seven of the top 10 flaring countries have held this position consistently for the last 10 years: Russia, Iraq, Iran, the United States, Venezuela, Algeria, and Nigeria. The remaining three: Mexico, Libya, and China, have shown significant flaring increases in recent years.").

[751] Global Gas Flaring Reduction Partnership (2022) 2022 GLOBAL GAS FLARING TRACKER REPORT, 11 ("Promising Reductions. … Nigeria: 2021 Flare volume rank 7th; 2012 – 2021 31% reduction in flaring.").

[752] Climate & Clean Air Coalition, *Nigeria* (*last visited* 25 January 2023) ("Nigeria has been a Climate and Clean Air Coalition (CCAC) partner since 2012. As a country with an agriculturally-based economy, widespread food insecurity, and where the effects of climate change are already evident, reaping the multiple benefits of short-lived climate pollutant (SLCPs) mitigation is critical.").

[753] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release. *See also* Nilsen E. & Dewan A. (11 October 2021) *More than 30 countries have joined pledge to slash climate-warming methane emissions by 30%*, CNN ("Canada, Nigeria, Japan and Pakistan are among 31 parties to join a global pledge, led by the US and EU, to slash planet-warming methane emissions by the end of the decade, US climate [envoy] John Kerry announced Monday.").

[754] Government of the Federal Republic of Nigeria (2018) NATIONAL ACTION PLAN TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS (SLCPS), 87 ("The National flare-out target is set for 2020 … Fig.4.8: "Implementation Pathway for Gas Flare-Out Abatement Measure" noting that this target is driven by the Paris Climate Agreement, the World Bank Global Gas Flaring Partnership and economic growth stimulation objectives). For a demonstration of this prior commitment, *see* World Bank (10 March 2017) *Nigeria's Flaring Reduction Target: 2020* ("Dr. Emmanuel Ibe Kachikwu, Nigeria's State Minister for Petroleum Resources, presented his country's high-level roadmap to end routine gas flaring by 2020, which is a full decade ahead of the target in the "Zero Routine Flaring by 2030" Initiative, a global effort to end routine flaring that Nigeria endorsed in 2016.").

[755] Government of the Federal Republic of Nigeria (2018) NATIONAL ACTION PLAN TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS (SLCPS) (Table S.1: "SLCP abatement measures adopted in the National SLCP Plan" provides a summary of key targets, including: 100% reduction in oil and gas sector flaring by 2020; 50% methane reduction by 2030 for fugitive emissions/leakages control; and methane leakage reduction in the oil and gas sector). *See also* Climate & Clean Air Coalition (12 January 2023) *Nigeria Cements Methane Guidelines, and its Role as an African Climate and Clean Air Leader*, News and Announcements ("The CCAC was pivotal to the development of the guidelines as they provided the support right at the drafting of the National Action Plan on SLCPs which was the first policy document that focused on methane abatement," said Muhammad."). *See also* World Bank (10 March 2017) *Nigeria's Flaring Reduction Target: 2020* ("Dr. Emmanuel Ibe Kachikwu, Nigeria's State Minister for Petroleum Resources, presented his country's high-level roadmap to end routine gas flaring by 2020, which is a full decade ahead of the target in the "Zero Routine Flaring by 2030" Initiative, a global effort to end routine flaring that Nigeria endorsed in 2016.").

[756] World Bank (2021) GLOBAL GAS FLARING TRACKER, 9 ("Another bright spot can be found in Nigeria, the seventh-largest flaring country in 2020. Although the country has remained in the top seven flaring countries, it has nonetheless steadily reduced its flaring by some 70 percent over the past 15 years. Flaring has declined from over 25 bcm in 2000 to close to 7 bcm in 2020, while oil production has remained essentially flat at around 2 million barrels a day.").

[757] Government of the Federal Republic of Nigeria, *Nigeria Energy Transition Plan* (*last visited* 15 November 2023) ("At COP26, H.E. President Muhammadu Buhari announced Nigeria's commitment to carbon neutrality by 2060. Nigeria's Energy Transition Plan (ETP) was unveiled shortly after– highlighting the scale of effort required to achieve the 2060 net zero target whilst also meeting the nation's energy needs. Since the announcement, the Climate Change Act 2021 has been passed, the ETP has been fully approved by the Federal Government and an Energy Transition Implementation working group (ETWG) chaired by H.E Vice President Yemi Osinbajo (SAN), comprising of several key ministers and supported by an Energy Transition Office (ETO) has been established.").

[758] Government of the Federal Republic of Nigeria, *Nigeria Energy Transition Plan* (*last visited* 15 November 2023) ("The Nigeria ETP sets out a timeline and framework for the attainment of emissions' reduction across 5 key sectors; Power, Cooking, Oil and Gas, Transport and Industry. Within the scope of the ETP, about 65% of Nigeria's emissions are affected.").

[759] Government of the Federal Republic of Nigeria, *Nigeria Energy Transition Plan Oil and Gas Milestones* (*last visited* 15 November 2023) (Milestones by 2030: "100% reduction of flaring emissions.").

[760] Government of the Federal Republic of Nigeria, Upstream Petroleum Regulatory Commission (2022) *Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria,* 16 ("To achieve Nigeria's emission mitigation and reduction targets of the NDCs in the Oil and Gas, the key abatement measures and their targets are; elimination of routine gas flaring (100% of gas flaring eliminated by 2030) and fugitive emissions/leakages control (60% Methane Reduction by 2030). This notwithstanding, the exemption provisions of the sections 104 and 107 of the Petroleum Industry Act (PIA) 2021 shall apply."). *See also* Clean Air Task Force (11 November 2022) *Nigeria announces rule to reduce methane emissions from the oil and gas sector*, News & Media ("Nigeria has shown great leadership on methane at COP27, giving the world a concrete example of the kinds of action necessary to slash methane emissions and bend the curve on climate change," said Jonathan Banks, Global Director of CATF's Methane Pollution Prevention program. "Nigeria is turning ambition into action on methane. We sincerely hope that other nations will step up and follow its lead.").

[761] Afinotan U. (2022) *How serious is Nigeria about climate change mitigation through gas flaring regulation in the Niger Delta?*, ENVIRON. LAW REV. 24(4): 288–304, 291 ("In the meantime, the deadline for the cessation of gas flaring has been shifted several times −2004, 2008, 2012 and 2020, with no end yet in sight."). *See also* Koop F. (3 October 2023) Nigeria: *Shell's Controversial Data Raises Questions About Efforts to Control Methane Emissions in Nigeria, Others*, PREMIUM TIMES ("According to statistics provided by Nigeria's National Oil Spill Detection and Response Agency (NOSDRA) and the Gas Flaring Tracker satellite of the World Bank, oil companies throughout the nation, including Shell, have flared about $3.9 billion worth of gas in the last four years. However, Shell's Sustainability Report 2022, scope 1 emissions for upstream flaring in Nigeria witnessed 2 million metric tons of emissions reduction, with a figure of 3 million metric tonnes in 2022 compared to 5 million metric tonnes in 2021. Their data also shows that between 2018 and 2019, the metric tonnes emissions were pegged at 4 million, respectively. For 2020 it increased to 5 million metric tonnes of emissions. "They have to explain their data," said Segun Omidele, President of the Polaseo Group, a Nigerian oil and gas service company and former Shell employee. Given all the many crude thefts throughout the Niger Delta, leading many operators to reduce, shut down or abandon production, "it is difficult to accept there's been an emissions reduction," he said.").

[762] Afinotan U. (2022) *How serious is Nigeria about climate change mitigation through gas flaring regulation in the Niger Delta?*, ENVIRON. LAW REV. 24(4): 288–304, 304 ("Currently, as part of its new set of climate change commitments under the Glasgow Climate Pact at COP26, Nigeria has unequivocally pledged to phase out GHG emissions (i.e gas flaring) by 2060. Cynics might regard it as another shifting of the goal post. Nevertheless, if its new commitments are to be realistically and effectively achieved, Nigeria has more than a few legislative, regulatory and judicial measures to put in place to achieve the actualization of these international commitments on combating and mitigating climate change.").

[763] Government of the Federal Republic of Nigeria (2021) *Nigeria's First Nationally Determined Contribution - 2021 update*, 22 (Table 1: Mitigation measures in the energy sector (conditional)).

[764] Government of the Federal Republic of Nigeria (2021) *Nigeria's First Nationally Determined Contribution - 2021 update*, 27 ("In 2019, the Federal Executive Council endorsed Nigeria's National Action Plan to reduce SLCPs. This National Action Plan includes 22 specific actions that would substantially reduce SLCPs. As part of this NDC update, many of these actions have been integrated into the sectoral mitigation measures highlighted in Sections 5.5.1-5.5.4, and the reductions in SLCP (and air pollutant) emissions from achieving the NDC targets have been evaluated. In

terms of SLCP reductions, the full achievement of Nigeria's NDC is estimated to reduce black carbon, methane and hydrofluorocarbon emissions by 42%, 28%, and 2% respectively, in 2030 compared to a baseline scenario. Other health-damaging air pollutants, such as particulate matter ($PM_{2.5}$) and nitrous oxides (NO_x) would also be reduced by 35% and 65%, respectively.").

[765] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("At COP28, Nigeria showcased major steps taken this year under the Nigeria Gas Flare Commercialization Program (NGFCP), including advancing projects it estimates will capture over half of all gas flaring volumes in Nigeria."). *See also* Isiah N. J. (2 December 2023) *In UAE, Tinubu Commits Nigeria To Ending Gas Flaring To Cut Methane Emissions*, LEADERSHIP TIMES ("President Bola Tinubu has expressed the commitment of his administration to ending gas-flaring in the country in line with the global push to halt methane emission. He made the declaration on Saturday in the ongoing United Nations Climate Conference (COP28) Summit on methane and other non-greenhouse gases in Dubai, United Arab Emirates (UAE).").

[766]Nigerian Upstream Regulatory Petroleum Commission (11 January 2024) *A Landmark Collaboration Between Nigerian Upstream Petroleum Regulatory Commission and Climate Clean Air Coalition for Methane Mitigation from Nigeria's Oil and Gas Sector* ("Nigeria is poised to receive substantial support in its endeavor to mitigate methane emissions originating from the oil and gas sector, through a collaboration between the Nigerian Upstream Petroleum Regulatory Commission and the Climate and Clean Air Coalition. This collaborative effort signifies a significant step towards addressing environmental challenges associated with the energy industry.").

[767] Nigerian Upstream Regulatory Petroleum Commission (11 January 2024) *A Landmark Collaboration Between Nigerian Upstream Petroleum Regulatory Commission and Climate Clean Air Coalition for Methane Mitigation from Nigeria's Oil and Gas Sector* ("As a prime regulator in Nigeria's Oil and Gas sector, the Nigerian Upstream Petroleum Regulatory Commission, is set to leverage the expertise and resources of Climate and Clean Air Coalition. This collaboration that encompasses a multifaceted approach, including knowledge sharing, technological support, and joint research efforts, is aimed at devising effective methane mitigation strategies.").

[768] United Kingdom Department for Business, Energy & Industrial Strategy (2023) 2021 UK GREENHOUSE GAS EMISSIONS, FINAL FIGURES, 7 ("Weighted by global warming potential, methane accounted for about 13% and nitrous oxide for about 4% of UK emissions in 2021.").

[769] Climate Watch, *United Kingdom Greenhouse Gas Emissions* (*last visited* 1 July 2023).

[770] United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy (2022) UNITED KINGDOM METHANE MEMORANDUM, 7 ("The UK signed up to the Global Methane Pledge at COP26, which aims to collectively reduce global anthropogenic methane emissions by at least 30 percent below 2020 levels by 2030. Under the Pledge, the UK has also committed to moving towards using the highest tier IPCC good practice inventory methodologies, as well as working to continuously improve the accuracy, transparency, consistency, comparability, and completeness of national greenhouse gas inventory reporting under the UNFCCC and Paris Agreement, and to provide greater transparency in key sectors.").

[771] United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy (2022) UNITED KINGDOM METHANE MEMORANDUM, 7 ("The UK is also a state partner of the Climate and Clean Air Coalition, a core implementing partner of the Pledge, and a member of the Oil and Gas Methane Partnership Steering Group.").

[772] United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy (2020) POWERING OUR NET ZERO FUTURE, 138 ("We will commit the UK to the World Bank's 'Zero Routine Flaring by 2030' initiative and will work with regulators towards eliminating this practice as soon as possible in advance of this date.").

[773] United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy (2022) UNITED KINGDOM METHANE MEMORANDUM, 7 (“The UK signed up to the Global Methane Pledge at COP26, which aims to collectively reduce global anthropogenic methane emissions by at least 30 percent below 2020 levels by 2030. Under the Pledge, the UK has also committed to moving towards using the highest tier IPCC good practice inventory methodologies, as well as working to continuously improve the accuracy, transparency, consistency, comparability, and completeness of national greenhouse gas inventory reporting under the UNFCCC and Paris Agreement, and to provide greater transparency in key sectors.”).

[774] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 85 (“In the six years from 2015 to 2021, methane emissions have fallen by an average of 0.9 MtCO2e (1.5%) per year.”).

[775] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 85 (“In the six years from 2015 to 2021, methane emissions have fallen by an average of 0.9 MtCO2e (1.5%) per year. This will need to accelerate to 2.0 MtCO2e (4%) per year if the UK is to achieve a 30% reduction by 2030.”).

[776] Riddick S. & Mauzerall D. (2023) *Likely substantial underestimation of reported methane emissions from United Kingdom upstream oil and gas activities*, ENERGY ENVIRON. SCI. 16: 295–304, 300. (“The 2019 NAEI estimated total emissions from upstream O&G operations (venting, flaring, process emissions, fuel combustion, offshore oil loading, transfer by pipeline and onshore oil/gas terminals) at 52 Gg CH4. Our integrated approach, which uses direct measurements and top-down studies and published data, estimates 2019 CH4 emissions at 289 Gg CH4, five times the current NAEI estimate. This may be a lower bound estimate as (i) venting in the North Sea is reported to have increased from 5 Gg CH4 year1 in 2016 to 136 Gg CH4 year1 in 2020 (reported as 112 Gg CH4 year1 in 2019) despite little change in oil or gas production15 (ii) although we assume flares operate at optimal efficiency it is likely they are not optimized46,48,49 and (iii) we assume that CH4 combustion slip from compressors, VRUs and condensate tanks are routed to the flare which is unlikely to occur.”).

[777] Riddick S. & Mauzerall D. (2023) *Likely substantial underestimation of reported methane emissions from United Kingdom upstream oil and gas activities*, ENERGY ENVIRON. SCI. 16: 295–304, 300 (“The 2019 NAEI estimated total emissions from upstream O&G operations (venting, flaring, process emissions, fuel combustion, offshore oil loading, transfer by pipeline and onshore oil/gas terminals) at 52 Gg CH4. Our integrated approach, which uses direct measurements and top-down studies and published data, estimates 2019 CH4 emissions at 289 Gg CH4, five times the current NAEI estimate. This may be a lower bound estimate as (i) venting in the North Sea is reported to have increased from 5 Gg CH4 year1 in 2016 to 136 Gg CH4 year1 in 2020 (reported as 112 Gg CH4 year1 in 2019) despite little change in oil or gas production15 (ii) although we assume flares operate at optimal efficiency it is likely they are not optimized46,48,49 and (iii) we assume that CH4 combustion slip from compressors, VRUs and condensate tanks are routed to the flare which is unlikely to occur.”).

[778] *See generally* United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy (2022) UNITED KINGDOM METHANE MEMORANDUM.

[779] *See generally* United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN.

[780] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 64 (“This is an Ofgem and Health and Safety Executive (HSE) policy to reduce methane leakage from the Gas Distribution Networks through the replacement of old iron mains pipes with new plastic pipes, through the Ofgem/HSE Iron Mains Risk Reduction Programme (IMRRP). Ofgem funds this work through the RIIO-2 price control (as set out in the price control framework). Leakage rates for plastic pipes are around 99% lower than for metallic pipes.”).

[781] United Kingdom Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy (2022) UNITED KINGDOM METHANE MEMORANDUM, 5 ("The Iron Mains Risk Reduction Programme (IMRRP) is a key driver to upgrade the gas network from iron pipes to plastic pipes. This improves the safety and resilience of the local gas network and reduces leakages of methane where the pipes have been changed. The IMRRP was introduced in 2002 to address 'societal concern' regarding the potential for failure of cast iron gas mains and the consequent risk of injuries, fatalities and damage to buildings. It has been designed to secure public safety whilst efficiency, environmental, strategic and customer service factors have also driven forward the programme.").

[782] *See generally* United Kingdom North Sea Transition Authority (2021) *Flaring and venting guidance*.

[783] United Kingdom North Sea Transition Authority (2021) *Flaring and venting guidance*, 5 ("All operator should have, or work towards, credible plans to achieve zero routine flaring and venting by 2030 or sooner. Operators should develop a Flaring and Venting Management Plan that demonstrates a credible pathway to achieving that goal, to be included as part of their Greenhouse Gas Emissions Reduction Actions Plans.").

[784] United Kingdom North Sea Transition Authority (2021) *Flaring and venting guidance*, 5 ("All new developments should be planned and developed on the basis of zero category A (routine) flaring and venting.").

[785] United Kingdom Department for Energy Security and Net Zero (2023) POWERING UP BRITAIN: THE NET ZERO GROWTH PLAN, 39 ("We will not accelerate the end to routine flaring from 2030 to 2025 as the 2030 target is already challenging due to the basin's maturity, noting that retrofitting facilities is expensive and technically challenging. The sector committed to accelerate compliance with the World Bank's 'Zero Routine Flaring by 2030' initiative ahead of 2030, and its Methane Action Plan committed to an ambitious 50% reduction in methane emissions by 2030. The government is working with regulators and industry to continue to drive down flaring and venting gas ahead of the 2030 target.").

[786] United Kingdom Landfill Tax Regulations 1996 ("These Regulations make provision for the administration and assurance of landfill tax.").

[787] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 103 ("Near elimination of biodegradable municipal waste from landfill - additional policies towards near elimination of this waste to landfill from 2028.").

[788] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 149 ("R&D to refine emissions estimates and explore further methane gas capture from landfill. Landfill gas is collected and is used to generate electricity, oxidised through flaring or natural processes. Whilst current practices capture some landfill gas, there is room for improvement. Previous research has indicated that most methane is lost at operational sites through uncapped waste and around infrastructure, such as gas wells. Industry practise could reduce this leakage. There are also other smaller opportunities for improvements at closed but permitted sites.").

[789] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 102–103. ("Collection and packaging reforms will support the reduction of biodegradable municipal waste going to landfill.").

[790] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 147 ("Increase the use of robust Monitoring, Reporting and Verification of GHG emissions (MRV). We will explore policies to increase the use of MRV across farm businesses as a mechanism to support improved understanding and behaviour change for decarbonisation. This will build on the recent UK ETS consultation call for evidence chapter which explored the use and application of MRV for the agriculture sector and ongoing research projects to examine opportunities to better harmonise and improve the robustness of emission reporting across farm, food, and drink businesses. We will develop a harmonised approach for measuring carbon emissions from farms and by 2024 will set

out how farmers will be supported to understand their emission sources through carbon audits and take further actions to decarbonise their businesses.").

[791] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 137 ("Additional mitigation intervention whereby the methane generated during storage of liquid manure is collected and burnt, converting it to carbon dioxide, a less potent GHG. There may also be potential to utilise heat or energy produced on combustion within the farm business.").

[792] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 138 ("Feeding insect protein to animals has the potential to reduce overall global emissions from feed production (in comparison to conventional protein production e.g. soya grown overseas) and support a circular economy (e.g. if insects are raised on waste). There is ongoing research to determine the potential of these measures and the sector is at an early stage of development. This measure is unlikely to have significant UK GHG or land use impacts. It could, however, reduce supply chain emissions from feed supply occurring outside the scope of UK carbon budgets.").

[793] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 93 ("Regulations to mandate retrofitting slurry tanks with a permeable cover will reduce both methane and ammonia emissions, subject to consultation. In the short term, focus is on improving compliance and supporting take up through e.g., Countryside Stewardship slurry grants. NB. This measure provides carbon savings starting before the start date. While government action or support to deliver implementation at pace may not yet be in place, there is existing, market led, uptake across sectors to deliver emission reductions. Additionally due to the significant lead in time for the projected savings to start, and the modelling system used, there may be minor emissions savings before the anticipated start year, e.g., due to proactive and engaged farmers and land managers taking steps themselves, ahead of policy. Regulations to mandate retrofitting slurry tanks with an impermeable cover to reduce both methane and ammonia emissions.").

[794] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 92 ("The measure involves improving breeding, using genetic testing (genomic tools), to ensure that breeding goals involve some low carbon traits. The measure involves farmers collecting performance information on the individual animals and genetic testing and feeding back this information to help with breeding goal development (the goals include lower methane emissions). Competitions in Defra's Farming Innovation Programme (FIP) are developing this measure ahead of further refinement of policy measures. NB. This measure shows carbon savings starting before the start date. While government action or support to deliver implementation at pace may not yet be in place, there is existing, market led, uptake across sectors to deliver emission reductions.").

[795] United Kingdom Department for Energy Security and Net Zero (2023) CARBON BUDGET DELIVERY PLAN, 90 ("Methane-suppressing feed products (for example 3NOP, nitrate additives) within feed rations to reduce the amount of methane produced by ruminant livestock (e.g. cattle). Food Standard Agency (FSA) and Food Standards Scotland (FSS) are responsible for the authorisation process of feed additives in Great Britain. We will continue to work with the FSA and FSS, industry and the sector to explore suitable policy options to encourage rapid and extensive uptake of methane suppressing feed products with proven safety and efficacy, including exploring mandating methane suppressing feed products in compound feed for cattle in England. We have already published research on these products and recently ran a call for evidence on methane suppressing feed products to better understand the opportunities and challenges associated with their use. This will inform our next steps to encourage the extensive update of methane supressing feed products.").

[796] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 52 ("International pledges launched at COPs must begin to deliver real-world action to accelerate emissions reduction this decade. While the UK has had a role in advancing progress on initiatives on forests and ZEVs, its contribution to the Global Methane Pledge remains weak.").

[797] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 66 ("The UK's action on methane is insufficient. The Government has not set out a UK-specific 30% reduction on 2020 levels by 2030 commitment to support the Global Methane Pledge and the Methane Memorandum brought forward high-level intentions rather than detailed plans for sectoral reduction").

[798] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 85 ("In our Balanced Pathway,* methane emissions fall by around 30% compared to actual emissions in 2020 by 2030. This is driven by reductions in waste, agriculture and fuel supply. The Government's ambition in all these sectors is less than in our Balanced Pathway, and Government plans all have significant delivery risks. This is particularly the case in agriculture where some plans are completely insufficient with a heavy reliance on voluntary uptake of measures (Chapter 9). It is therefore unlikely that the UK would achieve a 30% reduction in emissions by 2030 with current plans.").

[799] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 394 ("Set out plans for reducing domestic methane emissions in line with the collective aims of the Global Methane Pledge (a reduction in UK methane emissions of at least 30% from 2020 levels by 2030) and announce an intention to set a longer-term pathway for these emissions in 2023.")

[800] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 402 ("targets for methane flaring and venting should be strengthened and brought forward. For all facilities that will remain in operation post 2030, flaring and venting should only be permitted beyond 2025 when necessary for safety reasons.")

[801] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 411 ("As part of strengthening the regulatory baseline, introduce regulations under the Clean Air Strategy to reduce enteric methane emissions, specifically under environmental permitting to the dairy and intensive beef sectors.")

[802] United Kingdom Climate Change Committee (2023) 2023 PROGRESS REPORT TO PARLIAMENT, 416 ("Set out how methane capture and oxidisation rates at landfill sites will be improved. We will assess whether this is included in either the forthcoming final Waste Prevention Programme or the Resources and Waste Strategy addendum.").

[803] United Kingdom Government (19 December 2023) *New UK levy to level carbon pricing* ("Goods imported into the UK from countries with a lower or no carbon price will have to pay a levy by 2027, ensuring products from overseas face a comparable carbon price to those produced in the UK.").

[804] United Kingdom Government (19 December 2023) *New UK levy to level carbon pricing* ("Goods imported into the UK from countries with a lower or no carbon price will have to pay a levy by 2027, ensuring products from overseas face a comparable carbon price to those produced in the UK.").

[805] United Kingdom Government (19 December 2023) *New UK levy to level carbon pricing* ("Goods imported into the UK from countries with a lower or no carbon price will have to pay a levy by 2027, ensuring products from overseas face a comparable carbon price to those produced in the UK.").

[806] White House (22 April 2021) *FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies*, Statements and Releases ("Today, President Biden will announce a new target for the United States to achieve a 50-52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030 – building on progress to-date and by positioning American workers and industry to tackle the climate crisis. … The target is consistent with the President's goal of achieving net-zero greenhouse gas emissions by no later than 2050 and of limiting global warming to 1.5 degrees Celsius, as the science demands.").

[807] White House Office of Domestic Climate Policy (2021) *U.S. Methane Emissions Reduction Action Plan*. *See also* White House (2 November 2021) *FACT SHEET: President Biden Tackles Methane Emissions, Spurs Innovations, and Supports Sustainable Agriculture to Build a Clean Energy Economy and Create Jobs*, Statements and Releases.

[808] White House (31 January 2022) *FACT SHEET: Biden Administration Tackles Super-Polluting Methane Emissions*, Statements and Releases ("Today, the Biden Administration is announcing new actions in line with the Methane Emissions Reduction Action Plan to tackle methane emissions and support a clean energy economy, including: • The Department of the Interior announcing $1.15 billion for states to clean up orphaned oil and gas wells, a significant source of methane emissions. • The Department of Energy announcing the launch of a Methane Reduction Infrastructure Initiative to provide technical assistance to the orphaned well clean-up efforts of Federal agencies, states and tribes. • The Department of Transportation announcing new enforcement of the PIPES Act to requires pipeline operators to minimize methane leaks. • The Department of Agriculture highlighting ongoing research efforts and investments to reduce methane emissions from beef and dairy systems. • The White House announcing the formation of a new interagency working group to coordinate the measurement, monitoring, reporting and verification of greenhouse gas emissions and removals. • The President's Interagency Work Group on Coal and Power Plant Communities and Economic Revitalization announcing a national workshop for energy communities on repurposing fossil fuel infrastructure, including orphan oil and gas wells, for use in new industries.").

[809] United States Department of Energy (30 March 2022) *Repurposing Fossil Energy Assets Workshop*.

[810] Harris K., Johnson R., Orozco J., Kendrick J., & Gordon S. (2023) *Plugging the Leaks 2.0*, BlueGreen Alliance, 12 ("Updating industry practices and equipment to meet these proposed standards will not just make workers and communities around the facilities safer and healthier, but will also generate and support quality, family-sustaining jobs—over 136,000 direct and indirect jobs over 13 years. This is a two-fold increase in jobs compared to our analysis of the 2016 rule").

[811] White House (26 July 2023) *FACT SHEET: Biden-Harris Administration Hosts White House Methane Summit to Tackle Dangerous Climate Pollution, while Creating Good-Paying Jobs and Protecting Community Health*, Statements and Releases.

[812] White House (26 July 2023) *FACT SHEET: Biden-Harris Administration Hosts White House Methane Summit to Tackle Dangerous Climate Pollution, while Creating Good-Paying Jobs and Protecting Community Health*, Statements and Releases ("Establishing a New Cabinet-level Methane Task Force: The Biden-Harris Administration is announcing a new Cabinet-level Methane Task Force, which will advance a whole-of-government approach to proactive methane leak detection and data transparency, and support state and local efforts to mitigate and enforce methane emissions regulations. The Task Force will accelerate execution of the U.S. Methane Emissions Reduction Action Plan, building on over 80 Administration actions taken to date under the Plan").

[813] White House (26 July 2023) *FACT SHEET: Biden-Harris Administration Hosts White House Methane Summit to Tackle Dangerous Climate Pollution, while Creating Good-Paying Jobs and Protecting Community Health*, Statements and Releases ("The Task Force will accelerate execution of the U.S. Methane Emissions Reduction Action Plan, building on over 80 Administration actions taken to date under the Plan").

[814] White House (26 July 2023) *FACT SHEET: Biden-Harris Administration Hosts White House Methane Summit to Tackle Dangerous Climate Pollution, while Creating Good-Paying Jobs and Protecting Community Health*, Statements and Releases ("The Biden-Harris Administration is leveraging domestic action to raise global ambition and coordinating international efforts to mitigate methane emissions.").

[815] Inflation Reduction Act of 2022, Pub. L. No. 117-169 (2022) § 60113 ("(a) INCENTIVES FOR METHANE MITIGATION AND MONITORING.—In addition to amounts otherwise available, there is appropriated to the Administrator for fiscal year 2022, out of any money in the Treasury not otherwise appropriated, $850,000,000, to

remain available until September 30, 2028. … In addition to amounts other wise available, there is appropriated to the Administrator for fiscal year 2022, out of any money in the Treasury not otherwise appropriated, $700,000,000, to remain available until September 30, 2028, for activities described 21 in paragraphs (1) through (4) of subsection (a) at marginal conventional wells."). For broader support of monitoring provisions for methane under IRA *see* Senator Whitehouse., Senator Carpenter., & Congressman Pallone. (30 November 2023) *Letter to EPA*, ("We write to express our strong support for the Environmental Protection Agency's (EPA) proposal to amend requirements for oil and natural gas systems to report emissions under EPA's Greenhouse Gas Reporting Program (GHGRP). We also urge EPA to strengthen the final rule in several specific ways to meet Congress' directive in the Inflation Reduction Act (IRA) to ensure that oil and gas operators more accurately report their methane emissions. More accurate emissions reports are critical to support the deep, near-term reductions in methane emissions necessary to avoid the worst consequences of climate change."),

[816] Inflation Reduction Act of 2022, Pub. L. No. 117-169 (2022) § 60112 ("(e) Charge Amount.--The amount of a charge under subsection (c) for an applicable facility shall be equal to the product obtained by multiplying—"(1) the number of metric tons of methane emissions reported pursuant to subpart W of part 98 of title 40, Code of Federal Regulations, for the applicable facility that exceed the applicable annual waste emissions threshold listed in subsection (f) during the previous reporting period; and "(2)(A) $900 for emissions reported for calendar year 2024; "(B) $1,200 for emissions reported for calendar year 2025; or "(C) $1,500 for emissions reported for calendar year 2026 and each year thereafter."). ***See also*** United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; ***discussed in*** Friedman L. & Plumer B. (28 July 2022) *Surprise Deal Would Be Most Ambitious Climate Action Undertaken by U.S.*, THE NEW YORK TIMES ("The bill would also crack down on leaks of methane, a powerful greenhouse gas, from oil and gas wells, pipelines and other infrastructure. By 2026, polluters would face a penalty of $1,500 per ton of methane that escaped into the atmosphere in excess of federal limits. The methane fee will raise $6.3 billion from the oil and gas industry over a decade, much of which will be reinvested in measures to help prevent methane leaks.").

[817] Inflation Reduction Act of 2022, Pub. L. No. 117-169 (2022) §§ 50261–50263 ("For all leases issued after the date of enactment of this Act, except as provided in subsection (b), royalties paid for gas produced from Federal land and on the outer Continental Shelf shall be assessed on all gas produced, including all gas that is consumed or lost by venting, flaring, or negligent releases through any equipment during upstream operations.").

[818] Inflation Reduction Act of 2022, Pub. L. No. 117-169 (2022) § 21001(a)(1)–(4) ("(a) Appropriations … (1) to carry out, using the facilities and authorities of the Commodity Credit Corporation, the environmental quality incentives program under subchapter A of chapter 4 of subtitle D of title XII of the Food Security Act of 1985 (16 U.S.C. 3839aa through 3839aa-8)—(A)(i) $250,000,000 for fiscal year 2023; (ii) $1,750,000,000 for fiscal year 2024; (iii) $3,000,000,000 for fiscal year 2025; and (iv) $3,450,000,000 for fiscal year 2026 … (II) with the Secretary prioritizing proposals that utilize diet and feed management to reduce enteric methane emissions from ruminants; and (iii) the funds shall be available for 1 or more agricultural conservation practices or enhancements that the Secretary determines directly improve soil carbon, reduce nitrogen losses, or reduce, capture, avoid, or sequester carbon dioxide, methane, or nitrous oxide emissions, associated with agricultural production; (2) to carry out, using the facilities and authorities of the Commodity Credit Corporation, the conservation stewardship program under subchapter B of that chapter (16 U.S.C. 3839aa-21 through 3839aa-25)—(A)(i) $250,000,000 for fiscal year 2023; (ii) $500,000,000 for fiscal year 2024; (iii) $1,000,000,000 for fiscal year 2025; and (iv) $1,500,000,000 for fiscal year 2026; and (B) subject to the condition on the use of the funds that the funds shall only be available for 1 or more agricultural conservation practices, enhancements, or bundles that the Secretary determines directly improve soil carbon, reduce nitrogen losses, or reduce, capture, avoid, or sequester carbon dioxide, methane, or nitrous oxide emissions, associated with agricultural production; (3) to carry out, using the facilities and authorities of the Commodity Credit Corporation, the agricultural conservation easement program under subtitle H of title XII of that Act (16 U.S.C. 3865 through 3865d) for easements or interests in land that will most reduce, capture, avoid, or sequester carbon dioxide, methane, or nitrous oxide emissions associated with land eligible for the program—(A) $100,000,000 for fiscal year 2023; (B) $200,000,000 for fiscal year 2024; (C) $500,000,000 for fiscal year 2025; and (D) $600,000,000 for fiscal year 2026;

and (4) to carry out, using the facilities and authorities of the Commodity Credit Corporation, the regional conservation partnership program under subtitle I of title XII of that Act (16 U.S.C. 3871 through 3871f)—(A)(i) $250,000,000 for fiscal year 2023; (ii) $800,000,000 for fiscal year 2024; (iii) $1,500,000,000 for fiscal year 2025; and (iv) $2,400,000,000 for fiscal year 2026; and (B) subject to the conditions on the use of the funds that—(i) section 1271C(d)(2)(B) of the Food Security Act of 1985 (16 U.S.C. 3871c(d)(2)(B)) shall not apply; and (ii) the Secretary shall prioritize partnership agreements under section 1271C(d) of the Food Security Act of 1985 (16 U.S.C. 3871c(d)) that support the implementation of conservation projects that assist agricultural producers and nonindustrial private forestland owners in directly improving soil carbon, reducing nitrogen losses, or reducing, capturing, avoiding, or sequestering carbon dioxide, methane, or nitrous oxide emissions, associated with agricultural production.").

[819] Analyses by Princeton's REPEAT Project, Energy Innovation, and the Rhodium Group confirm the 40% GHG reductions capability of the 2022 Inflation Reduction Act. *See* Jenkins J. D., Mayfield E. N., Farbes J., Jones R., Patankar N., Xu Q., & Schivley G. (2022) *Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022*, REPEAT Project, Princeton University ZERO Lab, 6 (Table. Historical and Modeled Net U.S. Greenhouse Gas Emissions (Including Land Sinks); Mahajan M., Ashmoore O., Rissman J., Orvis R., & Gopal A. (2022) *Modeling the Inflation Reduction Act Using the Energy Policy Simulator*, Energy Innovation, 1 ("We find that the IRA is the most significant federal climate and clean energy legislation in U.S. history, and its provisions could cut greenhouse gas (GHG) emissions 37-41 percent below 2005 levels. If the IRA passes, additional executive and state actions can realistically achieve the U.S. nationally determined commitments (NDCs) under the Paris Agreement."); *and* Larsen J., King B., Kolus H., Dasari N., Hiltbrand G., & Herndon W. (12 August 2022) *A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act*, The Rhodium Group ("The IRA is a game changer for US decarbonization. We find that the package as a whole drives US net GHG emissions down to 32-42% below 2005 levels in 2030, compared to 24-35% without it. The long-term, robust incentives and programs provide a decade of policy certainty for the clean energy industry to scale up across all corners of the US energy system to levels that the US has never seen before. The IRA also targets incentives toward emerging clean technologies that have seen little support to date. These incentives help reduce the green premium on clean fuels, clean hydrogen, carbon capture, direct air capture, and other technologies, potentially creating the market conditions to expand these nascent industries to the level needed to maintain momentum on decarbonization into the 2030s and beyond."); *discussed in* Hirji Z. (4 August 2022) *How the Senate's Big Climate Bill Eliminates 4 Billion Tons of Emissions*, BLOOMBERG.

[820] Infrastructure Investment and Jobs Act, Pub. L. No. 117-58 (2021) § 40601 ("Orphaned Well Site Plugging, Remediation, and Restoration. … (h) Authorization of Appropriations.--There are authorized to be appropriated for fiscal year 2022, to remain available until September 30, 2030: ``(1) to the Secretary-- ``(A) $250,000,000 to carry out the program under subsection (b); ``(B) $775,000,000 to provide grants under subsection (c)(3); ``(C) $2,000,000,000 to provide grants under subsection (c)(4); ``(D) $1,500,000,000 to provide grants under subsection (c)(5); and (E) $150,000,000 to carry out the program under subsection (d).").

[821] United States Environmental Protection Agency (2 November 2021) *EPA Proposes New Source Performance Standards Updates, Emissions Guidelines to Reduce Methane and Other Harmful Pollution from the Oil and Natural Gas Industry* ("EPA is taking a significant step in fighting the climate crisis and protecting public health through a proposed rule that would sharply reduce methane and other harmful air pollution from both new and existing sources in the oil and natural gas industry. The proposal would expand and strengthen emissions reduction requirements that are currently on the books for new, modified and reconstructed oil and natural gas sources, and would require states to reduce methane emissions from hundreds of thousands of existing sources nationwide for the first time."). For comprehensive data on the pollution and health effects of oil and gas sources *See* Oil and Gas Threat Map, *About Oil and Gas Threat Map* (*last visited* 18 December 2023) ("The Oil & Gas Threat Map plots the location of all active oil & gas production facilities in the United States, draws a ½ mile health threat radius around all of those facilities counts the residents, and enrolled students and schools they attend, within that health threat radius.").

[822] United States Environmental Protection Agency (11 November 2022) *EPA Issues Supplemental Proposal to Reduce Methane and Other Harmful Pollution from Oil and Natural Gas Operations* ("EPA is taking a significant step in fighting the climate crisis and protecting public health through a proposed rule that would sharply reduce methane and other harmful air pollution from both new and existing sources in the oil and natural gas industry. The proposal would expand and strengthen emissions reduction requirements that are currently on the books for new, modified and reconstructed oil and natural gas sources, and would require states to reduce methane emissions from hundreds of thousands of existing sources nationwide for the first time.").

[823] United States Environmental Protection Agency (2022) *EPA's Supplemental Proposal to Reduce Pollution from the Oil and Natural Gas Industry to Fight the Climate Crisis and Protect Public Health: Overview*, 1 ("By improving standards in the 2021 proposal and adding proposed requirements for sources that proposal did not cover, the supplemental proposal signed November 8, 2022, would achieve more comprehensive emissions reductions from oil and natural gas facilities. In 2030 alone, the supplemental proposal would reduce methane emissions from the sources it covers by 87 percent below 2005 levels. It would increase recovery of natural gas that otherwise would go to waste – saving enough gas from 2023 to 2035 to heat an estimated 3.5 million homes for the winter.").

[824] environmental Protection Agency (2023) *Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review*. *See also* Tankersly J & Friedman L. (2 December 2023) *Biden Administration Announces Rule to Cut Millions of Tons of Methane Emissions*, NEW YORK TIMES ("The methane rule, which was first announced at COP28 by Michael S. Regan, the administrator of the Environmental Protection Agency, came with more certainty: It is an administrative action that does not require the approval of Congress and is scheduled to take effect next year."). *See generally* Jenks C., Dobie H., & Leahy R. (2023) *EPA's Final Methane Rule—Incorporating Advanced Technologies and Emissions Data to Reduce Methane Emissions from the Oil and Natural Gas Sector*, Harvard Environmental Law and Energy Program.

[825] Environmental Protection Agency (23 May 2023) *New Source Performance Standards for Greenhouse Gas Emissions From New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions From Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule*, FED. REG. 88: 33240–33420, 33420 ("In this document, the Environmental Protection Agency (EPA) is proposing five separate actions under section 111 of the Clean Air Act (CAA) addressing greenhouse gas (GHG) emissions from fossil fuel-fired electric generating units (EGUs). The EPA is proposing revised new source performance standards (NSPS), first for GHG emissions from new fossil fuel-fired stationary combustion turbine EGUs and second for GHG emissions from fossil fuel-fired steam generating units that undertake a large modification, based upon the 8-year review required by the CAA. Third, the EPA is proposing emission guidelines for GHG emissions from existing fossil fuel-fired steam generating EGUs, which include both coal-fired and oil/gas-fired steam generating EGUs. Fourth, the EPA is proposing emission guidelines for GHG emissions from the largest, most frequently operated existing stationary combustion turbines and is soliciting comment on approaches for emission guidelines for GHG emissions for the remainder of the existing combustion turbine category. Finally, the EPA is proposing to repeal the Affordable Clean Energy (ACE) Rule.")

[826] Environmental Protection Agency (1 February 2024) *Methane Emissions Reduction Program* ("The Inflation Reduction Act provides new authorities under Section 136 of the Clean Air Act to reduce methane emissions from the petroleum and natural gas sector through the creation of the Methane Emissions Reduction Program. This program will help reduce emissions of methane and other greenhouse gas (GHGs) from the oil and gas sector and will have the co-benefit of reducing non-GHG emissions such as volatile organic compounds and hazardous air pollutants. In keeping with the Administration's Justice40 Initiative, the program will also reduce emissions from oil and natural gas infrastructure in or near overburdened communities where people live, work, and go to school. The Methane Emissions Reduction Program will provide more than $1 billion in financial and technical assistance through multiple funding opportunities, establishes a Waste Emissions Charge (WEC) for methane, and requires EPA to revise the Greenhouse Gas Reporting Program (GHGRP) Subpart W regulations for the oil and gas sector.").

[827] Environmental Protection Agency (6 July 2023) *EPA Proposes Updates to Greenhouse Gas Emissions Reporting Requirements for the Oil and Gas Sector* ("Today, the U.S. Environmental Protection Agency (EPA) issued a proposal to amend reporting requirements for petroleum and natural gas systems under EPA's Greenhouse Gas Reporting Program. The proposed revisions would improve the accuracy of reported emissions of greenhouse gases (GHG), including methane, one of the primary drivers of the climate crisis, from applicable petroleum and natural gas facilities, consistent with the Methane Emissions Reduction Program under the Inflation Reduction Act."); *and* Environmental Protection Agency (1 August 2023) *Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems*, FED. REG. 88: 50282–50441, 50282 ("The Environmental Protection Agency (EPA) is proposing to amend requirements that apply to the petroleum and natural gas systems source category of the Greenhouse Gas Reporting Rule to ensure that reporting is based on empirical data, accurately reflects total methane emissions and waste emissions from applicable facilities, and allows owners and operators of applicable facilities to submit empirical emissions data that appropriately demonstrate the extent to which a charge is owed. The EPA is also proposing changes to requirements that apply to the general provisions, general stationary fuel combustion, and petroleum and natural gas systems source categories of the Greenhouse Gas Reporting Rule to improve calculation, monitoring, and reporting of greenhouse gas data for petroleum and natural gas systems facilities. This action also proposes to establish and amend confidentiality determinations for the reporting of certain data elements to be added or substantially revised in these proposed amendments.").

[828] Environmental Protection Agency (26 January 2024) *Waste Emissions Charge for Petroleum and Natural Gas Systems*, FED. REG. 89: 5318–5381, 5318 ("The Environmental Protection Agency (EPA) is proposing a regulation to implement the requirements of the Clean Air Act (CAA) as specified in the Methane Emissions Reduction Program of the Inflation Reduction Act. This program requires the EPA to impose and collect an annual charge on methane emissions that exceed specified waste emissions thresholds from an owner or operator of an applicable facility that reports more than 25,000 metric tons of carbon dioxide equivalent of greenhouse gases emitted per year pursuant to the petroleum and natural gas systems source category requirements of the Greenhouse Gas Reporting Rule. The proposal would implement calculation procedures, flexibilities, and exemptions related to the waste emissions charge and proposes to establish confidentiality determinations for data elements included in waste emissions charge filings.").

[829] Environmental Protection Agency (26 January 2024) *Waste Emissions Charge for Petroleum and Natural Gas Systems*, FED. REG. 89: 5318–5381, 5320 ("The waste emissions charge, or WEC, is specified in CAA section 136 to begin for emissions occurring in2024 at $900 per metric ton of methane exceeding the threshold, increasing to $1,200 per metric ton of methane in 2025, and to $1,500 per metric ton of methane in 2026 and years after. The WEC only applies to the subset of a facility's emissions that are above the waste emissions threshold."). *See also* Chennick J. (12 January 2024) *EPA proposes methane emission fees*, E&E NEWS ("And EPA's draft rule settles some questions about how excess emissions would be calculated — though the climate law itself established leak ratios for different segments of the oil and gas supply chain from production and processing to storage and pipelines. EPA is set to finalize the reporting rules and fee later this year, and the new reporting standards would be the basis for the fee starting in 2025.The fee could initially cover some of the same sources regulated under EPA's newly final methane rule. That's because states have two years to write plans for existing sources. Those must be approved by EPA, and the rule provides up to three years for controls for existing oil and gas infrastructure to phase in, meaning some onshore operations that might eventually receive exemptions from the fee may be required to pay it in the near term."); *and* Danish K. W. (23 January 2024) *EPA Proposes Rules to Implement IRA Methane Fee Provisions*, VAN NESS FELDMAN ("Among other things, the proposed rule outlines the EPA's interpretation of how the WEC should interact with the agency's recently finalized methane emission standards for the oil and gas sector under section 111 of the Clean Air Act (the "Section 111" regulations). Under the agency's proposed interpretation, the WEC could be in effect for multiple years until it is supplanted by the Section 111 regulations.").

[830] United States Environmental Protection Agency (17 August 2023) *FY 2024 – 2027 National Enforcement and Compliance Initiatives*, 2 ("The Mitigating Climate Change NECI will use OECA's criminal and civil enforcement authorities to address three separate and significant contributors to climate change: (1) methane emissions from oil

and gas facilities; (2) methane emissions from landfills; and (3) the use, importation, and production of hydrofluorocarbons (HFCs). Oil and gas systems and landfills are the second and third largest sources of methane emissions in the United States. Methane is a climate super-pollutant that is more than 25 times as potent as carbon dioxide at trapping heat in the atmosphere.").

[831] United States Environmental Protection Agency (17 August 2023) *FY 2024 – 2027 National Enforcement and Compliance Initiatives*, 2–3 ("By focusing on enforcement of long- standing air pollution requirements, such as New Source Performance Standards at oil and gas facilities and landfills, OECA can achieve the ancillary benefit of reducing methane emissions. If EPA promulgates new rules to reduce methane emissions in the future, enforcement of those requirements could be included in this initiative as well.").

[832] United States Environmental Protection Agency (17 August 2023) *FY 2024 – 2027 National Enforcement and Compliance Initiatives*, 2–3 ("By focusing on enforcement of long- standing air pollution requirements, such as New Source Performance Standards at oil and gas facilities and landfills, OECA can achieve the ancillary benefit of reducing methane emissions. If EPA promulgates new rules to reduce methane emissions in the future, enforcement of those requirements could be included in this initiative as well.").

[833] United States Office of Surface Mining Reclamation and Enforcement (July 2022) *Guidance on the Bipartisan Infrastructure Law Abandoned Mine Land Grant Implementation*, 1 ("The BIL authorized and appropriated $11.293 billion for deposit into the Abandoned Mine Reclamation Fund administered by the Office of Surface Mining Reclamation and Enforcement (OSMRE). Of the $11.293 billion appropriated OSMRE will distribute approximately $10.873 billion[1] in BIL Abandoned Mine Land (AML) grants to eligible States and Tribes on an equal annual basis—approximately $725 million a year—over a 15-year period.[2]").

[834] United States Office of Surface Mining Reclamation and Enforcement (July 2022) *Guidance on the Bipartisan Infrastructure Law Abandoned Mine Land Grant Implementation*, 4 ("States with unreclaimed mines on the list of EPA's Methane Coal Mine Opportunities Database (https://www.epa.gov/cmop/coal-mine-methane-abandoned-underground-mines) are encouraged to prioritize the reclamation of such sites where eligible for BIL AML funding in a manner that eliminates methane emissions to the greatest extent possible.").

[835] United States Department of Energy (5 August 2022) *DOE Announces $32 Million to Reduce Methane Emissions from Oil and Gas Sector* ("The U.S. Department of Energy (DOE) today announced up to $32 million in funding toward the research and development of new monitoring, measurement, and mitigation technologies to help detect, quantify, and reduce methane emissions across oil and natural gas producing regions of the United States.").

[836] United States Department of Energy & United States Environmental Protection Agency (21 July 2023) *Notice of Intent to issue Administrative and Legal Requirements Document Announcement (ALRD), titled "IRA: Mitigating Emissions from Marginal Conventional Wells"*, DE-FOA-0003108 ("The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) intends to issue an Administrative and Legal Requirements Document (ALRD) on behalf of the DOE Office of Fossil Energy and Carbon Management (FECM) and in collaboration with U.S. Environmental Protection Agency (EPA), entitled 'IRA: Mitigating Emissions from Marginal Conventional Wells. NETL anticipates issuing the ALRD in August 2023 with an application availability period of 30 days. The ALRD will be funded by the Clean Air Act (CAA), as amended by the Inflation Reduction Act (IRA). DOE is partnering with EPA to make funds available to States for the purpose of working with operators to voluntarily and permanently plug marginal conventional wells on non-Federal lands, supporting environmental restoration of the well pad, and enhancing industry's and States' capacities to monitor methane and other air pollutants from wells. If released, this ALRD is expected to make available up to $350 million for financial assistance in the form of grants to States via a formula.").

[837] Volcovici V (January 5 2024) *US approves $189 million loan for real-time methane oil and monitoring*, REUTERS ("The Department of Energy's loan office on Friday conditionally approved a $189 million loan to support the build-

out of a methane monitoring network in key oil-producing basins that would provide real-time data for tens of thousands of oil and gas sites, which it estimates could prevent the equivalent of at least 6 millions tons of carbon dioxide per year.").

[838] United States Department of Agriculture (2022) *Request for Applications: Bioproduct Pilot Program*, Fiscal Year 2023, 6 ("The Bioproduct Pilot Program, under assistance listing 10.236, will advance development of cost-competitive bioproducts with environmental benefits compared to incumbent products. The program seeks projects that will study the benefits of using materials derived from covered agricultural commodities for production of construction and consumer products (IMPORTANT: see Definitions in Appendix III). Applications must address all the following priorities: (1) Bioproduct development and production scale-up. (2) Cost savings relative to other commonly used materials; (3) Greenhouse gas emission reductions and other environmental and climate benefits relative to other commonly used materials; (4) Landfill quantity and waste management cost reductions, including life-cycle and longevity-extending or longevity-reducing characteristics relative to other commonly used materials...").

[839] United States Department of Agriculture (28 June 2022) *Vilsack Announces Bioproduct Pilot Program Funded by Bipartisan Infrastructure Law*, Press Release ("Today, Agriculture Secretary Tom Vilsack announced the U.S. Department of Agriculture is accepting applications for a new pilot program created under President Biden's historic Bipartisan Infrastructure Law to support the development of biobased products that have lower carbon footprints and increase the use of renewable agricultural materials, creating new revenue streams for farmers. This $10 million investment is part of the Biden-Harris Administration's ongoing work to rebuild our infrastructure and create good-paying jobs and economic opportunity in our rural communities.").

[840] United States Bureau of Land Management (18 November 2016) *Waste Prevention, Production Subject to Royalties, and Resource Conservation*, FED. REG. 87: 73588–73620, 73589, 73596 ("The proposed rule would establish the general rule that "operators must use all reasonable precautions to prevent the waste of oil or gas developed from the lease." It notes that the BLM may specify reasonable measures to prevent waste as conditions of approval of an Application for Permit to Drill and, after an Application for Permit to Drill is approved, the BLM may order an operator to implement, within a reasonable time, additional reasonable measures to prevent waste at ongoing exploration and production operations. Reasonable measures to prevent waste may reflect factors including, but not limited to, relevant advances in technology and changes in industry practice. … The proposed rule would require operators to submit a waste minimization plan with all applications for permits to drill oil wells. … The Act [IRA] authorizes, among other things, massive and unprecedented investments to enhance energy security and combat the climate crisis. Of particular relevance here, the IRA contains a suite of provisions addressing onshore and offshore oil and gas development under Federal leases. For example, Section 50265 requires, inter alia, the Department to maintain a certain level of onshore oil and gas leasing activity as a prerequisite to approving renewable energy rights-ofway on Federal lands. Importantly, that provision of the IRA is accompanied by other provisions that serve to ensure that lessees pay fair and appropriate compensation to the Federal Government in exchange for the opportunity to conduct their industrial activities under Federal leases. The BLM has for decades assessed royalties on upstream production and has exempted from royalties gas lost in emergency situations, ''beneficial use'' gas, and ''unavoidably lost'' gas. IRA Section 50263 is consistent with the BLM's prior agency practice regarding emergency situations and the unavoidable loss of gas, and it provides additional support for the approach set forth in this proposed rule. Importantly, IRA Section 50263 confirms that the concepts of ''avoidable'' and ''unavoidable'' loss are appropriate for assessing royalties.").

[841] United States Bureau of Land Management (18 November 2016) *Waste Prevention, Production Subject to Royalties, and Resource Conservation*, FED. REG. 87: 73588–73620, 73589 ("As detailed in the Regulatory Impact Analysis (RIA) prepared for this proposed rule, the BLM estimates that this rule would have the following economic impacts: Costs to industry of around $122 million per year (annualized at 7 percent); Benefits to industry in recovered gas of $55 million per year (annualized at 7 percent); Increases in royalty revenues from recovered and flared gas of $39 million per year; and Benefits to society of $427 million per year from reduced greenhouse gas emissions.").

[842] White House Office of Domestic Climate Policy (2021) *U.S. Methane Emissions Reduction Action Plan*, 7 ("As part of implementing the bipartisan PIPES Act, PHMSA is advancing a commonsense regulatory agenda that has the potential to provide annual methane reductions of as much as 20 MMT of CO_2e in methane emissions per year—a spur for new jobs for pipeline workers, welders, electricians, and other trades. The reductions will be achieved by reducing leaks throughout the gas pipeline system and by reducing the frequency and scope of ruptures. In addition to being a major safety hazard, ruptures are a particularly large source of pipeline methane emissions. More than 1,000 metric tons of methane are lost, on average, with each pipeline rupture. A single rupture from a large, high-pressure gas pipeline can release more than 1,300 metric tons of methane emissions.").

[843] Environmental Protection Agency (18 May 2023) *Pipeline Safety: Gas Pipeline Leak Detection and Repair*, FED. REG. 88: 31890–31979, 31890 ("PHMSA proposes regulatory amendments that implement congressional mandates in the Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2020 to reduce methane emissions from new and existing gas transmission pipelines, distribution pipelines, regulated (Types A, B, C and offshore) gas gathering pipelines, underground natural gas storage facilities, and liquefied natural gas facilities. Among the proposed amendments for part 192- regulated gas pipelines are strengthened leakage survey and patrolling requirements; performance standards for advanced leak detection programs; leak grading and repair criteria with mandatory repair timelines; requirements for mitigation of emissions from blowdowns; pressure relief device design, configuration, and maintenance requirements; and clarified requirements for investigating failures. Finally, PHMSA proposes expanded reporting requirements for operators of all gas pipeline facilities within DOT's jurisdiction, including underground natural gas storage facilities and liquefied natural gas facilities.").

[844] Department of Transport (18 May 2023) *Pipeline Safety: Gas Pipeline Leak Detection and Repair*, FED. REG. 88: 31890–31979, 31890 ("PHMSA estimates that emission reductions under the proposed rule correspond to approximately 72 percent of unintentional emissions from regulated gathering pipelines, 17 percent of unintentional emissions from transmission pipelines, and 44 to 62 percent of unintentional emissions from distribution pipelines. These shares are relative to modeled baseline emissions projected over the period of analysis based on the pipeline mileage, empirical emission factors, and existing survey and repair practices. Further, PHMSA estimates that the total avoided blowdown emissions under the proposed rule correspond to approximately 43 percent of baseline blowdown emissions. PHMSA estimates that the proposed rule would result in monetized net benefits between $341 to $1,440 million per year using a 3 percent discount rate. PHMSA also anticipates additional unquantified benefits to public safety and the environment, each discussed throughout this NPRM and its supporting documents (including the Preliminary Regulatory Impact Analysis (RIA) and draft Environmental Assessment (EA), each available in the docket for this NPRM).").

[845] United States Environmental Protection Agency, *Map of US Coal Mine Methane Current Projects and Potential Opportunities* (*last visited* 24 July 2023) (*See* mapping tool on U.S. Coal Mine Methane).

[846] United States Environmental Protection Agency (2019) *Coal Mine Methane Recovery at Active and Abandoned U.S. Coal Mines: Current Projects and Potential Opportunities* (Total, tables of underground and abandoned mines).

[847] United States Energy Information Administration, *U.S. Coalbed Methane Production* (*last visited* 30 June 2023) (*See* graph on U.S. Natural Gas Gross Withdrawals from Coalbed Wells. 2008: 2,022,228 million cubic feet. 2020: 821,141 million cubic feet. A conversion from million cubic feet to billion cubic meter (bcm) makes the 2008 total 57.263 bcm and the 2020 total 23.252 bcm.).

[848] Zibel A. (6 December 2021) *Biden's Oil Letdown*, PUBLIC CITIZEN ("Public Citizen's analysis[1] of federal public lands drilling permit data found: • The Bureau of Land Management has approved an average of about 336 drilling permits per month in 2021 (Figure 1) through November 30. • Excluding January, when former President Donald Trump was in office for most of the month, the agency approved 333 drilling permits per month in 2021. That average was up by more than 40% from when Trump took office in 2017, but still down by more than 25% from 2020. • Under

Biden, monthly public lands permit approvals peaked at 652 in April 2021 (Figure 2) but have been below 2020 levels since summer after falling under 300 in July."); *discussed in* Joselow M. (6 December 2021) *Biden is approving more oil and gas drilling permits on public lands than Trump, analysis finds*, The Climate 202, THE WASHINGTON POST ("During Biden's first year in office so far, BLM has approved an average of 333 drilling permits per month. That figure is more than 35% higher than Trump's first year in office, when BLM approved an average of 245 drilling permits per month."). *See also* Brown M. (12 July 2021) *US drilling approvals increase despite Biden climate pledge*, AP NEWS ("Approvals for companies to drill for oil and gas on U.S. public lands are on pace this year to reach their highest level since George W. Bush was president, underscoring President Joe Biden's reluctance to more forcefully curb petroleum production in the face of industry and Republican resistance. The Interior Department approved about 2,500 permits to drill on public and tribal lands in the first six months of the year, according to an Associated Press analysis of government data. That includes more than 2,100 drilling approvals since Biden took office January 20.").

[849] White House (26 January 2024) *FACT SHEET: Biden-Harris Administration Announces Temporary Pause on Pending Approvals of Liquefied Natural Gas Exports* ("Today, the Biden-Harris Administration is announcing a temporary pause on pending decisions on exports of Liquefied Natural Gas (LNG) to non-FTA countries until the Department of Energy can update the underlying analyses for authorizations. The current economic and environmental analyses DOE uses to underpin its LNG export authorizations are roughly five years old and no longer adequately account for considerations like potential energy cost increases for American consumers and manufacturers beyond current authorizations or the latest assessment of the impact of greenhouse gas emissions. Today, we have an evolving understanding of the market need for LNG, the long-term supply of LNG, and the perilous impacts of methane on our planet. We also must adequately guard against risks to the health of our communities, especially frontline communities in the United States who disproportionately shoulder the burden of pollution from new export facilities. The pause, which is subject to exception for unanticipated and immediate national security emergencies, will provide the time to integrate these critical considerations.").

[850] White House (26 January 2024) *FACT SHEET: Biden-Harris Administration Announces Temporary Pause on Pending Approvals of Liquefied Natural Gas Exports* ("Today, the Biden-Harris Administration is announcing a temporary pause on pending decisions on exports of Liquefied Natural Gas (LNG) to non-FTA countries until the Department of Energy can update the underlying analyses for authorizations. The current economic and environmental analyses DOE uses to underpin its LNG export authorizations are roughly five years old and no longer adequately account for considerations like potential energy cost increases for American consumers and manufacturers beyond current authorizations or the latest assessment of the impact of greenhouse gas emissions. Today, we have an evolving understanding of the market need for LNG, the long-term supply of LNG, and the perilous impacts of methane on our planet. We also must adequately guard against risks to the health of our communities, especially frontline communities in the United States who disproportionately shoulder the burden of pollution from new export facilities. The pause, which is subject to exception for unanticipated and immediate national security emergencies, will provide the time to integrate these critical considerations."). *See also* Davenport C. (24 January 2024) *White House Said to Delay Decision on Enormous Natural Gas Export Terminal* ("The White House is directing the Energy Department to expand its evaluation of the project to consider its impact on climate change, as well as the economy and national security, said these people, who spoke on condition of anonymity because they were not authorized to publicly discuss internal deliberations. The Energy Department has never rejected a proposed natural gas project because of its expected environmental impact.").

[851] United States Advanced Research Projects Agency-Energy (2 December 2021) *U.S. Department of Energy Awards $35 Million for Technologies to Reduce Methane Emissions*, Press Release ("The following teams selected for the REMEDY program will work to directly address the more than 50,000 engines, 300,000 flares, and 250 mine shafts that are producing methane emissions. Natural Gas Engines: MAHLE Powertrain (Plymouth, MI) will develop a catalytic system to oxidize methane in the exhaust gas of lean-burn natural gas fired engines, (selection amount: $3,257,089); Colorado State University (Fort Collins, CO) will develop hardware to redirect methane emissions to the engine's turbocharger, reducing emissions and improving fuel efficiency, (selection amount: $1,500,000); Marquette University (Milwaukee, WI) will demonstrate their Mixed Controlled Combustion (MCC) system which can be

retrofitted into lean-burn engines, (selection amount: $3,975,058); INNIO's Waukesha Gas Engines (Waukesha, WI) will develop a new line of pistons fabricated with friction welding that reduce the space for methane to "slip" past the combustion zone in the engine and can be installed as part of normal engine maintenance programs, (selection amount: $2,230,693); Texas A&M University (College Station, TX) will use plasma and advanced engine controls to reduce methane slip; the technology targets the large two-stroke engines used by gas pipeline companies, (selection amount: $2,824,814); Flares: Advanced Cooling Technologies, Inc. (Lancaster, PA) will adapt their combustor design to ensure 99.5% methane destruction efficiency for the highly variable gas sent to flares; the combustors will be made of silicon carbide, which can withstand more than 2500 degrees Fahrenheit, using a new 3D printing process, (selection amount: $3,300,000); Cimarron Energy, Inc. (Houston, TX) proposes a hybrid flare design coupled with advanced controls to ensure 99.5% destruction efficiency for flares that handle both high- and low-pressure gas streams, (selection amount: $1,000,000); University of Michigan (Ann Arbor, MI) will use additive manufacturing and machine learning to scale up their advanced burner which will be incorporated into a new flare system design that is robust to cross winds and low load conditions which can lead to poor methane destruction efficiency, (selection amount: $2,881,762); University of Minnesota (Minneapolis, MN) will use plasma-assisted combustion to enhance flare methane destruction efficiency, (selection amount: $2,141,876); and Methane from Coal Mine Shafts: Johnson Matthey, Inc. (Wayne, PA) is developing new technology, which uses a noble metal catalyst to combust the dilute methane in coal mine ventilation systems, (selection amount: $4,346,015); Massachusetts Institute of Technology (Cambridge, MA) is developing a low-cost copper-based catalyst for reducing methane emissions, (selection amount: $2,020,903); and Precision Combustion, Inc. (North Haven, CT) proposes an innovative modular system that promotes methane reaction and manages thermal loads in a novel reactor design, (selection amount: $3,720,317).").

[852] United States Advanced Research Projects Agency-Energy (8 April 2021) *Reducing Emissions of Methane Every Day of the Year*, ARPA-E Programs ("Program Description: REMEDY (Reducing Emissions of Methane Every Day of the Year) is a three-year, $35 million research program to reduce methane emissions from three sources in the oil, gas, and coal value chains: 1) Exhaust from 50,000 natural gas-fired lean-burn engines. These engines are used to drive compressors, generate electricity, and increasingly repower ships. 2) The estimated 300,000 flares required for safe operation of oil and gas facilities. 3) Coal mine ventilation air methane (VAM) exhausted from 250 operating underground mines. These sources are responsible for at least 10% of U.S. anthropogenic methane emissions. Reducing emissions of methane, which has a high greenhouse gas warming potential, will ameliorate climate change.").

[853] United States Advanced Research Projects Agency-Energy (30 September 2020) *Prevention and Abatement of Methane Emissions* ("We're open to all options – but specifically are looking for solutions that: Prevent methane emissions from anthropogenic activities. In other words, solutions which intervene before anthropogenic emissions escape to the atmosphere. Abate methane emissions at their source. Sources include vents, leaks, and exhaust stacks. Remove methane from the air. As mentioned above, methane only lasts about 9 years in the atmosphere. Nature is very good at getting rid of methane using reactions in the atmosphere and methanotrophs in the soil. Maybe we can learn from Nature, and help her out."). *See also* Lewnard J. (16 November 2020) *REMEDY – Reducing Emissions of Methane Every Day of the Year*, ARPA-E Presentation, Slide 7 ("Example Potential Approaches, Not Intended to Limit or Direct … "Geo-engineering": Accelerate tropospheric reactions; Accelerate soil/methanotroph reactions").

[854] *See* CHIPS and Science Act, Pub. L. No. 117-167 § 10771 (2022); United States Senate (2022) *CHIPS and Science Act of 2022: Section-by-Section Summary*; *and* White House (9 August 2022) *FACT SHEET: CHIPS and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China*, Briefing Room; *discussed in* Meyer R. (10 August 2022) *Congress Just Passed a Big Climate Bill. No, Not That One.*, THE ATLANTIC ("The bill could direct about $12 billion in new research, development, and demonstration funding to the Department of Energy, according to RMI's estimate. That includes doubling the budget for ARPA-E, the department's advanced-energy-projects skunk works."); *and* Ovide S. (10 August 2022) *Taxpayers for U.S. Chips*, THE NEW YORK TIMES.

[855] CHIPS and Science Act of 2022, Pub. L. No. 117-167 (2022) § 10221 ("The Director, in collaboration with the Administrator of the National Oceanic and Atmospheric Administration, the Administrator of the Environmental

Protection Agency, and the heads of other Federal agencies, as appropriate, shall establish a Center for Greenhouse Gas Measurements, Standards, and Information…."); *discussed in* Meyer R. (10 August 2022) *Congress Just Passed a Big Climate Bill. No, Not That One.,* ATLANTIC ("The CHIPS Act is not a comprehensive climate bill in the same way that the Inflation Reduction Act, or IRA, is. Unlike the IRA, the CHIPS bill isn't supposed to drive immediate reductions in carbon pollution or subsidize the replacement of fossil fuels with cleaner alternatives. It probably won't help the United States get closer to achieving its 2030 target under the Paris Agreement. Instead, the bill's programs focus on the bleeding edge of the decarbonization problem, investing money in technology that should lower emissions in the 2030s and beyond. That's an important role in its own right. The International Energy Association has estimated that almost half of global emissions reductions by 2050 will come from technologies that exist only as prototypes or demonstration projects today.").

[856] Natural Resources Defense Council (2022) REGENERATIVE AGRICULTURE: *FARM POLICY FOR THE 21ST CENTURY*, 7 ("Currently, federal agricultural policy disproportionately serves industrial agriculture over regenerative agriculture. To learn more about how we can change policy to advance regenerative agriculture, we interviewed 113 farmers and ranchers across the country. Our interviewees told us what regenerative agriculture means to them, the opportunities to bring more acres under regenerative management, and the barriers standing in the way. They stressed that the larger food system needs reform to enable more regenerative agriculture and to support existing regenerative growers."); 19 ("On the former point, federal farm subsidies, including crop insurance and direct payment programs, cost more than $68.1 billion annually.[56] These subsidies disproportionately support a few commodity crops (e.g., corn, soybeans, wheat, cotton, and sugar), which encourages and provides a safety net for large, monoculture farms. These same commodity subsidies benefit the livestock industry by providing a cheap source of feed that flows to industrial feedlots.[57] Regenerative farmers, however, try to grow a diversity of crops and vegetables that do not receive the same level of support from these federal subsidies.[58] Moreover, government subsidies artificially lower the price of some crops, making it harder for regenerative producers to compete in the market."). *See also* Laborde D., Mamun A., Martin W., Piñeiro V., & Vos R. (2021) *Agricultural subsidies and global greenhouse gas emissions*, NAT. COMMUN. 12(2601): 1–9; Ding H., Markandya A., Feltran-Barbieri R., Calmon M., Cervera M., Duraisami M., Singh R., Warman J., & Anderson W. (2021) *Repurposing Agricultural Subsidies to Restore Degraded Farmland and Grow Rural Prosperity*, World Resources Institute; *and* Food and Agriculture Organization, United Nations Dvelopment Programme, & United Nations Environment Programme (2021) A MULTI-BILLION-DOLLAR OPPORTUNITY – *REPURPOSING AGRICULTURAL SUPPORT TO TRANSFORM FOOD SYSTEMS*.

[857] United States White House (2023) ACCELERATING PROGRESS: DELIVERING ON THE U.S. METHANE EMISSIONS REDUCTION ACTION PLAN, 3 ("Meanwhile, USDA has invested more than $500 million to help farmers cut methane emissions under the Partnerships for Climate- Smart Commodities program, extended more than $150 million to support biogas projects under the Rural Energy for America Program, and offered local governments $9 million to reduce food waste under Composting and Food Waste Reduction cooperative agreements.").

[858] United States White House (2023) ACCELERATING PROGRESS: DELIVERING ON THE U.S. METHANE EMISSIONS REDUCTION ACTION PLAN, 7 ("Meanwhile, USDA's Agricultural Research Service is investing over $8 million annually in multi-year methane research projects focused on manure management processes, anaerobic digesters, feed additives and diet formulation, methane measurement, and rice breeding and management practices. USDA's National Institute of Food and Agriculture similarly funded two $5 million research and extension projects in 2023 to reduce enteric methane emissions from beef and dairy production systems.").

[859] Gustin G. (22 December 2023) *Reducing Methane From Livestock Is Critical for Stabilizing the Climate, but Congress Continues to Block Farms From Reporting Emissions Anyway*, INSIDE CLIMATE NEWS ("Written into a must-pass spending bill the House approved in November, the provision prevents the government from funding a law that requires big livestock farms to report how much methane their operations emit. Every spending bill Congress has passed in the last 14 years has contained similar disabling language. In effect, while Congress has said it wants big farms to report some of their methane emissions, it has also said it won't give regulators money to do that.").

[860] White House Office of Domestic Climate Policy (2021) *U.S. Methane Emissions Reduction Action Plan*, 10–11 ("As a complement to EPA's updated landfill regulations, EPA's voluntary Landfill Methane Outreach Program (LMOP) supports development of landfill gas energy projects by providing technical support at regulated landfills and helping smaller, unregulated landfills collect and direct methane gas into the renewable gas energy marketplace. This support includes connecting landfill owners and operators with LMOP Partners experienced in project development, providing technical tools and resources to facilitate project development. … Under the Biden-Harris Administration, USDA, EPA, and the U.S. Food and Drug Administration (FDA) are working more closely than ever to make the goal of 50% reduced food loss and waste by 2030 a reality. The Administration's vision for reducing food loss and waste seeks to improve food security and nutrition, increase farmer income and rural prosperity, reduce pressure on natural resources, and meet greenhouse gas emissions reduction targets. … The USDA is leveraging its authority under a variety of existing programs to encourage farmers and ranchers to install or upgrade equipment and/or adopt new practices that improve manure management and can substantially reduce methane emissions, in a way that also advances environmental justice. The Natural Resources Conservation Service (NRCS), for example, will provide incentives and technical assistance through Farm Bill programs such as the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP) to upgrade existing anaerobic lagoons by installing covers and collecting methane for use or destruction; installing anaerobic methane digesters that collect methane for use or destruction; install solid separators that reduce methane-producing slurries; providing conservation assistance for transitions to alternative manure management systems, such as deep pits, composting, transitions to pasture, or other practices that have a lower greenhouse gas profile; and supporting rice management that reduces methane emissions, such as alternate wetting and drying.").

[861] United States Environmental Protection Agency (29 August 2016) *Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills*, FED. REG. 81(167): 59276–59330, 59276, 59305 (codified at 40 C.F.R. Part 60) ("The EPA estimates that the final rule will achieve nearly an additional 3 percent reduction in NMOC from existing landfills, or 1,810 Mg/yr, when compared to the baseline, as shown in Table 2 of this preamble. The final rule would also achieve 0.285 million Mg of methane reductions (7.1 million mtCO2e) in 2025. These reductions are achieved by reducing the NMOC threshold from 50 Mg/yr to 34 Mg/yr open landfills."). *See also* United States Environmental Protection Agency (29 August 2016) *Standards of Performance for Municipal Solid Waste Landfills*, FED. REG. 81(167): 59332–59384, 59332, 59362 (codified at 40 C.F.R. Part 60) ("The EPA estimates that the final rule will achieve nearly an additional 3 percent reduction in NMOC from new, reconstructed, or modified landfills, or 281 Mg/yr, when compared to the baseline, as shown in Table 2 of this preamble. The final rule would also achieve 44,300 Mg/yr of methane reductions (1.1 million mtCO2e/yr). These reductions are achieved by reducing the NMOC threshold from 50 Mg/yr to 34 Mg/yr."); *and* United States Environmental Protection Agency (2023) *Wasted Food Scale* ("The Wasted Food Scale prioritizes actions that prevent and divert wasted food from disposal. Tiers of the scale highlight different pathways for preventing or managing wasted food, arranged in order from most preferred on the top left to least preferred on the top right. Within a given tier, pathways are ranked equally. The most preferred pathways – prevent wasted food, donate and upcycle food – offer the most benefits to the environment and to a circular economy. These "top" pathways prioritize using food for its intended purpose: to nourish people. The least preferred pathways – landfilling, incineration, and sending food down the drain – have the largest environmental impacts and have limited potential for circularity. Learn more about the wasted food pathways on the scale.").

[862] Wallace J. (1 February 2024) *Senate hearing puts landfill methane reduction strategies in the spotlight*, WASTE DIVE ("The hearing included discussion of actions EPA could take, including updating emissions standards for landfills and contracting with satellite emissions tracking firms. … Witnesses at a Senate Committee on Environment & Public Works hearing on Wednesday called on the federal government to ramp up its support for landfill emissions monitoring and mitigation efforts, noting regulators are facing a series of deadlines to reduce methane. Committee Chair Tom Carper, D-Del., said the waste sector needs to deploy "innovative methods" to address methane, a greenhouse gas about 80 times more potent than carbon dioxide within a 20-year time frame.") *See also* United States Senate Committee on Environment and Public Works (31 January 2024) *Avoiding, Detecting, and Capturing Methane Emissions from Landfills*.

[863] *See* United States Environmental Protection Agency (*last updated* 13 August 2023) *Livestock Anaerobic Digester Database* (Tracking anaerobic digester projects in the U.S.); *and* United States Environmental Protection Agency (*last updated* 3 August 2023) *LMOP Landfill and Project Database* (Tracking U.S. landfills, including candidates for landfill gas energy projects.).

[864] Environmental Protection Agency (2023) QUANTIFYING METHANE EMISSIONS FROM LANDFILLED FOOD WASTE. *See also* Environmental Protection Agency (2023) *Wasted Food Scale* ("The Wasted Food Scale prioritizes actions that prevent and divert wasted food from disposal. Tiers of the scale highlight different pathways for preventing or managing wasted food, arranged in order from most preferred on the top left to least preferred on the top right. Within a given tier, pathways are ranked equally. The most preferred pathways – prevent wasted food, donate and upcycle food – offer the most benefits to the environment and to a circular economy. These "top" pathways prioritize using food for its intended purpose: to nourish people. The least preferred pathways – landfilling, incineration, and sending food down the drain – have the largest environmental impacts and have limited potential for circularity. Learn more about the wasted food pathways on the scale."); *and* McCarthy G. (11 October 2023) *Methane from landfills is another climate emergency. Here's how to fix it*, THE HILL ("We have solutions. It starts with waste prevention, food donation and organics recycling. They all help avoid landfill methane generation and ensure materials are put to higher, better use, as outlined in the Environmental Protection Agency's recently updated wasted food scale.").

[865] United States Environmental Protection Agency (2023) QUANTIFYING METHANE EMISSIONS FROM LANDFILLED FOOD WASTE, iii ("Most estimates of methane emissions from landfills are calculated based on the biodegradation of municipal solid waste (MSW) as a whole. National estimates of methane emissions from particular components of the organic fraction of MSW, such as food waste, have not been previously quantified by EPA. In the United States, a significant fraction of food waste generated is sent to landfills (U.S. EPA, 2020a). In this analysis, EPA has quantified the methane emissions released into the atmosphere from degrading food waste in MSW landfills in the United States from 1990 to 2020. There is no other peer-reviewed national reference point for the amount of methane emissions attributable to food waste in U.S. MSW landfills.").

[866] United States Environmental Protection Agency (2023) QUANTIFYING METHANE EMISSIONS FROM LANDFILLED FOOD WASTE, 10 ("While total emissions from MSW landfills are decreasing, methane emissions from landfilled food waste are increasing. As shown in Figure 3, total methane emissions from MSW landfills decreased by 43 percent from 1990 to 2020 as federal and state regulations for gas collection requirements expanded. This has led to improvements in national gas collection efficiencies as more landfills have controlled their emissions, particularly at later points of the landfill lifetime (where gas generation is dominated by paper products and other non-food waste components). During this same time period, methane emissions from landfilled food waste increased steadily by 295 percent. This is due to annual increases in the amount of food and all other MSW components being landfilled. Food waste emissions occur earlier and landfill operators are collecting more gas later in the landfill lifetime. Thus, for materials like biodegradable textiles, paper products, and wood, which degrade more slowly, more of the landfill gas is collected.").

[867] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The United States announced new steps on waste methane. The Environmental Protection Agency (EPA) is planning a rule-making to review and, if appropriate, revise its Clean Air Act emission standards for new and existing municipal solid waste landfills, considering new monitoring technology, incentivization of organics waste diversion, and emissions controls at landfills not currently covered by current regulations. In 2024, EPA will release updates on emissions estimates for MSW landfills. In addition, the United States released for public comment a draft national strategy for Reducing Food Loss and Waste and Recycling Organics in line with its 2030 50% food loss and waste reduction goal.").

[868] Clean Air Act of 1970, 42 U.S.C. §7411(b). *See also* Environmental Integrity Project, *et al.* (22 June 2023) *Petition for Rulemaking to Revise the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills*, 2 ("In August of 2024, EPA is legally required under the Clean Air Act to reassess whether its standards

require the best systems of emission reduction for landfills. However, EPA should not wait until it is compelled to act. The Agency can and should immediately commence a rulemaking to revise and strengthen its nationwide Clean Air Act standards for landfills.").

[869] *See generally* Environmental Integrity Project (2023) TRASHING THE CLIMATE: *METHANE FROM MUNICIPAL LANDFILLS*.

[870] Oregon Department of Environmental Quality (*effective* 4 October 2021) *Landfill Gas Emissions 2021*; *and* California Air Resources Board (2022) 2022 ANNUAL REPORT TO THE JOINT LEGISLATIVE BUDGET COMMITTEE ON ASSEMBLY BILL 32, 33 ("U.S. EPA promulgated updates to the Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills, 40 CFR, Part 60, Subpart Cf (Emission Guidelines), which became effective on October 28, 2016. CARB submitted its State Plan to U.S. EPA in 2017 to demonstrate that CARB's Landfill Methane Regulation is equivalent to, or more stringent than, the Emission Guidelines."). *See also* Environmental Integrity Project, *et al.* (22 June 2023) *Petition for Rulemaking to Revise the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills*, 32–33 ("California, Oregon, and Maryland have surface emissions monitoring requirements that are more protective than EPA's and demonstrate the importance and feasibility of stronger EPA requirements in four ways. First, the states require a walking pattern with no more than 25-foot intervals. When compared with EPA's 30-meter (approximately 100 foot) intervals, these states require that more of the landfill's surface is actually traversed and measured by the person conducting the monitoring. Second, landfill operators must show that surface methane levels averaged across measurements taken within 50,000 square foot gridded sections of the landfill do not exceed 25 ppm (referred to as integrated monitoring) in addition to showing that levels at individual locations do not exceed 500 ppm (instantaneous monitoring). If either the instantaneous or integrated measurements exceed the specified limits, corrective action must be taken and the site re-monitored. California is currently considering reducing its instantaneous threshold to 200 ppm. Third, the states require better reporting of surface methane levels. Maryland and Oregon require submission of a report within 30 days following sampling. California and Oregon require reporting of all instantaneous measurements above 200 ppm, and Oregon requires reporting of instantaneous measurements over 100 ppm. Maryland requires reporting of "all results of surface emissions monitoring" with levels above 100 ppm clearly identified. Fourth, California limits the meteorological conditions under which monitoring can occur: average wind speeds must be less than 5 mph and instantaneous speeds less than 10 mph; and there must have been no measurable precipitation within the preceding 72 hours.").

[871] State of Washington Department of Ecology, *Chapter 173-408 WAC Landfill Methane Emissions* (*last visited* 1 December 2023) ("Ecology proposes a new rule: Chapter 173-408 WAC, Landfill Methane Emissions. The purpose of this rulemaking is to implement Chapter 70A.540 RCW, Landfills – Methane Emissions.").

[872] The U.S. EPA promulgated a New Source Performance Standard (NSPS) for municipal solid waste landfills in 2016, but the EPA delayed implementation during the Trump administration. In 2021, the EPA issued a new final rule creating a federal implementation plan for states that have not submitted implementation plans and issuing new regulations for states to submit state implementation plans. *See* United States Environmental Protection Agency (published 21 May 2021, effective 21 June 2021) *Federal Plan Requirements for Municipal Solid Waste Landfills That Commenced Construction On or Before July 17, 2014, and Have Not Been Modified or Reconstructed Since July 17, 2014*, FED. REG. 86: 27756–27790, 27756 ("In this action, the U.S. Environmental Protection Agency (EPA) is promulgating a Federal plan to implement the Emission Guidelines (EG) and Compliance Times for Municipal Solid Waste (MSW) Landfills (2016 MSW Landfills EG) for existing MSW landfills located in states and Indian country where state plans or tribal plans are not in effect. This MSW Landfills Federal Plan includes the same elements as required for a state plan: Identification of legal authority and mechanisms for implementation; inventory of designated facilities; emissions inventory; emission limits; compliance schedules; a process for the EPA or state review of design plans for site-specific gas collection and control systems (GCCS); testing, monitoring, reporting and record keeping requirements; and public hearing requirements. Additionally, this action summarizes implementation and delegation of authority of the MSW Landfills Federal Plan."). *See also* Congressional Research Service (20 September 2022) *The Legal Framework for Federal Methane Regulation* ("Under the CAA Landfills account for approximately 17%

of methane emissions in the United States. EPA promulgated a new NSPS for municipal solid waste landfills in 2016. 81 Fed. Reg. 59,276. The 2016 rule amended an earlier NSPS issued in 1996. The 2016 rule applies to landfills built, modified, or reconstructed after July 17, 2014, with a design capacity of at least 2.5 million metric tons. The rule reduced the threshold for when a landfill has to capture landfill gases from 50 metric tons per year of nonmethane organic compounds to 34 metric tons. The rule also altered monitoring requirements and expanded approved uses for landfill gas. Emissions guidelines for existing municipal solid waste facilities largely tracks the limitations in the NSPS for new landfills with the notable exception that the guidelines kept the threshold for capturing landfill gasses at 50 metric tons for closed landfills. During the Trump Administration, EPA delayed the implementation of the emissions guidelines, which delayed the submission and approval of SIPs. Forty-two states have yet to submit a SIP. On May 21, 2021, EPA issued a new final rule creating a federal implementation plan for states that have yet to submit a SIP and issuing new regulations for states to submit SIPs after the federal plan is in place. 86 Fed. Reg. 27,756.").

[873] United States Environmental Protection Agency (*last updated* 4 April 2023) *United States 2030 Food Loss and Waste Reduction Goal* ("On September 16, 2015, the U.S. Department of Agriculture (USDA) and EPA announced the U.S. 2030 Food Loss and Waste Reduction goal, the first-ever domestic goal to reduce food loss and waste. The goal seeks to cut food loss and waste in half by the year 2030. By acting on this goal, the U.S. can reduce climate and environmental impacts associated with food loss and waste while improving food security and saving money for families and businesses. Led by EPA, USDA, and the Food and Drug Administration (FDA), the federal government is seeking to work with communities, organizations and businesses along with our partners in state, tribal and local government to achieve this goal.").

[874] United States Environmental Protection Agency (*last updated* 3 August 2023) *About the Landfill Methane Outreach Program* ("LMOP is a voluntary program that works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills. LMOP encourages the recovery and beneficial use of biogas generated from organic municipal solid waste (MSW). Landfill gas (LFG) and other biogas generated from MSW (collectively referred to as biogas) contain methane, a potent greenhouse gas that can be captured and used as a renewable fuel for many end uses including electricity generation, industrial heat applications and vehicle fuel. Capturing and using biogas reduces local air pollution, creates health benefits, generates revenue and jobs in the community and may also offset the use of non-renewable resources.").

[875] United States Environmental Protection Agency (*last updated* 4 August 2023) *Coal Mine Methane – What EPA is Doing* ("Since 1994, EPA's Coalbed Methane Outreach Program (CMOP) has worked cooperatively with the coal mining industry in the United States – and other major coal-producing countries – to reduce CMM emissions. By helping to identify and implement methods to recover and use CMM instead of emitting it to the atmosphere, CMOP has played a key role in the United States' efforts to reduce GHG emissions and address global climate change.").

[876] United States Environmental Protection Agency (*last updated* 11 December 2023) *What EPA is Doing: AgSTAR* ("AgSTAR promotes the use of biogas recovery systems to reduce methane emissions from livestock waste. Biogas recovery also helps achieve other social, environmental, agricultural and economic benefits. AgSTAR assists those who enable, purchase or implement anaerobic digesters by identifying project benefits, risks, options and opportunities. AgSTAR provides information and participates in events to create a supporting environment for anaerobic digester implementation.").

[877] United States Department of Agriculture, *Partnerships for Climate-Smart Commodities* (*last visited* 29 June 2023) ("USDA is investing more than $3.1 billion for 141 projects through this effort and all the projects require meaningful involvement of small and underserved producers."). *See also* United States Department of Agriculture (7 February 2022) *USDA to Invest $1 Billion in Climate Smart Commodities, Expanding Markets, Strengthening Rural America*, Press Release ("Agriculture Secretary Tom Vilsack announced today at Lincoln University that the U.S. Department of Agriculture is delivering on its promise to expand markets by investing $1 billion in partnerships to support America's climate-smart farmers, ranchers and forest landowners. The new Partnerships for Climate-Smart Commodities opportunity will finance pilot projects that create market opportunities for U.S. agricultural and forestry

products that use climate-smart practices and include innovative, cost-effective ways to measure and verify greenhouse gas benefits."); *and* United States Department of Agriculture, *Partnerships for Climate-Smart Commodities* (*last visited* 5 February 2023) ("Highly competitive projects will include agricultural and forestry practices or combinations of practices, and/or practice enhancements that provide GHG benefits and/or carbon sequestration, including but not limited to: … Manure management; Feed management to reduce enteric emissions … . Alternate wetting and drying on rice fields.").

[878] (19 November 2022) *COP27: 'Global Methane Pledge' Announces Pathway to Reduce Agriculture Emissions*, ASHARQ-AL-AWSAT ("IFAD and United States a partnership to advance climate resilience and methane mitigation with smallholder farmers including by prioritizing methane mitigation in IFAD's pipeline of country and regional projects with combined investment of over $500 million dollars in methane-emitting sectors. Washington announced $5 million for the African Development Bank to advance agriculture and waste methane work within the Africa Climate Change Fund.").

[879] United States Department of Commerce (2023) METHANE ABATEMENT FOR OIL AND GAS - A HANDBOOK FOR POLICYMAKERS, 9 ("This handbook introduces government officials to a range of options for methane abatement in the oil and gas sector and guides the design and implementation of regulations. It builds on lessons learned from regulatory schemes in various countries. Government officials involved in all oil and gas sector aspects can benefit from this handbook."). IGSD experts Gabrielle Dreyfus and Richard ("Tad") Ferris were involved in commenting and proposing content for this Handbook.

[880] United States Securities and Exchange Commission (2022) *The Enhancement and Standardization of Climate-Related Disclosures for Investors*, FED. REG. 87: 21334–21473, 21335, 21374 ("The proposed rules would require information about a registrant's climate-related risks that are reasonably likely to have a material impact on its business, results of operations, or financial condition. The required information about climate-related risks would also include disclosure of a registrant's greenhouse gas emissions, which have become a commonly used metric to assess a registrant's exposure to such risks. In addition, under the proposed rules, certain climate-related financial metrics would be required in a registrant's audited financial statements. … The proposed rules would define "greenhouse gases" as carbon dioxide ("CO_2"); methane ("CH_4"); nitrous oxide ("N_2O"); nitrogen trifluoride ("NF_3"); hydrofluorocarbons ("HFCs"); perfluorocarbons ("PFCs"); and sulfur hexafluoride ("SF_6").").

[881] The Environmental Partnership, *Taking Action* (*last visited* 5 February 2023) ("The Environmental Partnership has developed six separate Environmental Performance Programs for participating companies to implement and phase into their operations [a pneumatic controller program, a manual liquids unloading program, a leak detection/repair program, a compressor program, a pipeline blowdown program, and a flare management program]. These programs were designed to further reduce emissions using proven, cost-effective technologies."). *See also* The Environmental Partnership, *Participants* (*last visited* 26 January 2023).

[882] ONE Future Coalition, *About Us* (*last visited* 5 February 2023) ("The ONE Future Coalition is a group of more than 50 natural gas companies working together to voluntarily reduce methane emissions across the natural gas value chain to 1% (or less) by 2025 and is comprised of some of the largest natural gas production, gathering & boosting, processing, transmission & storage and distribution companies in the U.S. and represents more than 20% of the U.S. natural gas value chain.").

[883] Natural Gas Sustainability Initiative (2021) *NGSI Methane Emissions Intensity Protocol Version 1.0* ("Version 1.0 of the Natural Gas Sustainability Initiative (NGSI) protocol details a methodology for companies to consistently calculate and report methane emissions intensity. The protocol is intended to support voluntary reporting by companies operating within the natural gas supply chain in the United States from onshore production through distribution. NGSI is a voluntary, industry-led initiative to advance innovative efforts to address environmental, social and governance (ESG) issues throughout the natural gas supply chain. Launched by a CEO task force on natural gas issues convened by the Edison Electric Institute (EEI) and the American Gas Association (AGA), NGSI is working to advance a

voluntary, industry-wide approach for companies to report methane emissions intensity by the segments of the natural gas supply chain in which they operate.”).

[884] *See* S.1863, PROVE IT Act of 2023. *See also* Office of Senator Chris Coons (9 August 2023) *Senators Coons, Cramer introduce legislation to study global emissions intensity and hold countries with dirty production accountable*, Press Release (“U.S. Senators Chris Coons (D-Del.) and Kevin Cramer (R-N.D.) today introduced the bipartisan Providing Reliable, Objective, Verifiable Emissions Intensity and Transparency (PROVE IT) Act that would direct the Department of Energy to conduct a comprehensive study comparing the emissions intensity of certain goods produced in the United States to the emissions of those same goods produced in the other countries. U.S. Senators Angus King (I-Maine), Lisa Murkowski (R-Alaska), Martin Heinrich (D-N.M.), Lindsey Graham (R-S.C.), Sheldon Whitehouse (D-R.I.), Bill Cassidy (R-La.), and John Hickenlooper (D-Colo.) are also co-sponsors.”).

[885] U.S. Senate Committee on Environment & Public Works (18 January 2024) *Committee Business Meeting*; Hoenig D., (30 January 2024) *The PROVE IT Act Explained* (“The Providing Reliable, Objective, Verifiable Emissions Intensity Act, or PROVE IT Act, directs the Department of Energy (DOE) to study and report the average emissions intensity of nearly two dozen products made in the United States and other major economies. It recently passed out of the Senate Environment and Public Works Committee (EPW) with a decisive and bipartisan vote. PROVE IT is led in the Senate by Sens. Chris Coons (D-DE) and Kevin Cramer (R-ND) with 11 additional co-sponsors: Sens. Angus King (I-ME), Lisa Murkowski (R-AK), Martin Heinrich (D-NM), Lindsey Graham (R-SC), Sheldon Whitehouse (D-RI), Bill Cassidy (R-LA), John Hickenlooper (D-CO), Dick Durbin (D-IL), John Boozman (R-AR), Alex Padilla (D-CA), and Mark Kelly (D-AZ). A companion PROVE IT bill in the House is anticipated, led by Reps. John Curtis (R-UT-3) and Scott Peters (D-CA-50).”).

[886] Dumain E. (7 December 2023) *Popular Senate carbon tariff bill gains House champions*, E&E NEWS (“Sen. Sheldon Whitehouse has reintroduced his legislation to slap a tariff on carbon-intensive goods — this time in tandem with partners in the House. A House companion bill to the Rhode Island Democrat's "Clean Competition Act," to be championed by Rep. Suzan DelBene (D-Wash.), signals a new phase in the debate over how to tie climate policy to trade policy.”).

[887] *See generally* House of Representatives (2023) *Clean Competition Act*.

[888] S.B. 1383, 2016 Leg. (Cal. 2016) (“The California Global Warming Solutions Act of 2006 designates the State Air Resources Board as the state agency charged with monitoring and regulating sources of emissions of greenhouse gases. The state board is required to approve a statewide greenhouse gas emissions limit equivalent to the statewide greenhouse gas emissions level in 1990 to be achieved by 2020. The state board is also required to complete a comprehensive strategy to reduce emissions of short-lived climate pollutants, as defined, in the state. This bill would require the state board, no later than January 1, 2018, to approve and begin implementing that comprehensive strategy to reduce emissions of short-lived climate pollutants to achieve a reduction in methane by 40%, hydrofluorocarbon gases by 40%, and anthropogenic black carbon by 50% below 2013 levels by 2030, as specified. The bill also would establish specified targets for reducing organic waste in landfills.”). For further examples of methane action California is seeking to take *See also* S.B 781 2023 Leg (Cal. 2023) (“This bill would require the state board to annually request and incorporate, as part of this quantification for annual publication, information from utilities and other large gas users regarding any contract for and use of natural gas certified to have a methane emissions intensity of less than 0.2% across the natural gas supply chain, as data are available, or the use of other best practices to minimize emissions of methane and greenhouse gases from natural gas supplying California. The bill would also require the state board to quantify and publish annually, commencing January 1, 2025, an estimate of potential greenhouse gas emissions reductions associated with the use of natural gas certified to have a methane emissions intensity of less than 0.2% across the natural gas supply chain, as data are available, or the use of other best practices applied to natural gas supplies to California.”)

[889] Venting or Flaring Natural Gas, 2 COLO. CODE REGS. § 404–1-903 (2022) ("Venting and Flaring of natural gas represent waste of an important energy resource and pose safety and environmental risks. Venting and Flaring, except as specifically allowed in this Rule 903, are prohibited.").

[890] Office of Governor Gavin Newsom (8 June 2022) *At Summit of the Americas, Governor Newsom Outlines California's World-Leading Efforts to Cut Methane Pollution* ("The Governor's California Climate Commitment, a historic $47.1 billion proposal, includes $200 million for remediating idle oil wells and $100 million for the methane-detecting satellites. These satellites will be critical for California regulators to hold polluters accountable, and the rest of the world will benefit as well from transparent and timely access to data on leaks when they occur. The $200 million would allow the State to quickly get to work plugging idle oil wells, especially orphaned idle wells, in anticipation of additional Federal support. The funding would also give the State the ability to expeditiously remediate wells owned by delinquent operators while regulators pursue reimbursement.").

[891] Control of Ozone via Ozone Precursors and Control of Hydrocarbons via Oil and Gas Emissions (Emissions of Volatile Organic Compounds and Nitrogen Oxides), 5 COLO. CODE REGS. § 1001–1009 (2022) ("Natural Gas-Actuated Pneumatic Controllers Associated with Oil and Gas Operations").

[892] Ozimek T. (13 October 2023) *New York's Ban on Gas Stoves Hit With Lawsuit by Industry Groups*, NTD ("Several industry groups have filed a lawsuit to block New York's controversial state ban on gas stoves and furnaces that came as dozens of Democrat-controlled cities and local governments took similar measures to fight the supposed dangers of climate change. The complaint, filed on Oct. 12 by the National Association of Home Builders, the National Propane Gas Association, and others, accuses New York State of violating federal law by banning gas stoves and other appliances in new buildings.").

[893] State of California (24 October 2023) *Memorandum of Understanding to Enhance Cooperation on Green Development Between the Government of Guangdong Province and the Government of the State of California* (Section II of the MOU identifies areas of cooperation, including: "(i) Air Pollution Prevention and Control; (ii) Zero Emission Vehicles / New Energy Vehicles; (iii) Climate Change Mitigation, Carbon Neutrality, and Deep Decarbonization; (iv) Climate Change Adaptation; (v) Nature-Based Solutions and Biodiversity Protection; (vi) Carbon Capture, Storage and Utilization; (vii) Carbon Emissions Trading; (viii) Climate Investment and Financing; (ix) Other areas of mutual consent).").

[894] State of California (24 October 2023) *Memorandum of Understanding to Enhance Cooperation on Green Development Between the Government of Guangdong Province and the Government of the State of California* (Section IV outlines specific activities for the MOU, including "a) Providing mutual advice on emissions reductions and air pollution control programs and policies, including strategies for legal compliance and enforcement; b) Sharing information and experiences regarding policies, programs, and incentives to strengthen low carbon development, reduce air pollution and accelerate ZEV/NEV deployment across economic sectors and regions; c) Co-organizing policy seminars and informational exchanges on best practices, new technologies and business models for the decarbonization of transport, energy and industry; d) Organizing annual meetings focused on carbon neutrality planning, climate change mitigation and adaptation; e) Activities that advance exchange and mutual visits among concerned personnel, businesses, universities and academic institutions of the Participants, including but not limited to field visits, meetings and webinars; f) Organizing symposia, seminars, workshops, informational exchanges, exhibitions, trainings, and other mutually agreed engagements, as appropriate.").

[895] State of California (24 October 2023) *Memorandum of Understanding to Enhance Cooperation on Green Development Between the Government of Guangdong Province and the Government of the State of California* (Paragraph II sets out the areas of cooperation for this MOU, including: "1. Energy Efficiency; 2. Carbon Peaking and Carbon Neutrality; 3. Air Quality; 4. Climate Adaptation and Mitigation; 5. Clean Transportation; 6. Clean Energy and Low Carbon Development; 7. Nature-Based Climate Solutions; 8. Circular Economy.").

[896] State of California (24 October 2023) *Memorandum of Understanding to Enhance Cooperation on Green Development Between the Government of Guangdong Province and the Government of the State of California* (Article II lists areas for cooperation under the MOU, including: "• Environmental management legislation, policy and regulation; • Climate mitigation actions; • Climate adaptation actions; • Air quality management; Informational exchange and capacity building (technical training, lectures, workshops, etc.); • Public education on environmental protection; • Implementation of a pilot project of mutual interest and benefit to the Parties; and • Water quality management, solid waste management, biodiversity protection and other environmental affairs; • Cooperation may also be undertaken in other areas as agreed by the Parties.").

[897] State of California (28 October 2023) *Memorandum of Understanding on Enhancing Cooperation on Climate and the Environment Between Shanghai Municipal Bureau of Ecology and Environment of the People's Republic of China and California Air Resources Board of the United States of America* (Section II identifies areas of cooperation under the MOU, including: "1. Air Quality; 2. Greenhouse Gas Emissions; 3. Clean Transportation, including Clean Ports and Green Shipping; 4. Clean Energy; 5. Climate Adaptation and Resilience; 6. Nature-Based Climate Solutions.").

[898] California Air Resources Board (3 December 2023) *California launches methane-cutting effort with subnational governments at COP28* ("California officially kicked off a new international climate initiative that creates a partnership of subnational governments that are committed to reducing methane today at the United Nations Climate Change Conference (COP28) hosted in Dubai. The effort, which was initially announced in September during Climate Week, has expanded to 15 signatories, which include additions from Brazil, Canada, South Korea, Bolivia, Germany, Spain, and the United States. The Subnational Methane Action Coalition creates collaboration with jurisdictions that oversee and regulate key sources of methane such as agriculture, energy and landfills to share goals and best practices in reducing the short-lived climate pollutant that accounts for almost 30% of current global warming and is 80 times more potent than carbon dioxide over a 20-year period.").

[899] ***See*** for example Climate & Clean Air Coalition, *Platform for Subnational Action to Reduce Short-Lived Climate Pollutants* (*last visited* 29 January 2024) ("The Climate and Clean Air Coalition's platform for subnational action drives comprehensive, integrated and region-wide climate actions to reduce short-lived climate pollutants (SLCPs) that can maximize air quality, human health and climate co-benefits. Many SLCP measures identified by UN Environment, the World Meteorological Organisation and the Coalition require the full engagement of subnational governments. Currently, more than 100 subnational governments are engaged in Coalition activities. Subnational governments that engage in the Coalition work together to: Empower and facilitate actions to reduce SLCPs, with a focus on integrating climate and clean air policies that reduce SLCPs. Showcase actions and share experience on integrating climate and clean air policies in cooperation with Coalition partners and initiatives. Access tools, including the Solution Centre and scientific updates from the Coalition's Scientific Advisory Panel. Enhance progress towards achieving the goals of the Paris Agreement in the context of the implementation of the Sustainable Development Goals.").

[900] International Energy Agency, *Global Methane Pledge* (*last visited* 24 January 2024) ("The Global Methane Pledge was launched at COP26 in November 2021 to catalyse action to reduce methane emissions. Led by the United States and the European Union, the Pledge now has 111 country participants who together are responsible for 45% of global human-caused methane emissions.").

[901] United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO2 Greenhouse Gases* ("The United States, People's Republic of China, and United Arab Emirates today convened a Summit to accelerate actions to cut methane and other non-CO2 greenhouse gases as the fastest way to reduce near-term warming and keep a goal of limiting global average temperature increase to 1.5 degrees Celsius within reach.").

[902] Executive Body Working Group on Strategies and Review (30 September 2020) *Preparations for the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012*, ECE/EB.AIR/2020/3 – EBE/EB.AIR/WG.5/2020/3 at ¶ 20, ("As per the long-term strategy for the Convention for 2020–2030 and beyond

(paragraph 50), the review should look at appropriate steps towards reducing emissions of black carbon, ozone precursors not yet addressed such as methane, and emissions from shipping with due consideration for International Maritime Organization (IMO) policies and measures... In line with the priorities identified in the long-term strategy for the Convention for 2020–2030 and beyond, the following should specifically be considered in answering the questions in annex I: (b) Hemispheric transport of ozone and particulate matter and their precursors and advancing efforts to address air pollution on a broader scale per paragraphs 63 and 78 of the long-term strategy for the Convention for 2020–2030 and beyond; health and ecosystem impacts from outside the ECE region; I Methane and its relationship to the hemispheric transport of ozone and its contribution to ozone in the ECE region …").

[903] White House (29 June 2016) *Leaders' Statement on a North American Climate, Clean Energy, and Environment Partnership*, Statements and Releases ("Today, Mexico will join Canada and the United States in committing to reduce their methane emissions from the oil and gas sector – the world's largest industrial methane source – 40% to 45% by 2025, towards achieving the greenhouse gas targets in our nationally determined contributions. To achieve this goal, the three countries commit to develop and implement federal regulations to reduce emissions from existing and new sources in the oil and gas sector as soon as possible. We also commit to develop and implement national methane reduction strategies for key sectors such as oil and gas, agriculture, and waste management, including food waste."). *See also* White House (29 June 2016) *North American Climate, Clean Energy, and Environment Partnership Action Plan*, Statements and Releases ("Reduce methane emissions from the oil and gas sector, the world's largest industrial methane source, 40-45% by 2025 towards achieving the greenhouse gas targets in our nationally determined contributions, and explore additional opportunities for methane reductions. The three countries commit to develop and implement federal regulations for both existing and new sources as soon as possible to achieve the target. We intend to invite other countries to join this ambitious target or develop their own methane reduction goal.").

[904] United States White House (29 June 2016) *Leaders' Statement on a North American Climate, Clean Energy, and Environment Partnership*, Statements and Releases ("Today, Mexico will join Canada and the United States in committing to reduce their methane emissions from the oil and gas sector – the world's largest industrial methane source – 40% to 45% by 2025, towards achieving the greenhouse gas targets in our nationally determined contributions. To achieve this goal, the three countries commit to develop and implement federal regulations to reduce emissions from existing and new sources in the oil and gas sector as soon as possible. We also commit to develop and implement national methane reduction strategies for key sectors such as oil and gas, agriculture, and waste management, including food waste."). *See also* United States White House (29 June 2016) *North American Climate, Clean Energy, and Environment Partnership Action Plan* ("Reduce methane emissions from the oil and gas sector, the world's largest industrial methane source, 40-45% by 2025 towards achieving the greenhouse gas targets in our nationally determined contributions, and explore additional opportunities for methane reductions. The three countries commit to develop and implement federal regulations for both existing and new sources as soon as possible to achieve the target. We intend to invite other countries to join this ambitious target or develop their own methane reduction goal.").

[905] United States White House (12 July 2022) *President Biden and President Lopez Obrador Joint Statement*, Statements and Releases ("We commit to tackle methane emissions from oil and gas and other sectors, accelerate the transition to zero-emission vehicles, and deepen our efforts to seek nature-based solutions, enabling our two countries to become global leaders in clean energies and actions to combat climate change. In support of the Global Methane Pledge and Global Methane Pledge Energy Pathway, Mexico and Pemex, in cooperation with the U.S., will develop an implementation plan to eliminate routine flaring and venting across onshore and offshore oil and gas operations and identify priority projects for investment.").

[906] United States White House (25 March 2022) *Joint Statement between the United States and the European Commission on European Energy Security*, Statements and Releases ("The United States will strive to ensure, including working with international partners, additional liquified natural gas (LNG) volumes for the EU market of at least 15 bcm in 2022 with expected increases going forward. The United States and European Commission will undertake efforts to reduce the greenhouse gas intensity of all new LNG infrastructure and associated pipelines,

including through the use of clean energy to power onsite operations, the reduction of methane leakage, and the construction of clean and renewable hydrogen ready infrastructure. The United States commits to maintaining an enabling regulatory environment with procedures to review and expeditiously act upon applications to permit any additional export LNG capacities that would be needed to meet this emergency energy security objective and support the RePowerEU goals, affirming the joint resolve to terminate EU dependence on Russian fossil fuels by 2027.").

[907] United States Federal Energy Regulatory Commission (24 March 2022) *FERC Seeks Comment on Draft Policy Statements on Pipeline Certification*, News Releases ("FERC today voted to seek comments on two policy statements it issued last month that provide guidance regarding the certification of interstate natural gas pipelines and consideration of greenhouse gas (GHG) emissions in natural gas project reviews. In February, the Commission issued an update to its 1999 Certificate Policy Statement and also issued an interim policy statement focused on the Commission's assessment of the impact of a project's GHG emissions. After further consideration, the Commission today designated both documents as draft policy statements on which the Commission is seeking further public comment. The two draft policy statements will not apply to pending project applications or filed applications before the Commission issues any final guidance in these dockets."); *discussed in* Willson M. (23 March 2022) *FERC retreats on gas policies as chair pursues clarity*, ENERGYWIRE ("The Federal Energy Regulatory Commission has rolled back sweeping new policies for large natural gas projects, including a framework for assessing how pipelines and other facilities contribute to climate change, weeks after prominent lawmakers panned the changes. In a decision issued unanimously at the commission's monthly meeting yesterday, FERC will revert back to its long-standing method for reviewing natural gas pipeline applications — while opening changes announced in February to feedback rather than applying them immediately. While the policy changes issued in February were intended to update and improve the agency's approach for siting new gas projects, the commission has concluded that the new guidelines 'could benefit from further clarification,' said FERC Chair Richard Glick. 'I'm all for providing further clarity, not only for industry but all stakeholders in our proceedings, including landowners and affected communities,' said Glick, a Democrat who supported the initial changes.").

[908] McKibben B. (October 31 2023) *A Smoking Gun for Biden's Big Climate Decision?*, NEW YORKER ("The Biden Administration faces one of its most profound climate choices this autumn: Should it continue to allow the expansion of liquefied-natural-gas exports, or should it halt the rapid buildout of this industry at least until it can come up with new guidelines? The stakes are enormous—the buildout of L.N.G. infrastructure in the United States is by far the largest example of fossil-fuel expansion currently proposed anywhere in the world. But there's some new data that may make the Administration's choice easier—or certainly starker. The data are from an analysis by Robert Warren Howarth, a professor of ecology and environmental biology at Cornell who is one of the world's premier methane scientists. The analysis attempts to establish the greenhouse-gas footprint of L.N.G. exported to Europe and Asia, and the numbers presented are astonishing. Coal-fired power has long been the standard for measuring climate damage: when burned, coal releases carbon dioxide into the air in large quantities. In recent years, Howarth has demonstrated that, domestically, natural gas is no better for the climate than coal, largely owing to the methane leaks associated with it; now, though, it appears that exporting L.N.G., because of the extra leakage of the supercooled gas during transit, could allow even larger amounts of methane to escape into the atmosphere and, hence, could do much more damage to the climate than coal does.").

[909] Thompson R. L. & Peters G. (25 April 2022) *How achievable is the Methane Pledge?*, CICERO ("Although world leaders are rightfully concerned about the war in Ukraine, it is important that they do not forget the Methane Pledge. Tackling methane emissions now is a must in order to have a chance of limiting global warming to 1.5°C. It is technically feasible to make significant reductions by 2030 - about 24% relative to 2020 levels given the projected production increases. Achieving the Methane Pledge of 30% will be very challenging but not impossible if increases in production could be curbed as well. The deciding factor is how quickly governments, businesses and local authorities will act.").

[910] United States White House (12 May 2022) *FACT SHEET: U.S.-ASEAN Special Summit in Washington, DC*, Statements and Releases ("Reducing Methane Emissions: The United States is committed to working with the nations

of Southeast Asia to reduce the region's methane emissions. The United States welcomed Indonesia, Vietnam, Malaysia, the Philippines, and Singapore joining the Global Methane Pledge at COP-26, and we are accelerating technical assistance, financial resources, and project pipeline development for methane mitigation in Global Methane Pledge countries, including through the EPA, USTDA, DFC, and EXIM, as well as the newly-created Global Methane Hub, a philanthropic fund that can support methane mitigation priorities in the region.").

[911] United States Department of Energy Office of International Affairs (22 August 2022) *United States and Brazil Strengthen Bilateral Cooperation on Energy and Launch a New Public Private Cooperation to Promote Clean Energy*, Press Release ("The United States of America and the Federative Republic of Brazil reaffirmed today their commitment to joint energy cooperation at the second U.S.-Brazil Energy Forum (USBEF) Ministerial in Washington, D.C. Secretary of Energy Jennifer Granholm hosted the meeting with Brazil's Minister of Mines and Energy Adolfo Sachsida. The USBEF was established as a mechanism to collaborate on technical, regulatory, and policy issues of mutual interest, as well as address critical barriers to bilateral energy trade and investment. Secretary Granholm and Minister Sachsida endorsed a bilateral cooperation plan for technical, regulatory, and policy cooperation in three areas: Carbon and Methane Management, Civil Nuclear Power, and Renewables, Energy Efficiency, and Grid Modernization: • The two governments agreed to exchange expertise in carbon and methane management, and carbon sequestration and storage. • There was also agreement to continue and expand cooperation on civil nuclear power and launch new efforts on civil nuclear regulation and new nuclear power generation. • The Ministers emphasized their interest in increasing the cooperation on renewable energy and energy efficiency, particularly on strategic sectors such as clean hydrogen, offshore wind, sustainable fuels, grid modernization and storage, and industrial energy efficiency.").

[912] Vasconcellos R. B. (4 August 2022) *Energy Is Up on U.S.-Brazil Relations,* United States Chamber of Commerce ("Offshore wind energy is a common priority for these two continental countries, and there is fertile ground for a productive dialogue on this topic. Wind (albeit onshore) already plays an important role as a source of energy in diversifying Brazil's energy grid, ranking second (13.4%) behind only hydropower (56.7%). Meanwhile, the U.S. contribution will come from the U.S. administration's vision of wind as a key pillar of the U.S. clean energy agenda and its work towards the deployment of 30 GW of offshore wind by 2030. Collaboration on sustainable fuels is also important for the dialogue. Brazil is known for having vehicles running on ethanol derived from sugarcane since the 1970s. On the other hand, U.S. industry, inspired by the U.S. administration's ambitious goal to rapidly increase the production of sustainable aviation fuels by 2030, has a lot of knowledge to offer to Brazil and the Latin America region.").

[913] United States Department of State (3 May 2023) *Joint Statement on the United States-Turkmenistan Annual Bilateral Consultations*, Press Release ("The United States and Turkmenistan emphasized the importance of fighting climate change, particularly by reducing methane emissions. The United States and Turkmenistan stated their intentions to cooperate on deploying leak detection and repair solutions as well as develop a methane reduction investment plan in 2023 to control methane emissions in the oil and gas sector. To advance this work, the United States and Turkmenistan will form a working group on methane mitigation and will endeavor to feature methane mitigation outcomes by COP28.").

[914] United States Department of State (3 May 2023) *Joint Statement on the United States-Turkmenistan Annual Bilateral Consultations*, Press Release ("The United States and Turkmenistan emphasized the importance of fighting climate change, particularly by reducing methane emissions. The United States and Turkmenistan stated their intentions to cooperate on deploying leak detection and repair solutions as well as develop a methane reduction investment plan in 2023 to control methane emissions in the oil and gas sector. To advance this work, the United States and Turkmenistan will form a working group on methane mitigation and will endeavor to feature methane mitigation outcomes by COP28."). *See also* Clarke, A. (2 December 2023) *US-Turkmenistan Methane Deal Progresses With Engineers on Ground*, BLOOMBERG ("Foreign petroleum engineers are in the reclusive state of Turkmenistan laying the groundwork for a plan to curb the nation's giant methane emissions with potential help from the US government.").

[915] The White House (20 April 2023) *FACT SHEET: President Biden to Catalyze Global Climate Action through the Major Economies Forum on Energy and Climate*, Statements and Releases ("The President will be joined by other leaders in new efforts aimed at accelerating progress in four key areas necessary for keeping a 1.5°C limit on warming within reach, specifically. . . Tackling potent, non-CO2 climate pollutants: Launching a Methane Finance Sprint to cut methane emissions and accelerating hydrofluorocarbon (HFC) phasedown under the Kigali Amendment.").

[916] The White House (20 April 2023) *FACT SHEET: President Biden to Catalyze Global Climate Action through the Major Economies Forum on Energy and Climate*, Statements and Releases ("At today's meeting, the President will highlight new steps the United States is taking to meet its ambitious 1.5°C-aligned goal of reducing emissions 50-52 percent in 2030. The President will also announce significant new steps the United States is taking to support developing countries in taking stronger climate action – including providing $1 billion to the Green Climate Fund and requesting $500 million for the Amazon Fund and related activities – and invite other countries to join the United States and others in fully leveraging the multilateral development banks to better address global challenges, like climate change.").

[917] Volcovici V. & Stanway D. (17 July 2023) *China-US climate progress could hinge on curbing of methane*, REUTERS ("Methane is particularly important for our cooperation," Kerry told a congressional hearing on Thursday in Washington. "China agreed to have a methane action plan out of our prior talks in Glasgow (in 2021), and again in Sharm el-Sheikh" in November.").

[918] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("The two countries will implement their respective national methane action plans and intend to elaborate further measures, as appropriate. The two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress. The two countries intend to cooperate on respective measures to manage nitrous oxide emissions. The two countries intend to work together under the Kigali Amendment to phase down HFCs and commit to ensure application of ambitious minimum efficiency standards for all cooling equipment manufactured.").

[919] United States Agency for International Development (11 November 2022) *USAID Reaffirms Commitments to Investments in Climate Smart Food Systems: Agriculture Innovation Mission for Climate, Investment Impacts, Innovation Sprints, and Methane Accelerator*, Press Release ("Additionally, USAID is partnering with the State Department to launch a new USAID Methane Accelerator program that will mainstream and scale up methane mitigation programming across the Agency. Methane emissions, including emissions from the agricultural sector, are supercharging global warming. Subject to Congressional Notification, USAID and the Department of State will dedicate $12 million to this program, with the goal of leveraging substantial additional resources. Administrator Power also announced two new AIM for Climate Innovation Sprints and USAID partnerships that will increase private sector investments in climate smart food systems:

- **Bayer Crop Science and the International Rice Research Institute:** USAID is partnering with Bayer Crop Science and the International Rice Research Institute on an Innovation Sprint to improve the quality of life of smallholder rice farmers through the introduction, on-farm testing, and scaling of improved, climate-smart rice varieties that are sown directly in the field as opposed to the labor-intensive process of transplanting seedlings by hand. Bayer has committed up to $4 million of in-kind support.
- **Olam Food Ingredients (ofi) and partners:** USAID, ofi, Nestlé, Mars Wrigley, Costco Wholesale, Mondelēz International, and Blommer Chocolate Company have launched RESTORE: "Resilient Ecosystems and Sustainable Transformation of Rural Economies", that will help smallholder cocoa farmers use more climate-smart agricultural practices. Through this Innovation Sprint, Ofi and partners are investing

$7 million towards this effort to support 15,000 cocoa farmers by 2027, of which at least 25% will be women.").

[920] *See* Gordon D., Guccione L., & Conway T. (2024) *Mission Critical Methane: Aligning Policies and Markets to Cut Oil and Gas Emissions*, Rocky Mountain Institute, 22 ("US export policy priorities must support global gas markets with methane leakage below 0.2%. This necessarily involves DOE MMRV priorities that intend to establish a global framework for estimating and accounting for methane emissions across the global oil and gas value chain. … The aim is to incentivize rapid emissions reductions by buyers, sellers, traders, and investors in the global market. This requires alignment with major LNG buyers, such as Japan and South Korea, as well as top global LNG suppliers, from Australia to Qatar. Suppliers in greatest need of support to achieve this goal are in the Global South. … Leaky gas is costly, wasteful, and harmful to the climate and to people. Bringing systemwide gas intensity to below 0.2% leakage can serve as a force multiplier to reduce global methane on the order of 60 million tons by 2030, which equates to a five gigatons CO2e emissions reduction in the short term when methane's warming is most potent. This reduction would put the world well on its way to meeting the Global Methane Pledge." (Citations omitted.)). For an example of a digital resource to support oil and gas companies in identifying and adopting methane emissions reduction technologies, *see* Chubb, *Chubb Methane Resource Hub* (*last visited* 2 December 2023).

[921] AIM For Climate, *Innovation Sprints* (*last visited* 26 January 2023) (Innovation sprints with the closest link to agricultural methane include "Climate Resilience Through Crop Protection Innovation," "Greener Cattle Initiative: Addressing Enteric Methane Emissions," and "Satellite monitoring of quantity and quality of available biomass in pastoral livestock systems").

[922] AIM For Climate, *Partners* (*last visited* 26 January 2023).

[923] *See* Alliance of Champions, *About ACF: Building an Alliance of Champions* (*last visited* 19 December 2023) ("The Alliance of Champions for Food Systems Transformation (ACF) is a strategic coalition of ambitious countries determined to act urgently, together. Brazil BR | Cambodia KH | Norway NO | Rwanda RW | Sierra Leone SL |Signatories to the Alliance are committing to driving systemic change, taking a 'whole of government' approach and inspiring others to go further, faster to deliver better outcomes for people, nature and climate."); *and* Alliance of Champions (10 December 2023) *Alliance of Champions launched at COP28 to supercharge global food systems transformation efforts*, Press Release ("Brazil, Cambodia, Norway, Sierra Leone and Rwanda are united in their commitment to 'whole of government' approaches to transforming food systems so that they deliver better outcomes across five key themes: food and nutrition security; adaptation and resilience; equity and livelihoods; nature and biodiversity; and climate mitigation.").

[924] Alliance of Champions, *Ten Priority Intervention Areas* (*last visited* 19 December 2023) ("Rationale: Food systems, including their energy consumption, account for ~30% of global emissions. Reducing these emissions by 83% is essential to mitigating climate change and meeting existing global agreements and targets (e.g., SDGs, Paris Agreement, Global Methane Pledge). The agrifood system has the potential to contribute actively to the energy transition, in coordination with better use of renewables. Priority activities • Reduce methane emissions from agriculture (e.g., rice cultivation, livestock management including enteric fermentation, manure management and herd reduction where necessary.").

[925] Alliance of Champions (10 December 2023) *Alliance of Champions launched at COP28 to supercharge global food systems transformation efforts*, Press Release ("Each country is pledging to: 1. Strengthen national visions and food systems transformation pathways, inclusive of ten priority action areas and consistent with science-based targets. 2. Update Nationally Determined Contributions (NDCs), National Adaptation Plans (NAPs), Long-Term Low Emission Development Strategies (LT-LEDS), and National Biodiversity Strategies and Action Plans (NBSAPs) in line with these updated National Food System Transformation Pathways and/or Implementation Plans, by 2025 at the latest. 3. Report annually on targets and priority intervention areas.").

[926] PETRONAS (27 June 2023) *PETRONAS Collaborates with Partners to Accelerate Methane Emissions Reduction*. *See also* Eco Business (11 August 2023) *Cutting methane emissions is key to slowing down climate change: EDF president Fred Krupp* ("When I was in Kuala Lumpur [to attend the Energy Asia conference], the Asean Methane Leadership Programme was announced in Malaysia. This 18-month initiative, in which EDF is a key stakeholder, will focus on capacity building to help strengthen Asean companies' plans, targets and financing options in reducing methane emissions.").

[927] Chew N. (11 July 2023) *PETRONAS collaborates with partners to accelerate methane emissions reduction*, ASIAN DOWNSTREAM INSIGHTS ("PETRONAS, in collaboration with ASEAN energy operators, governmental agencies, and international organisations, has launched the ASEAN Energy Sector Methane Leadership Program (MLP), and announced methane abatement flagship projects in collaboration with Japan Organization for Metals and Energy Security (JOGMEC).").

[928] United Nations Environment Programme (6 December 2023) *The Buildings Breakthrough: Global push for near-zero emission and resilient buildings by 2030 unveiled at COP28* ("The Governments of France and Morocco, together with the UN Environment Programme (UNEP), launched the Buildings Breakthrough today at COP28, which will see countries joining forces to accelerate the transformation of the sector – which accounts for 21 per cent of global greenhouse gas emissions – with a view to making near-zero emissions and climate resilient buildings the new normal by 2030. Twenty-seven countries have so far pledged their commitment to the Buildings Breakthrough."). *See also* Global Cement and Concrete Association (6 December 2023) *Canada launches the Cement & Concrete Breakthrough initiative at COP28* ("Today, the Honourable François-Philippe Champagne, Minister of Innovation, Science and Industry, and His Excellency Omar Ahmed Suwaina Al Suwaidi, Undersecretary of the Ministry of Industry and Advanced Technology in the United Arab Emirates (UAE), announced the launch of the Cement & Concrete Breakthrough initiative at COP28 in Dubai. This initiative reaffirms Canada's commitment to working with countries, businesses and international partner organizations to accelerate investments in the technologies, tools and policies that the cement and concrete industry needs to realize net-zero solutions by 2050.").

[929] International Energy Agency, International Renewable Energy Agency, & United Nations Climate Change High Level Champions (2023) *THE BREAKTHROUGH AGENDA REPORT 2023*, 3 ("The Breakthrough Agenda was launched by 45 world leaders at COP 26 and is a commitment to work together this decade to accelerate innovation and deployment of clean technologies, making them accessible and affordable for all this decade. To kick-start this Agenda, countries endorsed Breakthrough goals to make clean technologies and sustainable practices more affordable, accessible and attractive than their alternatives by 2030 in the power, road transport, steel, hydrogen and agriculture sectors. This report also covers the buildings and cement sectors, where new breakthroughs are being considered. The Breakthrough Agenda establishes an annual cycle to track developments towards these goals, identify where further co-ordinated international action is urgently needed to accelerate progress and then galvanise public and private international action behind these specific priorities in order to make these transitions quicker, cheaper and easier for all.").

[930] Climate Champions (14 September 2023) *Breakthrough Agenda Report 2023: Stronger international cooperation in high emissions sectors crucial to get on track for 1.5C climate goal*, Race to Resilience ("The second annual report assesses progress made since 2022 in priority areas for international collaboration, and sets out a series of recommendations for countries to work together in each sector to help reduce emissions over the next decade and stave off the worst effects of climate change … The report's recommendations span financial assistance, research and development, demand-creation, infrastructure, standards and trade, to accelerate the transition in each sector. Coordinated actions in each of the seven sectors will help mobilise investment, and can create the economies of scale required to bring down the price of crucial technologies and sustainable agriculture solutions. The report found that in the past year, only modest progress has been made in strengthening international collaboration in the areas where it is most needed. Progress has been made in expanding financial assistance to developing countries in some sectors, and in joint research and development initiatives.").

[931] Climate & Clean Air Coalition, *Our Partners* (*last visited* 5 February 2023) ("The Coalition is a voluntary partnership led by states and regional integration organisations. These partners have committed to accelerate action to reduce short-lived climate pollutants through their participation in the Coalition's activities and local action.").

[932] Climate & Clean Air Coalition, *Global Methane Pledge* (*last visited* 12 December 2023) ("As of September 2023, the Climate and Clean Air Coalition (CCAC) provides secretariat services to the Global Methane Pledge (GMP). This function reinforces the CCAC's core mandate to address methane as part of its broader goal to reduce short-lived climate pollutants while responding to GMP countries' need for support to deliver on their commitment. As the GMP secretariat, CCAC will work with GMP countries and supporters to strengthen engagement and coordination, track progress, monitor policy actions and project successes, maintain and update resources, provide direct support through one-on-one advice, engage participants and supporters through CCAC hubs, meetings, and the Scientific Advisory Panel, and ministerial engagements.").

[933] Climate & Clean Air Coalition, *National policy and planning support* (*last visited* 5 February 2023) ("Since 2013, the CCAC has helped 16 countries develop national plans that integrate climate and clean air objectives through actions to reduce short-lived climate pollutants (SLCPs). Eight of these plans have received national endorsement and are moving towards implementation."). *See also* Climate & Clean Air Coalition, *Increasing Ambition of NDCs* (*last visited* 5 February 2023) ("As countries update their Nationally Determined Contributions (NDCs) and enhance ambition to achieve the Paris Agreement temperature goals, the Climate and Clean Air Coalition is encouraging and supporting them to include short-lived climate pollutant (SLCP) and air pollution actions into their climate commitments.").

[934] United Nations Environment Programme (2021) *September 2021 Report of the Technology and Economic Assessment Panel, Volume 6: Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 2021-2023*, 59 ("The funding approved for IS support has played a paramount role in establishing and maintaining the capacity of national ozone units and is recognized as a major factor in the success of A5 parties achieving compliance with the Montreal Protocol's control measures.120"), *citing* Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol (17 April 2015) *Review of Funding of Institutional Strengthening Projects (Decision 61/43(b)*, UNEP/OzL.Pro/ExCom/74/51, ¶¶ 11–13.

[935] Climate & Clean Air Coalition, *Technology and Economic Assessment Panel* (*last visited* 15 December 2023) ("In 2023, the CCAC established its Technology and Economic Assessment Panel (CCAC-TEAP) to develop and share knowledge with countries about promising, innovative and underfinanced short-lived climate pollutant (SLCP) mitigation measures which can improve both climate and air quality outcomes.").

[936] Climate & Clean Air Coalition (15 November 2022) *Sharm el-Sheikh Communiqué* ("We will seek to expand our work with the private sector and state-owned enterprises. We welcome exploring the formation of a Technology and Economic Assessment Panel on Methane, or similar, as suggested by Senegal, to better understand and advise CCAC Partners on the landscape of innovative methane mitigation technologies, including methane removal and sector-specific methane reduction technologies.").

[937] Climate & Clean Air Coalition (9 November 2021) *Climate and Clean Air Coalition Ministers approve strategy to significantly cut short-lived climate pollutants this decade*, Press Release ("Ministers approved the implementation of a Methane Flagship, which, starting in 2022, will foster and strengthen high level commitments to reduce methane, amplify and raise awareness, support planning and delivery of strategies and plans, provide analysis and tools to support action, and scale up financing. There was strong and broad support for the recently launched Global Methane Pledge and ministers welcomed the CCAC having a leadership role in supporting its implementation.").

[938] *See generally* Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT; *and* Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030.

[939] Explore mitigation amounts and impacts at: http://shindellgroup.rc.duke.edu/apps/methane/.

[940] Economic Commission for Europe (8 September 2015) *UNECE joins Climate and Clean Air Coalition*, Press Release ("At a Working Group meeting in Paris (8–9 September), CCAC welcomed UNECE to the Coalition. By joining the Coalition, UNECE gains access to a broad network of experts and partners. Drawing on its long-standing expertise, UNECE will contribute through exchanges of experiences, knowledge and best practices, particularly as they relate to the work under the Committee on Sustainable Energy and the Convention on Long-Range Transboundary Air Pollution, including its amended Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol).").

[941] *See Global Methane, Climate and Clean Air Forum* (*last visited* 5 February 2023) ("The Global Methane, Climate and Clean Air Forum is a joint event sponsored by the Global Methane Initiative (GMI) and the Climate & Clean Air Coalition (CCAC). The Forum is a premier global event that brings together policymakers, industry leaders, technical experts, and researchers from around the world to discuss opportunities to protect the climate and improve air quality with a special focus on methane.").

[942] Climate & Clean Air Coalition Secretariat (7 October 2022) *At The Global Methane, Climate and Clean Air Forum, Experts Stress the Need for #FastClimateAction* ("**Martina Otto, Head of Secretariat, CCAC**, stated that joint efforts and methane action must be taken 'right' now given the narrow window to achieve the goals of the Paris Agreement on climate change. She also reminded participants of several initiatives funded by the CCAC Trust Fund, especially on methane source sectors.").

[943] Climate & Clean Air Coalition (15 November 2022) *Ministerial Communique*, 1 ("In a year in which the devastating and horrendous impacts of climate change have become ever-more apparent around the globe, and when the UN General Assembly recognized the right to a clean, healthy and sustainable environment (Res. 76/300), we the Ministers and Leaders of the Climate and Clean Air Coalition (CCAC) have met today to: … Reaffirm and renew our commitment to reduce emissions of methane and other short-lived climate pollutants (SLCPs) quickly and decisively – as a complement to scaled-up action on carbon dioxide (CO_2) – noting that reducing SLCP emissions is the most effective pathway to avoid 0.6℃ of predicted global warming in the near term[i] and slow sea-level rise by 20% by mid-century,[ii] slowing the rate of Arctic warming by up to two-thirds[iii] and the rate of global warming by half; … Launch new collaborative actions to further drive emissions reductions, as a concrete and practical affirmation of our commitment, noting the importance of mobilizing financing to deliver results.").

[944] Climate & Clean Air Coalition (15 November 2022) *Ministerial Communique*, 3 ("We welcome exploring the formation of a Technology and Economic Assessment Panel on Methane, or similar, as suggested by Senegal, to better understand and advise CCAC Partners on the landscape of innovative methane mitigation technologies, including methane removal and sector-specific methane reduction technologies.").

[945] Climate & Clean Air Coalition (15 November 2022) *Ministerial Communique*, 4 ("And, we request the CCAC Scientific Advisory Panel to put forward a proposal on how we can highlight and better calculate the near-term climate benefits of our methane commitments, for instance through the use of GWP20 or temperature change over time in our NDCs.[vii]").

[946] Climate & Clean Air Coalition, *Technology and Economic Assessment Panel* (*last visited* 15 December 2023) ("In 2023, the CCAC established its Technology and Economic Assessment Panel (CCAC-TEAP) to develop and share knowledge with countries about promising, innovative and underfinanced short-lived climate pollutant (SLCP) mitigation measures which can improve both climate and air quality outcomes.").

[947] Climate & Clean Air Coalition (13 June 2023) *At the Climate and Clean Air Conference 2023, Nations Call for Action,* News and Announcements ("A pilot CCAC Technology and Economic Assessment Panel (TEAP), which will

provide guidance and support to countries on which best available technologies exist for implementation of SLCP reductions in different contexts – focusing initially on methane.").

[948] *See generally* Climate & Clean Air Association (undated) *Science Policy*.

[949] *See generally* Climate & Clean Air Coalition & International Energy Agency (2023) THE IMPERATIVE OF CUTTING METHANE FROM FOSSIL FUELS.

[950] Climate & Clean Air Coalition, *CCAC at COP28* (*last visited* 30 January 2024) ("The Climate and Clean Air Coalition is participating in and co-organizing events during COP28. Our governance meeting, the Climate and Clean Air Ministerial, will also meet on the margins of the Conference, and we will be co-hosting the Global Methane Pledge (GMP) Ministerial.").

[951] Clean Air Task Force (8 December 2023) *Turning pledges into action: COP28 Global Methane Pledge Ministerial*, ("This year, Global Methane Partners announced: Over $1 billion in new grant funding for methane action mobilized since COP27, more than triple current levels, which will mobilize billions in investment to reduce methane. New national commitments and legislation from top oil and gas methane emitters alongside decisive action on waste, food, and agriculture – including strong methane emissions standards for oil and gas from the U.S. and new methane regulations from Canada. Transformational data tools including the full launch of the Methane Alert and Response System, a new Data for Methane Action Campaign, and a new platform to better track waste methane emissions in cities around the world. New members and expanded leadership. Canada, Federated States of Micronesia, Germany, Japan, and Nigeria joined the United States and European Union as Global Methane Pledge Champions. Turkmenistan, Kazakhstan, Kenya, Kosovo, Romania, and Angola joined the Global Methane Pledge, bringing total participation to 156 governments.").

[952] Climate & Clean Air Coalition (9 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* ("Over one hundred ministers, heads of agencies and non-state partners came together in the Climate and Clean Air Ministerial to unveil groundbreaking initiatives, commitments and a call to action during the 28th Conference of Parties of the UNFCCC (COP28). The 2023 Ministerial was focused on financing for short-lived climate pollutants (SLCPs). State partners showed up, making new commitments to climate and clean air and calling for further action and support.").

[953] Climate & Clean Air Coalition (9 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* ("The Coalition also announced the initiation of a landmark assessment on nitrous oxide (N2O) to be delivered in advance of COP29, which will expose impacts of the often-overlooked greenhouse gas. This proactive approach aims to ensure that no opportunities are missed in the pursuit of a 1.5 degrees Celsius future. A global assessment on the cost of inaction on short-lived climate pollutants and an assessment on the integrated agriculture and food systems will be prepared in advance of COP30.").

[954] Climate & Clean Air Coalition (9 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* ("Ministers also called for increased efforts to support highly vulnerable Small-Island Developing States (SIDS), especially in the context of rapid mitigation of methane and black carbon to slow sea level rise and increasing frequency and intensity of climate-exacerbated weather events.").

[955] International Institute for Sustainable Development (2023) *Climate and Clean Air Coalition's Ministerial Meeting: Immediate Action on Climate and Clean Air, Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* ("Germany pledged EUR 20 million for the GMP, EUR 8 million of which will go to the CCAC's budget… Ireland announced EUR 2 million in support of the CCAC… Monaco reported a contribution of EUR

500,000 for 2024.. Sweden announced a pledge of USD 180,000 to support the CCAC."). For a full outline of all funding provided to the CCAC, *see* Climate & Clean Air Coalition, *CCAC Trust Fund* (*last visited* 14 February 2024).

[956] Climate & Clean Air Coalition Secretariat (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Launch of the Lowering Organic Waste Methane (LOW-Methane) initiative. The ambition of LOW-Methane is to deliver at least 1 million metric tons of annual waste sector methane reductions well before 2030 with 40 subnational jurisdictions and their national government counterparts, including by working to unlock over $10 billion in public and private investment. The consortium effort will be supported by a coordination group housed within the UNEP-convened CCAC."). *See also* United States Department of State (4 December 2023) *Lowering Organic Waste Methane Initiative (LOW-Methane)* ("The inaugural cohort of national governments intending to participate in the LOW-Methane initiative includes Chile, Dominican Republic, Nigeria, and Indonesia. Initial LOW-Methane jurisdictions intending to participate include Lagos, Rio de Janeiro, and Santiago. Proposed subnational participants will work toward a clear and ambitious waste methane reduction target, coordinating as appropriate with national government counterparts and the LOW-Methane consortium in their efforts to achieve that target. This work will be supported by a consortium of LOW-Methane stakeholders. Over 20 governments and organizations intend to participate, including Bloomberg Philanthropies, C40 Cities, Canada, Carbon Mapper, Catalytic Finance Foundation, Center for Global Sustainability at the University of Maryland, Clean Air Task Force, the European Union, GAIA, GHGSat, the Global Covenant of Mayors for Climate and Energy (GCoM), the Global Methane Hub, the Global Methane Initiative, Google, the Inter-American Development Bank, the International Solid Waste Association, Pacific Northwest National Laboratory, RMI, SRON, the Under2 Coalition, UNEP-convened Climate and Clean Air Coalition (CCAC), UNEP's International Methane Emissions Observatory, the United States, the World Bank, and the World Resources Institute. The consortium will provide support for jurisdiction priorities related to data, technical capacity, policy, and finance.").

[957] Climate & Clean Air Coalition (2023) *Clean Air Flagship* ("At the Climate and Clean Air Ministerial 2022, CCAC Partners requested a new effort to achieve clean air across the world. At the Climate and Clean Air Ministerial 2023, the CCAC launched the "Clean Air Flagship" to mobilise the partnership and 'move the needle' on this important topic. It is aimed at: Saving lives: Supporting governments to achieve cleaner air as quickly as possible, consistent with improved WHO air quality interim targets. Slowing climate change: Taking full advantage of win-win opportunities to reduce the emissions of short-lived climate pollutants simultaneously with other harmful pollutants. Maximizing co-benefits: Improving agricultural productivity, economic development and the overall quality of life.").

[958] Climate & Clean Air Coalition (2023) *Clean Air Flagship 2024-2026*, 6 ("Support science cooperation and information-sharing initiatives within the regional frameworks, especially with respect to tropospheric ozone, black carbon, and methane (See Annex 1).").

[959] Climate & Clean Air Coalition (2023) *Clean Air Flagship 2024-2026*, 4 ("Strengthen and support regional and sub-regional cooperation and the implementation of political commitments to achieve the WHO Air Quality Guidelines and Global Methane Pledge.").

[960] Arab Republic of Egypt (2022) *Global Waste Initiative 50 by 2050: From Egypt to Africa, for a global impact* ("Key Facts • Waste in Africa 20% Contribution of waste on global methane emissions").

[961] Scarlat N., Motola V., Dallemand J.F., Mofnorti-Ferrario F., & Mofor L. (2015) *Evaluation of energy potential of Municipal Solid Waste from African urban areas, Renewable & Sustainable Energy Reviews* 50:1269–1286, 1279 ("It is also worth noticing that the future set up of landfills in Africa is expected to induce a significant increase of methane emissions, in comparison with the current methane emissions from landfills in Africa (as mentioned above, estimated at of about 1.3 Mt CH_4 for 2010) [17]. If deposited in managed landfills, waste can release significant amounts of CH_4 into the atmosphere that could be avoided by installing proper LFG recovery systems.").

[962] Arab Republic of Egypt (2022) *Global Waste Initiative 50 by 2050: From Egypt to Africa, for a global impact* ("The holistic Initiative will be implemented over all waste types and for the next 28 years, from 2022 to 2050, with an initial 5-year initiation phase until 2027, which will launch the five key missions: 1. Develop a platform for partnerships and projects to address both mitigation and adaptation effects; 2. Create transparency and align key initiatives; 3. Facilitate trade of recyclables between African nations; 4. Support knowledge and innovation transfer to Africa on recycling and infrastructure for all waste types; 5. Ensure implementation and track performance of the Initiative in the WM sector in Africa, impacting the globe").

[963] COP27 (17 November 2022) *Solutions Day*. *See also* Samir S. (17 August 2022) *Egypt launches national campaign to raise awareness of climate change impact*, EGYPT TODAY ("'Green Africa' is one of the essential topics that would be tackled during the COP 27 Conference, where a session will convene to discuss climate change impacts on Africa, putting forward two initiatives for the continent: one aims at reducing waste in Africa by 50 percent by 2050, while the other focuses on climate adaptation in Africa."); *and* Africa NDC Hub (14 November 2022) *Doubling Down on Delivering Africa's Climate Action Priorities – Policy recommendations from the Africa NDC Hub* ("The UNFCCC COP27, also dubbed "The African COP," aims to amplify the African voice at COP. The overall objective of the joint NDC Hub publication is to assess progress on the delivery of the adaptation and mitigation targets in the NDCs and provide policy recommendations on hastening scale and reach.").

[964] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP) announced that it will, with funding from the U.S. State Department and Global Methane Hub, support 15 governments to incorporate agricultural methane into their nationally determined contributions and 10 governments to build investment pipelines in low-methane agricultural development.").

[965] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The United States, the European Commission, and twelve other natural gas importing and exporting countries formed an international working group to advance comparable and reliable information about methane and CO_2 emissions across the natural gas supply chain to drive global emissions reductions.").

[966] COP28, *COP28 UAE Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action* (*last visited* 19 December 2023) ("We affirm that agriculture and food systems must urgently adapt and transform in order to respond to the imperatives of climate change.").

[967] COP28, *COP28 UAE Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action* (*last visited* 19 December 2023) ("In fulfilling this commitment, by 2025 we intend to strengthen our respective and shared efforts to … 3. Continue to scale-up and enhance access to all forms of finance from the public, philanthropic and private sectors – including through blended instruments, public-private partnerships and other aligned efforts – to adapt and transform agriculture and food systems to respond to climate change. … To maintain momentum, we intend to benefit from relevant regional and global convenings in order to share experiences and to accelerate national and collaborative action. We will review our collective progress next year at COP29 with a view to considering next steps in 2025 and beyond.").

[968] United States Department of Energy (9 March 2022) *U.S. Secretary of Energy Jennifer M. Granholm Hosts The First Net-Zero Producers Forum Ministerial in Houston* ("U.S. Secretary of Energy Jennifer M. Granholm, together with Energy Minsters from Canada, Norway, Qatar, and Saudi Arabia, today formally launched the Net-Zero Producers Forum (NPF) through an inaugural ministerial meeting. During the meeting, Ministers endorsed the initiative's Terms of Reference, which codifies the objectives and framework of the NPF.").

[969] United States Department of Energy (23 April 2021) *Joint Statement on Establishing a Net-Zero Producers Forum between the Energy Ministries of Canada, Norway, Qatar, Saudi Arabia, and the United States*, Press Release ("Canada, Norway, Qatar, Saudi Arabia, and the United States, collectively representing 40 percent of global oil and

gas production, will come together to form a cooperative forum that will develop pragmatic net-zero emission strategies, including methane abatement, advancing the circular carbon economy approach, development and deployment of clean-energy and carbon capture and storage technologies, diversification from reliance on hydrocarbon revenues, and other measures in line with each country's national circumstances.").

[970] United States Department of Energy (13 May 2022) *The United Arab Emirates Joins as Sixth Member of the Net-Zero Producers Forum* ("The United States, Canada, Norway, Qatar, and Saudi Arabia welcome the United Arab Emirates as the sixth member of the Net-Zero Producers Forum (NPF). Collectively representing 45 percent of global oil production and 40 percent of natural gas production, the NPF is focusing on accelerating the scale and speed of reaching net-zero emissions.").

[971] Climate & Clean Air Coalition (5 December 2023) *Net-Zero Producers Forum and Reducing Methane Emissions* ("The Net-Zero Producers Forum (NPF) was established to bring together key oil and gas producers to demonstrate that we collectively are taking ambitious steps towards net zero by around mid-century. This panel will bring together the member countries' heads of delegation to highlight members' progress towards net zero and work to implement key decarbonisation and methane mitigation initiatives, to discuss plans for future activities, and to launch the Methane Abatement Toolbox.").

[972] United States Office of International Affairs (4 December 2023) *Net-Zero Producers Forum - Launch of the Upstream Abatement Toolkit* ("The "Upstream Methane Abatement Toolkit" is a resource developed by Net-Zero Producers Forum (NPF) member countries highlighting measures to date and lessons learned regarding the implementation of methane abatement technologies. NPF members will update the toolkit, adding new resources and revisiting the description of existing programs on an annual basis to show increasing action. This toolkit intends to highlight existing and planned methane abatement policies, resources, and initiatives across the member countries for the benefit of the group and for others who are interested in learning from our experiences with methane abatement, which is critical to ensuring we begin to slow and eventually reverse the impacts of climate change.").

[973] World Bank (5 December 2023) *GGFR to evolve to the Global Flaring & Methane Reduction Partnership* ("Today the World Bank launched the Global Flaring and Methane Reduction (GFMR) Partnership, a new multi-donor trust fund focused on helping developing countries cut carbon dioxide and methane emissions generated by the oil and gas industry. GFMR will provide more than $250 million and mobilize billions from the private sector to support those countries with the least capacity and resources to address these emissions. The partnership will focus on providing grant funding, technical assistance, policy and regulatory reform advisory services, institutional strengthening, and mobilizing financing to support action by governments and operators.").

[974] World Bank, *Global Gas Flaring Reduction Partnership (GGFR), About the Partnership* (*last visited* 5 February 2023)
("GGFR helps identify solutions to the array of technical and regulatory barriers to flaring reduction. To achieve this, we develop country-specific flaring reduction programs, conduct research, share best practices, raise awareness, secure global commitments to end routine flaring, and advance flare measurements and reporting."). *See also* World Bank (5 December 2023) *GGFR to evolve to the Global Flaring & Methane Reduction Partnership* ("GFMR will establish eligibility criteria so that support drives long term emissions reduction projects and initiatives. For example, access to project development and financing support through GFMR will be subject to a commitment to measure and report emissions through the Oil and Gas Methane Partnership 2.0 framework, achieve near-zero absolute methane emissions by 2030 by reducing methane intensity to below 0.2%, and achieve zero routine flaring by 2030.").

[975] World Bank (5 December 2023) *GGFR to evolve to the Global Flaring & Methane Reduction Partnership* ("GFMR will establish eligibility criteria so that support drives long term emissions reduction projects and initiatives. For example, access to project development and financing support through GFMR will be subject to a commitment to: measure and report emissions through the Oil and Gas Methane Partnership 2.0 framework, achieve near-zero absolute methane emissions by 2030 by reducing methane intensity to below 0.2%, and achieve zero routine flaring by 2030.").

[976] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The World Bank launched its Global Flaring and Methane Reduction Partnership (GFMR) with $255 million in new grant funding to catalyze oil and gas methane and flaring reduction in developing countries. The GFMR is supported by financial contributions from the United Arab Emirates, United States, Norway, BP, ENI, Equinor, Occidental, Shell, and TotalEnergies.").

[977] World Bank, *Zero Routine Flaring By 2030 (ZRF) Initiative* (*last visited* 5 February 2023) ("Launched in 2015, the ZRF Initiative commits governments and oil companies, to end routine flaring no later than 2030.").

[978] World Bank, *Zero Routine Flaring by 2030, Initiative Endorsers* (*last visited* 5 February 2023) (List of endorsers).

[979] Global Gas Flaring Reduction Partnership (2022) 2022 GLOBAL GAS FLARING TRACKER REPORT, World Bank, 6 ("In 2021, the top 10 flaring countries (on an absolute volume basis) accounted for 75 percent of all gas flaring and 50 percent of global oil production. Seven of the top 10 flaring countries have held this position consistently for the last 10 years: Russia, Iraq, Iran, the United States, Venezuela, Algeria, and Nigeria. The remaining three; Mexico, Libya, and China, have shown significant flaring increases in recent years.").

[980] Climate & Clean Air Coalition Secretariat (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The World Bank launched the Global Methane Reduction Platform for Development (CH4D) to support low-and mid-income countries to realize the 'methane triple-wins' of abating emissions, enhancing resilience, and empowering livelihoods. Through partnerships, including with the CCAC Methane Roadmap Action Programme (M-RAP), CH4D will mobilize expertise, affordable technologies, and catalytic finance for methane abatement in the agriculture and waste sectors.").

[981] American Petroleum Institute (2023) *Methane Action Plan*, 1 ("6 actions industry is taking to tackle methane emissions through The Environmental Partnership's programs:

1. Reducing Flaring through facility design, takeaway capacity planning and alternative beneficial use. In 2022, there was a 14% reduction in total flare volumes and a 2.4% reduction in flare intensity from the previous year.
2. Replacing, Removing or Retrofitting High-bleed Pneumatic Controllers with low- or zero-emitting devices. Since the program started in 2017, more than 14,100 zero-emissions controllers have been installed and more than 114,000 gas-driven controllers have been replaced.
3. Monitoring Manual Liquids Unloading to minimize emissions by ensuring all wellhead vents are closed to atmosphere. In 2022, participants monitored more than 23,100 liquid unloading events.
4. Minimizing Compressor Emissions by implementing design and operation changes. In 2022, participants facilitated rod packing changes on more than 10,000 reciprocating compressors.
5. Detecting and Repairing Leaks through regular component inspections. In 2022, companies implemented detection and monitoring plans that resulted in a 0.07% leak occurrence rate (or less) across more than 202 million components at 157,000 sites.
6. Minimizing Pipeline Blowdown Emissions through operational changes prioritizing alternative beneficial use of gas that would otherwise be vented. In 2022, emission reduction practices were implemented during 3,600 pipeline blowdowns.").

[982]American Petroleum Institute (21 September 2023) *API Releases Methane Action Plan Highlighting Industry Actions, Key Policy Priorities for Effectively Reducing Methane Emissions*, Press Release ("Through The Environmental Partnership's focus on facility design, innovative technology, and operational practices, Partnership members are: Reducing flaring through facility design, takeaway capacity planning and alternative beneficial use. Replacing, removing or retrofitting high-bleed pneumatic controllers with low- or zero-emitting devices. Monitoring manual liquids unloading to minimize emissions by ensuring all wellhead vents are closed to atmosphere. Minimizing compressor emissions by implementing design and operation changes. Detecting and repairing leaks through regular

component inspections. Minimizing pipeline blowdown emissions through operational changes prioritizing alternative beneficial use of gas that would otherwise be vented.").

[983] Inagaki K. (17 July 2023) *Big LNG buyers and producers to tighten methane monitoring*, FINANCIAL TIMES ("Japan, the US, the EU, Australia and South Korea have agreed the creation of a mechanism for monitoring methane emissions that will bring together some of the world's largest buyers and producers of liquefied natural gas to combat global warming. People directly involved in the discussions said the public-private initiative would involve setting up a database of real-time methane pollution data on individual LNG projects, a move backers hope will accelerate the reduction of emissions of the potent global warming gas.").

[984] Inagaki K. (17 July 2023) *Big LNG buyers and producers to tighten methane monitoring*, FINANCIAL TIMES ("Japan, the US, the EU, Australia and South Korea have agreed the creation of a mechanism for monitoring methane emissions that will bring together some of the world's largest buyers and producers of liquefied natural gas to combat global warming. People directly involved in the discussions said the public-private initiative would involve setting up a database of real-time methane pollution data on individual LNG projects, a move backers hope will accelerate the reduction of emissions of the potent global warming gas.").

[985] Japan Ministry of Economy, Trade, and Industry (19 July 2023) *Joint Statement on Accelerating Methane Mitigation from the LNG Value Chain*, Press Release ("To support the Coalition, Japan and the European Commission expressed their vision to create a globally aligned methane emission assessment of LNG projects and to incentivize methane mitigation by LNG producers by facilitating the information collection process of methane leakage counter measures and methane reduction targets announced by LNG producers, moving toward collection of methane emissions and emissions intensity data at the cargo, portfolio, and operator level"). *See also JERA* (18 July 2023) *Launch of the methane emission reduction initiative (CLEAN) by KOGAS and JERA* ("Korea Gas Corporation ("KOGAS") and JERA Co., Inc. ("JERA") today launched an initiative of the "Coalition for LNG Emission Abatement toward Net-zero ("CLEAN")". CLEAN is an initiative taken by LNG buyers, together with LNG producers, to reduce methane emissions in the LNG value chain. In accordance with the Memorandum of Understanding regarding cooperation in the LNG Business concluded in April 2023, KOGAS and JERA as the world's largest LNG buyers, have confirmed that they will strengthen their strategic relationship and work to ensure a stable supply of energy for both Korea and Japan.").

[986] Japan Ministry of Economy, Trade, and Industry (19 July 2023) *Joint Statement on Accelerating Methane Mitigation from the LNG Value Chain*, Press Release ("Within Japan, JOGMEC will provide support mechanisms for LNG producers and consumers by creating an initiative that collects methane measures and best practices, complementing the work of other existing platforms such as the OGMP 2.0. Japan also resolved to provide support for accelerated methane measurement and mitigation by LNG producers, especially in Asian countries, by leveraging its expertise from ongoing support on emission assessment and reduction in gas and LNG projects.").

[987] Environmental Defense Fund (5 December 2023) *Leadership in Action: Global Food Corporations and Environmental Defense Fund Unite to Tackle Dairy Methane Emissions* ("Today, a historic group of global food companies, led by the Bel Group, Danone, General Mills, Kraft Heinz, Lactalis USA (a U.S. affiliate of Lactalis Group), and Nestlé was convened by Environmental Defense Fund to launch the Dairy Methane Action Alliance (DMAA). The Alliance was announced on stage at a COP Presidency event with company representatives and EDF president Fred Krupp. These leading food companies together represent more than $200 billion in revenue.").

[988] Douglas L. (5 December 2023) *COP28 summit: Global dairy companies join alliance to cut methane*, REUTERS ("The six members of the Dairy Methane Action Alliance - Danone (DANO.PA), Bel Group, General Mills (GIS.N), Lactalis USA, Kraft Heinz (KHC.O) and Nestle (NESN.S) - will begin reporting their methane emissions by mid-2024 and will write methane action plans by the end of that year.").

[989] Global Methane Initiative, *About the Global Methane Initiative* (*last visited* 5 February 2023) ("Launched in 2004, the GMI is an international public-private initiative that advances cost-effective, near-term methane abatement and recovery and use of methane as a clean energy source in three sectors: biogas (including agriculture, municipal solid waste, and wastewater), coal mines, and oil and gas systems. Focusing collective efforts on methane emission sources is a cost-effective approach to reduce greenhouse gas (GHG) emissions and increase energy security, enhance economic growth, improve air quality and improve worker safety.").

[990] Global Methane Initiative, *Partner Countries* (*last visited* 5 February 2023) ("GMI Partner Countries account for approximately 70 percent of global manmade methane emissions. These countries offer special expertise and interest in developing solutions for mitigating methane emissions and using methane as a renewable energy source. As members of the GMI, Partner Countries are encouraged to develop and submit to the Secretariat action planning documents that outline key country activities and priorities, and provide a mechanism to advance cooperation among Partners.").

[991] Global Methane Initiative, *GMI Fact Sheet* (*last visited* 26 January 2023) ("GMI Partner Countries account for approximately 70 percent of global manmade methane emissions. These countries offer special expertise and interest in developing solutions for mitigating methane emissions and using methane as a renewable energy source. As members of the GMI, Partner Countries are encouraged to develop and submit to the Secretariat action planning documents that outline key country activities and priorities, and provide a mechanism to advance cooperation among Partners.").

[992] Safety4Sea (17 March 2022) *Seven companies join the Methane Abatement in Maritime Innovation Initiative* ("The Methane Abatement in Maritime (MAM) Innovation Initiative, launched on September 6th, 2022 by a coalition of shipping leaders, aims to reduce the environmental impact of liquefied natural gas (LNG) in shipping while assisting the transition to future fuel solutions. MAMII's current members include Maran Gas Maritime, Mediterranean Shipping Company, Carnival Corporation & Plc, Seaspan Corporation, Shell, Lloyd's Register and Knutsen Group. New members of the MAMII include CoolCo, United Overseas Management, Capital Gas, Celsius Tankers, Global Meridian Holdings, Mitsui O.S.K. Lines, and TMS Cardiff Gas. Led by Safetytech Accelerator, MAMII was formed to identify, accelerate and advocate technology solutions for the maritime industry to measure and manage methane emissions activity. In doing so, it aims to minimize the environmental impact of liquefied natural gas (LNG) in shipping, whilst aiding the transition to future fuel solutions.").

[993] Manifold Times (28 February 2024) *Chevron, TotalEnergies, Seapeak join maritime methane reducing initiative* ("The three companies join the now more than 20 members of MAMII, emphasising its pivotal role in addressing methane abatement within the maritime sector. Chevron, a global energy company, Seapeak, an owner-operator of liquefied gas vessels, and TotalEnergies, the world's third largest LNG player, will bring their valuable insights and commitment to MAMII's mission: tackling the critical challenge of 'methane slip'. The initiative also announced that it has selected four providers to produce feasibility studies on the technologies which will reduce methane emissions from ships, with further details to be released soon.").

[994] Methane Guiding Principles, *The Methane Guiding Principles* (*last visited* 15 November 2023) ("1. Continually reduce methane emissions. … 2. Advance strong performance across the gas supply chain. … 3. Improve accuracy of methane emissions data. … 4. Advocate sound policy and regulations on methane emissions. … 5. Increase transparency."). Shell Corporation initiated the Methane Guiding Principles in 2017: *see* Shell (2019) *Shell Sustainability Report 2019* ("We encourage industry-wide action on methane emissions reduction by participating in a number of voluntary initiatives, including: the Methane Guiding Principles coalition, which we initiated in 2017."); *and* Methane Guiding Principles (30 November 2023) *The Methane Guiding Principles launches initiative supporting 20 countries on methane emissions reduction* ("The Methane Guiding Established in 2017, the MGP is a senior-executive-led methane coalition counting 50 members today. It focuses on five key areas of action to drive down methane emissions").

[995] Methane Guiding Principles, *Oil and Gas Sector Toolkit for the Global Methane Pledge* (*last visited* 3 February 2024) ("In line with the fourth Methane Guiding Principle, this Oil and Gas Sector Toolkit supports policy makers as they develop sound policy and regulation to drive down oil and gas methane emissions. Fulfilling the Global Methane Pledge will require widespread implementation efforts, including policies aimed at reducing flaring, venting and fugitive emissions. This toolkit connects policy makers and regulators to key resources and institutions supporting these policy efforts.").

[996] Methane Guiding Principles (4 December 2023) *Leading technical experts team up to help oil and gas companies meet OGDC methane emissions and flaring goals | Methane Guiding Principles* ("The International Association of Oil and Gas Producers (IOGP), Methane Guiding Principles (MGP), Oil and Gas Climate Initiative (OGCI) and Environmental Defense Fund (EDF) today announced their intention to build a framework to share expertise to help companies reduce methane emissions and flaring in line with the Oil & Gas Decarbonization Charter (OGDC) ambitions.").

[997] Methane Guiding Principles (30 November 2023) *The Methane Guiding Principles launches initiative supporting 20 countries on methane emissions reductions* ("The Methane Guiding Principles (MGP) launched the Advancing Global Methane Reduction (AGMR) initiative which aims to instigate and accelerate country-level methane emissions reductions.Under the AGMR, MGP members are currently working with governments and industry in 20 countries representing more than 25% of global oil and gas production, informing methane policies and regulations and disseminating best practice. The AGMR follows on the Oil and Gas sector toolkit for the Global Methane Pledge developed under the MGP in 2022. The toolkit connects policymakers and regulators with resources and institutions to support methane policy and regulation development in countries that joined the Global Methane Pledge.").

[998] Oil and Gas Climate Initiative, *About Us* (*last visited* 5 February 2023) ("OGCI member companies commit to: **Methane Intensity** -> By 2025, reduce the collective average methane intensity of aggregated upstream oil and gas operations to well below 0.20%, from a 2017 baseline of 0.30%. **Carbon Intensity** -> Reduce member companies' aggregate upstream carbon intensity from 23 kg of greenhouse gases per barrel of oil or gas in 2017 to 17 kg by 2025. **CCUS Kickstarter** -> By 2030, help to decarbonize multiple industrial hubs and kickstart a commercial CCUS industry that can have a significant impact on greenhouse gas emissions. **OGCI Climate Investments** -> Invest OGCI's $1B+ fund over a ten-year period to deliver a tangible impact on greenhouse gas emissions through accelerated innovation across the energy and industrial sectors. **Zero Routine Flaring** -> Support explicitly the aims of Zero Routine Flaring by 2030.").

[999] Oil and Gas Climate Initiative, *What OGCI is doing* (*last visited* 25 January 2023) ("OGCI launched the Aiming for Zero Methane Emissions Initiative in 2022 to encourage the whole industry to eliminate its methane footprint by 2030. Adopting a near zero methane emissions mindset has helped OGCI member companies to accelerate the pace of reduction using existing and emerging technologies. We met our initial 2025 upstream methane intensity target in 2020 and reached 0.17% in 2021. Absolute upstream methane emissions have fallen by 40% from 2017 to 2021.").

[1000] Aiming for Zero Methane Emissions Initiative, *About Us* (*last visited* 25 January 2023) ("The Aiming for Zero Methane Emissions Initiative aims to eliminate the oil and gas industry's methane footprint by 2030. It calls for an all-in approach that treats methane emissions as seriously as the oil and gas industry already treats safety: aiming for zero and striving to do what is needed to get there. Aiming for Zero acts as a complement for key initiatives such as the Methane Guiding Principles, the Oil and Gas Methane Partnership 2.0 and the Global Methane Alliance.").

[1001] Craft L. (9 June 2023) *OGCI Shifts Methane Focus from Location to Elimination*, Energy Intelligence ("Tackling methane emissions — and actually slashing them all the way down to zero — is the best opportunity for the industry to advance on its decarbonization goals, Oil and Gas Climate Initiative Chairman Bjorn Otto Sverdrup said Thursday.").

[1002] Oil and Gas Climate Initiative (2023) RECOMMENDED PRACTICES FOR METHANE EMISSIONS DETECTION AND QUANTIFICATION TECHNOLOGIES – UPSTREAM, 7 ("This document and an accompanying set of technology data sheets2 provide oil and gas operators with guidelines for selecting and deploying methane emissions detection and quantification technologies tailored to the situation at their sites, with the aim of improving upstream methane management and emissions reporting.").

[1003] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Oil and Gas Climate Initiative (OGCI) is expanding its Satellite Monitoring Campaign to provide actionable data to reduce emissions from large-magnitude methane plumes and flares, supported by in-kind contributions from OGCI companies. ExxonMobil also intends to provide up to $25 million in in-kind assistance to address capability shortcomings to reduce methane emissions.").

[1004] COP28 (2 December 2023) *Oil & Gas Decarbonization Charter launched to accelerate climate action* ("To date, 50 companies, representing more than 40 percent of global oil production have signed on to the OGDC, with National Oil Companies representing over 60 percent of signatories - the largest-ever number of NOCs to commit to a decarbonization initiative. COP28 President Dr. Sultan Al Jaber said, "The launch of the OGDC is a great first step - and whilst many national oil companies have adopted net-zero 2050 targets for the first time, I know that they and others, can and need to do more. We need the entire industry to keep 1.5C within reach and set even stronger ambitions for decarbonization." Signatories have committed to net-zero operations by 2050 at the latest, and ending routine flaring by 2030, and near-zero upstream methane emissions."). *See also* Puko T. (2 December 2023) *Oil companies' unexpected plan to tackle climate change*, WASHINGTON POST ("The unexpected pledge, which could be one of the most consequential results from the United Nations Climate Change Conference, or COP28, underscores the fossil fuel industry's profound influence at this year's talks in Dubai. Sultan Al Jaber — the Emirati oil executive leading COP28 — had pushed for the international pact as a way to demonstrate how petrostates and oil and gas companies can speed the transition to cleaner energy. The plan commits state-owned giants such as Saudi Aramco, along with corporate supermajors including ExxonMobil, to limit emissions of the climate superpollutant from their drilling and production work. It also includes international monitoring efforts intended to hold companies to their promises, and came out on the same day that U.S. officials announced new rules they say would limit methane emissions from the oil and gas industry by nearly 80 percent over the next 15 years.").

[1005] COP28 (2 December 2023) *Oil & Gas Decarbonization Charter launched to accelerate climate action* ("To date, 50 companies, representing more than 40 percent of global oil production have signed on to the OGDC, with National Oil Companies representing over 60 percent of signatories - the largest-ever number of NOCs to commit to a decarbonization initiative. COP28 President Dr. Sultan Al Jaber said, "The launch of the OGDC is a great first step - and whilst many national oil companies have adopted net-zero 2050 targets for the first time, I know that they and others, can and need to do more. We need the entire industry to keep 1.5C within reach and set even stronger ambitions for decarbonization." Signatories have committed to net-zero operations by 2050 at the latest, and ending routine flaring by 2030, and near-zero upstream methane emissions."). See also Gupte E. (2 December 2023) *COP28: Fifty oil and gas companies sign net zero, methane pledges*, S& P ("Some 50 oil and natural gas producers, including Saudi Aramco and 29 other national oil companies, have signed an agreement to reduce their carbon emissions to net zero by 2050 and curb methane emissions to near-zero by 2030, the COP presidency of the UN Climate Change Conference in Dubai said Dec. 2."). *See generally* (7 December 2023) *Big oil agrees to slash methane emissions*, THE ECONOMIST.

[1006] Oil Change International (1 December 2023) *Open Letter: The World Needs A Transformational Outcome, Not More Voluntary Pledges* ("By refusing to commit to address the emissions from oil and gas being burned and to end fossil fuel expansion, the proposed 'Global Decarbonization Accelerator' would serve as a smokescreen to hide the reality that we need to phase out oil, gas, and coal. Voluntary commitments are a dangerous distraction from what is needed at COP28. Oil and gas companies meeting to sign a pledge that only deals with their operational emissions is like a group of arsonists meeting to promise to light fires more efficiently.").

[1007] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Oil and Gas Methane Partnership 2.0 announced new members. The Partnership now represents over 120 companies with assets in more than 60 countries on five continents and covers over 35% of the world's oil and gas production and over 70% of LNG flows.").

[1008] United Nations Environment Programme (24 November 2020) *Oil and Gas Industry commits to new framework to monitor, report and reduce methane emissions*, Press Release ("Crucially, the OGMP 2.0 includes not only a company's own operations, but also the many joint ventures responsible for a substantial share of their production. The OGMP 2.0 framework applies to the full oil and gas value chain, not only upstream production, but also midstream transportation and downstream processing and refining – areas with substantial emissions potential that are often left out of reporting today.... In order to support the realization of global climate targets, OGMP 2.0 aims to deliver a 45 per cent reduction in the industry's methane emissions by 2025, and a 60-75 per cent reduction by 2030.").

[1009] Climate and & Clean Air Coalition (2020) *Oil and Gas Methane Partnership (OGMP) 2.0 Framework* ("To achieve 'gold standard', a company must demonstrate an explicit and credible path to the required reporting levels (according to 4.3.2) within the required period (according to 4.2.2 and 4.4). The path should be demonstrated through a multi-year plan that shows how the company plans to achieve these objectives. For clarity, 'gold standard' includes the credible path towards the agreed endpoint within the agreed timeline, rather than just the endpoint itself.")

[1010] European Commission (14 October 2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, 11 ("The Commission will deliver legislative proposals in 2021 on: • Compulsory measurement, reporting, and verification (MRV) for all energy related methane emissions, building on the Oil and Gas Methane Partnership (OGMP 2.0) methodology. • Obligation to improve leak detection and repair (LDAR) of leaks on all fossil gas infrastructure, as well as any other infrastructure that produces, transports or uses fossil gas, including as a feedstock. 7. The Commission will consider legislation on eliminating routine venting and flaring in the energy sector covering the full supply chain, up to the point of production. 8. The Commission will work to extend the OGMP framework to more companies in the gas and oil upstream, midstream and downstream as well as to the coal sector and closed as well as abandoned sites. 9. The Commission will promote remedial work under the initiative for Coal Regions in Transition. Best-practice recommendations and/or enabling legislation will be brought forward if necessary.").

[1011] United Nations Environment Programme (24 November 2020) *Oil and Gas Industry commits to new framework to monitor, report and reduce methane emissions*, Press Release ("Crucially, the OGMP 2.0 includes not only a company's own operations, but also the many joint ventures responsible for a substantial share of their production. The OGMP 2.0 framework applies to the full oil and gas value chain, not only upstream production, but also midstream transportation and downstream processing and refining – areas with substantial emissions potential that are often left out of reporting today.... In order to support the realization of global climate targets, OGMP 2.0 aims to deliver a 45 per cent reduction in the industry's methane emissions by 2025, and a 60-75 per cent reduction by 2030."). OGMP 2.0 signatories are expected to provide continually updated implementation plans showing continuous improvement in measurement, coverage, and technical guidelines. *See* Climate & Clean Air Coalition (2020) *Oil and Gas Methane Partnership (OGMP) 2.0 Framework* ("To achieve 'gold standard', a company must demonstrate an explicit and credible path to the required reporting levels (according to 4.3.2) within the required period (according to 4.2.2 and 4.4). The path should be demonstrated through a multi-year plan that shows how the company plans to achieve these objectives. For clarity, 'gold standard' includes the credible path towards the agreed endpoint within the agreed timeline, rather than just the endpoint itself.").

[1012] World Biogas Association, *What is our mission?* (*last visited* 5 February 2023) ("The World Biogas Association is the global trade association for the biogas, landfill gas and anaerobic digestion (AD) sectors, dedicated to facilitating the adoption of biogas globally. We believe that the global adoption of biogas technologies is a multi-faceted opportunity to produce clean, renewable energy while resolving global issues related to development, public health and economic growth. We seek to represent all organisations working in the biogas industry at the international level across the world, including; national associations, biogas operators and developers, equipment providers, water companies, the agricultural sector, waste companies, and academic & research institutions.").

[1013] World Biogas Association, *Membership benefits* (*last visited* 5 February 2023) ("At the same time we will support our industry members to take advantage of these growing markets through direct contact, our networking events and numerous publications. And continue to promote and develop industry standards, support best practice across all areas including health & safety and invest in research and innovation to ensure that we as an industry perform to the highest levels and deliver maximum value from the resources we process.").

[1014] World Biogas Summit, *2021 Programme* (*last visited* 5 February 2023).

[1015] World Biogas Association (29 November 2023) *No time to waste – World Biogas Association hosts side event at COP28 in Dubai on the role of the waste sector in delivering the Global Methane Pledge* ("No time to waste – World Biogas Association hosts side event at COP28 in Dubai on the role of the waste sector in delivering the Global Methane Pledge The global biogas trade body will host a COP28 official side event in partnership with the Climate and Clean Air Coalition (CCAC), the International Solid Waste Association (ISWA) and the Institute for Governance and Sustainable Development (IGSD)").

[1016] *See generally* Lackner M. & Mohlin K. (2022) *Certification of Natural Gas With Low Methane Emissions: Criteria for Credible Certification Programs*, Environmental Defense Fund; *and* Hmiel B., Lyon D. R., Warren J. D., Yu J., Cusworth D. H., Duren R. M., & Hamburg S. P. (2023) *Empirical quantification of methane emission intensity from oil and gas producers in the Permian basin*, ENVIRON. RES. LETT. 18(2): 024029. *See also* Ball J. (30 January 2023) *Inside the high-dollar race to sell natural gas as low-carbon*, CANARY MEDIA.

[1017] *See* The Payne Institute for Public Policy (30 May 2023) *MINES Responsible Gas: Glossay of Terminology related to Responsible Gas*.

[1018] MiQ, *Why Methane & Certification* (*last visited* 25 January 2023) ("We are already certifying 4% of the global gas market. Our aim is to differentiate all natural gas within the next decade.").

[1019] MiQ, *Welcome to the MiQ Registry* (*last visited* 25 January 2023) ("An MiQ Certificate represents the methane emissions performance attributes of 1 MMBtu of natural gas. Each certificate, which has a unique identifier, evidences where and when the gas was produced and the methane intensity of production. Unlike other frameworks that assess emissions at the national or company level, MiQ Certification is based on an independent Standard that is assessed at the facility or platform level. This more granular assessment by a third party provides transparent metrics for practically comparing gas supplies based on their methane emissions performance.").

[1020] MiQ, *What is the MiQ standard for operators* (*last visited* 25 January 2023) ("What requirements does MiQ's Standard look at? Methane Intensity – The MiQ Standard uses the Natural Gas Sustainability Initiative (NGSI) protocol for calculating the methane intensity of natural gas, or robust alternative methodologies. Company Practices – The MiQ Standard requires operators to deploy monitoring technology at source and facility level (bottom up and top down) to detect unintended methane emissions, specifying frequencies and minimum detection levels. Monitoring Technology – The MiQ Standard requires operators to deploy monitoring technology at source and facility level to detect unintended methane emissions. As the grading increases, operators will be required to implement best practices, leading to more robust methane emissions management.").

[1021] MiQ (2022) *Main Document – Onshore Production v1.0*, 15 (Table 2).

[1022] MiQ (8 June 2023) *MiQ-Highwood Index Reveals Up-to-Date, Measurement-Informed Estimate of U.S. Average Methane Intensity*, Press Release. *See also* Rutherford J., Romo J., Fox T., & Owens L. (2023) THE MIQ-HIGHWOOD

INDEXTM: A NATIONAL-SCALE MEASUREMENT- INFORMED METHANE INTENSITY FOR THE UNITED STATES, MiQ & Highwood Emissions Management.

[1023] https://www.equitableorigin.org/

[1024] Project Canary, *About* (*last visited* 3 February 2023); Project Canary, *TrustWell by Project Canary* (*last visited* 3 February 2023) ("TrustWell certifications evaluate the highest number of data points within 24 operational categories, including 12 dynamic scores for continuous performance improvement."). *See also* International Environmental Standards PBC (1 September 2020) *TrustWell Standard Definitional Document*.

[1025] American Gas Association, *Natural Gas Sustainability Initiative (NGSI)* (*last visited* 5 February 2023) ("NGSI is a voluntary, industry-wide approach for companies to calculate methane emissions intensity by segment—the Methane Emissions Intensity Protocol (Protocol). This consistent, transparent and comparable method for measuring and reporting methane emissions throughout the natural gas supply chain will improve the quality of information available and will help companies more effectively identify ways to reduce methane emissions and communicate progress.").

[1026] Project Canary, *About* (*last visited* 3 February 2023); Project Canary, *TrustWell by Project Canary* (*last visited* 3 February 2023) ("TrustWell certifications evaluate the highest number of data points within 24 operational categories, including 12 dynamic scores for continuous performance improvement."). *See also* International Environmental Standards PBC (1 September 2020) *TrustWell Standard Definitional Document*.

[1027] Project Canary, *Emissions Management* (*last visited* 3 February 2023).

[1028] Project Canary, *Measure and Reduce, Measured Total Site Emissions for Upstream Facilities: Operators Need Reportable Data & Actionable Insights* (*last visited* 3 February 2023) ("Our quantification model is underpinned by machine learning to measure total site emissions versus single emission events; We provide an accurate inventory of emissions generated by all sources on a pad, from consistent flux of small emissions off tanks, to the larger discrete emission events; Our model identifies offsite emissions and allows the user to choose whether to receive alerts on those or not; We track the cumulative effect of extremely short duration emissions sources, such as pneumatic releases.").

[1029] Project Canary, *Environmental Assessments* (*last visited* 3 February 2023).

[1030] Project Canary & Colorado State University Center for Energy Water Sustainability (24 August 2021) *Certification of Freshwater Resource Use as Part of a Responsibly Sourced Gas ESG Strategy*. *See also* Project Canary, *Environmental Assessments* (*last visited* 3 February 2023).

[1031] *See* Project Canary, *Emissions Management* (*last visited* 3 February 2023); Project Canary, *Sensing Devices* (*last visited* 3 February 2023); *and* Project Canary (8 November 2022) *Seize the Methane Moment* ("We believe you can't improve what you don't measure. Today, our Canary X/ monitors, software and analytics measure, visualize, and quantify methane. We are also evolving our innovative platform to aggregate and analyze data from other sensors, including aerial devices. Our customers now have more sensor options to choose from to help impact climate change positively, while future-proofing their methane detection and quantification strategies. Our Aeris by Project Canary line of infrared spectrum monitors can measure methane and ethane to differentiate between biogenic and thermogenic methane in real time, ethylene oxide, formaldehyde, and numerous other hazardous air sources pollutants. These same monitors, coupled with Project Canary's models and analytics, can tune carbon dioxide measurements down to 2 parts per trillion (PPT). In the new Canary portal, multiple sensor data sources can be reconciled, giving operators more choices about sensor types and deployment. A comprehensive set of technologies (both hardware and software) will be needed to make a lasting impact on the world around us.).

[1032] Project Canary (24 August 2022) *Kellas Midstream Installs Project Canary Continuous Emissions Monitoring at Teesside CATS Terminal, Showcasing Peer-Leading ESG Commitment* ("Kellas Midstream, the BlackRock and GIC backed company responsible for transporting 40 percent of the U.K.'s domestic gas production, announced today that it has deployed continuous emissions monitoring at its Teesside Central Area Transmission System (CATS) terminal in partnership with Project Canary®, a U.S.-based SaaS-focused ESG data analytics firm. The ultra-sensitive Canary sensors have been installed at multiple points around CATS to precisely detect, monitor, and measure methane emissions at the site level in real-time.").

[1033] For a recently-published guide for journalists on covering methane and investigating specific sources, *see* McIntosh T. (6 February 2022) *GIJN's Guide to Investigating Methane — A Key to Fighting Climate Change*, GLOBAL INVESTIGATIVE JOURNALISM NETWORK. *See also* Francis D., Weston M., Fonseca R., Temimi M., & Alsuwaidi A. (2023) *Trends and variability in methane concentrations over the Southeastern Arabian Peninsula*, FRONT. ENVIRON. SCI. 11: 1–17, 14 ("Policy and procedures to reduce emissions through mitigation and adaptation. Ground-based CH4 measurements, collected through a dense network of surface observations, and higher spatial and temporal resolution satellite products are needed to identify the major sources and further our understanding of the processes behind the observed CH4 variability in the region.").

[1034] For an overview of new measurement techniques and technologies in the oil and gas sector, *see generally* Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development.

[1035] Lee M. (25 October 2021) *The key for EPA rules? Inside the methane tech revolution*, E&E NEWS ("The laboratory, known as the Methane Emissions Technology Evaluation Center (METEC), was built five years ago at Colorado State University with a grant from the Energy Department. It has since become a central player in a boom of methane detection companies — a surge being driven partly by corporate pressure to cut emissions and looming EPA regulations. In the past four years, the number of such firms has doubled, with many testing their specialized drones and cutting-edge sensors on staged gas releases at METEC.").

[1036] *For example, see* Clarke A. (29 September 2023) *The Climate Sleuth Uncovering Methane Leaks for the United Nations*, BLOOMBERG ("The 27-year-old Ph.D. student isn't a detective but she may be the closest thing the world has to climate police. She's one of the world's foremost remote sensing scientists who uses satellite observations to identify some of the most damaging emissions.").

[1037] Duran R. (2021) *Towards a multi-scale methane monitoring system of systems* (Carbon Mapper presentation at Day 2 of U.S. EPA Methane Detection Technology Workshop on August 24, 2021, starting at 5:05:00).

[1038] Schlingler R. (15 April 2021) *Carbon Mapper launches satellite program to pinpoint methane and CO_2 super emitters*, PLANET ("Carbon Mapper, a new nonprofit organization, and its partners – the State of California, NASA's Jet Propulsion Laboratory (NASA JPL), Planet, the University of Arizona, Arizona State University (ASU), High Tide Foundation and RMI – announced a pioneering program to help improve understanding of and accelerate reductions in global methane and carbon dioxide (CO_2) emissions. In addition, the Carbon Mapper consortium announced its plan to deploy a ground-breaking hyperspectral satellite constellation with the ability to pinpoint, quantify and track point-source methane and CO_2 emissions.").

[1039] Carbon Mapper (14 September 2023) *Road to Launch: The Carbon Mapper Coalition achieves key satellite milestones* ("While these milestones are an exciting step on our journey to develop and deploy the first two Carbon Mapper Coalition satellites, we now turn efforts toward integrating the instrument with the satellite bus this fall and preparing for launch, targeting early 2024.").

[1040] Schlingler R. (15 April 2021) *Carbon Mapper launches satellite program to pinpoint methane and CO_2 super emitters*, PLANET ("Carbon Mapper, in collaboration with its public and private partners, is developing the satellite constellation in three phases. The initial study phase is complete and included two years of preliminary engineering development and manufacturing. Phase 1 is underway and includes development of the first two satellites by Planet and NASA JPL, planned to launch in 2023, accompanying data processing platforms, and ongoing cooperative methane mitigation pilot projects using aircraft in California and other US states. Phase 2, which is in development, would encompass the expansion to an operational multi-satellite constellation starting in 2025.").

[1041] Carbon Mapper Data Portal (*last visited* 4 February 2023).

[1042] Carbon Mapper, *Carbon Mapper Launches New Initiative to Guide Global Action on Solid Waste Methane Emissions Thanks to $8M Commitment from the Grantham Foundation* (*last visited* 4 February 2023).

[1043] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial*, ("Further Progress in Collecting and Disseminating Actionable Methane Data, including the release of a beta version of IMEO's Methane Data Platform, which integrates data from dozens of public Earth observing satellites, the launch of complementary efforts like new United States Greenhouse Gas Center, and MethaneSAT and Carbon Mapper announcing plans for satellite launches in 2024.").

[1044] Copernicus, *About Copernicus* (*last visited* 5 February 2023) ("Copernicus is the European Union's Earth observation programme, looking at our planet and its environment to benefit all European citizens. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data.").

[1045] Copernicus, *About Copernicus* (*last visited* 5 February 2023) ("The European Commission manages the Programme. It is implemented in partnership with the Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), EU Agencies and Mercator Océan.").

[1046] Copernicus, *Copernicus in detail* (*last visited* 5 February 2023) ("Copernicus is served by a set of dedicated satellites (the Sentinel families) and contributing missions (existing commercial and public satellites). The Sentinel satellites are specifically designed to meet the needs of the Copernicus services and their users. Since the launch of Sentinel-1A in 2014, the European Union set in motion a process to place a constellation of almost 20 more satellites in orbit before 2030.").

[1047] Copernicus, *Atmosphere* (*last visited* 5 February 2023) ("The service focuses on five main areas: 1. Air quality and atmospheric composition; 2. Ozone layer and ultra-violet radiation; 3. Emissions and surface fluxes; 4. Solar radiation; 5. Climate forcing.").

[1048] Copernicus, *Land* (*last visited* 5 February 2023) ("It supports applications in a variety of domains such as spatial and urban planning, forest management, water management, agriculture and food security, nature conservation and restoration, rural development, ecosystem accounting and mitigation/adaptation to climate change.").

[1049] Copernicus, *Climate Change* (*last visited* 5 February 2023) ("The C3S mission is to support adaptation and mitigation policies of the European Union by providing consistent and authoritative information about climate change. We offer free and open access to climate data and tools based on the best available science. We listen to our users and endeavour to help them meet their goals in dealing with the impacts of climate change.").

[1050] Climate Trace, *Our Vision* (*last visited* 7 February 2024) ("Climate TRACE is a non-profit coalition of organizations building a timely, open, and accessible inventory of exactly where greenhouse gas emissions are coming from.").

[1051] Climate Trace, *Approach* (*last visited* 7 February 2024) ("We use satellites, other remote sensing techniques, and artificial intelligence to deliver a detailed look at global emissions that gets even better over time."). *See also* Gordan D. (24 January 2024) *From Global to Local: Climate TRACE Helps Prioritize Emissions Reductions from the Oil and Gas Industry*, ROCKY MOUNTAIN INSTITUTE ("There is increasing urgency to immediately address the climate impacts of oil and gas, a major yet easy-to-abate source of methane worldwide. Following a year of mounting climate catastrophes, methane — and especially methane satellite data — took center stage in shaping COP28 negotiations. Improved inventories and advances in emissions monitoring are playing a growing and important role in making emissions visible and actionable. Climate TRACE is a perfect example. At COP28, Climate TRACE unveiled updates to its open emissions database — an inventory that includes every country and territory in the world, every major sector of the economy, and nearly every major source of greenhouse gas emissions encompassing more than 352 million assets.").

[1052] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial*, ("Launch of the Data to Methane Action Campaign. The Global Methane Hub, in collaboration with IMEO and its partners, launched a Campaign to comprehensively deliver increased funding to enable governments, businesses, and other actors to radically reduce methane emissions, including harmful leaks, and drive effective policy change through never-before-leveraged data. At COP28, the Global Methane Hub announced $10 million in seed funding toward the Campaign and a funding target of $300 million by COP29.").

[1053] National Aeronautics and Space Administration Jet Propulsion Laboratory (25 October 2022) *Methane 'Super-Emitters' Mapped by NASA's New Earth Space Mission* ("NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission is mapping the prevalence of key minerals in the planet's dust-producing deserts – information that will advance our understanding of airborne dust's effects on climate. But EMIT has demonstrated another crucial capability: detecting the presence of methane, a potent greenhouse gas.").

[1054] Thorpe A. K., *et al*. (2023) *Attribution of individual methane and carbon dioxide emission sources using EMIT observations from space*, SCI. ADV. 9(46): 1–13, 7 ("Compared to airborne results (AVIRIS-NG and GAO) across a number of regions in the United States, the EMIT distribution is shifted to larger emissions. This is expected both because EMIT is observing a class of emissions far larger than those seen in U.S. airborne surveys and because EMIT is less sensitive to smaller emission rates due to the coarser spatial resolution. … The total EMIT detected emissions by sector is shown in Fig. 6B, with 88.7% from oil and gas (63.5% upstream, 24.3% midstream, and 0.9% downstream). Emissions from the waste sector represent 8.6% of total observed emissions, including examples from 11 landfills and one wastewater treatment facility (Fig. 2C). … Emissions can be quantified and attributed to specific sectors, which is particularly important when multiple emissions from different sectors are present in close proximity (Fig. 3). We highlight the first examples of EMIT imaging spectrometer observations of methane and carbon dioxide emissions from sources spanning the oil and gas (upstream, midstream, and downstream), waste (landfill and wastewater treatment), and energy sectors (power plant).").

[1055] National Aeronotics and Space Administration Jet Propulsion Laboratory (25 October 2022) *Methane 'Super-Emitters' Mapped by NASA's New Earth Space Mission* ("In the data EMIT has collected since being installed on the International Space Station in July, the science team has identified more than 50 "super-emitters" in Central Asia, the Middle East, and the Southwestern United States. Super-emitters are facilities, equipment, and other infrastructure, typically in the fossil-fuel, waste, or agriculture sectors, that emit methane at high rates.").

[1056] National Aeronautics and Space Administration Jet Propulsion Laboratory (25 October 2022) *Methane 'Super-Emitters' Mapped by NASA's New Earth Space Mission* ("EMIT's methane observations came as scientists verified the accuracy of the imaging spectrometer's mineral data. Over its mission, EMIT will collect measurements of surface minerals in arid regions of Africa, Asia, North and South America, and Australia. The data will help researchers better understand airborne dust particles' role in heating and cooling Earth's atmosphere and surface. … With wide, repeated coverage from its vantage point on the space station, EMIT will potentially find hundreds of super-emitters – some of them previously spotted through air-, space-, or ground-based measurement, and others that were unknown.").

[1057] Thorpe A. K., *et al*. (2023) *Attribution of individual methane and carbon dioxide emission sources using EMIT observations from space*, SCI. ADV. 9(46): 1–13, 8 ("Building on the design heritage and capabilities of the EMIT instrument, the JPL as part of the Carbon Mapper Coalition is supporting the launch of the first two satellites equipped with a JPL-developed imaging spectrometer in late 2023. Those instruments will feature an improved 5-nm spectral sampling and finer spatial resolution (30 m) and will be hosted on Planet Labs' satellites, offering target tracking (higher effective SNR) in noon-crossing sunsynchronous orbits, resulting in greater sensitivity for methane and carbon dioxide point source emissions. Combining measurements obtained from different instruments improves global coverage and revisit frequency, which is critical to improving understanding of global emissions and informing mitigation strategies. To this end, the EMIT greenhouse gas applications online mapping tool (https://earth.jpl.nasa.gov/data/data-portal/ Greenhouse-Gases) will facilitate the distribution of scientific findings in support of NASA's Open Source Science Initiative.").

[1058] MethaneSAT, *Purpose* (*last visited* 9 March 2024) ("MethaneSAT will located and quantify methane emissions from oil and gas operations almost anywhere on Earth and track progress over time. The free data will enable both companies and countries to identify, manage and reduce their emissions, and allow investors, gas buyers and the public to see and compare results."). Google Cloud will provide computing capabilities to process the information and create a map of oil and gas infrastructure to be used with the MethaneSAT DATA. *See* Google Sustainability (14 February 2024) *How satellites, algorithms and AI can help map and trace methane sources* ("EDF's new satellite, MethaneSAT, will map, measure and track methane with unprecedented precision, offering a comprehensive view of methane emissions. Launching in early March on a SpaceX Falcon 9 rocket, MethaneSAT will orbit the Earth 15 times a day at an altitude of over 350 miles. It will measure methane levels in the top oil and gas regions in the world for regular analysis. MethaneSAT is highly sophisticated; it has a unique ability to monitor both high-emitting methane sources and small sources spread over a wide area. To calculate the amount of methane emitted in specific places and track those emissions over time, EDF developed algorithms powered by Google Cloud in collaboration with scientists at Harvard University's School of Engineering and Applied Science and its Center for Astrophysics, and scientists at the Smithsonian Astrophysical Observatory.").).

[1059] spaceQ (9 September 2019) *GHGSat Signs Data Agreement with the Canadian Space Agency and the European Space Agency* ("The deal will see GHGSat providing 5% of the GHGSat-C1 Iris satellite imaging capacity for free. The CSA and ESA will use that capacity for remote sensing, climate research, and data validation projects according to a GHGSat Tweet.").

[1060] European Space Agency (3 November 2021) *ESA and GHGSat support new International Methane Emissions Observatory* ("The new initiative builds on the success of long-term and evolving data-sharing partnership between ESA and GHGSat, through the Canada–ESA Cooperation Agreement. Having proved the concept of high-resolution emissions monitoring from space, GHGSat launched its commercial constellation in 2019, rapidly building its capability and data archive. A Memorandum of Intent, between ESA, the Canadian Space Agency and GHGSat was signed that same year, with the aim of stimulating scientific uptake of this unique dataset.").

[1061] (4 May 2022) *Methane from cow burps seen from space for the first time*, NEWSROUND ("The researchers at GHG Sat decided to use satellite technology to accurately measure the levels of methane produced by farms - because previously it has been difficult to do. Looking at their results, the scientists found the amount of methane released at the farm they studied in Joaquin Valley was between 361 to 668 kilogrammes per hour. GHGSat share their findings with the United Nation's International Methane Emissions Observatory programme (IMEO). The hope is that this information can be used to help set official targets to limit the amount of methane produced. The company is aiming to put around 10 satellites into orbit by next year to help continue their research."). *See also* GHGSat.com.

[1062] Maasakkers J. D., Varon D. J., Elfarsdóttir A., McKeever J., Jervis D., Mahapatra G., Pandey S. Lorente A., Borsdorff T., Foothuis L. R., Schuit B. J., Tol P., van Kempen T. A., van Hees R., & Aben I. (2022) *Using satellites to uncover large methane emissions from landfills*, SCI. ADV. 8(32): 1–8, 1 ("We use the global surveying

Tropospheric Monitoring Instrument (TROPOMI) to identify large emission hot spots and then zoom in with high-resolution target-mode observations from the GHGSat instrument suite to identify the responsible facilities and characterize their emissions. Using this approach, we detect and analyze strongly emitting landfills (3 to 29 t hour^{-1}) in Buenos Aires, Delhi, Lahore, and Mumbai. Using TROPOMI data in an inversion, we find that city-level emissions are 1.4 to 2.6 times larger than reported in commonly used emission inventories and that the landfills contribute 6 to 50% of those emissions. Our work demonstrates how complementary satellites enable global detection, identification, and monitoring of methane superemitters at the facility level."); *discussed in* Dickie G. (11 August 2022) *Landfills around the world release a lot of methane - study*, REUTERS.

[1063] GHGSat (5 December 2023) *GHGSat Signs Strategic Partnership With Yahsat and ADNOC Supporting the Mitigation of Global Energy Sector's Methane Emissions*, NEWSWIRE ("GHGSat, the global leader in emissions monitoring with satellites, today announced a strategic collaboration with Al Yah Satellite Communications Company (ADX: YAHSAT) and Abu Dhabi National Oil Company (ADNOC), aimed at reducing methane emissions from the global energy sector.The three entities signed a Memorandum of Understanding (MoU) during the Canada-UAE Future Energy Forum, organized by the Canada UAE Business Council in Dubai on 5th December. The new strategic partnership has also been selected by the COP28 Energy Transition team as a Lighthouse Project due to its ambitious scope and potential to reduce climate change.").

[1064] GOSAT Project, *Home* (*last visited* 7 February 2024) ("The Greenhouse Gases Observing Satellite "IBUKI" (GOSAT) is the world's first spacecraft to measure the concentrations of carbon dioxide and methane, the two major greenhouse gases, from space. The spacecraft was launched successfully on January 23, 2009, and has been operating properly since then. Through analyzing the GOSAT observational data, scientists will be able to ascertain the global distribution of carbon dioxide (CO2) and methane (CH4), and how the sources and sinks of these gases vary with seasons, years, and locations. These new findings will enhance scientific understanding on the causes of global warming. Also, they will serve as fundamental information for improving climate change prediction and establishing sound plans for mitigating global warming. The GOSAT Project is a joint effort of the Ministry of the Environment (MOE), the National Institute for Environmental Studies (NIES), and the Japan Aerospace Exploration Agency (JAXA).").

[1065] GOSAT Project, *Home* (*last visited* 7 February 2024) ("The Greenhouse Gases Observing Satellite "IBUKI" (GOSAT) is the world's first spacecraft to measure the concentrations of carbon dioxide and methane, the two major greenhouse gases, from space. The spacecraft was launched successfully on January 23, 2009, and has been operating properly since then. Through analyzing the GOSAT observational data, scientists will be able to ascertain the global distribution of carbon dioxide (CO2) and methane (CH4), and how the sources and sinks of these gases vary with seasons, years, and locations. These new findings will enhance scientific understanding on the causes of global warming. Also, they will serve as fundamental information for improving climate change prediction and establishing sound plans for mitigating global warming. The GOSAT Project is a joint effort of the Ministry of the Environment (MOE), the National Institute for Environmental Studies (NIES), and the Japan Aerospace Exploration Agency (JAXA).").

[1066] International Energy Forum, *IEF Methane Initiative: Methane Measurement Methodology Project* (*last visited* 5 February 2023) (The International Energy Forum (IEF) launched the IEF Methane Initiative in June 2021 to develop a methane emissions measurement methodology, enabling its member countries to collect standardized data to mitigate methane emissions from the energy industry and address its share of climate change goals.").

[1067] International Energy Forum, *IEF Methane Initiative: Methane Measurement Methodology Project* (*last visited* 5 February 2023) ("Experts estimate that currently reported methane emissions are about 10 percent of what is observed by satellite. The new methodology will allow IEF member countries to consider the best available data on methane emissions, define their historical methane baseline and set mitigation goals in a transparent and consistent manner. With these targets, IEF members would be able to present credible plans for reducing their countries' methane emissions in their Nationally Determined Contributions (NDC) ahead of the 26th UN Climate Change Conference of the Parties (COP26) in November 2021.").

[1068] United Nations Environment Programme (2021) *An Eye on Methane: International Methane Emissions Observatory 2021* Report, VI ("IMEO's Theory of Change - IMEO has a clear proposition to catalyze change in the reality of the political economy. At the heart of IMEO's Theory of Change is the need for an independent and trusted entity to integrate data from multiple sources, such as companies, satellites, scientific studies and national inventories. Using scientific insights, IMEO will integrate these multiple sources of heterogeneous data into a coherent and policy relevant dataset that highlights the confidence of each data element.").

[1069] United Nations Environment Programme (31 October 2021) *Methane Observatory launched to boost action on powerful climate-warming gas*, Press Release ("IMEO will improve the reporting accuracy and public transparency of human-caused methane emissions. IMEO will initially focus on methane emissions from the fossil fuel sector, and then expand to other major emitting sectors like agriculture and waste.").

[1070] United Nations Environment Programme (31 October 2021) *Methane Observatory launched to boost action on powerful climate-warming gas*, Press Release ("IMEO will provide the means to prioritize actions and monitor commitments made by state actors in the Global Methane Pledge – a US- and EU-led effort by over thirty countries to slash methane emissions by 30 per cent by 2030.").

[1071] United Nations Environment Programme, *International Methane Emissions Observatory* (*last visited* 5 February 2023) ("Launched at the G20 Summit, the International Methane Emissions Observatory (IMEO) is a data-driven, action-focused initiative by the UN Environment Programme (UNEP) with support from the European Commission to catalyse dramatic reduction of methane emissions, starting with the energy sector.").

[1072] United Nations Environment Programme (31 October 2021) *Methane Observatory launched to boost action on powerful climate-warming gas*, Press Release ("Critical to this effort are data collected through OGMP 2.0, launched in November 2020 in the framework of the Climate and Clean Air Coalition. OGMP 2.0 is the only comprehensive, measurement-based reporting framework for the oil and gas sector, and its 74 member companies represent many of the world's largest operators across the entire value chain, with assets that account for over 30 per cent of all oil and gas production.").

[1073] *See generally* United Nations Environment Programme (2021) AN EYE ON METHANE: INTERNATIONAL METHANE EMISSIONS OBSERVATORY 2021 REPORT; United Nations Environment Programme (2022) AN EYE ON METHANE: INTERNATIONAL METHANE EMISSIONS OBSERVATORY 2022 REPORT; *and* United Nations Environment Programme (2023) AN EYE ON METHANE: INTERNATIONAL METHANE EMISSIONS OBSERVATORY 2022 REPORT.

[1074] United States Department of State (17 November 2022) *Fact Sheet, Global Methane Pledge: From Moment to Momentum* (describing progress on the Global Methane Pledge Energy Pathway).

[1075] Kayrros Methane Watch, *FAQ* (*last visited* 18 December 2023) ("Our primary collaboration is with the UNEP's International Methane Emission Observatory (IMEO), where we serve as a key data provider for the Methane Alert and Response System (MARS)"). *See also* Kayrros Methane Watch, *Kayrros Methane Watch* (*last visited* 18 December 2023) ("Access consolidated data from multiple satellite constellations into a single platform, allowing you to access real-time insights and make informed decisions.").

[1076] United Nations Environment Programme, *MARS* (*last visited* 2 December 2023) ("UNEP's International Methane Emissions Observatory launched the Methane Alert and Response System (MARS) at COP27, a new initiative to accelerate implementation of the Global Methane Pledge by transparently scaling up global efforts to detect and act on major methane emissions sources. At COP28 results of the MARS pilot period have gone live, publicly sharing satellite data for notified emissions events.").

[1077] Clarke A. (1 December 2023) *Methane Leak in Argentina Halted After Satellite Observation*, BLOOMBERG ("Scientists working for the United Nations' International Methane Emissions Observatory in March spotted a leak in satellite data in Argentina, and relayed that information to government officials who quickly shared the data with the responsible operator. The energy company, which wasn't identified, found that a heat exchanger had suffered ruptured tubes causing the potent greenhouse gas to leak and quickly conducted repairs. "This is the first example of how we really can make this data actionable,'' Manfredi Caltagirone, the head of IMEO, said in an interview referring to a new wave of satellites that are allowing scientists to track global methane emissions. "It's just the first of what we expect is going to be many use cases that this data and these capabilities will be giving us.'').

[1078] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("Continued Progress on Methane Data Science, including IMEO's support for 34 new science studies to fill existing knowledge gaps about the location and magnitude of emissions, including the first scientific measurement campaigns in Sub-Saharan Africa (Angola and Gabon) and the Middle East (Oman).").

[1079] Gordon D., Koomey J., Brandt A., & Bergerson J. (2022) *Know Your Oil and Gas: Generating Climate Intelligence to Cut Petroleum Industry Emissions*, ROCKY MOUNTAIN INSTITUTE, 8–9 ("The OCI+ model offers a way forward. This life-cycle assessment model was first unveiled in 2015 by the Carnegie Endowment. The OCI+ has since received significant attention and use by governments, industry, nongovernmental organizations, and academics.[ii] The OCI+ offers an alternative to opaque and overly simplistic emissions assessments done by countries and companies using equipment counts and basic emissions factors. Instead, the OCI+'s suite of advanced models, together with operational inputs and satellite data, estimates GHG emissions through the entire oil and gas supply chain. Emissions intensities can be parsed in different ways—by resource category, region, operation, pollutant, and more—to identify significant reduction potential."). Access the Oil Climate Index plus Gas tool at: ociplus.rmi.org.

[1080] Malik N. S. (23 June 2022) *World's Dirtiest Oil and Gas Fields Are in Russia, Turkmenistan and Texas*, BLOOMBERG (Created by researchers at RMI, Stanford University, the University of Calgary and Koomey Analytics, the OCI+ tool and an accompanying report conclude that significant fossil-fuel emissions occur not just at the point of combustion, but directly at the wellhead and during processing, refining, and transportation.").

[1081] Malik N. S. (23 June 2022) *World's Dirtiest Oil and Gas Fields Are in Russia, Turkmenistan and Texas*, BLOOMBERG ("Methane, a greenhouse gas that is the primary component of natural gas and a powerful global warming agent, accounts for more than half of operational emissions at sites worldwide. Curbing the flaring and venting of the gas and ensuring that oil-field equipment is working properly can help significantly reduce upstream emissions, the report says, calling methane reductions 'the highest priority for the oil and gas sector.'").

[1082] Gordan D., Kornbluh E., Huffman M., Marchan E., & Conway T. J. (2023) NEW CLIMATE TOOLS FOR FINANCIAL INSTITUTIONS: METHANE DATA TRANSPARENCY FOR TARGETED INVESTMENTS, ROCKY MOUNTAIN INSTITUTE, 2 ("Banks and other financial institutions (FIs) have an opportunity to leverage emissions models and detection and measurement technologies to inform near-term investment decisions that reduce methane in their energy portfolios. This is part of FIs' broader strategy to transition oil and gas portfolios in line with climate goals. Methane is a highly potent greenhouse gas (GHG) that is routinely emitted by the oil and gas industry, which accounts for an estimated one-half of their corporate GHG emissions. Yet, equivalent barrels of oil and gas have wide-ranging methane emissions. Combining asset-level emissions modeling — using publicly available, peer-reviewed tools such as RMI's Oil Climate Index plus Gas (OCI+) — with top-down emissions detection via satellites and aircraft offers climate intelligence to pinpoint methane hot spots and mitigate leakage.").

[1083] Dooren J. M. (4 December 2023) *NASA, Partners Launch US Greenhouse Gas Center to Share Climate Data*, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION ("The U.S. Greenhouse Gas Center will serve as a hub for collaboration between agencies across the U.S. government as well as non-profit and private sector partners. Data, information, and computer models from observations from the International Space Station, various satellite and airborne missions, and ground stations are available online. As the lead implementing agency of the center, NASA partnered with the EPA, National Institute of Standards and Technology, and National Oceanic and Atmospheric Administration. Science experts from each of these U.S. federal agencies curated this catalog of greenhouse gas datasets and analysis tools."). *See generally* *U.S. Greenhouse Gas Center* (*last visited* 5 December 2023).

[1084] National Aeronautics and Space Administration (4 December 2023) *NASA, Partners Launch US Greenhouse Gas Center to Share Climate Data* ("The center's data catalog includes a curated collection of data sets that provide insights into greenhouse gas sources, sinks, emissions, and fluxes.").

[1085] National Aeronautics and Space Administration (4 December 2023) *NASA, Partners Launch US Greenhouse Gas Center to Share Climate Data* ("The center's data catalog includes a curated collection of data sets that provide insights into greenhouse gas sources, sinks, emissions, and fluxes. Initial information in the center website is focused on three areas: Estimates of greenhouse gas emissions from human activities. Naturally occurring greenhouse gas sources and sinks on land and in the ocean. Large methane emission event identification and quantification, leveraging aircraft and space-based data.").

[1086] GTI Energy, *GTI Energy's Methane Emissions Measurement and Verification Initiative* (*last visited* 3 November 2023) ("Veritas, GTI Energy's Methane Emissions Measurement and Verification Initiative, is meeting the urgent need for credible, comparable methane emissions measurement and accelerating actions that reduce methane emissions reductions. The standardized, science-based, technology-neutral, and measurement-informed protocols were built to assemble methane emissions inventories that are verified by direct field measurements.").

[1087] Moore C., Weller Z., Blanton E., Rai S., Harmon A., Van Wagener D., Merino Guerrero M., Salahshoor S., Wong H. X., Harrison M., Rufael T., Van Horne J., Shumlich J., & Fox T. (2023) *Veritas Demonstrations: Results, Challenges, and Implications for Creation of Measurement Informed Inventories Veritas*, GTI Energy, 1 ("The Veritas protocols provide a guiding framework for operators across the natural gas supply chain to use measurements to estimate their methane emissions. As part of protocol development, 14 operators from across the natural gas supply chain participated in pilot demonstrations of the protocols in 2022. These operators executed draft versions of the protocols to examine their expected emissions and deploy a variety of detection and quantification technologies, from handheld instruments to aircraft surveys.").

[1088] Waste MAP, *About WasteMAP* (*last visited* 30 January 2024) ("The Waste Methane Assessment Platform, or WasteMAP, was created by RMI and Clean Air Task Force, with funding from the Global Methane Hub, to improve waste methane emissions transparency, highlight mitigation opportunities and best practices to reduce solid waste methane emissions.").

[1089] Waste MAP, *About WasteMAP* (*last visited* 30 January 2024) ("WasteMAP consolidates modeled and reported waste data and methane emissions data from Carbon Mapper, Climate TRACE, EDGAR, RMI, SRON, UNFCCC, UN-Habitat, and the World Bank. You can learn more on the data and methodologies page.").

[1090] Waste MAP, *Data and Methodology*, (*last visited* 30 January 2024) ("One unique feature of WasteMAP is the decision support tool (DST), which allows users to estimate baseline methane emissions from current waste management practices in a given city and project alternative methane emission scenarios with improved waste management practices. The DST is a step forward on emissions data transparency, because it enables users to uncover the material impact of certain waste management practices on methane emissions mitigation. This extra know-how makes it possible for users to translate emissions transparency into actionable policies and practices that lead to emissions mitigation.").

[1091] National Academies of Sciences, Engineering, and Medicine (2022) GREENHOUSE GAS EMISSIONS INFORMATION FOR DECISION MAKING: A FRAMEWORK GOING FORWARD, The National Academies Press, 4 ("As more GHG emissions information becomes available and as more decision makers use this information, a common evaluation framework can help users determine what information products best meet their needs and understand the limitations of that information. A common framework can also provide guidance to researchers for designing more useful and trusted data and information. The Committee has identified six criteria or "pillars" that form a common framework to evaluate current and future GHG emissions information: 1. usability and timeliness: information is comparable and responsive to decision maker needs and available on timescales relevant to decision-making; 2. information transparency: information is both publicly available and traceable by anyone; 3. evaluation and validation: review, assessment, and comparison to independent datasets; 4. completeness: comprehensive spatial and temporal coverage of GHG emissions information; 5. inclusivity: who is involved in GHG emissions information creation and who is covered by the information; and 6. communication: methodologies and assumptions are described in understandable forms, well documented, and openly accessible.").

[1092] Intergovernmental Panel on Climate Change (2021) CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 (This report confirms the findings of the Global Methane Assessment that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near-and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*)."). *See also* Lean G. (30 May 2023) *Biden plan is the world's best hope to avoid critical warming – but Britain's dragging its feet*, INEWS ("An international methane agreement is inevitable, because it's not possible to solve climate change without it," says Durwood Zaelke, president of the DC-based Institute for Governance and Sustainable Development. "The question is: will it come early enough?").

[1093] AzerNews (7 March 2024) *Azerbaijan's joining Global Methane Pledge aligns with international efforts to limit global warming* ("Methane reduction is of global significance. The fact that 155 countries, contributing to around 50% of global methane pollution, have pledged to reduce emissions underscores the widespread recognition of the urgency to address this potent greenhouse gas. Azerbaijan's decision to join the "Global Methane Pledge" is a notable step. The voluntary commitment to reduce methane emissions by at least 30% by 2030 aligns with the overall goal set by the initiative at COP26. This demonstrates Azerbaijan's recognition of the role it can play in combating climate change and its willingness to contribute to international efforts. On March 4th, Azerbaijan announced its participation in the "Global Methane Pledge," which involves voluntary commitments by states to reduce methane emissions."). *See also* *Global Methane Pledge* ("With 155 country participants, representing a little over 50% of global anthropogenic methane emissions, we are well on our way to achieving the Pledge goal"); *and* United States Department of State (2 November 2021) *United States, European Union, and Partners Formally Launch Global Methane Pledge to Keep 1.5°C Within Reach*, Press Release ("Today, the United States, the European Union, and partners formally launched the Global Methane Pledge, an initiative to reduce global methane emissions to keep the goal of limiting warming to 1.5 degrees Celsius within reach. A total of over 100 countries representing 70% of the global economy and nearly half of anthropogenic methane emissions have now signed onto the pledge."). As noted, the Global Methane Pledge sets a collective target to reduce global methane emissions by at least 30% from 2020 levels by 2030, would reduce warming by at least 0.2 °C by 2050 and keep the planet on a pathway consistent with staying below 1.5 °C. *See* United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.").

[1094] Climate & Clean Air Coalition (7 December 2023) *Opportunities for Increasing Ambition of NDCs Through Integrated Air Pollution and Climate Change Planning: Progress & Looking Ahead to 2025*, 3 ("As of November 2023, 95% of NDCs include methane within the scope of their overall mitigation target. The absolute number of NDCs including methane in their overall target has more than doubled, from 90 to 184. Forty countries (~20%) include methane as a supplementary target or assessment of the mitigation potential of the measure(s) identified, growing from a base of two in 2016. Most of the countries who include methane in this way (88%) are GMP partners."). *See also* Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on* *climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 131 ("A closer look into the NDCs shows that some go beyond simply listing CH_4 under the scope of covered gases and provide more detailed information on CH_4 mitigation. For instance, a number of NDCs include sector-specific policies in the areas of agriculture, waste, oil and gas, and coal that will reduce CH_4 emissions (Ross et al., 2018; Walderdorff, 2020). An even smaller number of NDCs include a quantitative, CH_4-specific reduction target, such as Canada, Japan, and New Zealand. Table 2 provides a summary of NDCs that include a quantitative descriptor of CH_4 mitigation as of January 1, 2021. While some of the NDCs shown in Table 2 include true quantitative CH_4 reduction targets, others quantify the potential for CH_4 reductions, or specify goals expressed in terms of efficiency or intensity. In aggregate, very few NDCs provide concrete or quantitative details on CH_4 mitigation activities – indeed, the NDCs summarized in Table 2 are among those that provide the greatest amount of specificity on CH_4 mitigation, which still tends to be very little."). IGSD makes the following note re: the following three countries included in Mar *et al*. (2022): • Afghanistan: Afghanistan included methane reduction targets within its quantitative emissions reductions goals, but this is not reflected in Mar et al. (2022); • China: China's 2016 Intended NDC included a numeric target for coal-bed methane capture, but this target is absent from its updated 2021 submission; China was therefore not included as a country with a numeric methane target; and • Dominica: Dominica's Intended NDC included plans to install methane capture at a landfill. This project was slated for 2016–2021, but project completion remains unconfirmed. *See* United Nations Framework Convention on Climate Change (2022) *Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat*, Conference of the Parties, Fourth Session, 15 ("All NDCs cover CO_2 emissions, almost all (91 per cent) cover CH_4 and most (89 per cent) cover N_2O emissions, many (53 per cent) cover HFC emissions and some cover PFC and SF_6 (36 per cent) and NF_3 (26 per cent) emissions."); *and* United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release. *See also* Paris Agreement Article 4(2) and Article 4(3) ("2. Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions. 3. Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.").

[1095] Unites States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("11. The two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress.").

[1096] United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO2 Greenhouse Gases*, Fact Sheet ("*The United States, People's Republic of China, and United Arab Emirates today convened a Summit to accelerate actions to cut methane and other non-CO2 greenhouse gases as the fastest way to reduce near-term warming and keep a goal of limiting global average temperature increase to 1.5 degrees Celsius within reach.").*

[1097] United Nations Framework Convention on Climate Change (2023) *Draft decision -/CMA.5 Outcome of the first global stocktake* ("Further recognizes the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts, in a nationally determined manner, taking into account the Paris Agreement and their different national circumstances, pathways and approaches").

[1098] *See generally* (3 December 2021) *Methane matters*, Editorial, NAT. GEOSCI. 14: 875. *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common.. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”); *and* Steffen W., *et al*. (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254 (“This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. The challenge that humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System's stability landscape without human stewardship to create and maintain it.”).

[1099] *See, e.g.*, Volcovici V. (27 November 2023) *COP28 climate summit puts spotlight on turning methane pledges into action*, REUTERS (“'If it's just a pledge, it will land with a thump,' said Rachel Kyte, the World Bank's former climate envoy. 'The UAE needs to commit companies and countries to sit down and negotiate a binding agreement to x-out methane' and 'there are a lot of pieces coming together,' said Durwood Zaelke, president of the Institute for Governance and Sustainable Development, a Washington, D.C.-based think tank. 'With major emitters like the U.S., China and EU announcing new rules, the time is right for an agreement.'”). *See also* International Chamber of Commerce (23 November 2023) *Strengthening the Global Methane Pledge to keep 1.5 °C within reach* (“While businesses across our network are firmly committed to reducing methane emissions, clear policy signals from governments – backed by strong accountability measures within the GMP framework – are urgently needed to scale-up the mitigation efforts that are ultimately required by the end of this decade.”); Climate & Clean Air Coalition (9 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* (“As CCAC High-level Advocate for Finance Rachel Kyte, who moderated the session, said in her closing: “It's 2023. With peak oil, peak coal, and peak emissions, we are also 'peak-pledge'.” This Coalition has proven to turn ambition into action, it set out as the Coalition of the Working.”); Clausing K., Garicano L., & Wolfram C. (2023) *How an international agreement on methane emissions can pave the way for enhanced global cooperation on climate change*, Peterson Institute for International Economics, 2 (“Under the IRA, the United States has for the first time implemented a methane emissions fee as a backstop to new methane regulations in the oil and gas sectors. The European Union is also implementing new methane regulations on fossil energy, and the European Parliament proposal would penalize imports from countries that do not meet certain regulatory standards. Building on these parallel approaches, this Policy Brief proposes transatlantic coordination that uses an import charge as a lever to seek similarly ambitious regulatory reforms in the oil and gas sectors abroad. Specifically, oil and gas exporters can be encouraged to adopt regulations comparable to those in the United States and the European Union or, if they fail to implement regulations, pay a border adjustment fee on exports to the two jurisdictions. With time, most major energy importers would ideally join the coalition of countries cooperating on both stringent domestic regulations on oil and gas production (if applicable) and border adjustments on any dirty, nonregulating exporters.”); *and* Salata Institute for Climate and Sustainability (2023) RESEARCH BRIEF*: METHANE AND TRADE: PAVING THE WAY FOR ENHANCED GLOBAL COOPERATION ON CLIMATE CHANGE* (“As a first step, the United States, the European Union, and partner countries can work to coordinate their methane reduction policies, with an eye toward the eventual imposition of border adjustments on imports from countries that fail to raise their standards. The Biden administration could work with Congress on next steps for implementing a US methane border adjustment, while simultaneously leading efforts with the European Union, the G7, and other potential coalition members to develop a framework for a multilateral agreement. Ideally, a proposed framework could be presented at the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP28) in Dubai in late 2023.”).

[1100] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release (“Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.”). It would also keep the planet on a pathway consistent with staying within 1.5 °C. *See* United Nations Environment Programme & Climate & Clean Air Coalition (2021) *Briefing on the Global Methane Pledge* (“The

Global Methane Pledge is a strong first step as the first-ever Heads-of State global commitment to cut methane emissions at a level consistent with a 1.5 C pathway.").

[1101] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989). For a discussion of the Montreal Protocol on Substances that Deplete the Ozone Layer, *see generally* Miller A. S., Zaelke D., & Andersen S. O. (2021) Resetting Our Future: *Cut Super Climate Pollutants Now! The ozone treaty's urgent lessons for speeding up climate action*, John Hunt Publishing; *and* Andersen S., Zaelke D., Taddonio K., Ferris R., & Sherman N. (2021) *Ozone Layer, International Protection*, *in* Max Planck Encyclopedia of Public International Law, Oxford University Press, Peters A., & Wolfrum R. (eds.).

[1102] Weiss E. B. (2009) *Introductory Note on the Vienna Convention for the Protection of the Ozone Layer and Montreal Protocol on Substances that Deplete the Ozone Layer*, United Nations Audiovisual Library of International Law ("A working group under UNEP began negotiations on a protocol, and the Montreal Protocol was concluded in September, 1987, only nine months after the formal diplomatic negotiations opened in December, 1986. It went into effect on January 1, 1989.").

[1103] Velders G. J. M., Andersen S. O., Daniel J. S., Fahey D. W., & McFarland M. (2007) *The importance of the Montreal Protocol in protecting climate*, PROC. NAT'L. ACAD. SCI. 104(12): 4814–4819, 4814 ("The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer is a landmark agreement that has successfully reduced the global production, consumption, and emissions of ozone-depleting substances (ODSs). ODSs are also greenhouse gases that contribute to the radiative forcing of climate change. Using historical ODSs emissions and scenarios of potential emissions, we show that the ODS contribution to radiative forcing most likely would have been much larger if the ODS link to stratospheric ozone depletion had not been recognized in 1974 and followed by a series of regulations. The climate protection already achieved by the Montreal Protocol alone is far larger than the reduction target of the first commitment period of the Kyoto Protocol. Additional climate benefits that are significant compared with the Kyoto Protocol reduction target could be achieved by actions under the Montreal Protocol, by managing the emissions of substitute fluorocarbon gases and/or implementing alternative gases with lower global warming potentials.").

[1104] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, NATURE 596: 384–388, 384 ("Overall, at the end of the century, worldAvd warms by an additional 2.5 K (2.4–2.7 K) above the RCP 6.0 baseline in worldProj. Of this warming, 1.7 K comes from the previously explored[19] additional radiative forcing due to the higher CFC concentrations in worldProj. Newly quantified here is the additional warming of global-mean air temperature of 0.85 K (0.65–1.0 K)—half as much again—that arises from the higher atmospheric CO_2 concentrations due to the damaging effect of UV radiation on terrestrial carbon stores.").

[1105] Secretariat of the United Nations Framework Convention on Climate Change (2 November 2021) *World Leaders Kick Start Accelerated Climate Action at COP26*, Press Release ("Today is also the first time a COP in recent history has hosted a major event on methane, with 103 countries, including 15 major emitters including Brazil, Nigeria and Canada, signing up to the Global Methane Pledge.").

[1106] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("At the Major Economies Forum on Energy and Climate (MEF) on September 17, 2021, President Biden and European Commission President Ursula von der Leyen announced, with support from seven additional countries, the Global Methane Pledge—an initiative to be launched at the World Leaders Summit at the 26th UN Climate Change Conference (COP-26) this November in Glasgow, United Kingdom.").

[1107] Global Methane Pledge, *About the Global Methane Pledge* (*last visited* 15 November 2023) ("Participants joining the Pledge agree to take voluntary actions to contribute to a collective effort to reduce global methane emissions at least 30 percent from 2020 levels by 2030, which could eliminate over 0.2˚C warming by 2050. This is a global, not a national reduction target.").

[1108] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using best available inventory methodologies to quantify methane emissions, with a particular focus on high emission sources.").

[1109] Climate & Clean Air Coalition (20 September 2023) *New Global Methane Pledge Champions Call for Accelerated Action on Methane to Keep 1.5°C Within Reach*, News and Announcements ("Canada, Federated States of Micronesia (FSM), Germany, Japan, and Nigeria have joined the United States and the European Union as Champions of the Global Methane Pledge (GMP) to advocate for accelerated methane action to achieve the Pledge – to reduce global anthropogenic methane emissions by at least 30 per cent below 2020 levels by 2030.").

[1110] United States Department of State (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial*, ("New members and expanded leadership. Canada, Federated States of Micronesia, Germany, Japan, and Nigeria joined the United States and European Union as Global Methane Pledge Champions. Turkmenistan, Kazakhstan, Kenya, Romania, and Angola joined the Pledge, bringing total participation to 155 governments."); AzerNews (7 March 2024) *Azerbaijan's joining Global Methane Pledge aligns with international efforts to limit global warming* ("Methane reduction is of global significance. The fact that 155 countries, contributing to around 50% of global methane pollution, have pledged to reduce emissions underscores the widespread recognition of the urgency to address this potent greenhouse gas. Azerbaijan's decision to join the "Global Methane Pledge" is a notable step. The voluntary commitment to reduce methane emissions by at least 30% by 2030 aligns with the overall goal set by the initiative at COP26. This demonstrates Azerbaijan's recognition of the role it can play in combating climate change and its willingness to contribute to international efforts. On March 4th, Azerbaijan announced its participation in the "Global Methane Pledge," which involves voluntary commitments by states to reduce methane emissions.").

[1111] European Commission (4 December 2023) *2023 Global Methane Pledge Ministerial: decisive action to curb emissions*, ("At today's COP28 Global Methane Pledge Ministerial, Ministers welcomed transformational national actions and catalytic grant funding to deliver on the goal to cut methane at least 30 percent by 2030.").

[1112] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge*, Press Release ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050."). Note that studies that assume a declining baseline in methane emissions calculate a lower avoided warming. *See* Forster P., Smith C., & Rogelj J. (2021) *Guest Post: The Global Methane Pledge needs to go further to help limit warming to 1.5C*, CARBONBRIEF; *and* International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 19 ("Meeting the Global Methane Pledge target has the potential to make an enormous impact on climate change, similar to the entire global transport sector adopting net zero emission technologies (see Methodology). Action will be particularly important in the period up to 2030 because sharp cuts in methane can deliver a net cooling effect within a relatively short period. This could keep the door open to a 1.5 °C stabilisation in global average temperatures, while the world pursues lasting reductions in CO_2.").

[1113] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 9 ("Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1).").

[1114] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 8 ("Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts.").

[1115] United Nations Framework Convention on Climate Change (2023) *Draft decision -/CMA.5 Outcome of the first global stocktake*, ("Further recognizes the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts, in a nationally determined manner, taking into account the Paris Agreement and their different national circumstances, pathways and approaches").

[1116] United Nations Framework Convention on Climate Change (2023) *Draft decision -/CMA.5 Outcome of the first global stocktake* ("Accelerating and substantially reducing non-carbon-dioxide emissions globally, including in particular methane emissions by 2030").

[1117] (8 November 2021) *LIVE: President Obama delivers a speech at COP26 climate summit in Glasgow, Scotland*, YAHOO FINANCE, YouTube (from 23:12–23:19).

[1118] (13 November 2021) Parties to the Paris Agreement, Decision -/CP.26 ¶19, *Glasgow Climate Pact Advance unedited version*.

[1119] United States White House (12 May 2022) *FACT SHEET: U.S.-ASEAN Special Summit in Washington, DC*, Statements and Releases ("Reducing Methane Emissions: The United States is committed to working with the nations of Southeast Asia to reduce the region's methane emissions. The United States welcomed Indonesia, Vietnam, Malaysia, the Philippines, and Singapore joining the Global Methane Pledge at COP-26, and we are accelerating technical assistance, financial resources, and project pipeline development for methane mitigation in Global Methane Pledge countries, including through the EPA, USTDA, DFC, and EXIM, as well as the newly-created Global Methane Hub, a philanthropic fund that can support methane mitigation priorities in the region.").

[1120] G7 (27 May 2022) *G7 Climate, Energy and Environment Ministers' Communiqué* ("65. Methane: We highlight that in order to keep 1.5 °C within reach and to reduce the likelihood of overshoot, significant methane emission reductions must be achieved globally by 2030. In this context and in the light of the latest findings of the IPCC, we highlight the need to reduce global methane emissions by 34 percent by 2030 and by 44 percent by 2040 relative to the 2019 level to limit global warming to 1.5 °C by 2100 with no or limited overshoot. We therefore reaffirm our commitment made at COP26 to implement the Global Methane Pledge, whose endorsers are committed to collectively reduce global anthropogenic methane emissions by at least 30 percent below 2020 levels by 2030. In order to accelerate its implementation, those of us who have not already done so endeavour to implement domestic methane emission reductions by developing national climate plans and strategies and implementing accompanying measures, and we encourage those who do not yet have such plans to develop them. We stand ready to support the Climate and Clean Air Coalition as a core implementing partner of the Pledge. While the generation of waste is not encouraged, we recognise the opportunities to mitigate methane emissions from the waste sector, primarily by diversion of organic waste from landfills through best management practice and processes aiming at material and energy recovery and as appropriate by sound management of landfill sites as well as by using waste-to-fuel technologies to produce renewable methane from organic waste, agricultural residues and biomass that does not depend on arable land or cannot be utilised in a better way. The waste sector can contribute to a reduction in atmospheric methane emissions if the infrastructure in place to transport the renewable methane does not allow for intentional or unintentional venting of methane. We also recognise the opportunities to mitigate methane emissions from the energy sector by capturing and using methane from the oil and gas sector that would otherwise have been vented, wasted, flared or lost in transport, and by using best practices to minimise methane from coal mining. We further recognise that more efforts are needed to reduce agricultural methane emissions. We recognise the need to continuously improve emissions measurement, reporting and verification to inform national emissions inventories and the work of the International Methane Emissions Observatory (IMEO), launched during G20 2021 by the UN Environment Programme (UNEP) with the support from the European Union, in collecting, reconciling and verifying anthropogenic methane emissions data at a global level and encourage continued cooperation with relevant stakeholders such as the International Energy Agency. In addition to our national efforts, we highlight the importance of reducing the methane emissions associated with energy production and consumption. We therefore will consider providing increased support to methane reduction and elimination projects in developing and emerging economies. In particular, we are committed to working with other oil and gas producing countries to accelerate flaring and methane abatement projects and strengthen policies to reduce methane emissions in the oil and gas sector.... We acknowledge that investment in this sector is necessary in response to the current crisis, in a manner consistent with our climate objectives and without creating lock-in effects. The current crisis highlights the real, urgent need and the opportunity for Europe to reduce its dependency on Russia by diversifying supply, accelerating the roll out of clean, safe and sustainable energy technologies, and critically enhancing energy efficiency, with significant progress possible by the end of the year.").

[1121] G7 (28 June 2022) *G7 Leaders' Communiqué*.

[1122] United States Department of State (17 June 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Release ("Today, the United States, the European Union, and 11 countries launched the Global Methane Pledge Energy Pathway to catalyze methane emissions reductions in the oil and gas sector, advancing both climate progress and energy security.... Countries and supporting organizations announced nearly $60 million in dedicated funding to support implementation of the Pathway. Countries and supporting organizations have announced $59 million in dedicated funding and in-kind assistance in support of the GMP Energy Pathway that was announced at today's MEF, including: $4 million to support the World Bank Global Gas Flaring Reduction Partnership (GGFR). The United States intends to support the transfer by the World Bank of at least $1.5 million in funding to the GGFR. Germany intends to provide $1.5 million, and Norway intends to provide approximately $1 million to GGFR. $5.5 million to support the Global Methane Initiative (GMI). The United States will provide $3.5 million. Guided by the recommendations of the GMI, Canada will contribute $2 million over the next four years, as part of its global climate finance commitment, to support methane mitigation projects in developing countries including in the oil and gas sector. Up to $9.5 million from the UNEP International Methane Emissions Observatory to support scientific assessments of methane emissions and mitigation potential in the oil and gas sector that are aligned with the Global Methane Pledge Energy Pathway. Up to $40 million annually from the philanthropic Global Methane Hub to support methane mitigation in the fossil energy sector. These funds will be critical to improve methane measurements in the oil and gas sector, identify priority areas for methane mitigation, develop technical assessments for project development, strengthen regulator and operator capacity, support policy development and enforcement, and other essential activities to achieve reductions in methane emissions.").

[1123] United States Department of State (17 November 2022) *Fact Sheet, Global Methane Pledge: From Moment to Momentum* (describing progress on the Global Methane Pledge Energy Pathway).

[1124] European Commission (11 November 2022) *Joint Declaration from Energy Importers and Exporters*.

[1125] United Nations Environmental Programme, *Methane Alert and Response System (MARS)* (*last visited* 30 August 2023)

[1126] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release ("Mobilizing multilateral funding for methane action: The World Bank Global Gas Flaring Reduction Partnership will launch the next phase of its trust fund in 2023 to become the Global Flaring and Methane Reduction (GFMR) Partnership and address all methane emissions across the oil and gas value chain."),

[1127] For a general overview of methane developments that took place during COP28 *see* Escudero JP. (19 December 2023) *COP28: "The Methane COP"*, LEGAL PLANET.

[1128] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The United States announced final standards to sharply reduce methane emissions from oil and gas operations, which will reduce over 1.5 Gt of CO2 equivalent and achieve a nearly 80% reduction below future methane emissions expected without the rule.").

[1129] Council of Europe (15 November 2023) *Climate action: Council and Parliament reach deal on new rules to cut methane emissions in the energy sector* ("The Council and the Parliament agreed on three implementation phases. The first phase will focus on data collection and the creation of a methane emitters global monitoring tool and a super emitter rapid reaction mechanism. In the second and third phases, equivalent monitoring, reporting and verification measures should be applied by exporters to the EU by 1 January 2027, and maximum methane intensity values by 2030. The competent authorities of each member state will have the power to impose administrative penalties if these provisions are not respected.").

[1130] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The United States announced final standards to sharply reduce methane emissions from oil and gas operations, which will reduce over 1.5 Gt of CO2 equivalent and achieve a nearly 80% reduction below future methane emissions expected without the rule.").

[1131] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("Brazil announced that its National Council of Energy Policy will establish guidelines on methane reduction in the oil and gas sector by the end of 2024, and the National Agency for Petroleum, Natural Gas and Biofuels (ANP) aims to finalize regulations by the end of 2025 based on these guidelines.").

[1132] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("Egypt announced its intention to develop domestic methane regulations in its oil and gas sector by the end of 2024, as part of developing the sector's detailed methane emission reduction roadmap.").

[1133] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("Nigeria showcased major steps taken this year under the Nigeria Gas Flare Commercialization Program (NGFCP), including advancing projects it estimates will capture over half of all gas flaring volumes in Nigeria. Nigeria is committed to accelerate implementation of these projects and to ensure robust enforcement of its oil and gas methane guidelines launched at COP27.").

[1134] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("Kazakhstan joined the Global Methane Pledge and announced cooperation with the United States to develop national standards to eliminate non-emergency venting of methane and require leak detection and repair in the oil and gas sector as soon as possible before 2030.").

[1135] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Oil and Gas Methane Partnership 2.0 announced new members. The Partnership now represents over 120 companies with assets in more than 60 countries on five continents and covers over 35% of the world's oil and gas production and over 70% of LNG flows.").

[1136] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The World Bank launched its Global Flaring and Methane Reduction Partnership (GFMR) with $255 million in new grant funding to catalyze oil and gas methane and flaring reduction in developing countries. The GFMR is supported by financial contributions from the United Arab Emirates, United States, Norway, BP, ENI, Equinor, Occidental, Shell, and TotalEnergies. Access to project development and financing support through GFMR will be contingent on commitments to achieve near-zero methane emissions by 2030 by reducing methane intensity to below 0.2%, achieve zero routine flaring by 2030, measure and report methane emissions through the Oil and Gas Methane Partnership 2.0 framework, and endorse the Global Methane Pledge.").

[1137] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The United States, the European Commission, and twelve other natural gas importing and exporting countries formed an international working group to advance comparable and reliable information about methane and CO2 emissions across the natural gas supply chain to drive global emissions reductions.").

[1138] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Oil and Gas Climate Initiative (OGCI) is expanding its Satellite Monitoring Campaign to provide actionable data to reduce emissions from large-magnitude methane plumes and flares, supported by in-kind contributions from OGCI companies. ExxonMobil also intends to provide up to $25 million in in-kind assistance to address capability shortcomings to reduce methane emissions.").

[1139] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release ("In the year since it launched at COP26, the Global Methane Pledge has generated unprecedented momentum for methane action. Country endorsements of the GMP have grown from just over 100 last year to 150, more than 50 countries have developed national methane action plans or are in the process of doing so, substantial new financial resources are being directed to methane action, and partners have launched "pathways" of policies and initiatives to drive methane reductions in key methane-emitting sectors – a GMP Energy Pathway launched at the June 2022 Major Economies Forum on Energy and Climate and a GMP Food and Agriculture Pathway and GMP Waste Pathway, both launched today at COP27.").

[1140] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release ("The Green Climate Fund, in partnership with the International Fund for Agricultural Development (IFAD), the Food and Agriculture Organization, Global Dairy Platform and Global Methane Hub, $3.5 million of project preparation funding with the objective of leveraging up to $400 million in financing that will help transition dairy systems to lower emission, climate resilient pathways in Kenya, Rwanda, Tanzania and Uganda.").

[1141] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release ("The Global Methane Hub announced raising $70 million in support for a new Enteric Methane Research and Development Accelerator to advance critical research on reducing methane emissions from enteric fermentation—the largest single source of methane emissions from agriculture—and has a $200 million fundraising goal by the first quarter of 2023.").

[1143] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Global Methane Hub formally launched the Enteric Fermentation R&D Accelerator with $200 million in funding, making it the largest ever globally coordinated research effort into livestock methane reduction.").

[1144] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The World Bank launched the Global Methane Reduction Platform for Development (CH4D) to support low-and mid-income countries to realize the 'methane triple-wins' of abating emissions, enhancing resilience, and empowering livelihoods. Through partnerships, including with the CCAC Methane Roadmap Action Programme (M-RAP), CH4D will mobilize expertise, affordable technologies, and catalytic finance for methane abatement in the agriculture and waste sectors. ").

[1145] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP) announced that it will, with funding from the U.S. State Department and Global Methane Hub, support 15 governments to incorporate agricultural methane into their nationally determined contributions and 10 governments to build investment pipelines in low-methane agricultural development.”).

[1146] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“The Dairy Methane Action Alliance is a global initiative to accelerate food industry action to drive down dairy methane emissions, launching on December 5 at COP28 with more than three major food companies, representing billions of dollars in global annual dairy sales.”).

[1147] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release (“SCALE-Methane, a new initiative of the Subnational Climate Action Leaders’ Exchange, will support accelerated subnational action on waste methane. This work will complement the Pathway Towards Zero Waste joined by 13 cities at the October 2022 C40 World Mayors Summit.”).

[1148] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release (“To advance both the GMP Waste Pathway and the GMP Food and Agriculture Pathway, a Food Waste Management Accelerator will develop methane mitigation projects in 10 countries in Latin America and the Caribbean, the Global Food Banking Network will launch a new effort to quantify and track food banking methane mitigation, the IDB project #SinDesperdicio is creating projects to reduce food loss, and a new USAID Food Loss and Waste Partnerships Facility will scale efforts in Bangladesh, Kenya, Nepal, Niger, Nigeria, and/or Tanzania.”).

[1149] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“The Launch of the Lowering Organic Waste Methane (LOW-Methane) initiative. The ambition of LOW-Methane is to deliver at least 1 million metric tons of annual waste sector methane reductions well before 2030 with 40 subnational jurisdictions and their national government counterparts, including by working to unlock over $10 billion in public and private investment. The consortium effort will be supported by a coordination group housed within the UNEP-convened CCAC.”).

[1150] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“The Inter-American Development Bank launched a new “Too Good to Waste” initiative which aims to contribute at least a 30% reduction in methane emissions in solid waste operations in Latin America and the Caribbean financed by the Bank, including three recently approved projects totaling $372.5 million.”).

[1151] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“The United States announced new steps on waste methane. The Environmental Protection Agency (EPA) is planning a rule-making to review and, if appropriate, revise its Clean Air Act emission standards for new and existing municipal solid waste landfills, considering new monitoring technology, incentivization of organics waste diversion, and emissions controls at landfills not currently covered by current regulations. In 2024, EPA will release updates on emissions estimates for MSW landfills. In addition, the United States released for public comment a draft national strategy for Reducing Food Loss and Waste and Recycling Organics in line with its 2030 50% food loss and waste reduction goal.”).

[1152] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“The leaders of Canada, the United States, and Mexico committed to reducing methane emissions from the waste sector by at least 15% by 2030 at the 2023 North American Leaders Summit.”). *See also* United States White House (10 January 2023) *Key Deliverables for the 2023 North American Leaders’ Summit*, Fact Sheet (“Committing to reduce methane emissions from the solid waste and wastewater sector by at least 15% by 2030 from 2020 levels and deepen collaboration on waste and agriculture methane measurement and mitigation, including achieving the Global Methane Pledge through trilateral cooperation on methane and black carbon emissions.”).

[1153] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“The CCAC’s new Technology and Economic Assessment Panel (CCAC-TEAP) released its first report. The CCAC-

TEAP, co-chaired by Ireland and Senegal, released a brief on Driving Innovation and Technology in the Waste Sector"). *See also* Climate & Clean Air Coalition (2023) BRIEF: SCALING UP UNDERFINANCED SLCP MITIGATION SOLUTIONS: DRIVING INNOVATION AND TECHNOLOGY IN THE WASTE SECTOR.

[1154] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Fact Sheet ("Launched today, the GMP Food and Agriculture Pathway advances climate and food security goals through new actions that increase agricultural productivity, reduce food loss and waste, and improve the viability of agriculture in the future. Initial components of the GMP Food and Agriculture Pathway include:

- Boosting Support for Smallholder Farmers: The Green Climate Fund, in partnership with the International Fund for Agricultural Development (IFAD), the Food and Agriculture Organization, Global Dairy Platform and Global Methane Hub, $3.5 million of project preparation funding with the objective of leveraging up to $400 million in financing that will help transition dairy systems to lower emission, climate resilient pathways in Kenya, Rwanda, Tanzania and Uganda. Costa Rica, Uruguay, Colombia, Pakistan, and Vietnam are planning to prepare similar programs through a partnership with Pathways to Dairy Net Zero. IFAD and United States a partnership to advance climate resilience and methane mitigation with smallholder farmers including by prioritizing methane mitigation in IFAD's pipeline of country and regional projects with combined investment of over $500 million dollars in methane-emitting sectors. In addition, the United States has announced $5 million for the African Development Bank to advance agriculture and waste methane work within the Africa Climate Change Fund.
- Increasing Innovation: The Global Methane Hub announced raising $70 million in support for a new Enteric Methane Research and Development Accelerator to advance critical research on reducing methane emissions from enteric fermentation—the largest single source of methane emissions from agriculture—and has a $200 million fundraising goal by the first quarter of 2023. Under the Agricultural Innovation Mission for Climate (AIM4C), seven methane innovation sprints have been launched related to both livestock and rice methane mitigation with total existing funding of $123 million.
- Highlighting Ambitious National Actions: The **United States** Department of Agriculture is investing over $500 million in methane reduction projects via Partnerships for Climate Smart Commodities, up to $90 million for domestic food loss and waste reduction, and last year supported dozens of anaerobic digester projects and a broader range of methane-reducing investments through over $64 million in additional grants and guaranteed loans. In the **European Union,** the new Common Agricultural Policy starting in 2023 increases the emphasis on climate action, including methane from livestock. In total, 40 percent of the budget will be dedicated to climate-related measures, including improved rules and monitoring requirements, and quantitative targets to reduce food waste, among others. The EU has also published a Biomethane Actions Plan with the goal of doubling production to reach 35 billion cubic meters by 2030.").

[1155] African Development Bank (15 September 2022) *US government announces $5 million grant to support African Development Bank in tackling methane emissions* ("The United States government has announced it will provide a $5 million grant to the African Development Bank to support efforts to abate methane gas emission, across Africa. Methane accounts for about half of the net rise in global average temperature since the pre-industrial era. The grant, subject to the completion of US domestic procedures and approvals, will go to the multi-donor Africa Climate Change Fund, which is managed by the African Development Bank. The Fund supports a broad range of activities covering climate resilience and low-carbon growth.").

[1156] United States Department of Agriculture (14 September 2022) *Biden-Harris Administration Announces Historic Investment in Partnerships for 70 Climate-Smart Commodities and Rural Projects*, Press Release ("Agriculture Secretary Tom Vilsack announced today that the Biden-Harris Administration through the U.S. Department of Agriculture is investing up to $2.8 billion in 70 selected projects under the first pool of the Partnerships for Climate-Smart Commodities funding opportunity, with projects from the second funding pool to be announced later this year…USDA will work with the applicants for the 70 identified projects to finalize the scope and funding levels in the coming months. A complete list of projects identified for this first round of funding is available at usda.gov/climate-smart-commodities. These include: …

- **Scaling Methane Emissions Reductions and Soil Carbon Sequestration:** Through this project, Dairy Farmers of America (DFA) climate-smart pilots will directly connect the on-farm greenhouse gas reductions with the low-carbon dairy market opportunity. DFA will use its cooperative business model to ensure that the collective financial benefits are captured at the farm, creating a compelling opportunity to establish a powerful self-sustaining circular economy model benefiting U.S. agriculture, including underserved producers. Lead partner: Dairy Farmers of America, Inc…
- **The Grass is Greener on the Other Side: Developing Climate-Smart Beef and Bison Commodities:** This project will create market opportunities for beef and bison producers who utilize climate-smart agriculture grazing and land management practices. The project will guide and educate producers on climate-smart practices most suited for their operations, manage large-scale climate-smart data that will be used by producers to improve decision-making, and directly impact market demand for climate-smart beef/bison commodity markets. Lead university: South Dakota State University.”).

[1157] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* (“In addition to the over $1 billion in new grant funding, international financial institutions approved over $3.5 billion in new investments for methane-reducing projects since COP27. Approvals include $375 million from the Green Climate Fund and partners, over $1.9 billion (€1.78 billion) from the European Investment Bank, over $218 million (€200 million) from the European Bank for Reconstruction and Development, and $372.5 million from the Inter-American Development Bank. The World Bank approved at least $700 million in investments, including a $255 million for rice project in China, $300 million for landfill methane reduction in Cote d'Ivoire, and $145 million for wastewater methane reduction in Malawi.”).

[1158] (17 May 2005) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 2319 U.N.T.S. 81 (Entered into force in accordance with article 17 which reads as follows: “1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depositary. 2. For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.”).

[1159] (16 May 1983) 1979 Convention on Long-Range Transboundary Air Pollution, 1302 U.N.T.S 217, Art. 2 (“The Contracting Parties, taking due account of the facts and problems involved, are determined to protect man and his environment against air pollution and shall endeavour to limit and, as far as possible, gradually reduce and prevent air pollution including long-range transboundary air pollution.”).

[1160] (17 May 2005) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 2319 U.N.T.S. 81 (Entered into force in accordance with article 17 which reads as follows: “1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depositary. 2. For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.”).

[1161] Economic Commission for Europe (8 September 2015) *UNECE joins Climate and Clean Air Coalition*, Press Release (“At a Working Group meeting in Paris (8–9 September), CCAC welcomed UNECE to the Coalition. By joining the Coalition, UNECE gains access to a broad network of experts and partners. Drawing on its long-standing expertise, UNECE will contribute through exchanges of experiences, knowledge and best practices, particularly as they relate to the work under the Committee on Sustainable Energy and the Convention on Long-Range Transboundary Air Pollution, including its amended Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol).")

[1162] Executive Body for the Convention on Long-Range Transboundary Air Pollution (2018) Decision 2018/5 Long-term Strategy for the Convention on Long-range Transboundary Air Pollution for 2020–2030 and Beyond, Annex ¶ 28 ("Although peak ozone concentrations have been reduced, there is evidence of widespread damage to human health, natural vegetation, crops and forests, and some materials in the ECE region. Even with full implementation of the Gothenburg Protocol and its 2012 amendments (e.g., reducing emissions of nitrogen oxides and non-methane volatile organic compounds, both of which are ozone precursors), wide-scale problems will remain. Model simulations indicate that background levels of tropospheric ozone will begin to increase again after 2020–2030, driven progressively by methane emissions outside the ECE region. Therefore, further reduction in precursors, including methane, will be required to reduce the formation of tropospheric ozone."). The Task Force on Techno-Economic Issues (TFTEI) updates and assesses emission abatement technologies to reduce emissions of many conventional air pollutants, including SO2, NOx, VOCs, and dust (including PM10, PM2.5 and black carbon). Its December 2020 report on methane emissions provides information on emissions from landfill gases, the natural gas grid, and biogas facilities as well as methods of emission abatement. The TFTEI held its 7th Meeting on 29 October 2021. The 7th Meeting agenda included a discussion on its contributions to the Gothenburg Protocol review. The documents from the meeting are forthcoming. The Task Force on Integrated Assessment Modelling (TFIAM) brings together information gathered from the Parties and from Convention bodies on cost-effective emission-control strategies. It provides regular reports to the negotiating bodies of the Convention to assist in the development of future legal instruments and to regularly review the existing legal instruments. The Task Force is modelling future trends, impacts, and mitigation measures for methane emissions. The Task Force on Hemispheric Transport of Air Pollution (TFHTAP) has examined methane emission as part of its mandate to examine the transport of air pollution across the northern hemisphere and its impacts within and outside of the UNECE region.

[1163] *See* 1984 (Geneva) Protocol on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe; 1985 (Helsinki) Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 per cent; 1988 (Sofia) Protocol concerning the Control of Nitrogen Oxides or their Transboundary Fluxes; 1991 (Geneva) Protocol concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes; 1994 (Oslo) Protocol on Further Reduction of Sulphur Emissions; 1998 (Aarhus) Protocol on Heavy Metals; 1998 (Aarhus) Protocol on Persistent Organic Pollutants (POPs); and the 1999 (Gothenburg) Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. *See also* Lawyers Responding to Climate Change (2 December 2010) *LRTAP and extending MEAs to non-party states – Part II* ("The initial Convention has been extended by 8 Protocols which have imposed specific measures and obligations on the parties. The 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30%, as its name suggests, established a commitment on all parties to reduce their national annual sulphur emissions or their transboundary fluxes by at least 30% as soon as possible and at the latest by 1993 using 1980 levels as the basis for calculation of the reductions. Further reductions were adopted by the 1994 Oslo Protocol on 'Further Reduction of Sulphur Emissions'. A commitment to control nitrogen oxides was addressed in the third Sofia Protocol on the 'Control of Emissions of Nitrogen Oxides or Their Transboundary Fluxes' in 1988. This required the reduction of 'total annual emissions' and introduced into international law the concept of 'national emission standards'. It also recognised the need to create more favourable conditions for exchange of technology. The fourth Protocol in Geneva in 1991 addressed the 'Control of Emissions of Volatile Organic Compounds (VOCs) and their Transboundary Fluxes'. In 1998 the Aarhus 'Heavy Metals Protocol' targeted 3 harmful heavy metals- lead, cadmium and mercury- and required the parties to reduce their emissions of those metals below the levels in a selected reference year between 1985 and 1995. The Aarhus Protocol on Persistent Organic Pollutants (POPs) was adopted at the same time with the objective of eliminating emissions and discharges of POPs to the atmosphere. This focused on 16 substances rated according to their risk to the environment The parties agreed to eliminate the production and use of some POPs and to restrict the use of others. Finally the 1999 Gothenburg Protocol to 'Abate Acidification, Eutrophication and Ground-

Level Ozone' aimed to control and reduce anthropogenic emissions of 4 pollutants- sulphur, NOx, ammonia and VOCs which are likely to cause adverse effects to human health, ecosystems and crops.").

[1164] Hunter D., Salzman J., & Zaelke D. (2021) INTERNATIONAL ENVIRONMENTAL LAW AND POLICY, Foundation Press, (6th Ed.), 529 ("Ultimately, LRTAP would require that countries develop the 'best available technology which is economically feasible and low-and non-waste technology.' Art. 6. The protocols to LRTAP adopt technology-based standards, targets, and timetables, as well as other policy responses. LRTAP and its protocols thus provide a good vehicle for exploring different potential policy approaches to air pollution.").

[1165] European Monitoring and Evaluation Programme (17 June 2021) *EMEP History and Structure* ("In this process, the main objective of the EMEP programme (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) is to regularly provide governments and subsidiary bodies under the LRTAP Convention with qualified scientific information to support the development and further evaluation of the international protocols on emission reductions negotiated within the Convention.").

[1166] (5 August 1998) Protocol on Further Reduction of Sulphur Emissions, 2030 U.N.T.S. 122, Art. 5(1) ("Each Party shall report, through the Executive Secretary of the Commission, to the Executive Body, on a periodic basis as determined by the Executive Body, information on: (a) The implementation of national strategies, policies, programmes and measures referred to in article 4, paragraph 1; (b) The levels of national annual sulphur emissions, in accordance with guidelines adopted by the Executive Body, containing emission data for all relevant source categories; and (c) The implementation of other obligations that it has entered into under the present Protocol, in conformity with a decision regarding format and content to be adopted by the Parties at a session of the Executive Body. The terms of this decision shall be reviewed as necessary to identify any additional elements regarding the format and/or content of the information that are to be included in the reports.").

[1167] UNECE is composed of 56 member States: Albania, Andorra, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Kazakhstan, Kyrgyzstan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, The Netherlands, Norway, Poland, Portugal, Republic of Moldova, North Macedonia, Romania, Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tajikistan, Turkey, Turkmenistan, Ukraine, United Kingdom of Great Britain and Northern Ireland, United States of America, and Uzbekistan. *See* United Nations Economic Commission for Europe, *Member States and Member States Representatives* (*last visited* 5 February 2023).

[1168] Monaco A., Ross K., Waskow D., & Ge M. (2021) *How Methane Emissions Contribute to Climate Change*, WORLD RESOURCES INSTITUTE ("Twelve countries are responsible for around two-thirds of global methane emissions: China, Russia, India, the United States, Brazil, the European Union, Indonesia, Pakistan, Iran, Mexico, Australia and Nigeria.").

[1169] (17 May 2005) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 2319 U.N.T.S. 81 (Entered into force in accordance with article 17 which reads as follows: "1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depositary. 2. For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.").

[1170] (*amended* 4 May 2012) 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution, ECE/EB.AIR/114, Art. 2(1) ("The objective of the present Protocol is to control and reduce emissions of sulphur, nitrogen oxides, ammonia and [non-methane] volatile organic compounds that are caused by anthropogenic activities and are likely to cause adverse effects on human health, natural ecosystems, materials and crops, due to acidification, eutrophication or ground-level ozone as a result of long-range transboundary atmospheric transport....").

[1171] Fiore A. M., Jacob D. J., Field B. D., Streets D. G., Fernandes S. D., & Jang C. (2002) *Linking ozone pollution and climate change: The case for controlling methane*, GEOPHYS. RES. LETT. 29(19): 25-1–25-4, 25-1 ("Methane is a known major source of the tropospheric O_3 background, but is not generally considered a precursor to regional O_3 pollution episodes in surface air because of its long lifetime (8–9 years)... Our global 3-D model analysis shows that reducing CH_4 emissions enables a simultaneous pursuit of O_3 air quality and climate change mitigation objectives. Whereas reductions in NO_x emissions achieve localized decreases in surface O_3 concentrations, reductions in CH_4 emissions lower the global O_3 background and improve surface air quality everywhere."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 45 ("Next, the linearity of the response to different magnitudes of methane concentration change was examined. At the national level, population weighted ozone changes are extremely linear across a range of methane increases and decreases (Figure 3.4). Though the response itself varies from country to country (i.e. the slopes are different), the ozone change at the national level is directly proportional to the methane concentration change regardless of the ozone metric chosen. This result is consistent with prior studies which also indicate that the ozone/methane relationship is approximately linear (Fiore *et al*. 2008) but its magnitude depends on the local availability of nitrogen oxides, and, through nitrogen oxides, of hydroxyl (West *et al*. 2006; Wang and Jacob 1998).").

[1172] (*amended* 4 May 2012) 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution, ECE/EB.AIR/114, Art. 1(11 quater) ("'Ozone precursors' means nitrogen oxides, volatile organic compounds, methane and carbon monoxide").

[1173] Executive Body for the Convention on Long-Range Transboundary Air Pollution (2018) Decision 2018/5 Long-term Strategy for the Convention on Long-range Transboundary Air Pollution for 2020−2030 and Beyond, Annex ¶ 28 ("Although peak ozone concentrations have been reduced, there is evidence of widespread damage to human health, natural vegetation, crops and forests, and some materials in the ECE region. Even with full implementation of the Gothenburg Protocol and its 2012 amendments (e.g., reducing emissions of nitrogen oxides and non-methane volatile organic compounds, both of which are ozone precursors), wide-scale problems will remain. Model simulations indicate that background levels of tropospheric ozone will begin to increase again after 2020−2030, driven progressively by methane emissions outside the ECE region. Therefore, further reduction in precursors, including methane, will be required to reduce the formation of tropospheric ozone.").

[1174] Executive Body Working Group on Strategies and Review (30 September 2020) *Preparations for the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012*, ECE/EB.AIR/2020/3–EBE/EB.AIR/WG.5/2020/3 at ¶ 20 ("As per the long-term strategy for the Convention for 2020–2030 and beyond (paragraph 50), the review should look at appropriate steps towards reducing emissions of black carbon, ozone precursors not yet addressed such as methane, and emissions from shipping with due consideration for International Maritime Organization (IMO) policies and measures. . . . In line with the priorities identified in the long-term strategy for the Convention for 2020–2030 and beyond, the following should specifically be considered in answering the questions in annex I: (b) Hemispheric transport of ozone and particulate matter and their precursors and advancing efforts to address air pollution on a broader scale per paragraphs 63 and 78 of the long-term strategy for the Convention for 2020–2030 and beyond; health and ecosystem impacts from outside the ECE region; (c)Methane and its relationship to the hemispheric transport of ozone and its contribution to ozone in the ECE region;").

[1175] Executive Body Working Group on Strategies and Review (30 September 2020) *Preparations for the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012*,

ECE/EB.AIR/2020/3–EBE/EB.AIR/WG.5/2020/3 at ¶ 14 (Item 6.3(d) in Annex I stating the question "how methane could be addressed in a future instrument?").

[1176] Executive Body Working Group on Effects & Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (2 July 2021) *2021 Joint progress report on contribution to the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, ECE/EB.AIR/GE.1/2021/3−ECE/EB.AIR/WG.1/2021/3 at ¶ 79 ("79. Methane proves to be the main driver behind increasing background ozone levels. CIAM has identified cost-effective measures to reduce methane emissions in world regions. In Europe, measures in the waste sector have the largest potential. In eastern Europe and central Asia, measures in oil and gas sector, and in the US measures in (unconventional) gas production can deliver most of the abatement potential. In all regions, emissions from agriculture (especially from cattle) tend to be a source with a low technical abatement potential. United Nations Environment's Global Methane Assessment estimates that reduced dairy and meat consumption could give a significant contribution to avoiding warming, ozone related deaths, morbidity as well as crop losses.").

[1177] Executive Body (2020) *Decision 2020/2*, ECE/EB.AIR.16, ¶ 4 ("Requests the Chair of the Working Group on Strategies and Review to compile the inputs and information received into an annotated outline for consideration at the fifty-ninth session of the Working Group on Strategies and Review; to undertake the policy-related work of the review, including assessing the policy implications of the information received; and to elaborate and prepare the report of the review, including its conclusions;").

[1178] LRTAP Gothenburg Protocol Review Group (21 September 2022) *Report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, as amended in 2012*, ECE/EB.AIR/2022/3, at ¶ 77 ("Even with full implementation of the Protocol, background levels of O_3 in the ECE region are expected to continue to increase due to methane, NO_x and VOC emissions outside the ECE region. Further reductions of O_3 precursor emissions within the ECE region are technically feasible and can decrease O_3 concentrations and impacts within the region. In addition, cooperation with other countries, organizations and forums outside of the ECE region to enable and motivate emissions reductions outside the ECE region will also be needed. Options should be explored for how this cooperation could be realized, including through the work of the Forum for International Cooperation on Air Pollution.").

[1179] LRTAP Gothenburg Protocol Review Group (21 September 2022) *Report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, as amended in 2012*, ECE/EB.AIR/2022/3, at ¶ 78 ("The expected increase in global methane concentrations offsets the decreases in surface O_3 due to NO_x and NMVOC controls within Europe and North America. Model studies consistently show that decreasing methane concentrations leads to lower levels of ground-level O_3, independent of other emission controls. In addition, decreasing methane concentrations has a larger impact on local O_3 concentrations in VOC-limited areas where NO_x emissions are high.").

[1180] LRTAP Gothenburg Protocol Review Group (21 September 2022) *Report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, as amended in 2012*, ECE/EB.AIR/2022/3, at ¶ 83 ("A number of options are available for addressing CH4 as an O3 precursor under the Convention. The methane contribution to transboundary O3 is significant enough to warrant considering potential policy action under the Air Convention (see annex II to the present report for additional information).").

[1181] EMEP Steering Body & the Working Group on Effects (29 September 2022) *Strategy for scientific bodies under the Convention on Long-range Transboundary Air Pollution*, ECE/EB.AIR/2022/10, at ¶ 72 ("Improving knowledge for some source categories, pollutants, and their fate: the following priorities have been identified: (b) PM speciation (condensable, carbonaceous aerosols, inorganic compounds, etc.) and CH4 are important issues highlighted by the Gothenburg Protocol review process;").

[1182] EMEP Steering Body & the Working Group on Effects (29 September 2022) *Strategy for scientific bodies under the Convention on Long-range Transboundary Air Pollution*, ECE/EB.AIR/2022/10, at ¶ 93 ("Linking the scales in integrated assessment modelling: echoing the atmospheric modelling priorities, extending the GAINS model to enable assessment of the cost effectiveness of additional local and hemispheric measures to reduce O_3 and PM levels in the ECE region. At the local scale, work will continue with the Expert Panel on Clean Air in Cities to develop nested control strategies. At the global scale, linking the scale also means taking into account the questions of CH_4 control strategies and the evaluation of the impacts and cost effectiveness of global and regional CH_4 measures to reduce O_3 levels in the ECE region.").

[1183] Task Force on Techno-economic Issues (12 June 2023) *Draft Guidance document on technical measures for reduction of methane emissions from landfill, the natural gas grid and biogas facilities*, ECE/EB.AIR/WG.5/2023/3, ¶ 1 ("The present draft Guidance document on measures for the reduction of methane (CH_4) emissions, developed by the Task Force on Techno-economic Issues, is aimed at supporting the Parties in reducing CH_4 emissions from the main non-agricultural sources. The Guidance document covers CH_4 emissions from municipal solid waste landfills, natural gas supply systems and biogas facilities. The document includes information on landfill gas emissions and techno-economic analyses of landfill gas collection and utilization systems. Furthermore, information on emissions from the natural gas grid and associated emissions along the entire value chain is addressed. Besides technical aspects of emission reduction through, for example, the application of zero-emitting pneumatic and compressor systems, more management measures, such as the reduction of maintenance emissions and inspection programmes, to identify non-intended fugitive emissions early on, also referred to as "leak detection and repair", are of key importance in reducing CH4 emissions from the natural gas supply system. An outlook on CH_4 emissions from biogas plants, which are also considered to be an important source of CH_4 emissions from technical applications, is also provided in the present document.").

[1184] Task Force on Reactive Nitrogen & Task Force on Techno-economic Issues (12 June 2023) *Co-mitigation of methane and ammonia emissions from agricultural sources: policy brief and guidance*, ECE/EB.AIR/WG.5/2023/5, 1 ("The present document was prepared by the Task Force on Reactive Nitrogen in cooperation with the Task Force on Techno-economic Issues in accordance with item 2.2.1 of the 2022–2023 workplan for the implementation of the Convention. It provides information on possible interactions between ammonia and methane mitigation measures and on considerations to be taken into account for simultaneous mitigation, as well as serving as a background document for future policy development.").

[1185] Executive Body (2023) *Draft decisions of the Executive Body*, ECE/EB.AIR/2023/4, Preamble, ¶ 2 (d) ("The Executive Body, … Acknowledging that global methane reduction (in addition to methane, nitrogen oxides and volatile organic compound control in the United Nations Economic Commission for Europe (ECE) region) will be needed to reduce ground-level ozone in the ECE region, … Also decides that the revision process could include consideration of, inter alia: … How to address methane emissions;").

[1186] Expert Group on Policy Option Development (22 September 2023) *Options to address the conclusions of the review of the Gothenburg Protocol, as amended in 2012*, ECE/EB.AIR/2023/9, ¶ 10 ("Two pathways for revisions have been identified: the first is through revision of annexes IV–XI to the Protocol only, as amendments thereto may become effective within one year of adoption for those Parties that have accepted the expedited amendment procedure pursuant to article 13 bis (6)–(7) of the Protocol regarding amendments to annexes IV–XI, which shall be adopted by consensus of the Parties present at a session of the Executive Body; and the second is a comprehensive revision of the Protocol text and all its annexes."), ¶ 14 ("This approach could include one or more new binding and/or non-binding instrument(s) or measure(s), or a combination thereof. A new instrument could be considered to replace or complement the amended Gothenburg Protocol (i.e. a new kind of multipollutant protocol and/or a complementary instrument for a specific pollutant (i.e. CH4). Under this approach, there are binding and non-binding options, some of which have overlaps with approaches 1–2 and 4."), ¶ 17 ("Regardless of which approach or options are chosen, capacity-building, awareness- raising, cooperation and other support are cross-cutting efforts that could be continued and/or expanded to help to further address the Gothenburg Protocol review's conclusions and long term Convention objectives. This is a flexible approach that includes actions that could be initiated in the short-term, sustained in the long-term, and adjusted to best serve the Convention's objectives. These activities could be tailored to and combined with any other approach (and/or options within the other approaches) presented in this document."), ¶ 18 ("The level of complexity, effort, timeline and resources required for this approach would depend largely on the number of activities selected and the extent to which the Executive Body would like to increase capacity-building, outreach and cooperation under the Convention. Selection of this approach would also require further discussion on the resources required and on who would be responsible for each action (e.g., the secretariat, the Chair of the Executive Body, task forces, Convention Parties, etc.). Political will would be important for the success of actions in cross-cutting approach 4. A visible political Executive Body decision could help to generate political will in support of expanded capacity-building and cooperation.").

[1187] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*.

[1188] United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO2 Greenhouse Gases*, Fact Sheet ("*The United States, People's Republic of China, and United Arab Emirates today convened a Summit to accelerate actions to cut methane and other non-CO2 greenhouse gases as the fastest way to reduce near-term warming and keep a goal of limiting global average temperature increase to 1.5 degrees Celsius within reach.").*

[1189] United States White House (21 April 2023) *Chair's Summary of the Major Economies Forum on Energy and Climate Held by President Joe Biden*, Statements and Releases ("Argentina, Australia, Brazil, Canada, People's Republic of China, Egypt, the European Commission, France, Germany, India, Indonesia, Italy, Japan, the Republic of Korea, Mexico, the Kingdom of Saudi Arabia, Türkiye, the United Arab Emirates, the United Kingdom, the United Nations Secretary General, and the International Energy Agency Director participated in the virtual meeting." "MEF participants Canada, the European Union, France, Germany, Japan, and the United States, as well as Ireland and Norway, joined in launching the Methane Finance Sprint, which aims to scale up methane finance. This includes mobilizing, by COP 28, at least $200 million in new public and philanthropic support for methane abatement activities, with a view to developing a pipeline of projects. Philanthropies have committed $100 million in new funding through the Global Methane Hub towards the $200 million goal.")

[1190] United States White House (8 June 2013) *United States and China Agree to Work Together on Phase Down of HFCs*, Press Release ("Today, President Obama and President Xi agreed on an important new step to confront global climate change. For the first time, the United States and China will work together and with other countries to use the expertise and institutions of the Montreal Protocol to phase down the consumption and production of hydrofluorocarbons (HFCs), among other forms of multilateral cooperation. A global phase down of HFCs could potentially reduce some 90 gigatons of CO2 equivalent by 2050, equal to roughly two years' worth of current global greenhouse gas emissions."). *See also* Sun X. & Ferris T. (2018) *The Kigali Amendment's and China's Critical Roles in Evolving the Montreal Protocol*, Natural Resources & Environment, American Bar Association ("China filled a key role in bringing about the global consensus that resulted in the Kigali Amendment's adoption. U.S. and China agreements reflected this diplomatic leadership, initially during the meeting between President Obama and President Xi in Sunnylands, California.").

[1191] Hunter D., Salzman J., & Zaelke D. (2021) INTERNATIONAL ENVIRONMENTAL LAW AND POLICY, Foundation Press, (6th Ed.), 545 ("With 24 nations and the EU signing in Montreal, the Protocol was universally hailed as a diplomatic triumph. Starting from low or no expectations in Vienna, within eighteen months strict international controls had been negotiated that would be refined and changed over time with the benefit of more scientific and technical knowledge. This structured evolution, employing first a framework convention followed by a protocol, marked a new feature of international environmental law following the "start and strengthen" strategy put forward by UNEP Executive Director Mostafa Tolba, who is often referred to as the father of the Montreal Protocol."); *see also* Andersen S. O., Zaelke D., Taddonio K., Ferris R., & Sherman N. (2021) *Ozone Layer, International Protection*, *in*

MAX PLANCK ENCYCLOPEDIA OF PUBLIC INTERNATIONAL LAW, Oxford University Press, Peters A. & Wolfrum R. (eds.).

[1192] United States White House (15 November 2023) *Readout of President Joe Biden's Meeting with President Xi Jinping of the People's Republic of China*, Press Release ("The two leaders underscored the importance of working together to accelerate efforts to tackle the climate crisis in this critical decade. They welcomed recent positive discussions between their respective special envoys for climate, including on national actions to reduce emissions in the 2020s, on common approaches toward a successful COP 28, and on operationalizing the Working Group on Enhancing Climate Action in the 2020s to accelerate concrete climate actions. President Biden stated that the United States stands ready to work with the PRC to address transnational challenges, such as health security and debt and climate finance in developing countries and emerging markets.").

[1193] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("4. The United States and China decide to operationalize the Working Group on Enhancing Climate Action in the 2020s, to engage in dialogue and cooperation to accelerate concrete climate actions in the 2020s. The Working Group will focus on the areas of cooperation that have been identified in the Joint Statement and the Joint Declaration, including on energy transition, methane, circular economy and resource efficiency, low-carbon and sustainable provinces/states & cities, and deforestation, as well as any agreed topics. … 6. Both countries support the G20 Leaders Declaration to pursue efforts to triple renewable energy capacity globally by 2030 and intend to sufficiently accelerate renewable energy deployment in their respective economies through 2030 from 2020 levels so as to accelerate the substitution for coal, oil and gas generation, and thereby anticipate post-peaking meaningful absolute power sector emission reduction, in this critical decade of the 2020s. 7. Both sides agree to restart the U.S.-China Energy Efficiency Forum to deepen policy exchanges on energy-saving and carbon-reducing solutions in key areas including industry, buildings, transportation, and equipment. 8. The United States and China intend to recommence bilateral dialogues on energy policies and strategies, carry out exchanges on mutually agreed topics, and facilitate track II activities to enhance pragmatic cooperation. 9. The two countries aim to advance at least 5 large-scale cooperative CCUS projects each by 2030, including from industrial and energy sources. … 24. Both countries are committed to working with each other and with other Parties to adopt a consensus Global Stocktake decision. In the view of both countries, the decision … should take account of equity and be informed by the best available science, including the most recent IPCC reports; … should send signals with respect to the energy transition (renewable energy, coal/oil/gas), carbon sinks including forests, non-CO2 gases including methane, and low-carbon technologies, etc.").

[1194] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("4. The United States and China decide to operationalize the Working Group on Enhancing Climate Action in the 2020s, to engage in dialogue and cooperation to accelerate concrete climate actions in the 2020s. The Working Group will focus on the areas of cooperation that have been identified in the Joint Statement and the Joint Declaration, including on energy transition, methane, circular economy and resource efficiency, low-carbon and sustainable provinces/states & cities, and deforestation, as well as any agreed topics. … 10. The two countries will implement their respective national methane action plans and intend to elaborate further measures, as appropriate. 11. The two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress. 12. The two countries intend to cooperate on respective measures to manage nitrous oxide emissions. 13. The two countries intend to work together under the Kigali Amendment to phase down HFCs and commit to ensure application of ambitious minimum efficiency standards for all cooling equipment manufactured.").

[1195] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("14. Recognizing the importance of developing circular economy and resource efficiency in addressing the climate crisis, relevant government agencies of the two countries intend to conduct a policy dialogue on these topics as soon as possible and support enterprises, universities, and research institutions of both sides to engage in discussions and collaborative projects. 15. The United States and China are determined to end plastic pollution and will work together and with others to develop an international legally binding instrument on plastic pollution, including the marine environment.”).

[1196] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* (“20. Both countries intend to cooperate in promoting relevant policies and measures and the deployment of technologies to enhance synergy of controlling GHG emissions and air pollutants, including NOx, VOCs, and other tropospheric ozone precursors.”).

[1197] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* (“16. The United States and China will support climate cooperation among states, provinces, and cities with regard to areas including, inter alia, the power, transportation, buildings, and waste sectors. … 17. The United States and China intend to hold a high-level event on subnational climate action in the first half of 2024. 18. Both sides welcome with appreciation existing subnational cooperation between the two countries and encourage states, provinces, and cities to promote practical climate cooperation.”).

[1198] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* (“19. Both sides commit to advance efforts to halt and reverse forest loss by 2030, including by fully implementing through regulation and policy, and effectively enforcing, their respective laws on banning illegal imports. They intend to engage in discussions and exchanges, including under the Working Group, on ways to improve efforts to strengthen implementation of this commitment.”).

[1199] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* (“21. Reaffirming the nationally determined nature of NDCs, and recalling Article 4.4 of the Paris Agreement, both countries’ 2035 NDCs will be economy-wide, include all greenhouse gases, and reflect the reductions aligned with the Paris temperature goal of holding the increase in global average temperature to well below 2 degrees C and pursuing efforts to limit the temperature increase to 1.5 degrees C.”).

[1200] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* (“3. The United States and China … stress the importance of COP 28 in responding meaningfully to the climate crisis during this critical decade and beyond. They are aware of the important role they play in terms of both national responses and working together cooperatively to address the goals of the Paris Agreement and promote multilateralism. They will work together and with other Parties to the Convention and the Paris Agreement to rise up to one of the greatest challenges of our time for present and future generations of humankind.”).

[1201] China Ministry of Ecology and Environment, Ministry of Foreign Affairs, National Development and Reform Commission, Ministry of Science and Technology, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Natural Resources, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture and Rural Affairs, Ministry of Emergency Management, and National Energy Administration, *China Methane Emissions Control Plan* [甲烷排放控制行动方案] (7 November 2023) (hyperlink to original Chinese). *See also* Institute for Governance & Sustainable Development, annotated English reference translation of the China Methane Emissions Control Plan (8 November 2023).

[1202] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* (“22. The United States and China, with the United Arab Emirates, invite countries to a Methane and Non-CO2 Greenhouse Gases Summit at COP 28.”).

[1203] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Press Release (“2. The United States and China, alarmed by reports including the

Working Group I Contribution to the IPCC Sixth Assessment Report released on August 9th, 2021, further recognize the seriousness and urgency of the climate crisis. They are committed to tackling it through their respective accelerated actions in the critical decade of the 2020s, as well as through cooperation in multilateral processes, including the UNFCCC process, to avoid catastrophic impacts.").

[1204] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Press Release ("8(C)(II). In addition to its recently communicated NDC, China intends to develop a comprehensive and ambitious National Action Plan on methane, aiming to achieve a significant effect on methane emissions control and reductions in the 2020s.").

[1205] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Press Release ("8(D). The United States and China intend to convene a meeting in the first half of 2022 to focus on the specifics of enhancing measurement and mitigation of methane, including through standards to reduce methane from the fossil and waste sectors, as well as incentives and programs to reduce methane from the agricultural sector.").

[1206] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Press Release ("16. The two sides intend to establish a 'Working Group on Enhancing Climate Action in the 2020s,' which will meet regularly to address the climate crisis and advance the multilateral process, focusing on enhancing concrete actions in this decade. This may include, inter alia, continued policy and technical exchanges, identification of programs and projects in areas of mutual interest, meetings of governmental and non-governmental experts, facilitating participation by local governments, enterprises, think tanks, academics, and other experts, exchanging updates on their respective national efforts, considering the need for additional efforts, and reviewing the implementation of the Joint Statement and this Joint Declaration.").

[1207] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Press Release ("15. Both countries intend to communicate 2035 NDCs in 2025.").

[1208] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("21. Reaffirming the nationally determined nature of NDCs, and recalling Article 4.4 of the Paris Agreement, both countries' 2035 NDCs will be economy-wide, include all greenhouse gases, and reflect the reductions aligned with the Paris temperature goal of holding the increase in global average temperature to well below 2 degrees C and pursuing efforts to limit the temperature increase to 1.5 degrees C.").

[1209] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Press Release ("In addition to its recently communicated NDC, China intends to develop a comprehensive and ambitious National Action Plan on methane, aiming to achieve a significant effect on methane emissions control and reductions in the 2020s.").

[1210] China Ministry of Ecology and Environment, Ministry of Foreign Affairs, National Development and Reform Commission, Ministry of Science and Technology, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Natural Resources, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture and Rural Affairs, Ministry of Emergency Management, and National Energy Administration, *China Methane Emissions Control Plan* [甲烷排放控制行动方案] (7 November 2023) (hyperlink to original Chinese); *see also* Institute for Governance & Sustainable Development, annotated English reference translation of the China Methane Emissions Control Plan (8 November 2023).

[1211] At COP27, China Special Envoy on Climate Change, Xie Zhenhua, announced that China "attaches great importance to methane" emissions reduction and has completed a draft National Action Plan on strictly controlling methane emissions from key sectors, including energy (oil, gas, and coal), agriculture, and waste. In separate remarks provided at the Global Methane Pledge Ministerial on 17 November 2022, at the invitation of U.S. Presidential Climate Envoy John Kerry, Xie noted that the Plan is currently undergoing administrative and legislative processes (necessary before the Plan's public release). At the time, Special Envoy Xie also mentioned that China's ability to control methane emissions remained "relatively weak," and the plan focuses on preliminary goals like improving monitoring capabilities and measurement, reporting, and verification (MRV) mechanisms, and promoting resource utilization efficiency. *See* World Bank (8 November 2022) *It's Time to Sprint: Targeting Methane Emissions* (COP27 Side Event). In early January 2023, China's Ministry of Ecology and Environment (MEE) announced progress that on laying the foundation for a National Action Plan on methane. In particular, MEE described work on greenhouse gas data access and monitoring and evaluation pilot projects, including pilot projects exploring preliminary technical methodologies for methane emissions data access and analysis. *See* Institute for Governance & Sustainable Development (17 January 2023) *China Announces Progress in Methane Monitoring and Evaluation In Preparation for the Release of Its National Action Plan on Methane* ("China's Ministry of Ecology and Environment (MEE) highlighted progress on carbon dioxide and other greenhouse gas monitoring and evaluation pilot projects aimed at answering critical questions on 'what to measure,' 'where to measure,' and 'how to measure.' This includes pilot projects exploring preliminary technical methodologies for methane leakage detection. In particular, MEE noted that the oil and gas industry pilots have established a methane leakage detection mechanism by implementing an integrated "satellite + unmanned aerial vehicle + cruise" monitoring system for tracking methane leakage in production processes. For the coal mining industry pilots, MEE observed that a collaborative methane emissions monitoring technology has been developed using existing coal mine safety monitoring systems. Last but not least, MEE commented that it has established a preliminary understanding of the concentrations and the spatial and temporal distributions of global methane emissions through analysis of satellite remote sensing data.").

[1212] People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, submission to the Secretariat of the UNFCCC. *See also* Institute for Governance & Sustainable Development (28 October 2021) *Ahead of COP 26, China Submits Update to NDC and Mid-Century Development Strategy* (listing actions to address non-CO2 greenhouse gases (GHGs) incorporated into China's updated NDCs.).

[1213] European Parliament (21 October 2021) *Resolution on an EU strategy to reduce methane emissions*, 2021/2006 (INI) ("The European Parliament 'calls on the Commission and the Member States to suggest and negotiate a binding global agreement on methane mitigation at the COP26 meeting in Glasgow in line with the modelled pathways that limit global warming to 1,5°C from the IPCC 1,5°C Special Report, the IPCC Sixth Assessment Report and the UNEP Global Methane Assessment. . . .' It also '[p]oints to the lack of global leadership on the mitigation of methane emissions, with very little action being taken on methane internationally; calls on the Commission to make methane emissions reduction a top priority in its climate diplomacy and to take action, notably through a UN-based pathway, within the framework of the EU's diplomatic and external relations in order to spearhead an international agreement on methane mitigation, promoting coordinated action to reduce methane emissions, as well as updating methane mitigation requirements . . . .'").

[1214] *See for example* United Nations Environment Assembly (2022) *End plastic pollution: towards an international legally binding instrument*; United Nations General Assembly (2023) *Draft agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction*; United Nations Environment Program (4 November 2023) *Minamata Convention COP-5 takes crucial steps in its mission of eliminating mercury pollution*; United Nations Economic Commission for Europe (15 December 2023) *Governments in Europe and North America agree to revise Gothenburg Protocol to avoid long-term damage from air pollution to health, ecosystems, yields and climate*; Climate Overshoot Commission (2023) REDUCING THE RISKS OF CLIMATE OVERSHOOT, 59 ("To supplement a fossil fuel phase-out, efforts to control short-lived climate pollutants should be boosted substantially, to reduce near-term warming and improve public health. Measures to reduce emissions of some hydrofluorocarbons, methane, and black carbon, including the Kigali Amendment to the Montreal Protocol and the Global Methane Challenge, should be strongly supported including through policy frameworks. Methane reduction options that should be promoted include methane fees, feed additives for livestock, upgrading pipelines, and capturing methane from extractive and agricultural activities."); *and* Parson E. (21 September 2023) *A Radical Proposal Hidden in Plain Sight in the Overshoot Commission Report*, LEGAL PLANET ("Third, the proposal is modeled on, and adopts a few key design elements from the extraordinarily successful provisions of the Montreal Protocol to cut CFCs and other ozone-depleting chemicals. Picking up these elements invokes the powerful symbolism of the only global environmental regime to have achieved a socio-technological transformation of remotely the scale required for greenhouse gases. In addition, and more concretely, these elements give credibility and force to the proposal, because they are the main points that enabled the Montreal Protocol to achieve what many thought impossible, and do it faster than even the most optimistic expected. There is a lot to unpack in the parallels between the Commission's proposal and the Montreal Protocol, far too much to do justice to in one post. And there are some real problems in porting the model from ozone-depleting chemicals to fossil-fuels, which will need serious effort to work out and may ultimately turn out to be unresolvable. But there are good reasons to hope that with creative design and strategy, these elements may be transportable. To the extent they are, they may make the proposal something that governments actually can do – and thus hold the promise of driving bigger and faster changes than any mitigation proposal currently being considered.").

[1215] United Nations Framework Convention on Climate Change (2023) *First global stocktake, Proposal by the President Draft decision -/CMA.5 Outcome of the first global stocktake*, S28 ("Further recognizes the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on Parties to contribute to the following global efforts, in a nationally determined manner, taking into account the Paris Agreement and their different national circumstances, pathways and approaches."). For a brief overview of the key takeaways of COP28, *see* Chandrasekhar A., *et al*. (15 December 2023) *COP28 DeBriefed*, CARBONBRIEF.

[1216] United Nations Framework Convention on Climate Change (2023) *First global stocktake, Proposal by the President Draft decision -/CMA.5 Outcome of the first global stocktake*, S28(f) ("Accelerating and substantially reducing non-carbon-dioxide emissions globally, including in particular methane emissions by 2030.").

[1217] Climate & Clean Air Coalition (9 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO2 Super Pollutant Greenhouse Gases* ("As CCAC High-level Advocate for Finance Rachel Kyte, who moderated the session, said in her closing: "It's 2023. With peak oil, peak coal, and peak emissions, we are also 'peak-pledge'." This Coalition has proven to turn ambition into action, it set out as the Coalition of the Working."). *See also* Mckenna P. (4 December 2023) *Government, Corporate and Philanthropic Interests Coalesce On Curbing Methane Emissions as Calls at COP28 for Binding Global Methane Agreement Intensify*, INSIDE CLIMATE NEWS ("Durwood Zaelke, president of the Institute for Governance and Sustainable Development, a climate advocacy organization based in Washington, pushed for mandatory action. "We can't catch up to solve the climate problem without realizing that voluntary measures are now unbelievably naive," Zaelke said, noting that past pledges from the oil and gas industry have failed to curb methane emissions. "We've got to toughen up and demand mandatory measures starting with the fossil fuel industry."). *See generally* (30 November 2023) *What the world must do to tame methane*, THE ECONOMIST.

[1218] Velders G. J. M., Andersen S. O., Daniel J. S., Fahey D. W., & McFarland M. (2007) *The importance of the Montreal Protocol in protecting climate*, PROC. NAT. ACAD. SCI. 104(12): 4814–4819, 4816 ("In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 $GtCO_2$-eq yr^{-1} in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO_2.").

[1219] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989). For a discussion of the Montreal Protocol on Substances that Deplete the Ozone Layer, *see generally* Miller A. S., Zaelke D., & Andersen S. O. (2021) RESETTING OUR FUTURE: *CUT SUPER CLIMATE POLLUTANTS NOW! THE OZONE TREATY'S URGENT LESSONS FOR SPEEDING UP CLIMATE ACTION*, John Hunt Publishing; *and* Andersen S., Zaelke D., Taddonio K., Ferris R., & Sherman N. (2021) *Ozone Layer, International Protection*, *in* MAX PLANCK ENCYCLOPEDIA OF PUBLIC INTERNATIONAL LAW, Oxford University Press, Peters A. & Wolfrum R. (eds.).

See also Zaelke, D., Bledsoe P., Dreyfus G. (9 November 2022) *COP27: A global methane agreement can prevent climate catastrophe*, THE HILL; *and* Zaelke D. & Murphy A. (16 December 2022) *A global methane agreement can prevent climate chaos*, ONE EARTH.

[1220] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989). *See also* United Nations General Assembly (1992) REPORT OF THE UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT (Rio Declaration on Environment and Development), A/CONF.151/26 (Vol. I), Principle 7 ("States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem. In view of the different contributions to global environmental degradation, States have common but differentiated responsibilities. The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command."); *and* (9 May 1992) United Nations Framework Convention on Climate Change, 1771 U.N.T.S. 107, 31 I.L.M. 849, Art. 3(1) ("The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.").

[1221] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989).

[1222] Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer (1990) Decision II/8: Financial Mechanism. *See also* Miller A. S., Zaelke D., & Andersen S. O. (2021) RESETTING OUR FUTURE: *CUT SUPER CLIMATE POLLUTANTS NOW! THE OZONE TREATY'S URGENT LESSONS FOR SPEEDING UP CLIMATE ACTION*, John Hunt Publishing, 83 ("The Multilateral Fund is replenished every three years by the developed countries, most recently at around $550 million. The fund has been extremely cost-effective. Considering only the climate benefits, the Multilateral Fund has reduced CO_2 at a cost of less than $0.10 a ton.").

[1223] United Nations Environment Programme, *National Ozone Officers' Capacity Building* (*last visited* 5 February 2023) ("Since 1991, UN Environment OzonAction has devoted itself to supporting and strengthening National Ozone Units in all 147 developing countries. The Compliance Assistance Programme (CAP) uses a participatory approach that draws on the experience of numerous NOOs, guidance from international agencies and individual experts. UN Environment promotes learning and skill growth through sharing the collective wisdom of the wider community of Ozone Officers who are leading National Ozone Units.").

[1224] United Nations Environment ProgrammeOzone Secretariat, *Scientific Assessment Panel (SAP)* (*last visited* 5 February 2023) ("The Scientific Assessment Panel (SAP) assesses the status of the depletion of the ozone layer and relevant atmospheric science issues. Pursuant to Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer, a report is prepared every three or four years by the SAP which consists of hundreds of top scientists from around the world.").

[1225] United Nations Environment Programme Ozone Secretariat, *Technical and Economic Assessment Panel* (*last visited* 5 February 2023) ("In 1990 the Technology and Economic Assessment Panel was established as the technology and economics advisory body to the Montreal Protocol Parties. The Technology and Economic Assessment Panel (TEAP) provides, at the request of Parties, technical information related to the alternative technologies that have been investigated and employed to make it possible to virtually eliminate use of Ozone Depleting Substances (such as CFCs and halons), that harm the ozone layer.").

[1226] Parson E. (2006) *Chapter 11: Ground for Hope: Assessing Technological Options to Manage Ozone Depletion*, *in* ASSESSMENTS OF REGIONAL AND GLOBAL ENVIRONMENTAL RISKS: DESIGNING PROCESSES FOR THE EFFECTIVE USE OF SCIENCE IN DECISIONMAKING, Resources for the Future, Farrell A. & Jager J. (eds.), 231 ("A series of design decisions made in these initial consultations were decisive for the subsequent effectiveness of the panels. Most importantly, organizational decisions made in the interests of fast work had the effect of substantially reducing the political control over the panels from what was originally envisioned in Protocol negotiations. Rather than authorizing a political body to supervise and integrate the work ... each of these four groups operated with substantial independence under its chair.”). *See also* Kuijpers L., Tope H., Banks J., Brunner W., & Woodcock A. (1998) *Scientific Objectivity, Industrial Integrity, and the TEAP Process*, *in* PROTECTING THE OZONE LAYER: LESSONS, MODELS, AND PROSPECTS, Springer, Le Prestre P. G., Reid J. D., & Morehouse E. T. (eds.), 167 (“The principles of scientific objectivity and industrial integrity are critical to the TEAP’s ability to provide useful policy-relevant, technical information to the Parties to the Montreal Protocol. … Reports are developed through a consensus approach and this leads to the quality technical data on which the parties can rely. … In many cases members are drawn from industry with direct experience in the use of ODS and their alternatives. It is important to have individuals with the integrity to remain independent despite the funding they receive from their sponsoring organisations or companies.”).

[1227] (22 March 1985) Vienna Convention for the Protection of the Ozone Layer, 26 I.L.M. 1516 (entered into force 22 September 1988) (“The Vienna Convention, among other things, provides that: Parties shall take appropriate measures in accordance with the provisions of this Convention and of those protocols in force to which they are party to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer. Article 2(1). To this end the Parties shall, in accordance with the means at their disposal and their capabilities: a. Co-operate by means of systemic observations, research and information exchange in order to better understand and assess the effects of human activities on the ozone layer and the effects on human health and the environment from modification of the ozone layer; b. Adopt appropriate legislative or administrative measures and co-operate in harmonizing appropriate policies to control, limit, reduce or prevent human activities under their jurisdiction or control should it be found that these activities have or are likely to have adverse effects resulting from modification or likely modification of the ozone layer; c. Co-operate in the formulation of agreed measures, procedures and standards for the implementation of this Convention, with a view to the adoption of protocols and annexes; d. Co-operate with competent international bodies to implement effectively this Convention and protocols to which they are party.”).

[1228] Miller A. S., Zaelke D., & Andersen S. O. (2021) RESETTING OUR FUTURE: *CUT SUPER CLIMATE POLLUTANTS NOW! THE OZONE TREATY’S URGENT LESSONS FOR SPEEDING UP CLIMATE ACTION*, John Hunt Publishing, 82 (“The Montreal Protocol’s sectoral approach can be thought of as a series of frames or lenses to look at the other super climate pollutants and gain insights that can help change climate strategy—themes we explore in the concluding section of this chapter. Another benefit of a sectoral approach is that it can make it easier to address the challenge of keeping the playing field level for businesses. No company wants to be put at a competitive disadvantage because it is the only one following the rules. All the companies in a sector need to follow the rules and need to help police one another. The sectoral focus has allowed the Parties to develop the expertise they need to solve their specific part of the climate problem, and this has given them the confidence to strengthen their treaty continuously.”).

[1229] Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., & Field C. B. (2019) *Methane removal and atmospheric restoration*, NAT. SUSTAIN. 2: 436–438, 436 (“In contrast to negative emissions scenarios for CO_2 that typically assume hundreds of billions of tonnes removed over decades and do not restore the atmosphere to preindustrial levels, methane concentrations could be restored to ~750 ppb by removing ~3.2 of the 5.3 Gt of CH_4 currently in the atmosphere. Rather than capturing and storing the methane, the 3.2 Gt of CH_4 could be oxidized to CO_2, a thermodynamically favourable reaction.... In total, the reaction would yield 8.2 additional Gt of atmospheric CO_2, equivalent to a few months of current industrial CO_2 emissions, but it would eliminate approximately one sixth of total radiative forcing. As a result, methane removal or conversion would strongly complement current CO_2 and CH_4 emissions-reduction activities. The reduction in short-term warming, attributable to methane’s high radiative forcing and relatively short lifetime, would also provide more time to adapt to warming from long-lived greenhouse gases such as CO_2 and N_2O.”). Klaus Lackner critiqued the Jackson *et al.* article in a published response, arguing that implementing zeolite mechanisms to facilitate CH_4 removal is not practical. Lackner noted CH_4 removal faces the challenge of extreme dilution in the atmosphere, so “the amount of air that would need to be moved [to facilitate CH_4

removal] would simply be too great" to be economically feasible. However, Lackner did note passive methods of CH_4 removal through the use of zeolites may still be a viable solution. Lackner further argues that N_2O may be a more worthy target for removal due to its long lifetime in the atmosphere. *See* Lackner K. S. (2020) *Practical Constraints on Atmospheric Methane Removal*, NAT. SUSTAIN. 3: 357. Jackson *et al.* published a response to Lackner, acknowledging his stature in the greenhouse gas removal field and his concerns about the feasibility and energy requirements of their proposed mechanism, offering additional explanation about alternative options for use of the captured methane instead of just converting it to CO_2 as suggested in the original study. *See* Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., Field C. B., & Abernethy S. (2020) *Reply to: Practical constraints on atmospheric methane removal*, NAT. SUSTAIN. 3: 358–359. Another study looking at removing non-CO2 GHGs investigated the potential of using solar chimney power plants (SCPPs) with select photocatalysts (depending on what GHGs desired to be captured). While the SCPP serves as a source of renewable energy that could remove methane and nitrous oxide among other atmospheric pollutants, scaling up the prototype would require a massive amount of land area (roughly 23 times the size of the entire Beijing municipality) and a chimney stretching 1000–1500 m into the air, which limits how practical the existing technology may be. *See* de Richter R., Tingzhen M., Davies P., Wei L., & Caillol S. (2017) *Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis*, PROG. ENERGY COMBUST. SCI. 60: 68–96 ("Large-scale atmospheric removal of greenhouse gases (GHGs) including methane, nitrous oxide and ozone-depleting halocarbons could reduce global warming more quickly than atmospheric removal of CO_2. Photocatalysis of methane oxidizes it to CO_2, effectively reducing its global warming potential (GWP) by at least 90%."). *See also* Methane Action (16 April 2021) *Scientists' Statement on Lowering Atmospheric Methane Concentrations* ("To deal with methane emissions that can't otherwise be mitigated, to reduce the overall methane burden, and to get atmospheric methane levels to a range consistent with meeting climate goals, we must combine prevention and mitigation of new methane emissions with actively lowering the concentration of methane already in the atmosphere."); Jackson R. B. & Wysham D. (28 September 2021) *Focus on methane is timely and appropriate*, THE HILL; *and* Nisbet E. G., Dlugokencky E. J., Fisher R. E., France J. L., Lowry D., Manning M. R., Michel S. E., & Warwick N. J. (2021) *Atmospheric methane and nitrous oxide: challenges along the path to Net Zero*, PHILOS. TRANS. R. SOC. A 379(20200457): 1–24, 10 ("Methane potentially provides many good near-future (this decade) mitigation targets. Cutting methane emission is broadly cost-effective compared to methane removal from ambient air [94], though with appropriate technology in appropriate high methane settings, removal may indeed be an option [95,96]. Jackson et al. [97] point in particular to the need to more research into removal methods.").

[1230] Molina M., Zaelke D., Sarma K. M., Andersen S. O., Ramanathan V., & Kaniaru D. (2009) *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions*, PROC. NAT'L. ACAD. SCI. 106(49): 20616–20621, 20616 ("Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of 'dangerous anthropogenic interference' (DAI). Scientific and policy literature refers to the need for 'early,' 'urgent,' 'rapid,' and 'fast-action' mitigation to help avoid DAI and abrupt climate changes. We define 'fast-action' to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades."). *See also* Molina M., Ramanathan V. & Zaelke D. (2020) *Best path to net zero: Cut short-lived climate pollutants*, BULLETIN OF THE ATOMIC SCIENTISTS ("And let us be clear: By 'speed,' we mean measures—including regulatory ones—that can begin within two-to-three years, be substantially implemented in five-to-10 years, and produce a climate response within the next decade or two.").

[1231] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5777 ("Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit."). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 593 ("A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic...."); Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-71–TS-72 ("It is *likely* that under stabilization of global warming at 1.5°C, 2.0°C, or 3.0°C relative to 1850–1900, the AMOC will continue to weaken for several decades by about 15%, 20% and 30% of its strength and then recover to pre-decline values over several centuries (*medium confidence*). At sustained warming levels between 2°C and 3°C, there is limited evidence that the Greenland and West Antarctic Ice Sheets will be lost almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss increases with higher surface temperatures (*high confidence*). At sustained warming levels between 3°C and 5°C, near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet is projected to occur irreversibly over multiple millennia (*medium confidence*); with substantial parts or all of Wilkes Subglacial Basin in East Antarctica lost over multiple millennia (*low confidence*). Early-warning signals of accelerated sea-level-rise from Antarctica, could possibly be observed within the next few decades. For other hazards (e.g., ice sheet behaviour, glacier mass loss and global mean sea level change, coastal floods, coastal erosion, air pollution, and ocean acidification) the time and/or scenario dimensions remain critical, and a simple and robust relationship with global warming level cannot be established (*high confidence*). … The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with climate change (*high confidence*). It is *very unlikely* that gas clathrates (mostly methane) in deeper terrestrial permafrost and subsea clathrates will lead to a detectable departure from the emissions trajectory during this century. Possible abrupt changes and tipping points in biogeochemical cycles lead to additional uncertainty in 21st century atmospheric GHG concentrations, but future anthropogenic emissions remain the dominant uncertainty (*high confidence*). There is potential for abrupt water cycle changes in some high-emission scenarios, but there is no overall consistency regarding the magnitude and timing of such changes. Positive land surface feedbacks, including vegetation, dust, and snow, can contribute to abrupt changes in aridity, but there is only low confidence that such changes will occur during the 21st century. Continued Amazon deforestation, combined with a warming climate, raises the probability that this ecosystem will cross a tipping point into a dry state during the 21st century (*low confidence*)."); Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4-96 (Table 4.10 lists 15 components of the Earth system susceptible to tipping points); *and* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C.").

[1232] Intergovernmental Panel on Climate Change (2021) CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.); *and* Intergovernmental Panel on Climate Change (2022) CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.).

[1233] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS.

[1234] The Arctic Council has two working groups and two expert groups that work on controlling methane emissions. These two working groups, the Arctic Contaminants Action Program (ACAP) and Arctic Monitoring & Assessment Programme (AMAP), each have an SLCP-specific expert group: the Expert Group on Short-Lived Climate Pollutants (within ACAP) and the Expert Group on Black Carbon and Methane (within AMAP). *See* Arctic Council, *Black Carbon and Methane Expert Group* (*last visited* 5 February 2023); Arctic Council, *Arctic Contaminants Action Program* (*last visited* 5 February 2023); *and* Arctic Council, *AMAP and the Arctic Council* (*last visited* 5 February 2023).

[1235] Intergovernmental Panel on Climate Change (28 February 2022) *Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future*, NEWSROOM ("Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all, said [AR6 WGII co-chair] Hans-Otto Pörtner."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-11 ("Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). … Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*)."), SPM-13 ("SPM.B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*).").

[1236] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years.").

[1237] Climate & Clean Air Coalition (7 December 2023) *Opportunities for Increasing Ambition of NDCs Through Integrated Air Pollution and Climate Change Planning: Progress and Looking Ahead to 2025* ("As of November 2023, 95% of NDCs include methane within the scope of their overall mitigation target. The absolute number of NDCs including methane in their overall target has more than doubled, from 90 to 184. Forty countries (~20%) include methane as a supplementary target or assessment of the mitigation potential of the measure(s) identified, growing from a base of two in 2016. Most of the countries who include methane in this way (88%) are GMP partners.").

[1238] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("As of October 2023, it is estimated that over 90% of Nationally Determined Contributions (NDCs) cover methane emissions within the scope of their target. At the Ministerial, Special Presidential Envoy for Climate John Kerry issued a challenge to all governments to include all greenhouse gases from all sectors in their revised 2035 NDC target.").

[1239] United States White House (17 September 2021) *Meeting of the Major Economies on Energy and Climate September 17 2021: Chair's Summary*, Press Release ("Recognizing that methane is a powerful, short-lived climate pollutant that already accounts for about half of 1.0 degrees C of net warming to date, the Global Methane Pledge, an effort co-initiated by the United States and the European Union, will involve a collective goal of reducing global methane emissions by at least 30 percent below 2020 levels by 2030 and implementation of related domestic actions. There was broad recognition at the meeting of the importance of rapidly reducing methane emissions, and many MEF members, including the European Union, Argentina, Indonesia, Italy, Mexico, the United Kingdom, and the United States, declared their intention to join. It was reported that non-MEF countries, including Ghana and Iraq, have also signaled intent to join the Global Methane Pledge. These early supporters of the Pledge include six of the top 15 methane emitters globally and together account for over one-fifth of global methane emissions and nearly half of the global economy.").

[1240] United States White House (18 September 2021) *Joint US-EU Press Release on the Global Methane Pledge*, Statements and Releases ("The European Union and eight countries have already indicated their support for the Global Methane Pledge: Argentina / European Union / Ghana / Indonesia / Iraq / Italy / Mexico / United Kingdom / United States").

[1241] G20 (31 October 2021) *Rome Leaders' Declaration*, 8 ("We commit to significantly reduce our collective greenhouse gas emissions, taking into account national circumstances and respecting our NDCs. We acknowledge that methane emissions represent a significant contribution to climate change and recognize, according to national circumstances, that its reduction can be one of the quickest, most feasible and most cost-effective ways to limit climate change and its impacts. We welcome the contribution of various institutions, in this regard, and take note of specific initiatives on methane, including the establishment of the International Methane Emissions Observatory (IMEO). We will further promote cooperation, to improve data collection, verification, and measurement in support of GHG inventories and to provide high quality scientific data.").

[1242] (30 June 2021) Commission Regulation 2021/1119, 2021 O.J.L. 243, Art. 4(1) ("In order to reach the climate-neutrality objective set out in Article 2(1), the binding Union 2030 climate target shall be a domestic reduction of net greenhouse gas emissions (emissions after deduction of removals) by at least 55 % compared to 1990 levels by 2030.").

[1243] European Commission (14 October 2020) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU strategy to reduce methane emissions*, 16 ("As the largest importer of oil and gas, the EU has the leverage to promote energy-related methane emission reductions globally. Estimates show that the external carbon or methane emissions associated with EU fossil gas consumption (i.e. the emissions released outside the EU to produce and deliver fossil gas to the EU) are between three to eight times the quantity of emissions occurring within the EU. The Commission therefore intends to mobilise a coalition of key import countries to coordinate efforts on energy sector methane emissions. Moreover, the EU will leverage its leadership in the circular economy and its advanced agricultural practices that balance animal welfare with productivity to accelerate international action. The Commission will also support international data sharing on methane emissions through the foreseen international methane emissions observatory as well as by making EU satellite data available to global partners. In this way, the EU will lead by example in international collaboration on data sharing.").

[1244] (*amended* 4 May 2012) 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution ("Gothenburg Protocol"), ECE/EB.AIR/114, Art. 1(11 quarter) ("'Ozone precursors' means nitrogen oxides, volatile organic compounds, methane and carbon monoxide"); *and* Executive Body Working Group on Strategies and Review (30 September 2020) *Preparations for the review of* *the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012*, ECE/EB.AIR/2020/3 – EBE/EB.AIR/WG.5/2020/3, 20 ("As per the long-term strategy for the Convention for 2020–2030 and beyond (paragraph 50), the review should look at appropriate steps towards reducing emissions of black carbon, ozone precursors not yet addressed such as methane, and emissions from shipping with due consideration for International Maritime Organization (IMO) policies and measures.... In line with the priorities identified in the long-term strategy for the Convention for 2020–2030 and beyond, the following should specifically be considered in answering the questions in annex I: (b) Hemispheric transport of ozone and particulate matter and their precursors and advancing efforts to address air pollution on a broader scale per paragraphs 63 and 78 of the long-term strategy for the Convention for 2020–2030 and beyond; health and ecosystem impacts from outside the ECE region; I Methane and its relationship to the hemispheric transport of ozone and its contribution to ozone in the ECE region.").

[1245] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 15 ("Global and national strategies for cutting methane emissions need to be fleshed out, but the GMP provides a potential platform for discussion. Some countries will pursue pricing and others non-pricing approaches. Thus, operational methodologies for comparing efforts across countries need to be approved. Continued refinement of methane monitoring technologies is needed, particularly atmospheric measures that can better map readings to specific emission sources. Successful methane abatement programs, such as Norway's methane tax, need to be disseminated, along with the lessons that can be drawn for other countries. Financing would need to be part of an international agreement, given that mitigation costs would fall disproportionately on emerging market economies. Last, dialogue is needed on design issues for internationally coordinated mitigation regimes as well as strategies for advancing critical methane abatement technologies.").

[1246] Climate & Clean Air Coalition (9 November 2021) *Climate and Clean Air Coalition Ministers approve strategy to significantly cut short-lived climate pollutants this decade*, Press Release ("Ministers approved the implementation of a Methane Flagship, which, starting in 2022, will foster and strengthen high level commitments to reduce methane, amplify and raise awareness, support planning and delivery of strategies and plans, provide analysis and tools to support action, and scale up financing. There was strong and broad support for the recently launched Global Methane Pledge and ministers welcomed the CCAC having a leadership role in supporting its implementation.").

[1247] Climate & Clean Air Coalition, *National Planning and Policy Development* (*last visited* 1 February 2024) ("The CCAC helps countries develop national plans that integrate climate and clean air objectives through actions to reduce short-lived climate pollutants (SLCPs). To date, 15 countries have endorsed national SLCP plans. The full list of national plans can be found on our policy database.").

[1248] United Nations Environment Program, *Oil and Gas Methane Partnership 2.0, About OGMP 2.0*, ("The Oil & Gas Methane Partnership 2.0 (OGMP 2.0) is the United Nations Environment Programme's flagship oil and gas reporting and mitigation programme. OGMP 2.0 is the only comprehensive, measurement-based reporting framework for the oil and gas industry that improves the accuracy and transparency of methane emissions reporting. This is key to prioritising methane mitigation actions in the sector. If you can't measure it, you can't fix it.").

[1249] United States Department of State (2022) *Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels* ("The United States, European Union, Japan, Canada, Norway, Singapore, and the United Kingdom are committed to taking rapid action to address the dual climate and energy security crises that the world faces. We affirm the need to accelerate global transitions to clean energy, recognizing that reliance on unabated fossil fuels leaves us vulnerable to market volatility and geopolitical challenges. We also recognize that under IPCC 1.5°C-aligned scenarios, fossil fuel consumption will persist, at rapidly declining levels, as the global energy transition unfolds. As such, we emphasize that dramatically reducing methane, CO2, and other greenhouse gas emissions across the fossil fuel energy value chain is a necessary complement to global energy decarbonization in order to limit warming to 1.5°C.We commit to taking immediate action to reduce the greenhouse gas emissions associated with fossil energy production and consumption, particularly to reduce methane emissions. We emphasize that reducing methane and other greenhouse gas emissions from the fossil energy sector enhances energy security by reducing avoidable routine flaring, venting, and leakage that wastes natural gas. We also note that these measures will also improve health outcomes by eliminating black carbon and other associated air pollutants. We call on fossil energy importers to take steps to reduce the methane emissions associated with their energy consumption, which can spur emissions reductions across the value chain. We also call on fossil energy producers to implement projects and supporting policies and measures to achieve emissions reductions across fossil energy operations. We call for global action to reduce methane emissions in the fossil energy sector to the fullest extent practicable, with the aim to reduce warming by 0.1°C by midcentury, consistent with International Energy Agency findings of the near-term warming reduction effects of fully deploying technically feasible mitigation in this sector. We reaffirm the call to action under the Global Methane Pledge to reduce collective anthropogenic methane emissions by at least 30 percent from 2020 levels by 2030 as an essential strategy to reduce warming in the near term and keep a 1.5°C limit on temperature rise within reach. We recognize that the fossil energy sector must lead in rapid methane mitigation given the abundance of technically feasible and cost-effective mitigation measures available in the fossil energy sector, as called for in the Global Methane Pledge Energy Pathway. Recognizing the urgency of reducing emissions from fossil energy value chains, we commit to working towards the creation of an international market for fossil energy that minimizes flaring, methane, and CO2 emissions across the value chain to the fullest extent practicable, as we also work to phase down fossil fuel consumption. We support the development of frameworks or standards for fossil energy suppliers to provide accurate, transparent, and reliable information to purchasers about the methane and CO2 emissions associated with their value chains.”).

[1250] International Energy Agency (2 October 2023) *International Climate and Energy Summit in Madrid builds momentum behind efforts to reach 1.5 °C goal* (“Highlight the critical role of, and opportunity for, the fossil fuel industry to reduce methane emissions from their operations, with the aim of cutting them 75% by 2030.”).

[1251] United States Department of Energy (15 November 2023) *Public Announcement of International Working Group to Establish a Greenhouse Gas Supply Chain Emissions Measurement, Monitoring, Reporting, and Verification (MMRV) Framework for Providing Comparable and Reliable Information to Natural Gas Market Participants* (“Therefore, twelve countries, the European Commission and the East Mediterranean Gas Forum have formed a multi-national working group to develop a consensus- based approach for the measurement, monitoring, reporting and verification (MMRV) of GHG
emissions across the international supply chain from pre-production through final delivery to enable the provision of comparable and reliable information. Natural gas producers and exporters, importers and end users, governments, and other key stakeholders have made significant progress towards addressing this challenge through various measurement, reporting and verification protocols at local and international levels. A number of well-established domestic and international emissions reporting approaches already exist, our efforts are aimed at building on these existing approaches. This includes, but is not limited to, the United Nations Environmental Program’s Oil and Gas Methane Partnership 2.0 (OGMP 2.0). The MMRV Working Group will advance comparability by reviewing and building upon existing standards and protocols to provide a consistent set of technical criteria for reporting emissions and operating data at various levels of data availability. The approach will encourage and prefer measured data over modeled data and estimation of emissions, while balancing economic and technical feasibility. The MMRV Framework will also be technology neutral with respect to approaches for measurement of emissions. These actions will improve the accuracy and representativeness of the reported data. Comparability will be further supported by using transparent and consistent tools for estimating GHG supply chain emissions and data quality from pre-production through final delivery of the natural gas. To provide comparable and reliable information, the MMRV Working Group will support independent third-party verification of the accuracy and representativeness of the emissions data and the aggregate supply chain GHG emissions intensity. It will also support accreditation to ensure that certifiers are independent of the reporting entity and are technically qualified to
conduct reviews.”).

[1252] Dreyfus G. & Ferris T. (2023) *Metrics and Measurement of Methane Emissions*, *in* INNOVATIVE TECHNOLOGIES FOR GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION MONITORING, China Council for International Cooperation on Environment and Development, 22 (“This section on Metrics and Measurement of Methane Emissions focuses on oil and gas methane emissions and will help answer the following questions: Why is it important to accurately measure methane emissions What are the main sources of methane gas emissions, and do these sources pose particular measurement challenges? Are there known gaps in current methane measurement approaches? Are there current or emerging methane monitoring systems that can improve the accuracy and timeliness of emissions data?

[1253] Clausing K., Garicano L., & Wolfram C. (2023) *How an international agreement on methane emissions can pave the way for enhanced global cooperation on climate change*, Peterson Institute for International Economics, 2 ("Under the IRA, the United States has for the first time implemented a methane emissions fee as a backstop to new methane regulations in the oil and gas sectors. The European Union is also implementing new methane regulations on fossil energy, and the European Parliament proposal would penalize imports from countries that do not meet certain regulatory standards. Building on these parallel approaches, this Policy Brief proposes transatlantic coordination that uses an import charge as a lever to seek similarly ambitious regulatory reforms in the oil and gas sectors abroad. Specifically, oil and gas exporters can be encouraged to adopt regulations comparable to those in the United States and the European Union or, if they fail to implement regulations, pay a border adjustment fee on exports to the two jurisdictions. With time, most major energy importers would ideally join the coalition of countries cooperating on both stringent domestic regulations on oil and gas production (if applicable) and border adjustments on any dirty, nonregulating exporters."). *See also* Salata Institute for Climate and Sustainability (2023) METHANE AND TRADE: *PAVING THE WAY FOR ENHANCED GLOBAL COOPERATION ON CLIMATE CHANGE*, Research Brief ("As a first step, the United States, the European Union, and partner countries can work to coordinate their methane reduction policies, with an eye toward the eventual imposition of border adjustments on imports from countries that fail to raise their standards. The Biden administration could work with Congress on next steps for implementing a US methane border adjustment, while simultaneously leading efforts with the European Union, the G7, and other potential coalition members to develop a framework for a multilateral agreement. Ideally, a proposed framework could be presented at the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP28) in Dubai in late 2023.").

[1254] United States Department of State (10 November 2021) *U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, Media Note ("8. Recognizing specifically the significant role that emissions of methane play in increasing temperatures, both countries consider increased action to control and reduce such emissions to be a matter of necessity in the 2020s. To this end: A. The two countries intend to cooperate to enhance the measurement of methane emissions; to exchange information on their respective policies and programs for strengthening management and control of methane; and to foster joint research into methane emission reduction challenges and solutions.").

[1255] United States Department of State (14 November 2023*) Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis* ("10. The two countries will implement their respective national methane action plans and intend to elaborate further measures, as appropriate. 11. The two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress. 12. The two countries intend to cooperate on respective measures to manage nitrous oxide emissions. 13. The two countries intend to work together under the Kigali Amendment to phase down HFCs and commit to ensure application of ambitious minimum efficiency standards for all cooling equipment manufactured.").

[1256] Good K. (22 August 2022) *Drought Negatively Impacting China, the U.S. and Europe, as Ukrainian Black Sea Exports Continue*, Farm Policy News ("Parts of China are experiencing their longest sustained heat wave since record-keeping began in 1961, according to China's National Climate Center, leading to manufacturing shutdowns owing to lack of hydropower. The drought affecting Spain, Portugal, France and Italy is on track to be the worst in 500 years, according to Andrea Toreti, a climate scientist at the European Commission's Joint Research Center. In the American

West, a drought that began two decades ago now appears to be the worst in 1,200 years, according to a study led by the University of California, Los Angeles.”).

[1257] Environment and Climate Change Canada (2019) *Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)* (“Companies must register their facilities before April 30th, 2020, or within 120 days of when the facility begins to be covered by any of the requirements. There are also provisions in the regulations to retain information for record-keeping, inspection purposes, and for on-demand reporting to Environment and Climate Change Canada. Regulatory requirements for fugitive equipment leaks, venting from well completions, and compressors, come into force on January 1, 2020. Regulatory requirements for facility production venting restrictions and venting limits for pneumatic equipment come into force on January 1, 2023.”).

[1258]Government of Mexico Agency for Safety, Energy and Environment (6 November 2018) *DISPOSICIONES Administrativas de carácter general que establecen los Lineamientos para la prevención y el control integral de las emisiones de metano del Sector Hidrocarburos* (“Que la información disponible a nivel internacional y nacional ha demostrado que, implementando mejoras operativas y tecnológicas disponibles, es factible reducir las emisiones de metano en el Sector Hidrocarburos. En ese sentido, la Agencia Internacional de Energía en la publicación Perspectiva Mundial de la Energía 2017, concretamente en lo relativo al caso ambiental del gas natural, reconoce que, aplicando las mejores prácticas internacionales, tales como las que este instrumento regulatorio integra, es factible y posible que a nivel mundial el sector reduzca las emisiones de metano hasta en un 75%.”); *discussed in* Clean Air Task Force (13 November 2018) *Mexico Takes a Giant Leap Forward in Regulating Methane Emissions*, Press Release; *and* Del Rio D., Evangelista R., & Arrieta Maza M. (21 November 2018) *Mexico: Program For The Prevention And Comprehensive Management Of Methane Emissions Within The Hydrocarbon Sector ("PPCIEM")*, MONDAQ.

[1259] United States White House (10 January 2023) *Fact Sheet: Key Deliverables for the 2023 North American Leaders' Summit* (“The United States, Mexico, and Canada recognize the urgency for rapid, coordinated and ambitious measures to build clean energy economies and respond to the climate crisis. At the NALS, the three leaders committed to combatting the climate crisis by: Committing to reduce methane emissions from the solid waste and wastewater sector by at least 15% by 2030 from 2020 levels and deepen collaboration on waste and agriculture methane measurement and mitigation, including achieving the Global Methane Pledge through trilateral cooperation on methane and black carbon emissions.”). *See also* United States White House (29 June 2016) *Leaders' Statement on a North American Climate, Clean Energy, and Environment Partnership*, Statements and Releases (“Today, Mexico will join Canada and the United States in committing to reduce their methane emissions from the oil and gas sector – the world's largest industrial methane source – 40% to 45% by 2025, towards achieving the greenhouse gas targets in our nationally determined contributions. To achieve this goal, the three countries commit to develop and implement federal regulations to reduce emissions from existing and new sources in the oil and gas sector as soon as possible. We also commit to develop and implement national methane reduction strategies for key sectors such as oil and gas, agriculture, and waste management, including food waste. Finally, we pledge to continue collaborating with one another and with international partners as we commit to significant national actions to reduce black carbon emissions in North America, and promote alternatives to highly polluting hydrofluorocarbons.”).

[1260] Climate & Clean Air Coalition (12 January 2023) *Nigeria Cements Methane Guidelines, and its Role as an African Climate and Clean Air Leader: Nigeria is the first country in Africa to regulate methane emissions in the energy sector*.

[1261] Institute for Governance & Sustainable Development (2023) *China Methane Emissions Control Action Plan*.

[1262] United States White House (26 July 2023) *Biden-Harris Administration Hosts White House Methane Summit to Tackle Dangerous Climate Pollution, while Creating Good-Paying Jobs and Protecting Community Health* (“Today, the Biden-Harris Administration will convene the first ever White House Methane Summit around the urgent need to dramatically reduce methane emissions, especially from leaks in the oil and gas sector, as a way to protect public health, create good-paying jobs, save consumers money, and advance President Biden's ambitious climate agenda. The President's Investing in America agenda is accelerating adoption of technologies and tools to address methane emissions and helping the U.S. unlock a win-win opportunity for communities and the economy. Just this week, new analysis from the Blue Green Alliance found that full adoption of the Biden-Harris Administration's proposed leak-reducing actions will create 10,000 net direct and indirect jobs each year, in sectors like manufacturing, construction, and operations and maintenance.").

1263 European Parliament (7 May 2024) REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942 ("This Regulation lays down rules for the accurate measurement, quantification, monitoring, reporting and verification of methane emissions in the energy sector in the Union, as well as the reduction of those emissions, including through leak detection and repair surveys, repair obligations and restrictions on venting and flaring. This Regulation also lays down rules on tools ensuring transparency as regards methane emissions.").

1264 *See, e.g.*, Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities, Cal. Code Regs. Tit. 17, §§ 95665–95677.

1265 New Mexico Administrative Code (26 July 2022) *Venting and Flaring of Natural Gas*, NMAC 19.15.27.8; *discussed in* Evans B. (26 March 2021) *New Mexico regulator puts in place rule requiring operators to eliminate gas flaring*, S&P GLOBAL ("The New Mexico Oil Conservation Commission finalized the rules to eliminate venting and flaring at new and existing wells across the state on March 25. Routine flaring occurs when operators burn off gas produced from oil-directed wells instead of capturing it because of limitations in gathering and processing capacity. New Mexico joins Colorado in becoming the first states in the Lower 48 to end flaring."). *See also* New Mexico Environment Department (14 April 2022) *New Mexico adopts nationally leading oil and gas emissions rule*, Press Release ("After two and half years of collaborative public and stakeholder engagement, the Environmental Improvement Board (EIB) adopted new air quality rules that will eliminate hundreds of millions of pounds of harmful emissions annually from oil and gas operations in New Mexico. The new rule will improve air quality for New Mexicans by establishing innovative and actionable regulations to curb the formation of ground-level ozone. The new rule will reduce harmful emissions of ozone precursor pollutants – volatile organic compounds and oxides of nitrogen – by approximately 260 million pounds annually, and will have the co-benefit of reducing methane emissions by over 851 million pounds annually. Starting this summer, compliance obligations for new and existing oil and gas operations in New Mexico counties with high ozone levels will begin to take effect. These counties are Chaves, Doña Ana, Eddy, Lea, Rio Arriba, Sandoval, San Juan, and Valencia counties."); *and* State of New Mexico Environmental Improvement Board (2022) *Hearing Officer's Report*, 20.2.50 NMAC – Oil and Gas Sector – Ozone Precursor Pollutants (*discussing* the methane emissions reduction co-benefit of adopting mitigation measures for volatile organic compounds (VOCs) and nitrogen oxides (NOx) in the oil and gas sector).

1266 Drilling units - pooling interests, Colo. Rev. Stat. § 34-60-116 (2020) ("To prevent or to assist in preventing waste, to avoid the drilling of unnecessary wells, or to protect correlative rights, the commission, upon its own motion or on a proper application of an interested party, but after notice and hearing as provided in this section, may establish one or more drilling units of specified size and shape covering any pool or portion of a pool."). *See also* Venting or Flaring Natural Gas, 2 Colo. Code Regs. § 404-1-903 (2022).

1267 British Columbia (2021) CLEANBC: ROADMAP TO 2030, 51 ("With this Roadmap, we are committed to building on that research and applying it across the industrial sector to achieve our goal of zero emissions from methane – or as close to zero as possible – by 2035, and to reduce methane emissions in the oil and gas sector by 75% (compared to 2014) by 2030, consistent with the federal commitment. Methane from industrial wood waste landfills can be converted to less-harmful greenhouse gases through landfill management.").

1268 C40 Cities, *Waste Management* (*last visited* 5 February 2023) ("Waste disposal is responsible for 3-5% of the overall direct GHG emissions in cities and those are projected to increase from 1.12 billion tonnes today to 2.38 billion tonnes of CO_2e per year by 2050. 97% of those emissions are in the form of methane, an extremely powerful greenhouse gas and climate forcer, emitted when organic waste breaks down in open dumps or landfills without gas collection. Because methane is a short-lived greenhouse gas, reducing its emissions would see impact within this generation. This is a particularly urgent opportunity for Global South cities where the organics content of waste is highest, and action taken here will improve its economic development, reduce social and climate vulnerability, reduce operational and opportunity costs, while extending the operational lifetime of disposal sites.”).

[1269] Climate Group, Under2 Coalition, *Methane Project* (*last visited* 5 February 2023) (“A forum for state and regional governments to share effective ways to reduce methane emissions, beginning with a focus on the oil and gas sector.”).

[1270] California Air Resources Board (3 December 2023*) California launches methane-cutting effort with subnational governments at COP28* (“California officially kicked off a new international climate initiative that creates a partnership of subnational governments that are committed to reducing methane today at the United Nations Climate Change Conference (COP28) hosted in Dubai. The effort, which was initially announced in September during Climate Week, has expanded to 15 signatories, which include additions from Brazil, Canada, South Korea, Bolivia, Germany, Spain, and the United States. The Subnational Methane Action Coalition creates collaboration with jurisdictions that oversee and regulate key sources of methane such as agriculture, energy and landfills to share goals and best practices in reducing the short-lived climate pollutant that accounts for almost 30% of current global warming and is 80 times more potent than carbon dioxide over a 20-year period.”).

[1271] United Nations Environment Programme (31 October 2021) *Methane Observatory launched to boost action on powerful climate-warming gas*, Press Release (“IMEO will improve the reporting accuracy and public transparency of human-caused methane emissions. IMEO will initially focus on methane emissions from the fossil fuel sector, and then expand to other major emitting sectors like agriculture and waste.”).

[1272] World Bank, *GGFR to evolve to the Global Flaring & Methane Reduction Partnership* (*last visited* 1 February 2024) (“At COP28 the World Bank launched the Global Flaring and Methane Reduction (GFMR) Partnership, a new multi-donor trust fund focused on helping developing countries cut carbon dioxide and methane emissions generated by the oil and gas industry.GFMR will provide more than $250 million and mobilize billions from the private sector to support those countries with the least capacity and resources to address these emissions. The partnership will focus on providing grant funding, technical assistance, policy and regulatory reform advisory services, institutional strengthening, and mobilizing financing to support action by governments and operators.”).

[1273] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 1 (“Limiting global warming to 1.5 to 2°C above preindustrial levels requires rapid cuts in greenhouse gas emissions. This includes methane, which has an outsized impact on temperatures. To date, 125 countries have pledged to cut global methane emissions by 30 percent by 2030. This Note provides background on methane emission sources, presents practical fiscal policy options to cut emissions, and assesses impacts. Putting a price on methane, ideally through a fee, would reduce emissions efficiently, and can be administratively straightforward for extractives industries and, in some cases, agriculture. Policies could also include revenue-neutral ‘feebates’ that use fees on dirtier polluters to subsidize cleaner producers. A $70 methane fee among large economies would align 2030 emissions with 2oC. Most cuts would be in extractives and abatement costs would be equivalent to just 0.1 percent of GDP. Costs are larger in certain developing countries, implying climate finance could be a key element of a global agreement on a minimum methane price.”).

[1274] International Monetary Fund, *Resilience and Sustainability Trust* (*last visited* 12 March 2024) (“The IMF’s Resilience and Sustainability Trust (RST) helps low-income and vulnerable middle-income countries build resilience to external shocks and ensure sustainable growth, contributing to their longer-term balance of payments stability. It complements the IMF’s existing lending toolkit by providing longer-term, affordable financing to address longer-term challenges, including climate change and pandemic preparedness.”).

[1275] Global Methane Initiative, *About the Global Methane Initiative* (*last visited* 5 February 2023) ("Launched in 2004, the GMI is an international public-private initiative that advances cost-effective, near-term methane abatement and recovery and use of methane as a clean energy source in three sectors: biogas (including agriculture, municipal solid waste, and wastewater), coal mines, and oil and gas systems. Focusing collective efforts on methane emission sources is a cost-effective approach to reduce greenhouse gas (GHG) emissions and increase energy security, enhance economic growth, improve air quality and improve worker safety.").

[1276] Oil and Gas Climate Initiative, *About Us* (*last visited* 5 February 2023) ("OGCI member companies commit to: **Methane Intensity** -> By 2025, reduce the collective average methane intensity of aggregated upstream oil and gas operations to well below 0.20%, from a 2017 baseline of 0.30%. **Carbon Intensity** -> Reduce member companies' aggregate upstream carbon intensity from 23 kg of greenhouse gases per barrel of oil or gas in 2017 to 17 kg by 2025. **CCUS Kickstarter** -> By 2030, help to decarbonize multiple industrial hubs and kickstart a commercial CCUS industry that can have a significant impact on greenhouse gas emissions. **OGCI Climate Investments** -> Invest OGCI's $1B+ fund over a ten-year period to deliver a tangible impact on greenhouse gas emissions through accelerated innovation across the energy and industrial sectors. **Zero Routine Flaring** -> Support explicitly the aims of Zero Routine Flaring by 2030.").

[1277] MiQ, *The Methane Mission* (*last visited* 5 February 2023) ("To tackle methane emissions, companies need a granular understanding of where these are coming from, as well as robust methane mitigation practices and technology to enable them to actually address the issue. That's where MiQ comes in. MiQ has developed a global solution for a global issue, grading gas on methane emissions to drive change in parallel with regulation through a not-for-profit and independently audited certification standard. Why? Because differentiating producers based on their methane emissions performance will incentivise businesses to improve because it simply makes good climate – and business – sense.").

[1278] American Gas Association, *Natural Gas Sustainability Initiative (NGSI)* (*last visited* 5 February 2023) ("NGSI is a voluntary, industry-wide approach for companies to calculate methane emissions intensity by segment—the Methane Emissions Intensity Protocol (Protocol). This consistent, transparent and comparable method for measuring and reporting methane emissions throughout the natural gas supply chain will improve the quality of information available and will help companies more effectively identify ways to reduce methane emissions and communicate progress.").

[1279] *See* Kaniaru D., Shende R., & Zaelke D. (2008) *Landmark Agreement to Strength Montreal Protocol Provides Powerful Climate Mitigation*, SUSTAIN. DEV. LAW POL. 8(2): 46–50, 46 ("The HCFC agreement and its climate benefits were possible largely because of the Montreal Protocol's unique history of continuous adjustment to keep pace with scientific understanding and technological capability. The Parties to the Protocol generally regard the treaty as fair, due to its objective technical assessment bodies and its effective financial mechanism, the Multilateral Fund. These features and others have made the Protocol the world's most successful multilateral environmental agreement, phasing out ninety-five percent of global production of ozone-depleting substances in just twenty years and placing the ozone layer on a path to recovery."); *and* Parson E. (2006) *Chapter 11: Ground for Hope: Assessing Technological Options to Manage Ozone Depletion*, *in* ASSESSMENTS OF REGIONAL AND GLOBAL ENVIRONMENTAL RISKS: DESIGNING PROCESSES FOR THE EFFECTIVE USE OF SCIENCE IN DECISIONMAKING, Resources for the Future, Farrell A. & Jager J. (eds.), 228 ("Indeed, although technical option assessments have been less frequently undertaken, less frequently effective, and less prominent in policy debate than scientific assessments of environmental risk, [the case of the Montreal Protocol TEAP] suggests that they may hold far greater prospect for exercising decisive influence on policy debate and action to manage environmental risks—if the factors contributing to their strong influence in this case can be repeated elsewhere.").

[1280] Climate & Clean Air Coalition (2023) *Clean Air Flagship* ("At the Climate and Clean Air Ministerial 2022, CCAC Partners requested a new effort to achieve clean air across the world. At the Climate and Clean Air Ministerial 2023, the CCAC launched the "Clean Air Flagship" to mobilise the partnership and 'move the needle' on this important topic. It is aimed at: Saving lives: Supporting governments to achieve cleaner air as quickly as possible, consistent with improved WHO air quality interim targets. Slowing climate change: Taking full advantage of win-win opportunities to reduce the emissions of short-lived climate pollutants simultaneously with other harmful pollutants. Maximizing co-benefits: Improving agricultural productivity, economic development and the overall quality of life.").

[1281] Climate & Clean Air Coalition (2023) *Clean Air Flagship 2024-2026*, 6 ("Support science cooperation and information-sharing initiatives within the regional frameworks, especially with respect to tropospheric ozone, black carbon, and methane (See Annex 1).").

[1282] Climate & Clean Air Coalition (2023) *Clean Air Flagship 2024-2026*, 4 ("Strengthen and support regional and sub-regional cooperation and the implementation of political commitments to achieve the WHO Air Quality Guidelines and Global Methane Pledge.").

[1283] Climate & Clean Air Coalition (2023) BRIEF: SCALING UP UNDERFINANCED SLCP MITIGATION SOLUTIONS: DRIVING INNOVATION AND TECHNOLOGY IN THE WASTE SECTOR.

[1284] *See* Breitmeier H., Underdal A., & Young O. R. (2011) *The Effectiveness of International Environmental Regimes: Comparing and Contrasting Findings from Quantitative Research*, INT'L. STUD. REV. 13(4): 579–605, 584 ("Although the nature of the project makes it somewhat harder to tease out findings of a general nature about effectiveness, the overall message that AIER generates is that regimes frequently do matter; sometimes they matter a lot."); Miles E. L., Andresen S., Carlin E. M., Skjærseth J. B., Underdal A., & Wettestad J. (2001) ENVIRONMENTAL REGIME EFFECTIVENESS: CONFRONTING THEORY WITH EVIDENCE, MIT Press; *and* Breitmeier H., Young O. R., & Zürn M. (2006) ANALYZING INTERNATIONAL ENVIRONMENTAL REGIMES: FROM CASE STUDY TO DATABASE, MIT Press.

[1285] Weiss E. B. (2009) *Introductory Note on the Vienna Convention for the Protection of the Ozone Layer and Montreal Protocol on Substances that Deplete the Ozone Layer*, United Nations Audiovisual Library of International Law ("A working group under UNEP began negotiations on a protocol, and the Montreal Protocol was concluded in September, 1987, only nine months after the formal diplomatic negotiations opened in December, 1986. It went into effect on January 1, 1989.").

[1286] United Nations Environment Assembly (2 March 2022) *Draft Resolution: End plastic pollution: Towards an international legally binding instrument*, UNEP/EA.5/L.23/Rev.1 ("... Underlining that further international action is needed by developing an international legally binding instrument on plastic pollution, including in the marine environment, 1. Requests the Executive Director to convene an intergovernmental negotiating committee, commencing its work during the second half of 2022, with the ambition of completing its work by the end of 2024; 2. Acknowledges that some legal obligations arising out of a new international legally binding instrument will require capacity building and technical and financial assistance in order to be effectively implemented by developing countries and countries with economies in transition; 3. Decides that the intergovernmental negotiating committee is to develop an international legally binding instrument on plastic pollution, including in the marine environment henceforth referred to as the instrument, which could include both binding and voluntary approaches, based on a comprehensive approach that addresses the full lifecycle of plastic, taking into account among other things, the principles of the Rio Declaration on Environment and Development, as well as national circumstances and capabilities....").

[1287] Rosane P., Naran B., Pastor A. O., Connolly J., & Wignarajah D. (2022) *The Landscape of Methane Abatement Finance*, Climate Policy Initiative & Global Methane Hub, 9 ("Methane abatement solutions are severely underfunded considering their climate change mitigation potential. While also underfunded, other climate change solutions with similar mitigation potential, such as low-carbon transport, received 15 times the investment of methane abatement measures, while solutions such as solar and wind received 26 times the investment. Wind and solar energy have an average of 8.35 $GtCO_2e$ mitigation potential (CO_2) by 2030, and received USD 296 billion in 2019/2020, while targeted methane abatement solutions received only USD 6.3 billion with an average mitigation potential of 3.3 $GtCO_2e$ – the ratio of investment flows to mitigation potential was almost 20 times lower than that of the renewable energy sector (Figure 4). Estimated mitigation potential of methane abatement solutions is 3 $GtCO_2e$ by 2030 over a

100-year timeframe (GWP_{100}). However, if a 20-year timeframe (GWP_{20}) is considered, the mitigation potential would be substantially higher.").

[1288] Banga A. (5 February 2024) *A Fireside Chat with World Bank President Ajay Banga* ("Methane is 80 times more dangerous than carbon dioxide. It gets 2% of climate financing. When something that is 80 times more dangerous gets 2% of financing, something is not right. In addition to flaring and the leaks in pipelines which is a real big issue with methane, there is rice paddy cultivation, waste management, agricultural and dairy methane, things the bank knows and has run for years. Getting those to scale is what I've committed to doing in these coming 18 months, and then try to fight methane in the atmosphere.").

[1289] Rosane P., Naran B., Pastor A. O., Connolly J., & Wignarajah D. (2022) *The Landscape of Methane Abatement Finance*, Climate Policy Initiative & Global Methane Hub, 8 ("Total tracked targeted methane abatement finance amounted to USD 11.6 billion in 2019/2020. Although methane emissions are responsible for almost half of global warming, targeted methane abatement finance represented about 2% of total climate finance tracked in CPI's Global Landscape of Climate Finance (Buchner et al., 2021). Even with data gaps factored in (see discussion on data limitations in Chapter 2), this initial stocktake indicates that actions to reduce methane are not in line with necessary actions to meet climate goals (Figure 3)."); 11 ("Estimates suggest targeted methane abatement finance falls well short of the average USD 119 billion needed each year through 2050 under a +2C of warming scenario (Harmsen et al., 2019): a 10-fold increase from currently tracked investments. Fossil fuel, at USD 32 billion per year, and AFOLU, at USD 43 billion per year, are the two sectors where the gap with current levels is the greatest."); *citing* Harmsen J. H. M., van Vuuren D. P., Nayak D. R., Hof A. F., Höglund-Isaksson L., Lucas P. L., Nielsen J. B., Smith P., & Stehfest E. (2019) *Long-term marginal abatement cost curves of non-CO_2 greenhouse gases*, ENVIRON. SCI. POLICY 99: 136–149.

[1290] Rosane P., Naran B., Pastor A. O., Connolly J., & Wignarajah D. (2022) *The Landscape of Methane Abatement Finance*, Climate Policy Initiative & Global Methane Hub, 10 ("As shown in Figure 6, almost two-thirds of methane abatement funding is concentrated in the waste and water sector, whereas 82% of emission sources comes from the AFOLU and energy sectors which only received 33% of the total tracked funding."), 11 ("As shown in Figure 6, almost two-thirds of methane abatement funding is concentrated in the waste and water sector, whereas 82% of emission sources comes from the AFOLU and energy sectors which only received 33% of the total tracked funding."; "Estimates suggest targeted methane abatement finance falls well short of the average USD 119 billion needed each year through 2050 under a +2C of warming scenario (Harmsen et al., 2019): a 10-fold increase from currently tracked investments. Fossil fuel, at USD 32 billion per year, and AFOLU, at USD 43 billion per year, are the two sectors where the gap with current levels is the greatest.").

[1291] Rosane P., Naran B., Pastor A. O., Connolly J., & Wignarajah D. (2022) *The Landscape of Methane Abatement Finance*, Climate Policy Initiative & Global Methane Hub, 11 ("As shown in Figure 6, almost two-thirds of methane abatement funding is concentrated in the waste and water sector, whereas 82% of emission sources comes from the AFOLU and energy sectors which only received 33% of the total tracked funding. … Estimates suggest targeted methane abatement finance falls well short of the average USD 119 billion needed each year through 2050 under a +2C of warming scenario (Harmsen et al., 2019): a 10-fold increase from currently tracked investments. Fossil fuel, at USD 32 billion per year, and AFOLU, at USD 43 billion per year, are the two sectors where the gap with current levels is the greatest.").

[1292] Climate Policy Initiative (2023) LANDSCAPE OF METHANE ABATEMENT FINANCE 2023, 7 ("At 13.7 billion, methane abatement finance is at its highest level yet, but annual flows need to be at least 3.5 times larger until 2030. Despite increased methane reduction pledges and their status among the most powerful contributors to global temperature rise, methane emissions continue to increase. Methane abatement is one of the most effective mitigation investments, but finance is still far below the global estimated needs of USD 48 billion annually by 2030 Funding for methane abatement has seen a small improvement of 18% since 2019/20: the annual average increased from USD 11.6 billion in fiscal years 2019/20 to USD 13.7 billion in 2021/22. Estimated needs are set to grow significantly from

2030 to 2050 there is urgent need to accelerate finance at a continuously increasing rate. Even considering data gaps, this implies that current methane emissions reduction measures fall short of those needed to meet climate goals.").

[1293] Clean Air Task Force (2023) BARRIERS AND SOLUTIONS TO SCALING-UP METHANE FINANCE (Figure 5 "Constraints to Scaling Methane Mitigation.").

[1294] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("Fossil fuel companies and governments around the world now need to deliver clear strategies for how they will implement these pledges effectively and rapidly. This needs to be accompanied by verification and accountability mechanisms to ensure that actors are taking the necessary steps towards their goals. Further commitments – particularly in financing – are needed to deliver the reductions required this decade." …" We estimate that around USD 170 billion in spending is needed to deliver the methane abatement measures deployed by the fossil fuel industry in the NZE Scenario. This includes around USD 100 billion of spending in the oil and gas sector and USD 70 billion in the coal industry. Through 2030, roughly USD 135 billion goes towards capital expenditures, while USD 35 billion is for operational expenditures.").

[1295] Dietz S., Rising J., Stoerk T., & Wagner G. (2021) *Economic impacts of tipping points in the climate system*, PROC. NAT. ACAD. SCI. 118(34): 1–9, 1 ("We provide unified estimates of the economic impacts of all eight climate tipping points covered in the economic literature so far using a meta-analytic integrated assessment model (IAM) with a modular structure. The model includes national-level climate damages from rising temperatures and sea levels for 180 countries, calibrated on detailed econometric evidence and simulation modeling. Collectively, climate tipping points increase the social cost of carbon (SCC) by ~25% in our main specification. The distribution is positively skewed, however. We estimate an ~10% chance of climate tipping points more than doubling the SCC. Accordingly, climate tipping points increase global economic risk. A spatial analysis shows that they increase economic losses almost everywhere. The tipping points with the largest effects are dissociation of ocean methane hydrates and thawing permafrost. Most of our numbers are probable underestimates, given that some tipping points, tipping point interactions, and impact channels have not been covered in the literature so far; however, our method of structural meta-analysis means that future modeling of climate tipping points can be integrated with relative ease, and we present a reduced-form tipping points damage function that could be incorporated in other IAMs."); 2 ("Combining all eight tipping points increases the expected SCC by 24.5%. As discussed below, this should be seen as a probable underestimate, given the literature we synthesize has yet to cover some tipping points, and misses possible impact channels and interactions even for those it does cover. Fig. 1 shows that the distribution of expected increases in the SCC is positively skewed. The median percentage increase in the SCC from all tipping points combined is 18.8%; the 75th percentile is 22.5%, and the 99.5th percentile is 132.2%.").

[1296] Bennett V. (2 November 2021) *World Leaders in Global Methane Pledge*, European Bank for Reconstruction and Development ("President Odile Renaud-Basso endorsed the declaration on behalf of the European Bank for Reconstruction and Development (EBRD), saying: 'The Bank is supporting the economies in which it invests in increasing their environmental sustainability, including by supporting methane abatement across the agribusiness, waste and energy sectors. We are committed to working closely with the signatories of the Global Methane Pledge to help achieve the important target it sets.'").

[1297] Bennett V. (2 November 2021) *World Leaders in Global Methane Pledge*, European Bank for Reconstruction and Development ("The EBRD has been at the forefront of efforts to reduce methane gas emissions. The Bank has historically financed projects of around €650 million per year in sub-sectors that are directly responsible for the vast majority of methane emissions, including energy and natural resources, municipal infrastructure and agribusiness.").

[1298] Renaud-Basso O. (2 November 2021) *Launch of Global Methane Pledge* ("Today, we are committing to supporting our countries of operation to advance their domestic methane emission reduction efforts. We will provide technical assistance to support the development of effective inventories, policies, regulations, and standards. And we stand ready to provide funding for methane abatement projects across key sectors of the economy. You can count on our support.").

[1299] European Commission (2 November 2021) *Launch by United States, the European Union, and Partners of the Global Methane Pledge to Keep 1.5 Within Reach*, Statement ("The U.S. and EU are also proud to announce a significant expansion of financial and technical support to assist implementation of the Pledge. Global philanthropies have committed $328 million in funding to support scale up of these types of methane mitigation strategies worldwide. The European Bank for Reconstruction and Development, the European Investment Bank, and the Green Climate Fund have committed to support the Pledge through both technical assistance and project finance. The International Energy Agency will also serve as an implementation partner.").

[1300] African Development Bank (15 September 2022) *US government announces $5 million grant to support African Development Bank in tackling methane emissions*, Press Release ("The United States government has announced it will provide a $5 million grant to the African Development Bank to support efforts to abate methane gas emission, across Africa… Additional funding was also promised by the Climate and Clean Air Coalition (CCAC) and the Global Methane Hub to tackle methane emissions in African countries. The Global Methane Hub will contribute $5 million dollars over the next three years. The Hub funds methane mitigation efforts. The Coalition, a voluntary partnership of governments, intergovernmental organizations, businesses, and research institutions, will provide $1.2 million.").

[1301] African Development Bank (15 September 2022) *US government announces $5 million grant to support African Development Bank in tackling methane emissions*, Press Release ("Welcoming the contributions, African Development Bank Vice President for Power, Energy, Climate and Green Growth, Kevin Kariuki said the Bank planned to create activities within the ACCF to support methane abatement. "With the support of the U.S. government, and other donors and non-state actors, we intend to create a dedicated pillar of activities within our Africa Climate Change Fund to support methane abatement including working with countries to include methane in their Nationally Defined Contributions and develop pipelines of methane abatement projects for further investment," Kariuki said.").

[1302] African Development Bank (2022) METHANE IN AFRICA*: A high-level assessment of anthropogenic methane emissions in Africa with case studies on potential evolution and abatement*.

[1303] United Nations Environment Programme (2021) REPORT OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL, *Volume 6: Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 2021-2023*, 59 ("The funding approved for IS support has played a paramount role in establishing and maintaining the capacity of national ozone units and is recognized as a major factor in the success of A5 parties achieving compliance with the Montreal Protocol's control measures.[120]"); *citing* Paragraphs 11 to 13 of UNEP/OzL.Pro/ExCom/74/51 (Review of Funding of Institutional Strengthening Projects (Decision 61/43(b)) (April 2015)).

[1304] William and Flora Hewlett Foundation (2 November 2021) *20+ philanthropies join to provide $328M to dramatically reduce methane emissions* (Remarks by Larry Kramer, "The speed with which the pledge came together has been remarkable—something for which we must thank the extraordinary leadership of Presidents Biden and von der Leyen. Now we must match that speed with similar speed in implementing and fulfilling it. And for that, I am proud (and humbled) to speak on behalf of the more than 20 philanthropies that likewise came together quickly to compile a fund well in excess of $325 million to assist nations that have taken the pledge. This flexible philanthropic aid can be used to provide technical assistance to countries that need it and to develop and deploy innovative new solutions. This means grant dollars that can be moved quickly and nimbly for feasibility studies, project development, and other efforts needed to create the conditions to scale investment in methane reduction now.").

[1305] William and Flora Hewlett Foundation (2 November 2021) *20+ philanthropies join to provide $328M to dramatically reduce methane emissions* (Remarks by Larry Kramer, "The speed with which the pledge came together has been remarkable—something for which we must thank the extraordinary leadership of Presidents Biden and von der Leyen. Now we must match that speed with similar speed in implementing and fulfilling it. And for that, I am proud (and humbled) to speak on behalf of the more than 20 philanthropies that likewise came together quickly to compile a fund well in excess of $325 million to assist nations that have taken the pledge. This flexible philanthropic aid can be used to provide technical assistance to countries that need it and to develop and deploy innovative new solutions. This means grant dollars that can be moved quickly and nimbly for feasibility studies, project development, and other efforts needed to create the conditions to scale investment in methane reduction now.").

[1306] Global Methane Hub (4 April 2022) *The Global Methane Hub Donates $10 Million to the Climate and Clean Air Coalition (CCAC) for Immediate Action to Reduce Methane Emissions* ("The $10M donation is part of the Hub's commitment to support and sustain action from civil society, government, and private industry, including the more than 100 countries that have signed on to the Global Methane Pledge by meaningfully investing in methane reduction solutions.").

[1307] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("In addition to the over $1 billion in new grant funding, international financial institutions approved over $3.5 billion in new investments for methane-reducing projects since COP27. Approvals include $375 million from the Green Climate Fund and partners, over $1.9 billion (€1.78 billion) from the European Investment Bank, over $218 million (€200 million) from the European Bank for Reconstruction and Development, and $372.5 million from the Inter-American Development Bank. The World Bank approved at least $700 million in investments, including a $255 million for rice project in China, $300 million for landfill methane reduction in Cote d'Ivoire, and $145 million for wastewater methane reduction in Malawi.").

[1308] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("In addition to the over $1 billion in new grant funding, international financial institutions approved over $3.5 billion in new investments for methane-reducing projects since COP27. Approvals include $375 million from the Green Climate Fund and partners, over $1.9 billion (€1.78 billion) from the European Investment Bank, over $218 million (€200 million) from the European Bank for Reconstruction and Development, and $372.5 million from the Inter-American Development Bank. The World Bank approved at least $700 million in investments, including a $255 million for rice project in China, $300 million for landfill methane reduction in Cote d'Ivoire, and $145 million for wastewater methane reduction in Malawi.").

[1309] Clean Air Task Force (2023) BARRIERS AND SOLUTIONS TO SCALING UP METHANE FINANCE, 18 ("Funders and development finance institutions should prioritize methane mitigation in their funding activities. Relevant climate and sector-specific funding vehicles should specify that methane mitigation projects are eligible for support. This includes funds that support project design and development of project pipelines, such as readiness funds, and those that support project implementation with both activity- and results-based financing."). *See also* International Energy Agency. (2023) FINANCING REDUCTIONS IN OIL AND GAS METHANE EMISSIONS, 3 ("Oil and gas companies carry primary responsibility for abatement. The spending required to cut methane emissions in the NZE Scenario is less than 2% of the net income received by the industry in 2022. Private sources of finance can provide capital where internal financing options are limited. Regulations and policies on methane abatement are essential to drive down methane emissions. These can be paired with public financing, either directly from governments or through multilateral development banks, to help catalyse private investments and fill gaps where private sources of finance may not be willing or able to invest at the levels needed."). *The Financial Times* reported that ADNOC "has earmarked $150bn in capital expenditure over the next five years towards expanding its oil and gas production, with $15bn set aside for low-carbon solutions over a longer period. … Jaber is also using dealmaking to strengthen Adnoc's renewables business.' 'In terms of their strategic thinking they are generally way ahead of most other state energy companies when it comes to thinking about their place in the energy transition,' said Amrita Sen at Energy Aspects." *See* Levingston I., Sheppard D., & England A. (9 August 2023) *Abu Dhabi oil giant builds internal 'investment bank' to chase $50bn in global deals*, FINANCIAL TIMES. In addition to strengthening their renewables business, this investment should support methane mitigation from all sectors, as well as other efforts to decarbonize and ensure a just energy transition during the phaseout of fossil fuels.

[1310] Inflation Reduction Act 2022 Sec. 60113. ("The Administrator shall impose and collect a charge on methane emissions that exceed an applicable waste emissions threshold under subsection (f) from an owner or operator of an applicable facility that reports more than 25,000 metric tons of carbon dioxide equivalent of greenhouse gases emitted"). *See also* Congressional Research Brief (2022) INFLATION REDUCTION ACT METHANE EMISSIONS CHARGE: IN BRIEF 9. ("the methane emissions charge in IRA starts in calendar year 2024 at $900 per metric ton of methane, increases to $1,200 in 2025, and increases to $1,500 in 2026. The charge remains at $1,500 in subsequent years.").

[1311] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 1 ("Putting a price on methane, ideally through a fee, would reduce emissions efficiently, and can be administratively straightforward for extractives industries and, in some cases, agriculture. Policies could also include revenue-neutral 'feebates' that use fees on dirtier polluters to subsidize cleaner producers. A $70 methane fee among large economies would align 2030 emissions with 2oC. Most cuts would be in extractives and abatement costs would be equivalent to just 0.1 percent of GDP. Costs are larger in certain developing countries, implying climate finance could be a key element of a global agreement on a minimum methane price.").

[1312] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 1 ("Putting a price on methane, ideally through a fee, would reduce emissions efficiently, and can be administratively straightforward for extractives industries and, in some cases, agriculture. Policies could also include revenue-neutral 'feebates' that use fees on dirtier polluters to subsidize cleaner producers. A $70 methane fee among large economies would align 2030 emissions with 2oC. Most cuts would be in extractives and abatement costs would be equivalent to just 0.1 percent of GDP. Costs are larger in certain developing countries, implying climate finance could be a key element of a global agreement on a minimum methane price.").

[1313] Global Methane Hub (23 March 2022) *Former environment minister of Chile, Marcelo Mena, named CEO of the newly formed Global Methane Hub* ("Funding from The Global Methane Hub will support and sustain action from civil society, government, and private industry, including in the more than 100 countries that have signed on to the Pledge by meaningfully investing in methane reduction solutions. Initiatives have already begun by developing sector-based strategies for waste, agriculture, and fossil fuels. In addition, The Global Methane Hub is currently forming a comprehensive Monitoring, Evaluation, and Learning (MEL) framework for strategy and grantmaking applications. This approach will focus on monitoring performance, evaluating activities, and supporting continuous learning.").

[1314] *Global Methane Hub* (*last visited* 1 February 2024) ("While many countries have methane reduction strategies in place, this will be the first coordinated approach to methane mitigation funding. We will move fast, be nimble and operate with ambition and vision. The Hub will focus on the energy, agricultural, and waste sectors which account for 96% of human-caused methane emissions. We will support ambitious catalytic investments, lay the groundwork for long-term transformation of challenging sectors, and also deliver quick wins in sectors that are ripe for action on the ground.").

[1315] Global Methane Hub (2022) ANNUAL IMPACT REPORT, 17 ("Most of our funding has focused on cross-cutting emissions in the highest methane emitting regions and sources around the globe. We believe directing efforts to where emissions are greatest is the most effective way to mitigate methane and meet our reduction targets.").

[1316] Global Methane Hub (1 December 2023) *Global Methane Hub Spearheads Transformative Climate Action at COP28* ("The Global Methane Hub organizes the field of philanthropists, experts, nonprofits, and government organizations to ensure we unite around a strategy to maximize methane reductions. We have raised over $200 million in pooled funds from more than 20 of the largest climate philanthropies to accelerate methane mitigation across the globe.").

[1317] United States Department of State (17 June 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Release ("Today, the United States, the European Union, and 11 countries launched the Global Methane Pledge Energy Pathway to catalyze methane emissions reductions in the oil and gas sector, advancing both climate progress and energy security.... Countries and supporting organizations announced nearly $60 million in dedicated funding to support implementation of the Pathway. Countries and supporting organizations have announced $59 million in dedicated funding and in-kind assistance in support of the GMP Energy Pathway that was announced at today's MEF, including: $4 million to support the World Bank Global Gas Flaring Reduction Partnership (GGFR). The United States intends to support the transfer by the World Bank of at least $1.5 million in funding to the GGFR. Germany intends to provide $1.5 million, and Norway intends to provide approximately $1 million to GGFR. $5.5 million to support the Global Methane Initiative (GMI). The United States will provide $3.5 million. Guided by the recommendations of the GMI, Canada will contribute $2 million over the next four years, as part of its global climate finance commitment, to support methane mitigation projects in developing countries including in the oil and gas sector. Up to $9.5 million from the UNEP International Methane Emissions Observatory to support scientific assessments of methane emissions and mitigation potential in the oil and gas sector that are aligned with the Global Methane Pledge Energy Pathway. Up to $40 million annually from the philanthropic Global Methane Hub to support methane mitigation in the fossil energy sector. These funds will be critical to improve methane measurements in the oil and gas sector, identify priority areas for methane mitigation, develop technical assessments for project development, strengthen regulator and operator capacity, support policy development and enforcement, and other essential activities to achieve reductions in methane emissions.").

[1318] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The Global Methane Hub formally launched the Enteric Fermentation R&D Accelerator with $200 million in funding, making it the largest ever globally coordinated research effort into livestock methane reduction.").

[1319] Global Methane Hub (19 December 2023) *COP28 Reflections* ("Alongside our project launches, we announced additional funding initiatives that will deliver necessary and critical resources to governments, businesses, and local climate organizations as they implement their methane mitigation strategies. One initiative was the Data to Methane Action Campaign on which we collaborated with UNEP's IMEO and its partners. GMH provided $10 million in funding to help support governments and businesses identify and reduce methane leaks through better data monitoring. GMH also supported the International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP), along with the U.S. State Department, which will develop agricultural methane strategies in 25 countries, helping pave a path forward for more sustainable agriculture.").

[1320] Global Methane Hub (19 December 2023) *COP28 Reflections* ("Alongside our project launches, we announced additional funding initiatives that will deliver necessary and critical resources to governments, businesses, and local climate organizations as they implement their methane mitigation strategies. One initiative was the Data to Methane Action Campaign on which we collaborated with UNEP's IMEO and its partners. GMH provided $10 million in funding to help support governments and businesses identify and reduce methane leaks through better data monitoring. GMH also supported the International Fund for Agriculture Development's Reducing Agricultural Methane Program (RAMP), along with the U.S. State Department, which will develop agricultural methane strategies in 25 countries, helping pave a path forward for more sustainable agriculture.").

[1321] United States White House (21 April 2023) *Chair's Summary of the Major Economies Forum on Energy and Climate Held by President Joe Biden,* Statements and Releases ("MEF participants Canada, the European Union, France, Germany, Japan, and the United States, as well as Ireland and Norway, joined in launching the Methane Finance Sprint, which aims to scale up methane finance. This includes mobilizing, by COP 28, at least $200 million in new public and philanthropic support for methane abatement activities, with a view to developing a pipeline of projects. Philanthropies have committed $100 million in new funding through the Global Methane Hub towards the $200 million goal.")

[1322] United States White House (21 April 2023) *Chair's Summary of the Major Economies Forum on Energy and Climate Held by President Joe Biden,* Statements and Releases ("MEF participants Canada, the European Union, France, Germany, Japan, and the United States, as well as Ireland and Norway, joined in launching the Methane Finance Sprint, which aims to scale up methane finance. This includes mobilizing, by COP 28, at least $200 million in new public and philanthropic support for methane abatement activities, with a view to developing a pipeline of projects. Philanthropies have committed $100 million in new funding through the Global Methane Hub towards the $200 million goal.")

[1323] Climate & Clean Air Coalition (4 December 2023) *Highlights from the 2023 Global Methane Pledge Ministerial* ("President Biden launched the Methane Finance Sprint in April 2023 at the Major Economies Forum, with the aim of raising at least $200 million in new high-impact grant funding by COP28. Today, governments, the European Commission, philanthropies, and the private sector significantly exceeded that target, announcing over $1 billion in new grant funding committed since COP27, which more than triples previous annual methane grant funding and will leverage billions more in urgently needed project investment. These funds will support cutting methane emissions across all sectors with a focus in low- and middle-income countries. The Sprint includes $255 million for the re-launch of the World Bank Global Flaring and Methane Reduction Partnership, $200 million for the launch of the Enteric Fermentation Accelerator, and additional support for the Climate and Clean Air Coalition (CCAC), the International Methane Emissions Observatory (IMEO), and other programs, elaborated below.").

[1324] Climate & Clean Air Coalition (4 December 2023) *Highlights from the 2023 Global Methane Pledge Ministerial* ("President Biden launched the Methane Finance Sprint in April 2023 at the Major Economies Forum, with the aim of raising at least $200 million in new high-impact grant funding by COP28. Today, governments, the European Commission, philanthropies, and the private sector significantly exceeded that target, announcing over $1 billion in new grant funding committed since COP27, which more than triples previous annual methane grant funding and will leverage billions more in urgently needed project investment. These funds will support cutting methane emissions across all sectors with a focus in low- and middle-income countries. The Sprint includes $255 million for the re-launch of the World Bank Global Flaring and Methane Reduction Partnership, $200 million for the launch of the Enteric Fermentation Accelerator, and additional support for the Climate and Clean Air Coalition (CCAC), the International Methane Emissions Observatory (IMEO), and other programs, elaborated below.").

[1325] World Bank (7 September 2023) *Enhancing IMF-World Bank Collaboration* ("Joint Statement of the IMF Managing Director and of the World Bank President … The two institutions will further strengthen coordination and focus on results. We will formalize the regular meetings of the new Bank-Fund Climate Advisory Group, tasked with ensuring coordination of our climate related work streams. The group will meet every two months to discuss global and country level engagements, including the results of CCDRs, country level climate analytical work, and the pipeline of key projects and policy-based lending (World Bank's DPLs and Fund's RST engagements). We will also incorporate climate considerations in our ongoing work on debt sustainability, including through the revised joint Low Income Country Debt Sustainability Framework.").

[1326] World Bank (7 September 2023) *Enhancing IMF-World Bank Collaboration* ("Joint Statement of the IMF Managing Director and of the World Bank President … The two institutions will further strengthen coordination and focus on results. We will formalize the regular meetings of the new Bank-Fund Climate Advisory Group, tasked with ensuring coordination of our climate related work streams. The group will meet every two months to discuss global and country level engagements, including the results of CCDRs, country level climate analytical work, and the pipeline of key projects and policy-based lending (World Bank's DPLs and Fund's RST engagements). We will also incorporate climate considerations in our ongoing work on debt sustainability, including through the revised joint Low Income Country Debt Sustainability Framework.").

[1327] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 11–12 ("The RST adds to the lending toolkit by helping members address risks to prospective BoP stability stemming from select macro-critical longer-term structural challenges. While not necessarily posing imminent BoP problems, longer-term challenges such as climate change make countries more prone to severe BoP problems in the longer run by raising the likelihood and impact of future shocks and undermining growth prospects. Policy inaction—including on account of scarce financing—to address these challenges could increase these risks and jeopardize *prospective BoP stability*, as defined in ¶9. Helping member countries to address such risks through policy support and financing is consistent with the Fund's mandate to support members' BoP stability.").

[1328] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 15 ("Global and national strategies for cutting methane emissions need to be fleshed out, but the GMP provides a potential platform for discussion. Some countries will pursue pricing and others non-pricing approaches. Thus, operational methodologies for comparing efforts across countries need to be approved. Continued refinement of methane monitoring technologies is needed, particularly atmospheric measures that can better map readings to specific emission sources. Successful methane abatement programs, such as Norway's methane tax, need to be disseminated, along with the lessons that can be drawn for other countries. Financing would need to be part of an international agreement, given that mitigation costs would fall disproportionately on emerging market economies. Last, dialogue is needed on design issues for internationally coordinated mitigation regimes as well as strategies for advancing critical methane abatement technologies.").

[1329] As of 2 February 2024, the SDR exchange rate of reference was 0.750289 SDR per USD.

[1330] United States White House (13 June 2021) *Carbis Bay G7 Summit Communiqué*, Statements and Releases ("65. We welcome the agreement by G7 Finance Ministers and Central Bank Governors to support a new $650 billion allocation of IMF Special Drawing Rights, urging implementation by the end of August 2021 accompanied by transparency and accountability measures. We encourage the IMF to work quickly with all relevant stakeholders to explore a menu of options for channeling SDRs to further support health needs, including vaccinations, and to help enable greener, more robust recoveries in the most affected countries, supporting the poorest and most vulnerable countries in tackling these urgent challenges. G7 countries are actively considering options that we can take as part of a global effort to magnify the impact of this general allocation for countries most in need, especially in Africa, including through voluntarily channeling SDRs and/or budget loans, in line with national circumstances and legal requirements. This includes scaling up financing to the IMF's Poverty Reduction and Growth Trust and the IMF's review of concessional financing and policies to strengthen its capacity to support low-income countries. To support our aim to reach a total global ambition of $100 billion, we call for contributions from other countries able to do so, alongside the G7. We task G7 Finance Ministers and Central Bank Governors to urgently consider the detail of this, including by working with the G20 and other stakeholders.").

[1331] G20 (31 October 2021) *Rome Leaders' Declaration*, 4 ("10. Support to vulnerable countries. We welcome the new general allocation of Special Drawing Rights (SDR), implemented by the International Monetary Fund (IMF) on 23 August 2021, which has made available the equivalent of USD 650 billion in additional reserves globally. We are working on actionable options for members with strong external positions to significantly magnify its impact through the voluntary channeling of part of the allocated SDRs to help vulnerable countries, according to national laws and regulations We welcome the recent pledges worth around USD [45] billion, as a step towards a total global ambition of USD 100 billion of voluntary contributions for countries most in need. We also welcome the ongoing work to significantly scale up the Poverty Reduction and Growth Trust's lending capacity and call for further voluntary loan and subsidy contributions from countries able to do so. We also call on the IMF to establish a new Resilience and Sustainability Trust (RST) – in line with its mandate – to provide affordable long-term financing to help low-income countries, including in the African continent, small island developing states, and vulnerable middle-income countries to reduce risks to prospective balance of payments stability, including those stemming from pandemics and climate change. The new RST will preserve the reserve asset characteristics of the SDRs channeled through the Trust. Our Finance Ministers look forward to further discussion of surcharge policy at the IMF Board in the context of the precautionary balances interim review.").

[1332] International Monetary Fund (18 April 2022) *IMF Executive Board Approves Establishment of the Resilience and Sustainability Trust*, Press Release ("Challenges from the pandemic, spillovers from geopolitical shocks, and long-standing structural problems pose an enormous impediment for balance of payments stability and resilient and sustainable growth, especially for low-income and vulnerable middle-income countries. In this context, on April 13, 2022, the Executive Board of the International Monetary Fund (IMF) approved the establishment of the Resilience and Sustainability Trust (RST) with effect from May 1, 2022.The RST will complement the IMF's existing lending toolkit by focusing on longer-term structural challenges— including climate change and pandemic preparedness—that entail significant macroeconomic risks and where policy solutions have a strong global public good nature.").

[1333] International Monetary Fund (11 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 8 ("The proposed RST would complement the IMF's existing lending toolkit by focusing on longer-term structural challenges. The RST's goal is to enhance economic resilience and sustainability thereby contributing to prospective balance of payments stability. This will be achieved by providing eligible members affordable, longer-maturity financing to (i) support reforms (including by covering BoP costs associated with them) that reduce macro-critical risks associated with select longer-term structural challenges and (ii) augment policy space and financial buffers to mitigate the risks arising from such longer-term structural challenges. This financing would complement traditional IMF support that focuses on resolving more near-term balance of payments difficulties.").

[1334] International Monetary Fund (7 April 2023) *IMF Executive Board Concludes the 2023 Review of the Resource Adequacy of the Poverty Reduction and Growth Trust, Resilience and Sustainability Trust, and Debt Relief Trusts* ("In relation to the recently established RST, the review highlighted strong and frontloaded demand for arrangements under the Resilience and Sustainability Facility (RSF). To date, five RSF arrangements have been approved since RST operationalization on October 12, 2022, and the pipeline of potential requests is building up quickly."); *and* Lawder D. (10 April 2023) *IMF's Georgieva says 44 countries interested in new resilience trust loans*, REUTERS ("International Monetary Fund (IMF) Managing Director Kristalina Georgieva said on Monday that 44 countries have expressed interest in borrowing from its $40 billion Resilience and Sustainability Trust after an initial five had arranged loans. ... Georgieva said the facility's current resources of around $40 billion were "modest in size." Rwanda, Barbados, Costa Rica, Bangladesh and Jamaica have reached agreements for loan programs from the facility, which come with certain economic policy requirements such as meeting fiscal targets.").

[1335] *See* International Monetary Fund, *Resilience and Sustainability Trust* (*last visited* 1 February 2024) ("RST Funding Status (as of end December 2023) Total pledges In SDR Billions 31.9 In USD billions 42.8"); *and* International Monetary Fund (2023) RESILIENCE AND SUSTAINABILITY TRUST-2023 CONTRIBUTION AGREEMENTS WITH ITALY, LUXEMBOURG, OMAN, AND THE UNITED KINGDOM ("This paper presents for the information of Executive Directors four Resilience and Sustainability Trust (RST) contribution agreements finalized between April 2023 and September 15, 2023. Shortly after the Executive Board's April 2022 approval of the establishment of the RST, the Managing Director wrote to 35 members with strong external positions who were identified as potential RST contributors seeking their contributions in a total amount of at least SDR 33 billion. To date, the Fund has received total pledges amounting to SDR 31.2 billion from 18 members, of which SDR 26.1 billion are pledged contribution packages to all three RST accounts (i.e., the Loan Account (LA), Deposit Account (DA) and the Reserve Account (RA)) that count toward the SDR 33 billion target, corresponding to 78 percent of the targeted loan contributions and projected demand for loan resources. The Fund has concluded contribution agreements with 15 members (or their institutions), eleven of which were already reported to the Executive Board in January 2023 and April 2023, and the remaining and most recent four are presented in this paper." (citations omitted)).

[1336] COP28 (4 December 2023) *COP28 Finance Day unlocks innovative financial mechanisms to support vulnerable countries fight climate change*, Press Release ("At the COP28 World Climate Action Summit, the UAE committed $200 million USD to help low-income and vulnerable countries fight climate change through the International Monetary Fund Resilience and Sustainability Trust (RST)"). In December 2022, the U.S. Congress approved a contribution of US$20 million to the Poverty Reduction and Growth Trust or the Resilience and Sustainability Trust.[1336]

[1337] Consolidated Appropriations Act, 2023, P.L. 117-328, 117th Cong., Title V ("For contribution by the Secretary of the Treasury to the Poverty Reduction and Growth Trust or the Resilience and Sustainability Trust of the International Monetary Fund, $20,000,000, to remain available until September 30, 2031.").

[1338] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 12 ("Longer-term structural challenges create a range of possible BoP needs. These needs that could be financed under the RST are typically multidimensional and can materialize over the short-, medium- or longer-term. In the case of climate change, potential sources of such needs—associated with adaptation, transition, and mitigation policies including energy security policies—include, *inter alia*[10]: • Costs of climate-related public and/or private investments, such as green energy generation, coastal protection infrastructure, energy-efficient retrofitting of existing building; • Costs associated with climate-focused reforms, such as transitioning to green technologies; • Offsetting the costs of policies typically required to enable a just transition, such as augmenting targeted social assistance in tandem with the unwinding of carbon subsidies;[11] and, • Building up policy space and buffers necessary to mitigate risks to longer-term BoP stability, such as establishing and augmenting disaster funds, establishing and financing a multi-layered financial framework for disaster resilience, and augmenting international reserves to face financial stability implications of climate change.").

[1339] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 63–64 ("RST measures would be informed and expected to be consistent with country diagnostics developed in both institutions relevant to the RST's purposes. On climate change, the Bank's Country Climate and Development Reports (CCDR), if available, will be a critical input, complemented with other products such as the Fund's Climate Change Policy Assessments (CCPAs) and its potential successor instrument, Climate Macroeconomic Assessments Programs (CMAPs). In practice, Bank and Fund staff will coordinate the production of CCDRs and CMAPs to complement and ensure consistent advice between the two products for member countries, in line with the agreed coordination between Bank and Fund staff on CCDRs and CMAPs. Fund staff are expected to discuss with their Bank counterparts areas of the CCDR or other diagnostics that they intend to include in the RST program to ensure complementarity. In instances where countries already have an advanced climate change framework, Fund staff could use these inputs flexibly as part of the analytics informing the RST program.").

[1340] International Monetary Fund (18 April 2022) *IMF Executive Board Approves Establishment of the Resilience and Sustainability Trust*, Press Release ("The RST will be a loan-based trust, with resources mobilized on a voluntary basis. About three quarters of the IMF's membership will be eligible for longer-term affordable financing from the RST, including all low-income countries, all developing and vulnerable small states, and lower middle-income countries. Access will be based on the countries' reforms strength and debt sustainability considerations and capped at the lower of 150 percent of quota or SDR 1 billion. The loans will have a 20-year maturity and a 10½-year grace period, with borrowers paying an interest rate with a modest margin over the three-month SDR rate, with the most concessional financing terms provided to the poorest countries.").

[1341] International Monetary Fund (*updated* July 2023) *The Resilience Sustainability Facility (RSF)* ("Repayment: 20-year maturity and a 10½ -year grace period during which no principal is repaid. … Access: Overall cumulative access cap set at 150 percent of quota or SDR 1 billion, whichever is smaller.").

[1342] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 15 ("RST support for the development and implementation of overarching policy frameworks such as green public financial management would improve the integration of climate in policy formulation and enhance governance, thereby giving more comfort to other public and private lenders and donors to provide project financing and technical assistance.")

[1343] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 14 ("The RST would focus on downside scenarios associated with select longer -term challenges. It would aim to lower the probability of such scenarios and/or reduce the severity of the BoP problems that would materialize should such a scenario come to pass. The recognition of these risks does not mean that the UCT program becomes inadequate in achieving its short- to medium-term goals").

[1344] The IMF, in a joint statement with the World Bank, indicated that RST engagements will be informed by the World Bank's CCDRs. *See* World Bank (7 September 2023) *Enhancing IMF-World Bank Collaboration* ("Joint Statement of the IMF Managing Director and of the World Bank President … The two institutions will further strengthen coordination and focus on results. We will formalize the regular meetings of the new Bank-Fund Climate Advisory Group, tasked with ensuring coordination of our climate related work streams. The group will meet every two months to discuss global and country level engagements, including the results of CCDRs, country level climate analytical work, and the pipeline of key projects and policy-based lending (World Bank's DPLs and Fund's RST engagements). We will also incorporate climate considerations in our ongoing work on debt sustainability, including through the revised joint Low Income Country Debt Sustainability Framework.").

[1345] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 15 ("Differentiated pricing and financial/technological support are likely to be key elements of an international agreement on minimum methane pricing. Varying methane taxes according to broad country groupings classified by development level would promote a more progressive distribution of emission reductions and mitigation costs. Support from high-income countries would also likely be needed to entice emerging market and developing economies into a minimum pricing regime. This might take the form, for example, of donor support (linked to verifiable emission reductions or technology adoption) and/or international transfer of methane mitigation technologies.").

[1346] World Bank (3 December 2018) *World Bank Group Announces $200 billion over Five Years for Climate Action*, Press Release ("The World Bank Group today announced a major new set of climate targets for 2021-2025, doubling its current 5-year investments to around $200 billion in support for countries to take ambitious climate action. The new plan significantly boosts support for adaptation and resilience, recognizing mounting climate change impacts on lives and livelihoods, especially in the world's poorest countries. The plan also represents significantly ramped up ambition from the World Bank Group, sending an important signal to the wider global community to do the same.")).

[1347] World Bank (3 December 2018) *World Bank Group Announces $200 billion over Five Years for Climate Action*, Press Release ("The $200 billion across the Group is made up of approximately $100 billion in direct finance from the World Bank (IBRD/IDA), and approximately $100 billion of combined direct finance from the International Finance Corporation (IFC) and the Multilateral Investment Guarantee Agency (MIGA) and private capital mobilized by the World Bank Group.").

[1348] World Bank, *The World Bank Group and Paris Alignment* (*last visited* 1 February 2024) ("The World Bank Group made a commitment to align all its financing operations with the goals of the Paris Agreement in its Climate Change Action Plan 2021-2025. The Paris Alignment of the Bank Group's new financing flows is the most comprehensive institutional undertaking ever done by the Bank Group to reconcile development and climate. The World Bank is on track to align 100% percent of new operations, starting from July 1, 2023. For IFC and MIGA, 85% of new operations will be aligned starting July 1, 2023, and 100% from July 1, 2025. This is part of a broader multilateral development bank (MDB) vision to align financing flows with the objectives of the Paris Agreement.").

[1349] World Bank Group (2021) CLIMATE ACTION PLAN, 13 ("Climate change and ecosystems degradation combined, in turn, push the planet ever closer to irrevocable tipping points.").

[1350] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 1–10, 7 ("Although NDCs and long-term national pledges are currently insufficient to keep warming below 2 °C, let alone 1.5 °C [50–52], the time horizons used for emission metrics should nevertheless be consistent with that central goal of the Paris Agreement. We therefore support the use of the 20 year time horizon over the 100 year version, when binary choices between these two must be made, due to the better alignment of the former with the temperature goals of the Paris Agreement. The 50 year time horizon, not yet in widespread use but now included in IPCC AR6, is in fact the only time horizon that the IPCC presents that falls within the range of time horizons that align with the Paris Agreement temperature goals (24–58 years). However, to best align emission metrics with the Paris Agreement 1.5 ° C goal, we recommend the use of the 24 year time horizon, using 2045 as the end point time, with its associated $GWP_{1.5°C} = 75$ and $GTP_{1.5°C} = 41$.").

[1351] United States White House (19 May 2012) *Fact Sheet: G-8 Action on Energy and Climate Change*, Statements and Releases ("Commission the World Bank to prepare a report on ways to integrate reduction of near-term climate pollution into their activities and ask the World Bank to bring together experts from interested countries to evaluate new approaches to financing projects to reduce methane, including through pay-for-performance mechanisms.").

[1352] World Bank (2013) METHANE FINANCE STUDY GROUP REPORT: USING PAY-FOR-PERFORMANCE MECHANISMS TO FINANCE METHANE ABATEMENT, 19 ("The Study Group encourages all interested donors to consider this innovative and highly attractive approach which combines immediate impact and maximum cost-effectiveness. Various implementation options can be envisaged. A fund could be established within an international financial institution, allowing interested funders to pool resources for maximum efficiency. A number of bilateral donors have developed deep in-house expertise on methane mitigation and carbon offsets and could implement such mechanisms rapidly. A sub-theme of the Green Climate Fund private sector facility may also be devoted to these approaches.").

[1353] Pilot Auction Facility, *About the PAF* (*last visited* 1 February 2024) ("In 2013, the G8 requested for innovative pay-for-performance approaches to addressing methane. A report by the Methane Finance Study Group supported the establishment of the facility. In its design and development phase, the facility benefited from the support of the Climate and Clean Air Coalition. … The PAF auctions are supported by Germany, Sweden, Switzerland (through a joint contribution of the State Secretariat of Economic Affairs (SECO) and the Climate Cent Foundation), and the United States.").

[1354] Pilot Auction Facility, *About the PAF* (*last visited* 1 February 2024) ("The PAF completed three auctions to allocate a guaranteed price for future carbon credits in the form of a tradable put option. Two auctions (July 2015 and May 2016) addressed methane abatement from landfill, animal waste, and wastewater sites, and one auction (January 2017) addressed nitrous oxide emissions from nitric acid (not adipic acid) production. The three auctions allocate up to $54 million with the potential to abate 20.6 million metric tons of CO_2 equivalent.").

[1355] Energy Sector Management Assistant Program (ESMAP) is another example. ESMAP is the home for the Sustainable Cooling Facility that received $157 million from the GCF for work in nine countries. *See* Green Climate Fund, *Projects & Programmes: FP177 Cooling Facility* (*last visited* 1 February 2024).

[1356] World Bank (19 September 2022) *World Bank Group Is Leading the Effort on Methane Emissions Reduction with Impactful Projects and Initiatives* ("The World Bank Group (WBG) has a long record of engagement on methane reduction across the key areas of agriculture, energy, and sanitation and waste. … The WBG is ramping up support to clients to reduce methane emissions. WBG support can include a wide range of interventions including analytical work, capacity building, support on regulatory reforms, leak detection/monitoring, investment prefeasibility studies, and direct lending or investment.").

[1357] World Bank (29 June 2021) *IFC Provides Landmark Loan to Reduce Gas Flaring, Boost Energy Access, and Power More Homes and Businesses Across Iraq*, Press Release ("IFC is investing in Basrah Gas Company (BGC) to support one of the largest gas flaring reduction projects in the world, helping to improve energy access, prevent associated greenhouse gas (GHG) emissions and support a more resilient, sustainable energy sector in Iraq. BGC is an Iraqi joint venture created to treat and process associated gas that would otherwise be flared. The project is expected to increase BGC's processing capacity, thereby avoiding more unnecessary flaring and associated GHG emissions by around 10 million tons per annum. It will support Iraq's transition to a lower carbon path and improve access to a domestic energy source, helping the country meet its growing power needs. IFC, a member of the World Bank Group, is the lead arranger of the five-year, $360 million loan to BGC.").

[1358] International Finance Corporation (2022) *New CWI Landfill Gas* ("IFC funds will be used to finance 24 identified LFGE projects (the "Project") which include ten sites that are currently under operation (Gaizhou, Lianyuan, Liling, Zhijiang, Nanning, Shanghang, Changting, Wuping, Dingnan, and Yangxin), three sites where construction has started or will commence soon (Wafangdian, Ankang, Shaowu), and one site where the development agreement with the landfills was recently signed (Jingchuan). NCWI is in discussion with landfill operators at multiple other locations to sign project development agreements. IFC funds will also be used for projects at ten of the sites were NCWI is currently in discussions for project development[.]").

[1359] International Finance Corporation (2022) *New CWI Landfill Gas* ("LFGE projects capture methane in the landfill gas and convert it to CO2 while also generating electricity. This has a positive impact on resource efficiency and contributes to GHG emission reduction. The project's gross carbon emission (for all 24 sites taken together) is estimated as 1,903,000 tCO2e per year, but with methane capture, the project is estimated to reduce about 3,428,900 tCO2e GHG.").

[1360] International Finance Corporation (2022) *Green Bond Framework*, 5–8 (*see* table of activities that are "potentially eligible for IFC Green Bond finance").

[1361] World Bank (12 September 2022) *What is IDA?* ("The World Bank's International Development Association (IDA) is one of the largest and most effective platforms for fighting extreme poverty in the world's lowest income countries.
•IDA works in 74 countries in Africa, East Asia & Pacific, South Asia, Europe & Central Asia, Latin America & Caribbean, and Middle East & North Africa. • IDA aims to reduce poverty by providing financing and policy advice for programs that boost economic growth, build resilience, and improve the lives of poor people around the world. •More than half of active IDA countries already receive all, or half, of their IDA resources on grant terms, which carry no repayments at all. Grants are targeted to low-income countries at higher risk of debt distress. •Over the past 62 years, IDA has provided about $458 billion for investments in 114 countries. IDA also has a strong track record in supporting countries through multiple crises.").

[1362] *See* World Bank (19 September 2022) *World Bank Group Is Leading the Effort on Methane Emissions Reduction with Impactful Projects and Initiatives* ("IDA provided $115 million for an urban sanitation project in Mozambique to improve access to safely managed sanitation and reduce methane emissions with improved wastewater collection and treatment."); *and* World Bank, *Mozambique Urban Sanitation Project* ("Approval Date (as of board presentation) May 22, 2019").

[1363] *See* World Bank (19 September 2022) *World Bank Group Is Leading the Effort on Methane Emissions Reduction with Impactful Projects and Initiatives* ("IDA provided $200 million for a project in Logone Valley in Cameroon to improve irrigation and drainage services and agricultural production, limit methane emissions from rice fields and train farmers on climate-smart agriculture approaches."); *and* World Bank, *Valorization of Investments in the Valley of the Logone* ("Approval Date (as of board presentation) November 30, 2021").

[1364] Multilateral Investment Agency (2021) *Annual Report — 2021*, 28 ("To increase its climate action, the World Bank Group announced a new Climate Change Action Plan (CCAP) to guide its interventions from 2021 through 2025. The CCAP provides a bold strategic road map for tackling climate change and helping client countries to fully integrate their climate and development goals. MIGA's products have helped cross-border investors protect their long-term investments in climate mitigation and adaptation activities across diverse markets and regions. As one of the few institutions that provides long-maturity guarantees, MIGA will be instrumental in fostering the lock-in of transformational climate action.").

[1365] World Bank Group (8 November 2021) *It's Time to Sprint: Targeting Methane Emissions*, COP27 Side Event, Sharm El-Sheikh, Egypt.

[1366] World Bank (19 September 2022) *World Bank Group Is Leading the Effort on Methane Emissions Reduction with Impactful Projects and Initiatives* ("The WBG is ramping up support to clients to reduce methane emissions. WBG support can include a wide range of interventions including analytical work, capacity building, support on regulatory reforms, leak detection/monitoring, investment prefeasibility studies, and direct lending or investment.").

[1367] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("In addition to the over $1 billion in new grant funding, international financial institutions approved over $3.5 billion in new investments for methane-reducing projects since COP27. Approvals include $375 million from the Green Climate Fund and partners, over $1.9 billion (€1.78 billion) from the European Investment Bank, over $218 million (€200 million) from the European Bank for Reconstruction and Development, and $372.5 million from the Inter-American Development Bank. The World Bank approved at least $700 million in investments, including a $255 million for rice project in China, $300 million for landfill methane reduction in Cote d'Ivoire, and $145 million for wastewater methane reduction in Malawi.").

[1368] Climate & Clean Air Coalition (4 December 2023) *Highlights from 2023 Global Methane Pledge Ministerial* ("The World Bank launched the Global Methane Reduction Platform for Development (CH4D) to support low-and mid-income countries to realize the 'methane triple-wins' of abating emissions, enhancing resilience, and empowering livelihoods. Through partnerships, including with the CCAC Methane Roadmap Action Programme (M-RAP), CH4D will mobilize expertise, affordable technologies, and catalytic finance for methane abatement in the agriculture and waste sectors.").

[1369] World Bank (5 December 2023) *GGFR to evolve to the Global Flaring & Methane Reduction Partnership* ("Today the World Bank launched the Global Flaring and Methane Reduction (GFMR) Partnership, a new multi-donor trust fund focused on helping developing countries cut carbon dioxide and methane emissions generated by the oil and gas industry. GFMR will provide more than $250 million and mobilize billions from the private sector to support those countries with the least capacity and resources to address these emissions. The partnership will focus on providing grant funding, technical assistance, policy and regulatory reform advisory services, institutional strengthening, and mobilizing financing to support action by governments and operators.").

[1370] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 63-66.

[1371] World Bank (2021) *COP26 Climate Brief: Country Climate and Development Reports (CCDRs).*

[1372] World Bank (19 September 2022) *World Bank Group Is Leading the Effort on Methane Emissions Reduction with Impactful Projects and Initiatives* ("WBG support can include a wide range of interventions including analytical work, capacity building, support on regulatory reforms, leak detection/monitoring, investment prefeasibility studies, and direct lending or investment. Methane reduction is also a key focus of a number of upcoming Country Climate and Development Reports, or CCDRs, which are new WBG core diagnostic reports that integrate climate change and development considerations and help countries prioritize the most impactful actions that can reduce greenhouse gas (GHG) emissions and boost adaptation.").

[1373] World Bank, *Country Climate and Development Reports (CCDRs)* (*last visited* 14 February 2024) ("The World Bank Group's Country Climate and Development Reports (CCDRs) are a core diagnostic that integrates climate change and development. They help countries prioritize the most impactful actions that can reduce greenhouse gas (GHG) emissions and boost adaptation and resilience, while delivering on broader development goals. CCDRs build on data and rigorous research and identify main pathways to reduce GHG emissions and climate vulnerabilities, including the costs and challenges as well as benefits and opportunities from doing so. The reports suggest concrete, priority actions to support the low-carbon, resilient transition. As public documents, CCDRs aim to inform governments, citizens, the private sector and development partners and enable engagements with the development and climate agenda. CCDRs feed into other core Bank Group diagnostics, country engagements and operations, and help attract funding and direct financing for high-impact climate action.").

[1374] *See* International Monetary Fund (18 April 2022) PROPOSAL TO ESTABLISH A RESILIENCE AND SUSTAINABILITY TRUST, 39 ("on climate change, the Bank's Country Climate and Development Reports (CCDR), if available, will be a critical input, complemented by other products such as the Fund's Climate Change Policy Assessments (CCPAs) and its potential successor instrument, Climate Macroeconomic Assessments Programs (CMAPs), Climate Public Investment Management Assessment (C-PIMA), and Disaster Resilience Strategies (DRS)."); *and* International Monetary Fund (2023) REVIEW OF THE CLIMATE MACROECONOMIC ASSESSMENT PROGRAM PILOTS, 5 ("This paper reviews the two Climate Macroeconomic Assessment Program (CMAP) pilots and proposes a way forward. It builds on the experience of the previous six Climate Change Policy Assessment (CCPA) pilots, and the recent rollout of the World Bank's Country Climate and Development Report (CCDR). It also accounts for early experience with countries requesting support under the Fund's Resilience and Sustainability Trust (RST). The review's main findings are that: (1) the pilot country authorities find the macro-fiscal section of the CMAP most valuable, but such a comprehensive assessment can be burdensome when there is limited capacity, (2) a CMAP involves a much higher resource cost than a typical CD mission and some of its tools can be further improved, and (3) the CMAP complements CCDRs in the areas of Fund's comparative advantage, while there are some overlaps. Staff proposes to: (1) streamline the CMAP to focus on the Fund's comparative advantage in the areas of mitigation, PFM, and macro-fiscal impact of climate change policies; (2) provide a streamlined CMAP only in exceptional circumstances; and (3) expand more targeted CD in particular in support of RST countries. This focused and tailored approach would benefit members as it is more agile, allows the Fund to serve more members within the same resource envelope, and enhances synergies with other Fund products and the WB's CCDR. … This CMAP review responds to a request of Executive Directors made at the time of the CCPA review. Six CCPA pilots in small developing states (SDS) were conducted jointly with the World Bank between 2017-2020. The CCPA review drew lessons from these pilots and presented the results of a stakeholder survey. It also proposed to develop an IMF-only CD product, the "CMAP," because the World Bank had decided to launch its own climate assessment, the Country Climate and Development Report (CCDR). Directors asked that staff test-run two CMAP pilots and report back to the Board.").

[1375] World Bank (2022) *Climate and Development: An Agenda for Action*; *and* World Bank (2023) *The Development, Climate, and Nature Crisis : Solutions to End Poverty on a Livable Planet - Insights from World Bank Country Climate and Development Reports covering 42 economies*.

[1376] World Bank (2023) *The Development, Climate, and Nature Crisis : Solutions to End Poverty on a Livable Planet - Insights from World Bank Country Climate and Development Reports covering 42 economies* ("There are cost-effective opportunities to reduce methane emissions At the global level, methane emission reductions offer opportunities for no- or low-cost GHG emissions reductions in three key sectors: agriculture, oil and gas, and waste management … In Cambodia, methane emissions from rice production account for 65 percent of all GHG emissions from agriculture. The shift from continuously flooded irrigation to irrigation with one single drainage could reduce the emissions intensity of rice by 40 percent, bring about up to 30 percent in water savings, and reduce fertilizer use. The Kenya CCDR explores options to reduce methane emissions from cattle. By improving animal feed and breeds, it would be possible to achieve the same levels of meat and milk production with 13 million rather than 28 million head of cattle, meeting a per capita milk/ beef consumption of 180 liters/30kg per person, per day, with better rangeland quality, using less water, and reducing methane emissions by 21–36 percent. Farmers in Cambodia are already using waste from livestock farms as input for biodigesters, providing biogas for clean cooking and organic fertilizer for better crops and healthier soil while reducing GHG emissions. This practice should be encouraged and supported to scale. The International Energy Agency estimates that almost 45 percent of oil and gas methane emissions can be avoided with measures that would come at no or negative net cost. Effective established policies include leak detection and repair requirements for fugitive sources, equipment mandates for sources known to emit significant volumes of methane, and measures designed to limit nonemergency flaring and venting, including energy efficiency measures, electrification and integration of renewable energy in operations, displacement of high-carbon fuels with low-carbon heat and power processes, improved operations and maintenance protocols, and carbon capture and storage. Côte d'Ivoire can reduce upstream methane emissions from the oil and gas sector. In 2022, it emitted close to 40 kilotonnes of methane—roughly equivalent to 1.2 million tonnes of carbon dioxide equivalent (MtCO2e). Of this, 63 percent was from venting, 30 percent from fugitive emissions, and 4 percent from incomplete flaring of natural gas. At 2.33 cubic meters of gas flared per barrel of oil produced, flaring intensity in Côte d'Ivoire in 2022 had dramatically improved over the past 10 years, and was well below world average of 4.72. In Azerbaijan, total fugitive emissions (mainly methane leakage in oil and gas operations and gas distribution and carbon dioxide emissions from natural gas flaring) have almost tripled since 2000 and today account for about a quarter of the country's total GHG emissions. Natural gas losses in the distribution network also remain far above international benchmarks (7.4 percent in 2021), despite improvements since 2015 and a recently announced effort to further reduce them. The Republic of Congo could reduce gas flaring by about 50 percent at no cost over a 10- year horizon, and optimized flaring performance could generate over $50 million per year in extra overall revenues.").

[1377] Alterra (*last visited* 9 March 2024) *About Altérra* ("ALTÉRRA has the ambition to activate and grow a new global climate economy, stimulating innovation, multiplying private capital and reducing barriers to investment in emerging markets and developing economies (EMDEs). With a focus on actionable investments, ALTÉRRA and its partners are committed to the rapid deployment of capital in high-impact projects across emerging markets. Alterra Management Limited is an Asset Manager incorporated in the ADGM, regulated by the ADGM Financial Services Regulatory Authority that manages the Alterra Climate Vehicles."). *See* Energy Connects (1 December 2023) *Explained: what is Alterra, the $30 billion fund launched at COP28?* ("The UAE on Friday announced the launch of Alterra, a groundbreaking US $30 billion investment fund for transformative climate partnerships at COP28, providing a major impetus to finance the energy transition on the second day of the UN climate summit. The launch of the investment vehicle is a "defining moment" in the history of global climate finance, said COP28 President Dr Sultan Al Jaber – who will also be the Board Chairman of Alterra.When was the fund announced? The creation of Alterra was announced at the opening of the World Climate Action Summit on the second day of COP28 on Friday.").

[1378] Energy Connects (1 December 2023) *Explained: what is Alterra, the $30 billion fund launched at COP28?* ("The UAE on Friday announced the launch of Alterra, a groundbreaking US $30 billion investment fund for transformative climate partnerships at COP28, providing a major impetus to finance the energy transition on the second day of the UN climate summit.The launch of the investment vehicle is a "defining moment" in the history of global climate finance, said COP28 President Dr Sultan Al Jaber – who will also be the Board Chairman of Alterra.When was the fund announced?The creation of Alterra was announced at the opening of the World Climate Action Summit on the second day of COP28 on Friday. "I am pleased to announce the establishment of a $30 billion fund for global climate solutions. This fund is designed to bridge climate finance gap," President His Highness Sheikh Mohamed Bin Zayed Al Nahyan said in his address to the Summit."When we committed to hosting COP28, we pledged to bring the world together to unite, build and to deliver," he added.What is the concept of Alterra?As the largest of its kind investment vehicle, Alterra seeks to bridge the climate financing gap by raising and investing a corpus of up to $250 billion of institutional and private capital by 2030. In collaboration with BlackRock, Brookfield and TPG as the inaugural launch partners, Alterra has already committed $6.5 billion to climate-dedicated funds for global investments, including in the Global South, according to a COP28 statement. Alterra will work with an increasing number of global partners to mobilise capital from other institutional investors and global entities.").

[1379] International Energy Agency (2024) GLOBAL METHANE TRACKER 2024 ("Investors and insurers are also starting to establish methane performance requirements as a condition for future lending. This includes requests for improved disclosures to promote transparency on emissions reporting and underwriting standards that include methane reductions. For example, Chubb's insurance coverage is now contingent on clients adopting evidence-based plans to reduce methane emissions, while Barclays announced that starting from 2026, energy clients will be required to have 2030 methane emissions reduction targets and a commitment to end all routine venting and flaring by 2030."). *See also* Barclays, *Addressing Climate Change* (*last visited* 19 March 2024) "From January 2026, to access financing, energy clients will be required to have 2030 methane emissions reduction targets, a commitment to end all routine/non-essential venting and flaring by 2030, and near-term net-zero aligned Scope 1 and 2 emissions reduction targets. The energy clients unable or unwilling to reduce their emissions or play a role in the energy transition may find it increasingly difficult to access financing from Barclays.").

[1380] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 13 ("A policy scenario is considered, with a fee starting in 2024 at $10 per tonne of CO2e and increasing $10 per tonne each year to reach $70 per tonne by 2030. The scenario applies to the top 35 methane-emitting countries (henceforth "T35"). This includes the top 25 overall emitters plus an additional 5 large emitters (each for extractives and agriculture). T35 countries account for 85 percent of BAU global methane emissions in 2030. The scenario involves methane taxes for the extractive and agricultural sectors and a regulation that reduces landfill emissions (with a shadow price or incremental mitigation cost equal to $70 per tonne).").

[1381] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) HOW TO CUT METHANE EMISSIONS, International Monetary Fund, 13 ("A policy scenario is considered, with a fee starting in 2024 at $10 per tonne of CO2e and increasing $10 per tonne each year to reach $70 per tonne by 2030. The scenario applies to the top 35 methane-emitting countries (henceforth "T35"). This includes the top 25 overall emitters plus an additional 5 large emitters (each for extractives and agriculture). T35 countries account for 85 percent of BAU global methane emissions in 2030. The scenario involves methane taxes for the extractive and agricultural sectors and a regulation that reduces landfill emissions (with a shadow price or incremental mitigation cost equal to $70 per tonne).").

[1382] European Parliament (13 December 2022) *Deal reached on new carbon leakage instrument to raise global climate ambition*, Press Release ("According to the deal reached, an EU Carbon Border Adjustment Mechanism (CBAM) will be set up to equalise the price of carbon paid for EU products operating under the EU Emissions Trading System (ETS) and the one for imported goods. This will be achieved by obliging companies that import into the EU to purchase so-called CBAM certificates to pay the difference between the carbon price paid in the country of production and the price of carbon allowances in the EU ETS. The law will incentivise non-EU countries to increase their climate ambition and ensure that EU and global climate efforts are not undermined by production being relocated from the EU to countries with less ambitious policies.").

[1383] Smirnov A. (6 September 2021) *Coal mine methane: a missed opportunity for EU's CBAM*, EURACTIV ("One of the many included proposals is the carbon border adjustment mechanism (CBAM), which seeks to prevent greenhouse gas emissions 'leaking' over the border by taxing carbon-intensive imports from regions with less stringent emissions policies. However, the CBAM applies mostly to carbon dioxide (CO2) emissions, excluding other climate-warming gases such as methane — a missed opportunity in the fight to address climate change.").

[1384] XV BRICS Summit (23 August 2023) *Johannesburg II Declaration*, 19 ("We oppose trade barriers including those under the pretext of tackling climate change imposed by certain developed countries and reiterate our commitment to enhancing coordination on these issues. We underline that measures taken to tackle climate change and biodiversity loss must be WTO-consistent and must not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade and should not create unnecessary obstacles to international trade. Any such measure must be guided by the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), in the light of different national circumstances. We express our concern at any WTO inconsistent discriminatory measure that will distort international trade, risk new trade barriers and shift burden of addressing climate change and biodiversity loss to BRICS members and developing countries."). Work is underway to design effective border GHG adjustment mechanisms that could align global trade and climate change law and policy. *See generally* Dominioni G. & Esty D. C. (2023) *Designing Effective Border Carbon Adjustment Mechanisms: Aligning the Global Trade and Climate Change Regimes*, ARIZONA L. REV 65: 1–41.

[1385] European Commission (29 September 2023) *Carbon Border Adjustment Mechanism (CBAM) starts to apply in its transitional phase* ("This Sunday, 1 October, the Carbon Border Adjustment Mechanism (CBAM) will enter into application in its transitional phase. CBAM is the EU's landmark tool to fight carbon leakage and one of the central pillars of the EU's ambitious Fit for 55 Agenda. It will equalise the price of carbon between domestic products and imports. This will ensure that the EU's climate policies are not undermined by production relocating to countries with less ambitious green standards or by the replacement of EU products by more carbon-intensive imports. CBAM is a WTO-compatible measure that encourages global industry to embrace greener and more sustainable technologies. In its transitional phase, CBAM will only apply to imports of **cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. EU importers of these goods** will have to report on the volume of their imports and the greenhouse gas (GHG) emissions embedded during their production, but without paying any financial adjustment at this stage.") (emphasis in original). *See also* Sholli S. (2 October 2023) *EU carbon border tax enters transitional phase*, International Tax Review, KPMG.

[1386] Clausing K., Garicano L., & Wolfram C. (2023) *How an international agreement on methane emissions can pave the way for enhanced global cooperation on climate change*, Peterson Institute for International Economics. *See also* Salata Institute for Climate and Sustainability (2023) Methane and Trade: *Paving the Way for Enhanced Global Cooperation on Climate Change*, Research Brief ("As a first step, the United States, the European Union, and partner countries can work to coordinate their methane reduction policies, with an eye toward the eventual imposition of border adjustments on imports from countries that fail to raise their standards. The Biden administration could work with Congress on next steps for implementing a US methane border adjustment, while simultaneously leading efforts with the European Union, the G7, and other potential coalition members to develop a framework for a multilateral agreement. Ideally, a proposed framework could be presented at the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP28) in Dubai in late 2023.").

[1387] Council of Europe (15 November 2023) *Climate action: Council and Parliament reach deal on new rules to cut methane emissions in the energy sector* ("The Council and the Parliament agreed on three implementation phases. The first phase will focus on data collection and the creation of a methane emitters global monitoring tool and a super emitter rapid reaction mechanism. In the second and third phases, equivalent monitoring, reporting and verification measures should be applied by exporters to the EU by 1 January 2027, and maximum methane intensity values by 2030. The competent authorities of each member state will have the power to impose administrative penalties if these provisions are not respected.").

[1388] Clausing K., Garicano L., & Wolfram C. (2023) *How an international agreement on methane emissions can pave the way for enhanced global cooperation on climate change*, Peterson Institute for International Economics, 2 ("Building on these parallel approaches, this Policy Brief proposes transatlantic coordination that uses an import charge as a lever to seek similarly ambitious regulatory reforms in the oil and gas sectors abroad. Specifically, oil and gas exporters can be encouraged to adopt regulations comparable to those in the United States and the European Union or, if they fail to implement regulations, pay a border adjustment fee on exports to the two jurisdictions. With time, most major energy importers would ideally join the coalition of countries cooperating on both stringent domestic regulations on oil and gas production (if applicable) and border adjustments on any dirty, nonregulating exporters."). The Inflation Reduction Act includes a Methane Emission Reduction Program that imposes a methane waste fee of up to $1,500 per ton of methane emitted by 2026, and raises royalty fees for oil and gas extracted from federal lands and waters, including fees on gas avoidably lost by emergency flaring or venting. *See* Inflation Reduction Act of 2022, Pub. L. No. 117-169 (2022) § 60112 ("(e) Charge Amount.--The amount of a charge under subsection (c) for an applicable facility shall be equal to the product obtained by multiplying—"(1) the number of metric tons of methane emissions reported pursuant to subpart W of part 98 of title 40, Code of Federal Regulations, for the applicable facility that exceed the applicable annual waste emissions threshold listed in subsection (f) during the previous reporting period; and "(2)(A) $900 for emissions reported for calendar year 2024; "(B) $1,200 for emissions reported for calendar year 2025; or "(C) $1,500 for emissions reported for calendar year 2026 and each year thereafter."). *See also* United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; *discussed in* Friedman L. & Plumer B. (28 July 2022) *Surprise Deal Would Be Most Ambitious Climate Action Undertaken by U.S.*, The New York Times ("The bill would also crack down on leaks of methane, a powerful greenhouse gas, from oil and gas wells, pipelines and other infrastructure. By 2026, polluters would face a penalty of $1,500 per ton of methane that escaped into the atmosphere in excess of federal limits. The methane fee will raise $6.3 billion from the oil and gas industry over a decade, much of which will be reinvested in measures to help prevent methane leaks."); *and* Inflation Reduction Act of 2022, Pub. L. No. 117-169 (2022) §§ 50261–50263 ("For all leases issued after the date of enactment of this Act, except as provided in subsection (b), royalties paid for gas produced from Federal land and on the outer Continental Shelf shall be assessed on all gas produced, including all gas that is consumed or lost by venting, flaring, or negligent releases through any equipment during upstream operations.”).

[1389] Austin S. (1 November 2021) *Prime Minister Mottley: Closing of Gaps Required*, Barbados Government Information Service.

[1390] Austin S. (1 November 2021) *Prime Minister Mottley: Closing of Gaps Required*, Barbados Government Information Service.

[1391] *For example, see* the support provided by the Bahamas to the efforts of Prime Minister Mottley: Office of the Prime Minister of the Bahamas (2 October 2023) *Prime Minister Davis' Remarks at the Climate Finance in The Americas Meeting's Opening Session* (“First, we need to drive progress on managing risks to investing in climate action in developing countries. Where risk is real, we need to deploy at scale the risk reduction instruments – such as guarantees, insurance, and local currency hedging and financing – necessary to unlock capital. Where risk is perceived, we need to address the biases that hinder investment at scale, and the expectation of high financial returns when engaging on climate change Second, we need to drive progress on financing a just and equitable transition. We need to develop transparent transition plans that shift investment portfolios over time, and that enable ramp-ups in climate investments to the same extent as we see a phasing out of harmful investments. Third, we need to drive progress on managing the debt crisis. We need to develop a shared understanding of climate-fiscal-debt links and ensure no country builds up excessive debt because of climate action.”).

[1392] Prime Minister Motley (2 December 2023) *Barbados' National Statement at COP28* (video of Statement).

[1393] COP28 (4 December 2023) *COP28 Finance Day unlocks innovative financial mechanisms to support vulnerable countries fight climate change*, Press Release (“Major international financial institutions and countries made new commitments to offer climate-resilient debt clauses (CRDCs) in their lending. These clauses allow debt service to be paused to provide breathing space when countries are hit by climate catastrophes. The UK, France, World Bank, Inter-American Development Bank (IDB), European Investment Bank (EIB), European Bank for Reconstruction and Development (EBRD) and African Development Bank (AfDB) made new commitments to expand CRDCs in their lending. In total 73 countries called on donors to expand the use of these clauses by 2025.”).

[1394] COP28 (4 December 2023) *COP28 Finance Day unlocks innovative financial mechanisms to support vulnerable countries fight climate change*, Press Release (“Major international financial institutions and countries made new commitments to offer climate-resilient debt clauses (CRDCs) in their lending. These clauses allow debt service to be paused to provide breathing space when countries are hit by climate catastrophes. The UK, France, World Bank, Inter-American Development Bank (IDB), European Investment Bank (EIB), European Bank for Reconstruction and Development (EBRD) and African Development Bank (AfDB) made new commitments to expand CRDCs in their lending. In total 73 countries called on donors to expand the use of these clauses by 2025.”).

[1395] COP28 (4 December 2023) *COP28 Finance Day unlocks innovative financial mechanisms to support vulnerable countries fight climate change*, Press Release (“Throughout COP28 Finance day, other announcements included: … • The IDB announced it had already offered $1.2 billion of loans covered through CRDCs.”).

[1396] COP28 (4 December 2023) *COP28 Finance Day unlocks innovative financial mechanisms to support vulnerable countries fight climate change* (“Japan and France announced a commitment to support the African Development Bank's facility to leverage Special Drawing Rights (SDRs) for climate and development.”).

[1397] Office of the Prime Minister of Barbados (23 September 2022) *Urgent and Decisive Action Required for an Unprecedented Combination of Crises The 2022 Bridgetown Agenda for the Reform of the Global Financial Architecture*, Press Release.

[1398] COP28 (2023) *UAE Leaders' Declaration on a Global Climate Finance Framework* ("Seizing the opportunity: Investing $5-7tn annually in greening the global economy by 2030 will be critical to achieving our shared climate goals. Our collective efforts to pursue the goals of the Paris Agreement present the opportunity to accelerate local, regional and global low-carbon, climate resilient, and nature-positive growth and inclusive economies, strengthening delivery of the Sustainable Development Goals(SDGs). We urge global leaders to seize this unprecedented economic opportunity for inclusive and shared prosperity so that no country has to choose between fighting poverty and fighting climate change. We need to build on flagship initiatives such as the Paris Pact for People and Planet (4P), Bridgetown Initiative, Accra Marrakesh Agenda, G20 New Delhi Leaders' Declaration, and African Leaders' Nairobi Declaration on Climate and Call to Action.".).

[1399] COP28 (4 December 2023) *COP28 Finance Day unlocks innovative financial mechanisms to support vulnerable countries fight climate change*, Press Release ("This marks significant progress to reform the global climate finance architecture by making climate finance available, accessible, and affordable. This has been the central vision of the COP28 UAE Declaration on a Global Climate Finance Framework launched at the World Climate Action Summit at the beginning of COP28. … The Declaration is endorsed by India, France, Barbados, Kenya, Ghana, Germany, UK, USA, Senegal, and Colombia. It lays out defining principles for a climate finance architecture that delivers for all.").

[1400] COP28 (2023) *UAE Leaders' Declaration on a Global Climate Finance Framework* ("3. Freeing up fiscal space for climate action: The international financial architecture, public and private, needs to be made fit for more frequent, profound shocks. This can be done through: wider use of climate-resilient debt clauses; consideration of debt-for-climate swaps; and sustainability linked bonds. Additional voluntary IMF Special Drawing Rights (SDRs) should be rechanneled, subject to national legal frameworks, including through the Resilience and Sustainability Trust. … 4. Widening the sources of concessional finance for climate action: Mitigating climate change and adapting and responding to climate impacts will require significant additional finance, including concessional finance. Laying the foundations for climate-smart growth in many geographies and sectors may not always offer returns compatible with private sector models. Efforts are needed to bridge these gaps, particularly for adaptation, which often requires non-debt financing. Innovative mechanisms to explore include: better use of hybrid capital; policy-based guarantees; portfolio guarantees of MDB loans; global philanthropy; re-channeling of inefficient subsidies; and emissions pricing and taxation mechanisms, as applicable and in line with national circumstances, and we note forthcoming initiatives in this regard. … 7. Building better, bigger, and more effective MDBs : Recognizing the Report of the G20 Independent Expert Group on Strengthening MDBs, the MDBs need to enhance operating models, improve responsiveness and accessibility, and increase financial capacity so that they can better address global challenges such as climate change. They need to work as a system, including through common country platforms, and collaborating with the multilateral funds to streamline access to finance, including local currency financing and making a difference in public adaptation finance.").

[1401] COP28 (2023) *UAE Leaders' Declaration on a Global Climate Finance Framework* ("LIST OF COUNTRIES
Barbados
Federal Republic of Germany
French Republic
Ireland
Republic of the Philippines
Republic of Colombia
Republic of Ghana
Republic of Kenya
Republic of India
Republic of Senegal
United Arab Emirates
United Kingdom of Great Britain and Northern Ireland
United States of America".)