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

5 February 2023

Institute for Governance & Sustainable Development

Suggested citation
Institute for Governance & Sustainable Development (2023) *A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030*.

Lead Authors
Richard “Tad” Ferris, Gabrielle Dreyfus, and Durwood Zaelke.

Contributing Authors
Valerie Fajardo, Caitlan Frederick, Erika Gerstenberger, Kiran Ghosh, Amelia Murphy, Zerin Osho Raina, Romina Picolotti, Connor Schiff, Xiaopu Sun, Olanrewaju Suraju, Trina Chiemi Thorbjornsen, and Jon Turner.

Acknowledgements
We thank Laura Bloomer, Ken Alex, Gil Damon, Daniel Taillant, and all readers for comments that allow us to continue to update and improve this *Primer*.

Institute for Governance & Sustainable Development

About the Institute for Governance & Sustainable Development

IGSD's mission is to promote fast climate mitigation, including protecting existing forest carbon sinks, 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 latest research shows 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 would help 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.

IGSD's theory of action is anchored in the urgency of responding rapidly and effectively to slow self-reinforcing feedbacks and avoid irreversible damage to the climate system with catastrophic consequences for all. *See* IGSD's Background Note on *The Need for Fast Near-Term Climate Mitigation to Slow Feedbacks and Tipping Points* (September 2022).

The fastest way to reduce near-term warming in the next decade or two is to cut the 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 phasedown schedule in the Kigali Amendment to the Montreal Protocol will capture about 90 percent of this. Parallel efforts to enhance 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-reinforcing 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 withing 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.

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

5 February 2023

Table of Contents

Table of Boxes, Figures, and Tables

Executive Summary

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 necessary to slow global warming in the near term[1] and limit the risk of triggering climate, economic, and social tipping points. Topics covered include the science of methane mitigation and why action is urgently needed; current and emerging mitigation opportunities by sector; national, regional, and international efforts that can inform emergency global action on methane; and financing initiatives to secure support for fast methane reduction. The *Methane Primer* also supports the need for research and development of technologies to remove methane from the atmosphere at scale.

Methane is a super-potent planet-warming gas—a ton of methane (CH_4) has over 80 times the warming power of a ton of carbon dioxide (CO_2) emissions over 20 years. 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,[2] which include the "short-lived climate pollutants" (SLCPs) with atmospheric lifetimes of, on average, under 15 years—methane, 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 pollutants also will reduce the build-up of heat in the ocean that otherwise would continue adding to warming for decades to centuries, long after the lifetime of the pollutant.[3]

While cutting CO_2 emissions remains important over the long term, cutting super climate pollutants can slow warming one to two decades sooner than CO_2-focused strategies alone, avoid two to six times more warming at 2050 than CO_2 cuts can,[4] and reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.[5]

Key messages include:

- Methane emissions from human activity are responsible for nearly 45% of current net warming.[6] Methane pollution has already caused 0.51 °C of the 1.06 °C of total observed warming (2010–2019) compared to pre-industrial.[7] Warming caused by methane will continue to increase if methane emissions continue to rise, with a 24–30% increase in anthropogenic emissions expected by 2050 under current policy scenarios.[8] Atmospheric methane concentrations set records for the fastest rate of increase since records started in 1983 with jumps of 15.1 parts per billion (ppb) in 2020 and 18.2 ppb in 2021, compared with an average growth rate over 2007–2019 of 7.3 ppb per year; methane exceeded 1900 ppb for the first time in September 2021 (**Box 1**).[9]

- Without fast action to slow warming, we are likely to exceed the 1.5 °C "guardrail" at least temporarily by the end of the decade,[10] with a 50-50 chance that at least one year will exceed 1.5 °C by 2026 and a 10% chance that the five-year mean from 2022 to 2026 will exceed this threshold.[11]

    - Crashing through the 1.5 °C guardrail increases the risk that self-reinforcing feedbacks will further accelerate rising temperatures and trigger a cascade of irreversible tipping points in the climate system (**Box 2**).[12]

- Over 3 billion people live in vulnerable contexts. 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.[13]

- The *Global Methane Assessment* from the United Nations Environment Programme and the Climate & Clean Air Coalition confirms that cutting methane emissions is the fastest strategy for the world to avoid crashing through the 1.5 °C guardrail.[14] 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%.[15] The Intergovernmental Panel on Climate Change (IPCC) *Sixth Assessment Report* (AR6) confirms that "strong, rapid, and sustained methane reductions" are key to limiting warming in the near- and longer-term.[16]

  - AR6 Working Group III further finds that "[d]eep 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…. 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*)."[17]

  - Limiting warming to 1.5 °C with no or limited overshoot requires reducing global 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 short-lived climate pollutants and nitrous oxide.[18]

- Technology exists to cut 45% of anthropogenic methane emissions by 2030 from energy production, agriculture, and waste (**Table 2**).[19] The International Energy Agency (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%.[20] Measures specifically targeting methane sources are essential, as broader decarbonization measures can only achieve 30% of the needed methane reductions.[21]

  - Roughly 60% of the available targeted measures have low mitigation costs (defined as 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.[22]

  - In energy production, the greatest potential for mitigation is in the oil and gas sector.[23] In the waste sector, reducing and managing solid waste holds the most promise.[24] And in agriculture, measures to reduce methane emissions from livestock could have the greatest impact.[25]

  - Methane mitigation also can support geographically diverse and well-paying jobs.[26]

- Successful implementation of the Global Methane Pledge, which 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 within 1.5 °C,[27] according to the *Global Methane Assessment*.[28] 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.[29]

- Cutting methane also increases resilience and promotes environmental justice.[30] 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.[31] 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 and crops, supporting food security.[32]

    - 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 transition to a net-zero economy, it is essential to stop methane leaks to slow warming and protect the health of local communities and food security.[33]

    - The transition away from fossil fuels will not only reduce CO_2 but also will reduce cooling aerosol emissions. The cooling aerosols are co-emitted with CO_2 when sulphur-containing fossil fuels, such as coal and diesel, are burned. 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 even accelerate warming over the first decade or more.[34]

    - Thus, cutting methane and other short-lived climate pollutants is also key to counteracting this increased rate of warming in the near term.[35]

- Out of the total global emissions of methane (550–594 million metric tonnes of methane, $Mt\,CH_4\,yr^{-1}$), 50–65% come from anthropogenic sources (336–376 $Mt\,CH_4\,yr^{-1}$) in three main sectors: energy production, agriculture, and waste.[36] Energy production accounts for about 35% of anthropogenic methane emissions,[37] agriculture accounts for about 40%,[38] and waste accounts for about 20%,[39] with biomass burning and biofuels as minor sources.

- Around 35–50% of global methane emissions are from natural sources.[40] 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-reinforcing climate-carbon cycle feedbacks as microbes increase their methane-producing activity and wildfires accelerate thaw.[41] In addition to the need to slow the rate of warming to reduce natural sources of methane emissions and risks associated with release of seabed methane hydrates, research is underway on atmospheric methane removal.[42]

- Many national and subnational governments (including major methane-emitting countries and regional organizations), as well as international initiatives and partnerships, are already pursuing mandatory and voluntary methane mitigation measures. These national efforts and bottom-up initiatives strengthen and expand national methane action and leadership.

- 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" responsible for 8–12% of global oil and gas sector methane emissions.[43] 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. This includes encouraging use of metrics that better reflect temperature impacts of strategies to meet the 1.5 °C goal, such as the 20-year global warming potential (GWP_{20}) for methane and other short-lived climate pollutants (**Box 3**).[44]

- Funding and financing are needed to support governments and organizations committed to fast methane reductions and associated governance. This includes financing made available through instruments such as the International Monetary Fund's new Resilience and Sustainability Trust (*see* **Section 11**).

- Multilateral action to rapidly cut methane emissions is critical. Methane is a well-mixed greenhouse gas, and methane mitigation by all countries and territories is the best means to achieve rapid and effective reductions of methane emissions. The Global Methane Pledge, which establishes a collective target to achieve at least 30% global methane emissions reductions below 2020 levels by 2030, is an important step for keeping the 1.5 °C guardrail in reach.[45] Nevertheless, strengthened and expanded national methane action and leadership that leaves some countries behind and fails to ensure accountability and support for methane mitigation commitments may not be sufficient to deliver methane reductions at the speed and scale needed to avoid potentially catastrophic climate impacts. Therefore, governments should build on the Global Methane Pledge and parallel agreements such as the U.S. China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s to open the door for a global methane agreement. This includes acting immediately to require 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.

1. Introduction

Ending dependence on fossil fuels, including fossil gas, by shifting to clean energy is essential for protecting the climate and for ensuring peace and security. But during the time it takes to shift the world's energy system to clean energy, it also is essential to reduce methane emissions as fast as possible to address the climate emergency.

Methane (CH_4) is a super-potent planet-warming gas with over 80 times the warming power of carbon dioxide over 20 years. 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."[46] 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,[47] and weakening of carbon sinks.[48] Addressing methane pollution will slow global warming, improve health, generate employment, enhance food security. and increase investment into developing countries. Nearly 95% of countries directly reference methane mitigation in their nationally determined contributions (NDCs) or will in their next revision.[49] As of February 2023, 150 countries including the European Union have joined the Global Methane Pledge (GMP),[50] which establishes a collective target to achieve at least 30% methane emissions reductions below 2020 levels by 2030, representing approximately 70% of the global economy and 45% of anthropogenic methane emissions.[51]

Methane pollution has already caused 0.51 °C of the total observed warming in 2010–2019 of 1.06 °C (0.88–1.21 °C) compared to pre-industrial (**Box 1**).[52] And warming will increase if methane emissions continue to rise. Atmospheric methane concentrations set records in 2020 and 2021 for the fastest rates of increase since records started in 1983, with jumps of 15.1 and 18.2 parts per billion (ppb), respectively, compared to an average yearly rate of increase of 7.3 ppb over 2007—2019.[53] Methane exceeded 1900 ppb for the first time in September 2021.[54] As noted in the joint U.S.-EU announcement of the GMP, "Methane is a potent greenhouse gas [GHG] and, according to the latest report of the Intergovernmental Panel on Climate Change, accounts for about half of the 1.0 °C net rise in global average temperature since the pre-industrial era."[55]

Box 1. Methane's contribution to current warming

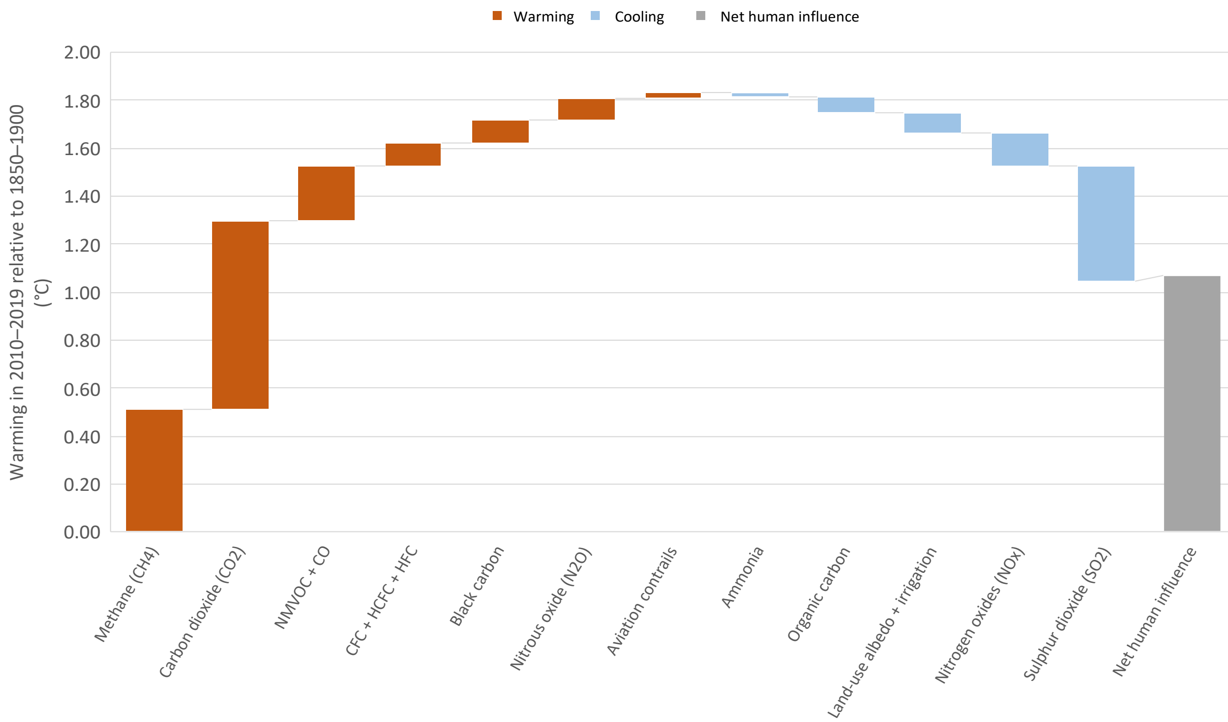
Methane emissions from human activity are responsible for nearly 45% of current net warming.[56] According to the IPCC, methane pollution caused 0.51 °C (0.29–0.84 °C) of warming in 2010–2019 relative to 1850–1900, and CO_2 caused 0.79 °C (0.52–1.25 °C) of warming (**Figure 1**). The total current net anthropogenic warming is about 1.07 °C (0.8 to 1.3 °C) through 2019. 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 to 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.[57]

Cutting methane emissions is the fastest and best strategy to slow warming and keep 1.5 °C within reach.[58] The *Global Methane Assessment* from the Climate & Clean Air Coalition (CCAC) and United Nations Environment Program (UNEP), led by Dr. Drew Shindell, 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.[59]

Fast and aggressive methane mitigation is critical because the window to reduce warming enough to slow self-reinforcing feedbacks and avoid tipping points may close by the end of this decade.[60] Many of these feedbacks are showing signs of activation, and there is evidence that we are nearing or have already crossed multiple climate tipping points.[61] The Intergovernmental Panel on Climate Change (IPCC) defines a tipping point as "a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly."[62] 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,[63] as confirmed by two IPCC Special Reports.[64] A recent assessment finds that exceeding 1.5 °C increases the likelihood of triggering or committing to six self-propagating climate tipping points.[65] Domino-like interactions among these systems risk triggering a global cascade of tipping points.[66] Additionally, as-yet-undiscovered tipping points are possible due to current model limitations and exclusion in these models of processes, including those related to biogeochemical feedbacks such as permafrost thaw.[67]

Decarbonizing the energy system and achieving net-zero carbon dioxide (CO_2) emissions is critical for stabilizing the climate and keeping temperatures below 1.5 °C by the end of this century.[68] However, phasing out CO_2-emitting fossil fuels, such as coal and diesel, also stops emissions of co-emitted cooling aerosols such as sulphur dioxide (SO_2).[69] 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 or more*.[70] The *Global Methane Assessment* and the IPCC *Sixth Assessment Report* (AR6) both highlight "strong, rapid, and sustained methane reductions" as key to counteracting this increased rate of warming from unmasking over the next decades.[71] 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 the 1.5 °C guardrail.[72]

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).

In addition to causing global warming on its own, methane is also a major precursor to tropospheric ozone,[73] which also causes warming and is linked to significant human respiratory and cardiovascular morbidity and mortality[74] and agricultural crop damage (estimated at US$63 billion annually in East Asia alone).[75] 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.[76] A recent study estimated methane's contribution to the present-day tropospheric ozone burden at 35%.[77] Methane is likely to play a greater role in tropospheric ozone formation as emissions of other precursors decrease due to air pollution controls.[78] 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 labour from extreme heat, and 26 million tonnes of crop losses globally.[79] Eliminating all anthropogenic methane emissions could avoid 690,000 premature deaths per year in 2050.[80] Each tonne of methane reduced generates US$4,300 in health, productivity, and other benefits.[81] 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 GMP was formally launched at the head of State level at the high-level segment of the 26th Conference of the Parties (COP26) on 2 November 2021.[82] The United States and the European Union originally announced the GMP at the Major Economies Forum on 17 September 2021.[83] The GMP commits governments to a collective global goal of reducing global methane emissions by at least 30% from 2020 levels by 2030. Signatories also commit to 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 GMP would reduce warming by at least 0.2 °C by 2050[84] and would keep the planet on a pathway consistent with staying within 1.5 °C, according to the *Global Methane Assessment*.[85] 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.[86] 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.[87] Nearly 85% of targeted measures have benefits that outweigh the net costs.[88]

The GMP marks 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. This initial commitment raises awareness of the opportunity and urgency of slowing warming by cutting methane. It also identifies the sectors involved and the level of ambition needed. Governments should build on the GMP 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 sourcing as the availability of Russian gas is reduced. Cutting methane is our best opportunity 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.[89]

Although this *Primer* focuses on the SLCP methane, deep cuts to similarly potent 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.[90] 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.[91]

Box 2. Self-reinforcing 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."[92] Some feedbacks, like the ice-albedo feedback, are self-reinforcing where initial warming reduces the volume and extent of reflective Arctic summer sea ice and exposes the darker ocean surface that absorbs more heat, and further reduces 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.[93] 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.[94]

For a fuller discussion of feedbacks and tipping points and fast-mitigation solutions, *see* Institute for Governance & Sustainable Development (2022) THE NEED FOR FAST NEAR-TERM CLIMATE MITIGATION TO SLOW FEEDBACKS AND TIPPING POINTS: *Critical Role of Short-lived Super Climate Pollutants in the Climate Emergency*.

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, like cutting methane emissions, that can slow warming in the near term. Assessing how strategies affect near-term warming requires considering individual emissions by pollutant in units of mass, as required under United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines and recommended by climate scientists.[95] 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, when comparing climate impacts for short-lived climate pollutants like methane, 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.[96] While the UNFCCC currently requires using the GWP_{100} metric when reporting aggregated emissions or removals, which systematically undervalues the climate impact of methane, reporting Parties may use other metrics in addition, such as GWP_{20} or absolute temperature potentials.[97] AR6 has updated the metrics for methane as follows: GWP_{20} is 81.2 and GWP_{100} is 27.9.[98] **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* are based on mathematical relationships that are intended to make SLCPs like methane comparable to the longer-term warming impact of CO_2 emissions.[99] 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.[100] 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.[101]

For these reasons, this *Methane Primer* follows the convention of the UNEP/CCAC *Global Methane Assessment* in using mass-based metrics, such as million metric tonnes of methane ($MtCH_4$), 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.[102] 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.[103] 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.[104] While the 20-year average temperature is not expected to exceed 1.5 °C before 2030, there is a 50-50 chance that at least one year will exceed 1.5 °C by 2026 and a 10% chance that the five-year mean from 2022 to 2026 will exceed this threshold.[105]

Speed must become a key factor in the selection of climate solutions, to quickly limit warming, slow self-reinforcing feedbacks, avoid tipping points, and protect the most vulnerable people and ecosystems. Therefore, we need "fast climate solutions," meaning measures—including regulations—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.[106] 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.[107]

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*,[108]

> "[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-reinforcing feedback loops pushing the planet past tipping points

Rapid warming over the near term threatens to accelerate a vicious cycle—self-reinforcing feedbacks where the planet starts to warm itself in a "Hothouse Earth" scenario. 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,[109] and could lead to uncontrollable warming, becoming the dominant force regulating the climate system.[110]

A prestigious group of climate scientists, in their 2019 Comment in *Nature* titled *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."[111]

Evidence from the latest review of feedbacks and tipping points suggests that we are already in a state of planetary emergency where both the risk and urgency of the emergency are acute. At about 1.1 °C of warming, there is a non-negligible risk that one or more cryosphere tipping points have already been passed.[112] 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. Limiting warming below 2 °C and the duration, or overshoot, of warming above 1.5 °C may avoid collapse of the ice sheets.[113] The melting Greenland Ice Sheet is the largest single contributor to the rate of global sea-level rise,[114] 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.[115] Delaying mitigation increases the risk of crossing one or more temperature thresholds from higher peak temperatures. More importantly, stabilization temperatures above 1.5 °C dramatically increase the risk of crossing multiple climate tipping points.[116] 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.[117]

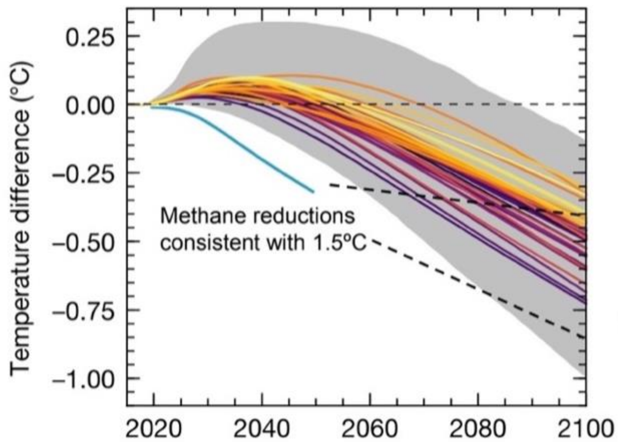
B. Reducing fossil-fuel burning is essential but does not slow near-term warming

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.[118] In fact, reducing the burning of fossil fuels like coal and diesel also cuts co-emitted cooling aerosols, primarily in the form of sulphates and nitrates. Co-emitted cooling aerosols are reflective particles that currently mask warming of about 0.5 °C.[119] 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, and this aerosol unmasking offsets reductions in warming from decarbonization until around 2050 and even adds warming over the first decade or more (*see* **Figure 2**).[120] 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,[121] 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 that cancels out the cooling benefits of decarbonization until around 2050, underscoring the importance of cutting non-CO_2 super climate pollutants:

> "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 [sulphur dioxide] reductions that would accompany decarbonization (*high confidence*)."[122]

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.

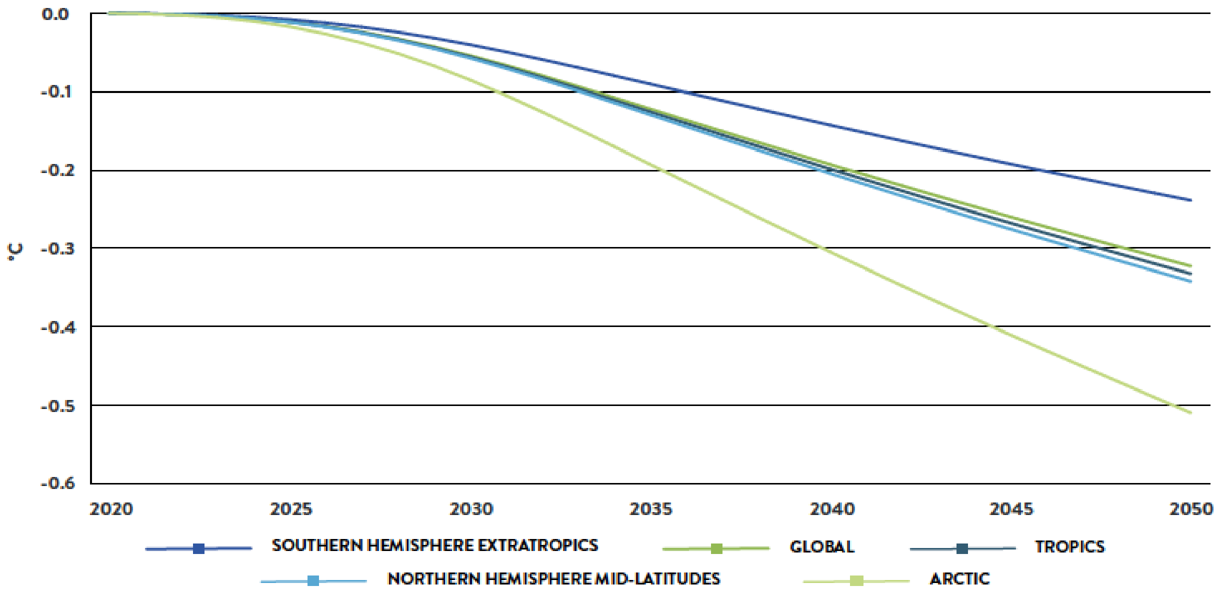
3. Cutting methane emissions is the fastest and best way to slow climate change in the near term

The *Global Methane Assessment* confirms that cutting methane emissions is the fastest strategy to limit warming over the next 20 years.[123] 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%.[124] AR6 confirms that "strong, rapid, and sustained methane reductions" are key to limiting warming in the near- and longer-term.[125] Further, the most recent IPCC report on climate solutions by Working Group III (AR6 WGIII) 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.[126] Limiting warming to 1.5 °C with little or no overshot requires reducing emissions by 34% below 2019 levels in 2030 and 44% below 2019 levels in 2040.[127]

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**).[128] 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.[129] Current methane emission levels place global average temperatures on a trajectory to breach the 1.5 °C guardrail, with anthropogenic methane emissions accounting for about one-third of the temperature increase.[130] 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.[131] Pursuing all available methane mitigation measures would cut the global rate of warming by 30% by mid-century.[132] If all anthropogenic methane emissions were eliminated, surface methane levels could drop below pre-industrial levels within 15 years.[133]

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

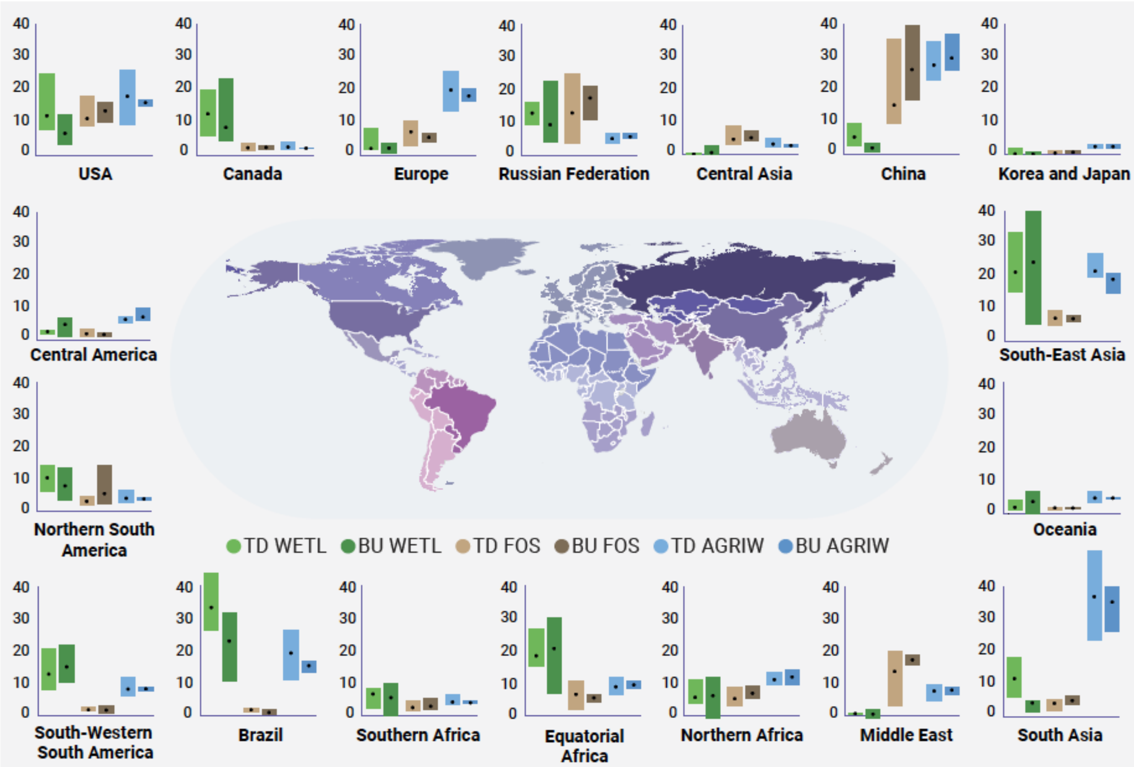


Source: United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Figure 5.1. *Note*: In addition to global mean responses, values are given for the southern hemisphere extratropics (90–28 °S), the tropics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

Rapid reductions in methane emissions could also reduce the risk of losing all of the summer Arctic sea ice.[134] If Arctic summer sea ice were to disappear for the sunlit months, as could happen as early as mid-century,[135] it would be the warming equivalent of 1,000 billion tonnes of CO_2 and up to three times this if cloud cover dissipates.[136]

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 over the next 20 years,[137] absent solar radiation management or other still speculative climate interventions.

Figure 4. Average methane emissions for 2008–17 in $MtCH_4$ per year for 18 continental regions

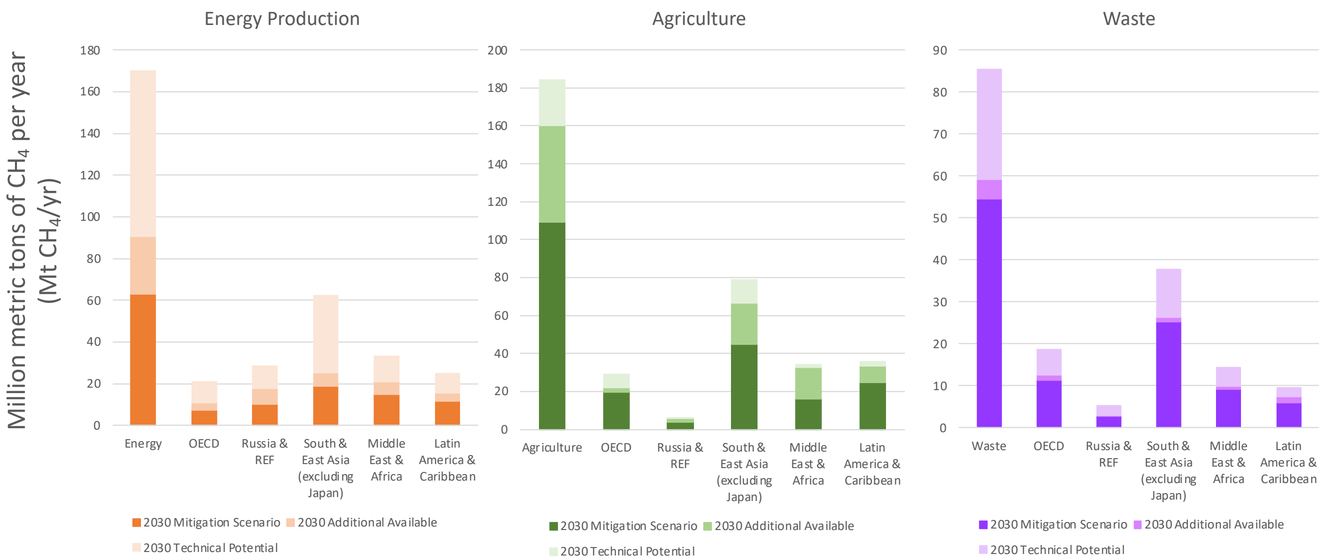


Source: United Nations Environment Programme (2021) EMISSIONS GAP REPORT 2021: THE HEAT IS ON – A WORLD OF CLIMATE PROMISES NOT YET DELIVERED, Figure 6.1. *Note*: Emissions are shown for three main emission categories: wetlands (WETL), fossil fuel-related (FOS) and agriculture and waste (AGRIW). Colored 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.[138] Three sectors are primarily responsible: energy production (~35%), agriculture (~40%), and waste (~20%), with regional differences and uncertainties in estimates shown in **Figure 4**.[139] In comparison, biomass burning and biofuels are minor sources.[140] 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**).[141] 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.[142] Recent studies attribute the record-breaking increase 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 in 2021 and is under investigation.[143] (**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., Hasegawa T., Masui T., Takahashi K., Silva Herran D., Dai H., Hijioka Y., & Kainuma M. (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 about 35% of anthropogenic methane emissions

About 35% of anthropogenic methane emissions come from energy production activities related to oil, gas, and coal.[144] Emissions in 2020 are estimated at close to 130 $MtCH_4$ globally, with about 80 $MtCH_4$ from oil and gas and 40 Mt from coal, with the IEA estimating a 5% increase in emissions in 2021.[145] Each fuel is similarly responsible for around one-third of methane emissions associated with energy production.[146] Most emissions from oil and gas come from onshore extraction, followed by downstream activities such as refining and distribution.[147] 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)[148] are considered, methane emissions from the energy production sector are about 70% higher than in reported data.[149] Note, however, these estimates generally do not include likely significant emissions from abandoned coal mines and oil and gas wells.[150]

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.[151] Recent analysis of coal mine emissions from Australia, including surface mines, found that methane emissions had been significantly underestimated in official reporting.[152] Even in the case of forecasted declining coal production,[153] 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.[154] 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.[155] However, extreme heatwaves and the shift to replace Russian gas in Europe is putting 2022 coal demand on track to meet the 2013 annual record and set a new all-time high in 2023.[156]

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

Agriculture accounts for around 40% of anthropogenic emissions, with anthropogenic emissions accounting for about 60% of total methane emissions. These agricultural emissions arise primarily from livestock and rice cultivation.[157] The largest contribution within agriculture is from cattle, sheep, and other ruminant animals that generate methane through their digestion processes (enteric fermentation),[158] with cattle accounting for 77% of these emissions.[159] Current manure management practices, especially for pigs and cattle, also release methane.[160] Emissions in 2020 are estimated at approximately 117 $MtCH_4$ from livestock and manure management.[161] 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).[162]

Flooded fields used for rice cultivation are another significant source of methane, especially in regions with high rice production.[163] In Asia, rice cultivation contributes around 20% of the region's methane emissions.[164] Emissions in 2020 are estimated at approximately 30 $MtCH_4$ from global rice cultivation.[165]

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

Of the 60% of global methane emissions from anthropogenic sources, approximately 20% of these anthropogenic emissions comes from the waste sector.[166] This includes both landfills and wastewater treatment where decomposition of organic waste produces methane. Waste sector emissions in 2017 are approximately 68 $MtCH_4$.[167] 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.[168]

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.[169]

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.[170] The GMP targets at least 30% reductions below 2020 levels by 2030, equivalent to at least 150 $MtCH_4$ reduction below 2030 baseline levels (**Figure 6**).[171] Measures specifically targeting methane sources are essential, as broader decarbonization measures can only achieve 30% of the needed methane reductions.[172] 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.[173] Methane mitigation also supports geographically diverse and well-paying jobs.[174]

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.[175] 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.[176]

Table 2. Emissions control measures by sector

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

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 $MtCH_4$/yr,[177] representing 20–40% of the reductions needed to meet the GMP 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 GMP target. The IEA identified pathways for achieving 75% reductions from the energy production sector, as called for in the IEA's Net Zero by 2050 Roadmap,[178] with 40–50% of the measures having no net cost at average gas prices over the past five years; almost all mitigation options from oil and gas operations worldwide could be implemented at no net cost at 2021 prices.[179] 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.[180] 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%.[181]

Measures to address leaks[182] and reduce flaring and venting[183] of methane are critical to lowering emissions, and hence methane intensity, in the oil and gas sector.[184] These actions include ramping up leak detection and repair programs (LDAR) and replacing leaking devices and older equipment with modern low-emitting equipment.[185] Prohibiting venting of natural gas at oil wells can reduce emissions by 95%.[186] 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.[187] 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.[188] 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.[189]

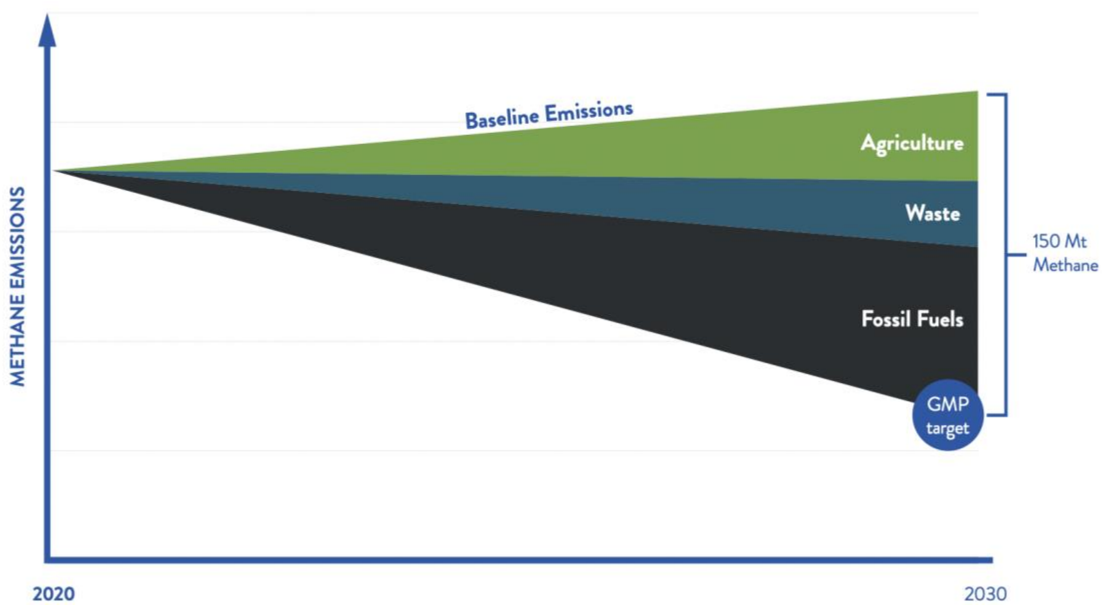
Reducing fugitive emissions of methane and associated air pollutants also promotes environmental justice. For example, over 18 million people in the United States live within one mile of wells and they are disproportionately marginalized groups; unemployment near wells is also found to be 4 to 12 times higher than the national average.[190] Efforts to plug and decommission the millions of abandoned and idle oil and gas wells would further reduce emissions while creating jobs, smooth the energy transition.[191]

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.[192] An airborne study of the Permian Basin in New Mexico estimated emissions 6.5 times larger than in an emissions factor-based inventory.[193] 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."[194] 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.[195] Taking satellite observations and scaled emissions intensities into consideration, IEA estimates that emissions from the energy sector were 70% higher than officially reported.[196] 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 that 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.[197] Methane monitoring efforts are discussed further in **Section 8**.

In addition to reductions in the oil and gas sector, measures to cut emissions from coal mining can provide additional mitigation of 12–25 $MtCH_4$/yr.[198] IEA estimates that eliminating the worst performing quartile of operating coal mines would remove about 25 $MtCH_4$ by 2050.[199] 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.[200] Although methane is recoverable before mining operations begin, the methane vented from mines is dilute and thus more expensive to use.[201] Additionally, because abandoned mines continue to leak methane, the CCAC recommends the flooding of abandoned coal mines to eliminate these emissions.[202] In some situations, abandoned mine methane can be recovered and used before flooding occurs.[203]

In sum, 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[204] are essential to reducing methane emissions in the coming decades.[205]

Figure 6. Illustrative example of 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.").

B. Agriculture sector

The agriculture sector can provide mitigation of 4–42 $MtCH_4$/yr from the livestock subsector and 6–9 $MtCH_4$/yr from rice cultivation, representing 7–34% of the reductions needed to meet the GMP target in 2030 (**Figure 6**).[206] Measures to reduce emissions from livestock involve improving feeding and manure management on farms to reduce methane generated per unit of animal productivity while also reducing livestock count (**Table 3**). Breeding schemes and new technologies, including feed and manure additives, are being developed to improve livestock health and productivity, manage enteric fermentation, and reduce emissions from manure.[207] The success of these strategies must be considered in terms of both methane abatement and related environmental impacts on land and fertilizer use for feed and associated emissions,[208] keeping in mind the potential perverse incentives to continue consolidation and industrialization of the meat and dairy sectors.[209]

Two promising feed additives shown to reduce enteric methane emissions include seaweed, specifically a type of red algae (*Asparagopsis taxiformis*), and methane inhibitor 3-nitrooxypropanol (3-NOP, marketed as Bovaer®). Additionally, some bacterial inoculants designed to improve plant growth and performance have been shown to decrease methane production when used on cattle silage, and additional studies are underway to verify this effect.[210] Scientists continue to find that including seaweed in livestock's diet can significantly reduce methane emissions.[211] California's Department of Food and Agriculture approved commercial use of Blue Ocean Barns' seaweed feed additive, Brominata, as a digestive aid for dairy cattle in May 2022.[212] This marked the first time a U.S. regulatory agency had approved seaweed for livestock digestion. Seaweed feed additives face scaling issues, as *Asparagopsis* has yet to be cultured in lab; however, efforts from companies such as Rumin8 are making headway in isolating the bioactive compounds that suppress methanogenis in cattle.[213] In September 2021, Brazil and Chile granted market authorization to Bovaer® for use with ruminants.[214] Following approval in February 2022, Bovaer® feed additive is expected to go on the market in the European Union within the year, with large-scale pilot programs planned.[215] A 2021 study led by Princeton and Cornell recommends multiyear studies for Bovaer® and red algae to observe sustained effects, including effects that are potentially negative to cattle and human health (i.e., bromoform concentrations in red algae), efficiencies, and the additives' production streams.[216] Red algae-fed beef products have already been sold at Swedish supermarkets.[217]

Manure additives, such as biochar (black carbon produced from pyrolysing biomass), acids, straw, or SOP LAGOON technology based on calcium sulphate dihydrate (gypsum) also can reduce methane and other pollutant emissions such as ammonia.[218] *See* **Section 5** for more on additives acting to prevent methane emissions. Manure emissions can also be tackled via anaerobic digestion—a technology that converts organic waste to biogas and nutrient-rich digestate that may be used for fertilizer application[219]—and alternative management options (i.e., separating sludge into solid and liquid components, and speedy removal of manure from barns) but should be assessed based on on-farm characteristics.[220] Altering size and promotion of anaerobic digestion biogas products should be evaluated for climate and environmental justice concerns involving potential increased odor and pollution, as well as its relation to the extension of fossil fuel infrastructure.[221] In addition, biogas production facilities tend to have high methane loss rates due to poor design, management, and maintenance according to one recent study.[222] Another concern with these measures is that "leakage" of methane emissions may occur in neighboring regions where restrictions on cattle operations may be less stringent (e.g., in scenarios where California herds move to other states with looser dairy regulations).[223]

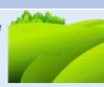
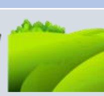
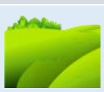
Reducing methane intensity per unit of productivity of livestock can limit methane emissions by increasing growth rate and thus requiring fewer livestock to produce the same amount of milk or meat.[224] Better digestible feed, grazing management, breeding strategies, and forage systems can increase animal growth rate, or efficiency.[225] In improving feed digestibility by reducing lignin, cows may consume more feed and produce more milk/meat, reducing methane emissions per product.[226] Breeding and selecting for genes that increase productivity and reduce emissions is another strategy.[227] This research is narrow in focus and becoming more selective. In Japan, black cattle are currently studied to determine the metabolic characteristics that produce methane, and how to suppress methane for this particular breed.[228] Ensuring high animal health standards reduces the need to replace diseased, low-producing animals (lowering methane emissions intensity), [229] and in some cases directly reduces methane emissions.[230]

Improving grazing management strategies, may directly affect feed digestibility and thus animal productivity, depending on the local context.[231] However, adopting new grazing strategies may lead to unintended consequences via land-use change, such as defoliation of native plants and exacerbation of climate change,[232] or net-positive results, such as feed improvement with decreasing production costs.[233] These solutions may also be considered at different life stages of livestock, when metabolic needs and meat/dairy production quotas differ.[234] The above strategies could have significant impacts for countries in Africa and developing countries that have lower animal productivity.[235]

Decreasing livestock count is another strategy to reduce methane, especially when productivity can be increased.[236] A shift towards lower meat consumption, especially in regions with higher-than-average meat consumption is an example of behavioral change that would reduce methane emissions from livestock by decreasing count and associated land use emissions together with health co-benefits.[237]

Researchers are also considering other innovative strategies, such as an anti-methane vaccination for livestock.[238] However, vaccines have demonstrated only short-term effects to date, and it could take decades to develop more permanent methane-mitigating vaccines.[239]

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 nitrous oxide emissions, cost, potential negative animal health	15%	neutral effect: decreased intake & increased milk yield[b]	not assessed	--
seaweed[a]	  *	"global-scale production, cost, toxicology, regulatory and market acceptance"[a]	20–50%	unknown[b]	0.5–1	2030 (*insufficient evidence for confidence*)
					1–10	
Diet Formulation						
tanniferous forages[b]	 	effect on manure CH_4, decreased palatability and feed intake, incomplete digestion[c]	10%	no/limited effect[b]	not assessed	--
oil/oilseeds and fat inclusion[b]		effect on manure CH_4, cost, impaired feed digestibility,[c] effect on upstream emissions	14–15%	negative effect (at high inclusion levels)[b]	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: increased weight gain & milk yield[b]	not assessed	--
Animal and Feed Management						
increasing feeding level[b]	 	effect on manure CH_4	17% (intensity)	positive effect: increased weight gain & digestibility[b]	not assessed	--
decreasing grass maturity[b]	 	effect on manure N_2O	13% (intensity)	positive effect: increased milk yield & digestibility[b]	not assessed	--
low-emissions breeding[b]	 	breeding programme	1% per year, 15% maximum[a]	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., Clark H., Cowie A. L., Emmet-Booth J., Gonzalez Fischer C., Herrero M., Howden M., & Leahy S. (2021) *How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals?*, PHILOS. TRANS. R. SOC. A 379(2210): 20200452; [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): e2111294119; *and* [c] Palangi V., Taghizadeh A., Abachi S., & Lackner M. (2022) *Strategies to Mitigate Enteric Methane Emissions in Ruminants: A Review*, SUSTAINABILITY 14(20): 13229. Relative emissions reductions are assessed as CH_4 per unit of feed dry matter intake, g kg^1.

For rice paddy fields, improved water management, alternate flooding and drainage of wetland rice, direct seeding, and improved yield gains can greatly reduce emissions.[240] The key mitigation strategy is to reduce the time that fields are flooded,[241] but responsive increases in emissions of nitrous oxide (N_2O)—another powerful greenhouse gas—must be considered.[242] 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%.[243] Yield gains may be improved through crop breeding (to select for breeds that are more productive) and biochar amendments,[244] as well as mechanization of what is otherwise manual work.[245] Searchinger *et al*. (2021) estimates that for every 1% increase in rice yield, methane emissions are reduced by 1%.[246] 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.[247] Certain strategies outlined above may be eligible to receive benefits through established regulatory programs, such as California's Air Resource Board Compliance Offset Protocol,[248] or other efforts to reduce Scope 1–3 emissions.[249]

A wide range of innovative research is seeking to reduce methane emissions from the agriculture sector. Successful examples of research in small trials or rooted in Indigenous teachings[250] that may reduce methane emissions includes but is not limited to: regenerative agriculture (*e.g.*, silvopasture, agroecology,[251] and solar grazing[252]); application of dung beetles[253] or worms (vermafiltration)[254] to cow dung; use of brewer's yeast to suppress enteric methane while promoting animal growth;[255] genetically-modifying yeast to inhibit methanogenic activity in the rumen;[256] using CRISPR, or gene-editing technology, to culture soil microbes in labs to better understand soil interactions that produce methane in rice paddy fields;[257] cellular agriculture to produce alternative proteins in the lab;[258] use of captured methane as fish food;[259] using electricity to convert livestock waste into fertilizer;[260] and introducing certain additives and processes to manure lagoons.[261] These solutions, excluding those originating from Indigenous practices, are still in their infancy and are yet to be formally assessed. Nevertheless, they are exciting prospects for the future of methane reduction in agriculture.

As described in **Section 8** on monitoring systems (including satellite and data integration), improving monitoring systems for agricultural sectors will be critical to assessing the impacts of these innovative methods. For example, methane emissions from cattle have been observed for the first time in California's San Joaquin Valley via GHGSat.[262] In addition, machine learning algorithms are becoming faster at estimating GHG emissions, (including N_2O, which has previously been difficult to quantify), from complex interactions in the soil.[263] Further improving methane observing systems, especially in hard-to-quantify sectors like agriculture, will be essential for monitoring effectiveness once these solutions have been implemented. These efforts will additionally be helpful in identifying super emitters in the agricultural sector, which are small in number but great in magnitude of methane emission.[264] *See* **Section 8** for examples of aerial observation tools for agricultural methane emissions.

C. Waste sector

The waste sector can provide mitigation of 29–36 MtCH_4/yr,[265] representing 19–24% of the reductions needed to meet the GMP target in 2030 (**Figure 6).** Solid waste mitigation makes up the bulk of the mitigation potential from the waste sector.[266] Landfill operators can capture and convert to energy the methane emitted from existing landfills.[267] Collecting landfill gas requires costly equipment (extraction wells and piping inside the dumpsite)[268] construction and continued operation, however there are financial benefits in producing a biogas product fit for energy use.[269] Where applicable, McKinsey estimates that the maximum technical opportunity for inclusion of capture technology may lead to 4.50Mt CH_4/year abatement by 2030.[270] As an alternative to combustion, which can contribute to air pollution, landfill gas can generate electricity using fuel cells.[271] In addition, improvements to landfill methane-gas capture are emerging to optimize such capture while minimizing infrastructural needs and frequent human intervention.[272] 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 release methane as it decomposes in landfills under low-oxygen (anaerobic) conditions. The diversion of organic waste from landfills can significantly reduce methane emissions.[273] Programs to reduce food waste can decrease methane emissions from both the waste and agriculture sectors.[274] This can include promoting strategies to manage extreme heat exposure and increasing cooling access for small-scale farm managers to reduce food waste due to earlier harvests caused by warmer weather.[275] Cutting food loss and waste in half, combined with improving crop and livestock productivity, also will help close the dietary nutrient gap and improve global food security.[276]

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.[277] 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,[278] in methane oxidation.[279] Biocovers may be used in inactive landfills as a control technology for remaining methane emissions following closure.[280] Due to their relatively low cost (compared to landfill gas collection), simple technical applicability,[281] and potential lifetime of 6-7 years with limited performance declines,[282] they may be a solution to reduce methane emissions in landfills operated in low-income countries with limited management.[283] 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.[284] Odor mitigation measures have also been found to correlate with reduced methane emissions.[285] When combined with improved landfill management, these measures could reduce landfill emissions in the U.S. by 50% by 2030.[286]

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.[287] 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.[288] Recent satellite data has found that landfill emissions in Buenos Aires, Delhi, Lahore, and Mumbai have been underestimated in common emissions inventory calculations.[289] The Waste Methane Assessment Platform launched in November 2022 will provide an open-source platform with information and best practices for operators, policymakers, and financiers.[290] Landfill methane emissions estimates and monitoring could also be improved by incorporating site-specific factors and cover-soil qualities into model estimates.[291]

For wastewater, McKinsey estimates that mitigation measures could reduce wastewater emissions by 27% by 2030 and 77% by 2050.[292] Methods to achieve this emissions reduction include improving the treatment of wastewater through upgraded processes, infrastructure, and technology.[293]

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.[294] While increasing anthropogenic emissions likely were the main cause of rising atmospheric concentrations over the past two decades, increases in emissions from natural sources likely are a major contributor to the recent rapid growth in methane concentrations.[295] As discussed in **Section 3**, the rate of growth of atmospheric methane concentrations surged in 2020 and 2021,[296] with evidence of increasing emissions from natural sources of methane principally warmer and wetter wetlands over the Northern Hemisphere, accounting for about half of the increase.[297] 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.[298] 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%.[299]

Some of these natural sources are expected to increase and act as self-reinforcing feedbacks to human-caused warming.[300] While permafrost methane feedback is well-established if poorly constrained,[301] 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.[302] 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.[303] However, the AR6 WGI finds *low confidence* in multi-decadal trends in the Indian Ocean dipole due to limited data prior to the 1960s.[304]

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 to the atmosphere to affect CO_2 and CH_4 concentrations.[305] 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.[306] Release of land-based methane hydrates as glaciers recede could further amplify the permafrost feedback.[307]

Research is underway on the best approach for removing atmospheric methane directly from the free atmosphere.[308] 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.[309] Although, on a molecular basis, methane is 220 times more dilute than CO_2 in the free atmosphere,[310] methane's high global warming potential and the relative simplicity of combustion without carbon storage make it an attractive target,[311] with the potential to reduce warming much faster than CO_2 removal.[312] 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.[313] However, care would need to be taken to avoid unintended atmospheric chemistry effects.[314]

A Stanford University-led modelling study calculates that 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).[315]

Two potential categories of methane removal strategies are catalytic oxidation[316] and enhanced microbial oxidation.[317] Other pathways, such as the augmentation of natural sinks,[318] or gathering and flaring natural emissions or using more efficient thermal oxidation designs,[319] could also develop into viable strategies. Many strategies and technologies are being explored within each category. Recently, a research group at MIT identified a clay material capable of oxidizing atmospheric levels of methane at relatively low temperatures.[320] Another example is iron salt aerosols that have been proposed as a cost-effective mechanism for augmenting the natural chlorine sink to oxidize atmospheric methane.[321] 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.[322]

In addition to methane removal, other strategies may prevent natural methane formation. Preliminary studies suggest the use of additives to manure lagoons or irrigated rice fields such as biochar (black carbon produced from pyrolysing biomass), acids, and straw can reduce methane emissions.[323] A recent study has shown the potential of additive technology based on calcium sulphate dihydrate (gypsum) to reduce methane emissions by up to 80% from manure lagoons in concentrated animal feeding units while controlling other necessary variables, such as pH and ammonia emission.[324] This product may have future potential application in rice paddies, and other anthropogenic methane sources.[325] Such strategies could employ a variety of mechanisms, including (1) using methane-eating bacteria to break down the gas before it is emitted, (2) inhibiting microbes' methane-producing activities, (3) introducing predator or competitor species, (4) reducing habitat or nutrient availability, or (5) killing methane-generating microbes directly. Similar methods might be applied to both natural and semi-natural sources, such as wetlands and reservoirs, though care would be required to avoid damaging local ecosystems.

For further reading, *see* Institute for Governance & Sustainable Development (2022) METHANE REMOVAL: *R&D needed for removing methane from the atmosphere*, Background Note.

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. However, these measures must be expanded and strengthened to achieve needed methane reductions in the near term.[326] 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.[327] The IEA policies database includes methane abatement policies from its member countries around the world. Examples of specific methane mitigation measures in the U.S., EU, Canada, Mexico, India, China, Brazil, and Iraq are described below. 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.[328]

A. United States

The United States 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 greenhouse gas emissions by 2030.[329] In November 2021, the White House published the *U.S. Methane Emissions Reduction Plan*, a whole-of-government initiative and model for taking a sectoral approach to reducing methane emissions.[330]

Under the Clean Air Act, the Environmental Protection Agency (EPA) proposed regulations for more stringent controls on emissions from new and existing oil and gas operations.[331] This proposal has since been updated to include more thorough life-cycle controls, tighter supervision of marginal wells, and a Super Emitter Response Program, among other measures.[332] The EPA estimates that for covered sources, the proposed rule would reduce emissions 87% below 2005 levels by 2030.[333] The Bureau of Land Management (BLM) has proposed to extend royalty fees to avoidably vented, flared and leaked methane, and require operators to submit waste minimization plans.[334] BLM estimates that the 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.[335] Rules proposed by the U.S. Securities and Exchange would require publicly listed companies to disclose climate emissions and related risks, including those related to methane.[336] In addition, the Department of Transportation is finalizing rules to reduce leaks throughout the gas pipeline system.[337] However, reports have indicated that the Biden administration is approving more drilling permits on public lands than previous administrations.[338]

On 31 January 2022, the Biden administration announced the next steps of the *U.S. Methane Emissions Reduction Plan*, starting with allocating $1.15 billion for states to clean up orphaned oil and gas wells.[339] The next steps in this Plan 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 interagency group to coordinate methane measurement, monitoring, reporting and verification, and convened a workshop for energy communities on repurposing fossil-fuel infrastructure.[340]

The *U.S. Methane Emissions Reduction Plan* also includes regulations and programs to reduce methane from other sources.[341] 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).[342] The EPA is also tracking multiple other efforts to reduce methane, including livestock anaerobic-digester and landfill gas-capture projects.[343]

In August 2022, the U.S. 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.[344]

Additionally, the 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 and the Food Loss and Waste 2030 Champions,[345] the Landfill Methane Outreach Program that promotes the capture and use of landfill gas,[346] the Coalbed Methane Outreach Program that promotes the use of coal mine methane,[347] and the AgStar Program that aims to reduce methane emissions from livestock waste.[348] The U.S. Department of

Agriculture also announced $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.[349]

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.[350] According to ARPA-E, these three sources contribute to at least 10% of U.S. anthropogenic methane emissions.[351] 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.[352] In July 2022, the CHIPS and Science Act doubled ARPA-E's budget[353] and expanded funding for climate and Earth-systems research, including for a Center for Greenhouse Gas Measurements, Standards, and Information.[354]

As part of the Infrastructure and Investment Jobs Act enacted in November 2021, the U.S. government is distributing grants to bolster climate action. The Department of Energy will distribute almost $11 billion in Abandoned Land Mine grants to eligible states and tribes over 15 years.[355] 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."[356] 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,"[357] including products that have lower carbon footprints.[358]

The Inflation Reduction Act of 2022, passed in August, contained nearly $370 billion climate funding, including $1.55 billion to monitor and reduce emissions from oil and gas.[359] The legislation includes a Methane Emission Reduction Program with a methane waste fee of up to $1,500 per ton of methane by 2026,[360] 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.[361] The Act will provide about $20 billion over the next four years in agricultural conservation grants, which would prioritize climate issues including methane mitigation.[362] This Act is estimated to reduce U.S. GHG emissions by 40% below 2005 levels by 2030.[363]

At the 10th North American Leaders' Summit, held in Mexico City, the U.S., Canada, and Mexico published a declaration renewing their focus on reducing methane from all sources with particular focus on waste methane.[364]

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.[365] Partners committed to developing and implementing federal regulations to reduce emissions from existing new sources in the oil and gas sector, as well as to develop and implement national methane reduction strategies for key sectors as soon as possible, including for oil and gas, agriculture, and waste and food management.[366] *See* subsections below 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."[367] Furthermore, 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**.[368]

Box 4. 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.[369] 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.[370] 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).[371] In 2021, Colorado adopted standards to reduce methane emissions from pneumatic controllers.[372] New Mexico followed suit, issuing stringent regulations for the oil and gas sector, and also banning all routine flaring and venting.[373] A more recent New Mexico rule is expected to reduce emissions still further.[374]

Members of the U.S. Climate Alliance, which includes the governments of 23 states and Puerto Rico[375] aim to reduce methane emissions across all sectors by 40–50% by 2030.[376] This target includes reducing emissions from the energy sector by 40–45% by 2025,[377] and from the waste sector by 40–50% by 2030.[378] Members also plan to reduce methane emissions from the agricultural sector, including reducing emissions by 30% from enteric fermentation,[379] and up to 70% from manure management, by 2030.[380] Moreover, states and municipalities have enacted policies that ban or divert organic waste from landfills and aim to reduce food waste.[381]

Research and other institutions are also developing tools for sub-national 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.[382]

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 liquefied natural gas (LNG) export capacities. However, it also agreed to "undertake efforts to reduce the greenhouse gas intensity of all new LNG infrastructure and associated pipelines."[383] The Federal Energy Regulatory Commission also rolled back a new policy on assessing the climate impact of pipeline emissions.[384] 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.[385]

On 12 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, D.C., 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."[386]

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.[387] 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.[388] A discussion of these developments can also be found in **Section 6.G.**

The U.S. oil and gas industry has founded multiple 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.[389] 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.[390] 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.[391]

In the coal sector, the U.S. EPA documented 53 current coal-mine methane recovery projects and profiles project opportunities at other gas-emitting mines.[392] 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.[393] However, overall coal-mine methane production has halved since 2008, falling from approximately 57 bcm in 2008 to 23 bcm in 2020.[394]

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.[395]

Additionally, in all methane-emitting sectors, the U.S. State Department, in partnership with USAID, has launched a new USAID Methane Accelerator program to mainstream and scale up methane abatement projects.[396]

B. European Union

The European Union addresses methane in its 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.[397] 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.[398] Additionally, the methane strategy prioritizes ensuring more accurate measurement and reporting of private-sector emissions.[399]

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.[400] 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%.[401] 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.[402] More than half of the European Union's domestic methane emissions occur in the agriculture sector,[403] with most methane emissions from energy use occurring abroad.[404] Some analysts have concluded that the European Union will not achieve large reductions in domestic methane emissions without "policies that drive the uptake of behavioural and technical measures in the livestock agriculture sector."[405]

In December 2021, the Commission proposed regulations and a directive[406] 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.[407]

Proposed regulations 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.[408] The regulations would also require operators to institute LDAR programs, and ban routine venting and flaring.[409] Regulatory inspections and information from relevant internationally available sources would verify compliance with these regulations.[410]

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.[411] 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.[412] Additionally, the proposed regulations call for mitigation plans, and would prohibit unnecessary venting and flaring.[413]

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.[414] Underground and surface mines estimate post-mining emissions based on relevant factors and report all emissions to regulators.[415] 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.[416]

The proposed regulations did not include specific, binding target reductions.[417] The European Union had considered setting methane intensity performance requirements for imported gas,[418] but such requirements have not yet appeared in any official proposals. The European Union 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.[419] 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.[420] 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.[421] In 2019, the European Union imported nearly 90% of its natural gas, mostly from Russia.[422] A July 2022 regulation controversially allowed the certification, under limited circumstances, of some natural gas under the EU sustainable investment taxonomy.[423] According to the Environmental Investigation Agency, the Council's first position on the text is "devoid of substance" and left aside "any meaningful measures" that could help the EU meet it climate goals.[424] The proposed regulation is under review by the European Parliament, with plenary deliberation scheduled on 29 March 2023.[425] The European Council has adopted a general approach—a political agreement between the Council and Parliament prior to first reading[426]—to speed up negotiation and adoption of the regulation.[427]

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.[428] Requirements to divert organic waste helped to achieve a 47% drop in EU landfill emissions between 1990 and 2017.[429]

The 2023 launch of the EU's revised Common Agriculture Policy (CAP) is expected to increase emphasis on climate actions within the agriculture sector and dedicate 40% of funding to climate-related measures.[430] The specific goals within the CAP include increasing monitoring restrictions, targets to reduce food waste, etc.

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.[431] The UNECE region includes all of Europe, as well as countries in North America, Central Asia, and Western Asia. For more information, *see* **Section 10**.

The newly adopted Carbon Border Adjustment Mechanism, designed to prevent outsourcing of carbon-intensive industries and incentivize sustainable practices abroad,[432] does not address imported methane. However, some have called for methane to be addressed in future measures.[433]

Prior to the February 2022 Russian invasion of Ukraine, the European Union imported more than 40% of its total gas consumption from Russia.[434] The European Union has responded to this changing geopolitical situation by announcing the acceleration of its transition from fossil energy.[435] On 23 March 2022, the European Commission tabled a legislative proposal to increase its gas storage levels to 80% by November 2022.[436] 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.[437] 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.[438] 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.[439]

The Joint Communication on EU External Energy Engagement, which was published on 18 May 2022, outlines the region's current efforts and future 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,[440] 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."[441] 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 decarbonisation objectives and is based on the principle of market-oriented pricing."[442] The European Union does not 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."[443] Further, it will prioritize energy savings and energy efficiency to achieve its target of 5% reduction in short-term demand for oil and gas.[444]

> ***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"; 2) leakage rate of methane if used as the source of hydrogen or energy source, with even low methane leakage rates of 1.54% resulting in higher GHG emissions than burning natural gas for power;[445] and 3) the leakage rate of the hydrogen itself, which can contribute to warming by extending the lifetime of methane and other GHGs. 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.[446] High hydrogen leakage combined with increasing methane emissions could add as much as 0.4 °C of warming.[447]

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.[448] As part of its participation in the GMP, Canada aims to reduce oil and gas methane emissions by 75%.[449] Current Canadian regulations 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.[450] In November 2022, the Canadian government proposed a regulatory framework to reduce oil and gas emissions in line with the 2030 target.[451] The proposed regulation will require methane destruction to operate at a control efficiency of 99% or higher,[452] prohibit flaring at all oil sites,[453] and require all facilities to have a fugitive emission management plan with monthly inspections.[454]

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 Alberta, British Columbia, and Saskatchewan,[455] which together produce about 99.8% of Canada's gas, and more than 92% of its oil. Most gas comes from Alberta, which produces twice as much as British Columbia, and more than 25 times as much as third-place Saskatchewan. Despite the national pledge and target, studies have suggested that oil and gas emissions in Alberta and Saskatchewan are much higher than reported in Canada's national inventory.[456]

For landfills, Canada committed to increasing the number of landfills that collect and effectively capture methane.[457] 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.[458] In turn, local and provincial governments developed goals,[459] plans,[460] and tax incentives[461] to reduce food waste.

Furthermore, the federal government implements programs to incentivize climate-smart agriculture and reductions in agricultural GHG emissions. The Agricultural Climate Solutions program invests in natural climate solutions, such as increasing carbon storage on farms.[462] 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.[463]

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."[464] 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**.[465]

D. Mexico

In addition to the methane targets arising from the 2016 North American Climate, Clean Energy, and Environment Partnership, 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.[466] 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 GMP and participates in the GMP Energy Pathway.[467] In July 2022, President Lopez Obrador agreed with U.S. president Joe Biden to cooperate with Mexico's national oil company, Petroleos Mexicanos (PEMEX), to eliminate routine flaring and venting.[468]

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.[469] 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.[470] 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.[471]

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.[472] 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.[473]

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.[474] In June 2022, President López Obrador announced that PEMEX will be spending $2 billion to lower its methane emissions by up to 98%.[475] 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.[476] 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.[477]

E. India

According to India's third Biennial Update Report to the UNFCCC, methane accounted for 19.5 million tonnes (409 $MtCO_2e$, using GWP_{100} of 21 per Indian reporting), or 14.43% of India's total GHG emissions in 2016.[478] Also according to this Report, India's main GHG emissions from the agricultural sector are methane from livestock enteric fermentation and rice cultivation.[479]

India is working to cut methane emissions 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,[480] and cultivation using the direct-seeded rice method is being deployed in India on nearly 100,000 hectares of land.[481] India also is shifting land used for paddy crops to other crops that require less water and thus enable reductions of methane emissions.[482] Furthermore, India is implementing methods, including feed additives, that increase productivity of milk-producing animals and reduce GHG emissions.[483] 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.[484] Such biorefinery programs may addresses challenges of waste disposal and fertilizer shortages aligned to the structure of farms in India.[485]

India's coalbed methane amount is estimated to be 91.8 trillion cubic feet spread over 11 states.[486] Further, India identified 233.30 trillion cubic feet of shale gas/oil, the commercialization of which can dramatically increase methane emissions.[487]

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.[488] 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.[489]

India's strategy to reduce methane emissions from the energy sector appears focused on transitioning to renewable energy and improving energy efficiency.[490] Coal mine methane and coalbed methane exchanges, training, and projects have been discussed and planned in India.[491] A pre-drainage project is under development at one underground mine,[492] and studies have been conducted to determine the feasibility of additional coal mine methane abatement projects.[493] Despite these efforts to reduce coal bed methane, India announced the auction of 67 new coal mines in 2021,[494] with an estimated 36 billion tons of coal.[495] These blocks represent fewer than a third of the 214 that the Ministry of Coal is statutorily obligated to develop.

In 2021, 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).[496] 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.[497] 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."[498] 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 (IDs 122973-122975 for underground mining and 124920-124921 for surface mining).[499]

The 2021 BUR further mentions that "the upcoming projects of Coal Bed Methane (CBM) extraction will also reduce the liberation of methane into the atmosphere during coal mining, which will be taken up in future."[500] Furthermore, Coal India Limited (CIL)—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.[501]

In May 2022, the Indian government made an announcement that may have implications for enhanced methane mitigation. 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 realising India's Nationally Determined Contributions under the Paris Agreement."[502]

F. China

On 22 September 2020, at the UN General Assembly, China announced its target of achieving carbon neutrality before 2060.[503] 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)."[504] 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.

On 28 October 2021, China submitted its updated NDC[505] and Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy (Mid-Century Strategy)[506] to the UNFCCC Secretariat. In the updated NDC, 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."[507] In its Mid-Century Strategy, China included its target of further increasing the percentage of non-fossil fuels to over 80% by 2060.[508] Both the updated NDC and the Mid-Century Strategy list policy actions for methane emissions reduction. Further, to support the achievement of non-fossil fuel targets and promote the deployment of renewable energy, China's 14th Five-Year Comprehensive Work Plan on Energy Conservation and Emission Reduction provides that renewable energy will not be counted in the total energy consumption caps for localities during the 14th Five-Year period (2021-2025).[509]

To support the development and implementation of national methane-mitigation policies and targets, China has launched a number of emissions monitoring pilots involving enterprises, municipalities, and regions.[510] 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.[511]

For the coal mine sector, China's targets 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%."[512] 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.[513] Furthermore, China's policy guidance on carbon peaking and carbon neutrality includes scaling up the development and utilization of coal-bed methane.[514] As next steps, the National Energy Administration will lead drafting and implementation of coalbed methane policies and targets, including coalbed methane development and utilization targets for the 14th Five-Year Plan period.[515] The Ministry of Science and Technology will lead promotion of coalbed methane development technology innovation.[516] The Ministry of Ecology and Environment will lead research on incorporating coalbed methane development and utilization projects into China's voluntary greenhouse-gas emissions trading system.[517]

Importantly, China's methane emissions reduction success or failure is closely linked to its ability to phasedown coal consumption. For example, China has announced that it will strictly control coal consumption during 2021-2025 and gradually reduce coal consumption during 2026-2030.[518] 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.[519] According to the 14th Five-Year Comprehensive Work Plan on Energy Conservation and Emission Reduction, renewable energy will not be counted in the total energy consumption of localities during the 14th Five-Year period.[520] This provision further incentivizes the deployment of renewable energy to achieve carbon neutrality before 2060. However, the same Plan also indicates that use of fuel as feedstocks for chemical processes will not figure in national and provinces' energy consumption or intensity calculations.[521] The exemption will likely boost the use of coal in the coal-to-chemical industry.

For the oil and gas sector, China set targets to reach the plateau stage for oil/petroleum consumption during 2026–2030.[522] China also aims to peak land-transportation petroleum consumption by 2030.[523] China's updated NDCs incorporate actions to reduce methane emissions in this sector, including through deployment of technologies for the recovery of associated gas.[524] China's 13th Five-Year Development Plan for Natural Gas (2016) includes promotion of recovery technologies for oilfield-associated gas, strengthening of natural gas leakage the detection, and reducing fugitive emissions of GHGs. 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.[525] 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.[526]

For the agriculture sector, China set targets in 2017 for achieving "comprehensive reutilization" of over 75% of livestock and poultry manure by 2020.[527] China raised this target in 2021 to over 80% of livestock and poultry manure nationwide by 2025.[528] China will also increase the efficiency of chemical fertilizers and pesticides to 43% by 2025,[529] 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.[530] China is also prioritizing agricultural emissions control measures, including promoting low-emission and high-yielding rice plants, improving farming techniques, encouraging the use of organic fertilizers, regulating the use of chemical fertilizers and pesticides, and advancing the comprehensive use of crop straw.[531] 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."[532]

For the waste sector, China set targets including reaching, by 2025, 90% harmless disposal of urban sludge,[533] 25% sewage resource utilization in water-scarce cities at the prefectural level and above,[534] and 40% domestic sewage treatment in rural areas,[535] and more than 95% of county sewage treatment.[536] Furthermore, by 2030, the national average utilization rate of urban recycled water will be increased to 30%.[537] 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.[538] Additionally, China committed to increase the reutilization of urban household waste to around 60% by 2025 and 65% by 2030.[539] 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.[540] 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.[541] At the subnational level, China announced a plan to build 100 zero-waste cities by 2025.[542] 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.[543]

In addition to the national methane-emissions 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[544] 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.[545]

As a show of commitment, China announced that it had drafted an action plan to curb methane emissions during the Methane Ministerial at COP27.[546] This announcement revived China's potential for methane action leadership stemming from the U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s announced at COP26,[547] or separately, despite the fact that China did not sign the GMP. China's future methane mitigation activities must consider that anthropogenic methane emissions are roughly 90% of total methane emissions in China with major sources from solid fuel (31%), rice production (24%), waste (18%), and livestock (15%).[548]

G. Brazil

Brazil is the fifth largest methane emitter in the world,[549] owing to its cattle industry, which accounts for 14% of the global bovine herd.[550] Brazil's total methane emissions amounted to approximately 400 $MtCO_2e$ in 2020, with ~285 $MtCO_2e$ coming from the livestock sector alone.[551]

Brazil is a signatory to the GMP. To fulfill its obligations in the GMP and the UNFCCC, Brazil enacted a decree that created the Federal Strategy to Incentivize the Sustainable Use of Biogas and Biomethane.[552] 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.[553] 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.

The Federal Strategy, which includes the Methane Zero Program, will introduce methane credits into existing market mechanisms.[554] 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.[555]

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."[556] 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.[557]

H. 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.[558] Iraq has also been among the top 10 flaring countries for the last 10 years.[559]

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.[560] 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.[561] 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.[562] The Iraqi government reportedly introduced a new law in October 2022 to encourage investment in producing electricity from methane gas generated by solid waste.[563]

I. Nigeria

Nigeria is at the forefront of countries experiencing climate change, as it has been for more than 50 years.[564] 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. It is appropriate, then, that Nigeria became the first African country to regulate methane emissions in its energy sector.[565]

Nigeria has made broad progress beyond security and economic programmes to respond to international climate mitigation agreements and policies. For instance, to fulfill its responsibilities as a UNFCCC Party and its Kyoto Protocol and Paris Agreement, Nigeria enacted the national Climate Change Act in 2021[566] to help drive responses to the need for climate change adaptation and mitigation, including cutting methane.[567]

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,[568] 2018 National Action Plan to Reduce Short-Lived Climate Pollutants,[569] National Climate Change Policy 2021–2030,[570] and the 2050 Long-Term Vision for Nigeria.[571]

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

- The Flare Gas (Prevention of Waste and Pollution) Regulations (2018);[572]
- The Petroleum Industry Act (2021);[573]
- The Gas Flaring (Prohibition and Punishment) Bill (draft 2020) (still under review within Parliament);[574] and
- Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria (November 2022).[575]

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.[576] 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.[577]

Nigeria has been a CCAC partner since 2012[578] and was one of the original 31 countries that joined the GMP in 2021.[579] Largely in response to their partnership with the CCAC, Nigeria developed its National Action Plan to Reduce Short-Lived Climate Pollutants, which includes a targets for the oil and gas sector to eliminate 100% of gas flaring by 2020, control fugitive methane emissions and leakage by 50%, and reduce methane leakage by 50%, by 2030.[580] 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.

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 contain targets for elimination of routine gas flaring (100% of gas flaring eliminated by 2030) and control of fugitive emissions/leakages (60% methane reduction by 2030).[581] 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).

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.[582] 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.[583]

While it remains to be seen if Nigeria will meet all of its targets, including those in its National Determined Contributions, Nigeria's promises and ambition is helpful to other developing countries seeking leadership models and gaining inspiration from an African-country methane mitigation champion.

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 natural gas supply and focuses on assessing the methane intensity of available gas volumes and associated producer performance.

i. Quasi-governmental organizations and initiatives

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

The Climate & Clean Air Coalition (CCAC) facilitates methane mitigation and information sharing at all levels, including through publication of leading science. The CCAC is a voluntary partnership with over 70 State and regional partners, and a similar number of non-state partners.[584] It has been proposed that the CCAC will act as Secretariat for the GMP. The CCAC assists countries with developing plans to reduce SLCPs.[585] 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 further below under ***Industry-led initiatives***. 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**).[586] The November 2022 Ministerial communiqué raised the possibility of establishing a Technology and Economic Assessment Panel on Methane, to advise partners on "innovative methane mitigation technologies, including methane removal and sector-specific methane reduction technologies."[587]

On 9 November 2021, the CCAC Ministerial launched 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."[588]

The CCAC's efforts resulting in the *Global Methane Assessment* raised awareness of and political attention to the opportunities of methane abatement. In addition to their work with the *Global Methane Assessment*, the CCAC's work with Dr. Shindell's group at Duke University resulted in a publicly accessible, online methane mitigation tool.[589] The CCAC plans to improve this online 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, 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 the LRTAP Convention.[590] This relationship can help inform efforts to develop a global methane agreement on an emergency basis. 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.[591] 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, 10A, and 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,"[592] 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.[593] 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[594] and requested the CCAC Scientific Advisory Panel to develop a proposal to highlight and better calculate near-term climate benefits of methane action.[595]

- *Agriculture Innovation Mission for Climate*

The Agriculture Innovation Mission for Climate (AIM4C), co-created by the U.S. and United Arab Emirates, is an initiative to increase funding and participation in climate-smart agriculture and food system innovation from 2021 to 2025. AIM4C "innovation sprints" will guide participants to address specific goals using coordinated funding. Innovation sprints that have direct relation to methane mitigation are the "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."[596] Over 40 countries and nearly 300 organizations have partnered with this initiative.[597]

- *Net-Zero Producers Forum*

In April 2021, Canada, Norway, Qatar, Saudi Arabia, and the U.S. announced their intention to establish the Net-Zero Producers Forum, which convened its first ministerial meeting in March 2022.[598] 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."[599]

- *World Bank Global Gas Flaring Reduction Partnership and Zero Flaring Initiative*

The World Bank's Global Gas Flaring Reduction Partnership (GGFR) is a multi-donor trust fund composed of 20 governments (with the U.S., Canada, and Germany scheduled to join in 2023), 12 oil companies, and 3 multilateral organizations.[600] The GGFR 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.[601] The GGFR seeks commitments to the Zero Routine Flaring by 2030 initiative. Governments and companies that participate in the World Bank Zero Flaring Initiative commit to end routine flaring by 2030.[602] 34 governments, 54 oil and gas companies, and 15 development organizations support the Initiative.[603] The GGFR 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."[604]

- *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. One year after its launch, 28 priority actions were recommended at COP27 to have improvements to share by COP28. Decarbonization of heavy emitting sectors, including agriculture, is high on the agenda, especially as these actions pertain to climate adaptation, environmental protection, and food security.[605]

- *The Global Waste Initiative 50 by 2050*

Egypt, which had the COP27 Presidency in 2022, launched the Global Waste Initiative 50 by 2050 in November. This initiative estimates that the waste sector contributes 20% of global methane emissions.[606] Methane emissions from landfilling of solid waste reached about 1.3 $MtCH_4$ in 2010, which was projected to increase if waste management practices did not improve.[607] 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.[608] The COP also hosted a session on creating a "Green Africa," including the goal of cutting waste by 50% in African countries.[609]

ii. Industry-led initiatives

- *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.[610] 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.[611] GMI claims that its support has enabled partner countries to reduce methane emissions by more than 500 $MtCO_2e$ since 2004.[612]

- *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 OGMP 2.0 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.[613] OGMP 2.0 members are expected to provide continually updated implementation plans showing continuous improvement in measurement, coverage, and technical guidelines.[614] The European Union intends to build on this framework in developing its measurement, reporting, and verification requirements for the energy sector.[615]

- *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, among other things, 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.[616] OGCI reported a collective methane intensity of 0.17% in 2021,[617] 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.[618]

- *The World Biogas Association*

The World Biogas Association serves as a global trade association for biogas, landfill gas, and anaerobic digestion industry sectors.[619] 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.[620] The Association convenes the World Biogas Summit, which in 2021 focused on methane mitigation.[621]

- *The Methane Guiding Principles*

The 24 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 the continual reduction of methane emissions, improving the accuracy of emissions data, and increasing transparency.[622] 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.[623]

iii. Performance rating 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 validation of methane intensity claims.[624]

- *MiQ*

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 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.[625] MiQ maintains a digital registry of these certificates to avoid double-counting.[626] MiQ incorporates the Natural Gas Sustainability Initiative protocol or alternate "robust alternative methodologies" for calculating methane intensity.[627] 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.[628]

- *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.[629] Project Canary's emissions management program provides a platform for 24/7 real-time quantification and understanding of emissions data.[630] 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."[631] Project Canary's environmental assessment program includes qualitative and quantitative Trustwell operational performance reviews of wellbores/facilities around the world.[632] 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 (ESG) strategy.[633]

Further, the Project Canary SENSE platform combines data from all sensors, equipment, inventory, and emissions factors, using ML-based regression and Gussian plume models to quantify total site operational and fugitive methane emissions.[634] 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."[635]

- *Natural Gas Sustainability Initiative*

The Natural Gas Sustainability Initiative (NGSI) developed the NGSI Methane Emissions Intensity Protocol as a voluntary approach for companies to calculate methane emissions intensity.[636]

8. Monitoring 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.[637]

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

The rapid improvement in methane detection technologies and data analytics is fueling a boom in private monitoring and data analytics companies.[638] 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, and public-interest minded citizens tracking and mitigating methane emissions.[639]

Methane measurement and monitoring initiatives include the following:

- *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.[640] The first two satellites are in development and will be launched in 2023. Expansion to an operational multi-satellite constellation will start in 2025.[641] Additionally, Carbon Mapper is developing a data portal in collaboration with California's Air Resources Board to make the data publicly available.[642] In 2023, CarbonMapper 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.[643]

- *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.[644] The European Commission manages Copernicus and implements the program in partnership with Member States, European agencies, and centers.[645] In addition to collecting information from in-situ systems, the European Union will place a constellation of about 20 satellites in orbit before 2030.[646] Among the six information services, the Copernicus Atmosphere Monitoring Service,[647] the Copernicus Land Monitoring Service,[648] and the Copernicus Climate Change Service[649] are closely relevant to methane monitoring. All of these information services are open for free access by all.

- *Environmental Defense Fund's MethaneSAT*

The Environmental Defense Fund (EDF)'s MethaneSAT program plans to launch a new methane satellite 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.[650] MethaneSAT signed a contract with SpaceX in January 2021 for delivering its new methane satellite into orbit, scheduled for 1 October 2022.[651] Once launched, MethaneSAT will stream its data online with no charge for non-commercial users.

- *GHGSat*

GHGSat, a global emissions monitoring company, signed a memorandum of intent in 2019 with the Canadian Space Agency and the European Space Agency.[652] GHGSat will be collaborating with the International Methane Emissions Observatory by providing free data on methane emissions from their satellites.[653] On 4 May 2022, GHGSat shared its first findings using satellite technology of livestock methane emissions from a farm in Joaquin Valley, California.[654] More recently, 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.[655]

- *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.[656] 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.[657]

- *The 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.[658] The IMEO will initially focus on the energy sector and later expand to waste and agriculture.[659] Additionally, the IMEO will play an important role in implementing the GMP by helping countries prioritize actions and by monitoring commitments.[660] UNEP hosts the IMEO, with public funding support of €100 million over five years (including funding from the European Commission as a founding member).[661] 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**.[662] The IMEO has published two annual reports, *An Eye on Methane*, which describe progress on OGMP 2.0 and remaining challenges in methane monitoring and measurement.[663] 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.[664]

- *Oil and Climate Index Plus (OCI+)*

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.[665] 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.[666] The report also refers to cutting methane as "the highest priority for the oil and gas sector.[667]

- *Earth Surface Mineral Dust Source (EMIT)*

The U.S. 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.[668] 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.[669] As EMIT monitors areas that are also methane hotspots, it is expected to detect more super-emitters in the future.[670]

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:

1) An asset map and inventory of methane sources with geospatial coordinates that allow detailed identification of sources and related contacts for operators;
2) 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;
3) A mechanism for accessing emissions data from monitoring systems and rapidly converting the data into usable formats for accountability actors; and
4) 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.[671]

At the government level, National Methane Offices 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 sub-national 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. A Technology and Economic Assessment Panel (modeled after the Montreal Protocol's Technology and Economic Assessment Panel) and a Methane Tracker (housed by the CCAC) could assess and recommend technology solutions on a regular basis to encourage continued innovation and support for implementation of best practices.

10. International efforts including the Global Methane Pledge are catalysing other 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.[672]

The Global Methane Pledge (GMP) is an important platform for global action, encouraging signatories to pursue a reduction of at least 30 percent of human-caused methane emissions by 2030. However, the GMP is voluntary. Because cutting methane emissions is the single most important action humanity can take to slow near-term warming, it critical to start moving from a pledge to mandatory measures in the form of bilateral, plurilateral, and regional efforts as the foundation for a global methane agreement, which finds inspiration in the successful 1987 Montreal Protocol. The Montreal Protocol has not only solved the first great threat to the global atmosphere by putting the stratospheric ozone on the path to recovery by 2065, it also has done more to avoid climate warming than any other agreement,[673] avoiding an amount of warming that otherwise would have equaled or even exceeded the warming that CO_2 is causing today.[674]

The Montreal Protocol provides a useful architectural structure for a sectoral approach that can be included in an international agreement, which is discussed below. In addition, there are further discussions below of the GMP, the Convention on Long-Range Transboundary Air Pollution's Gothenburg Protocol, and the U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s.

A. The Global Methane Pledge and the Glasgow Climate Pact

The GMP was formally launched at the Head-of-State level at the high-level segment of COP26 on 2 November 2021 in Glasgow.[675] The U.S. and EU first announced the GMP at the Major Economies Forum on 17 September 2021.[676] The GMP commits governments to a collective global goal of reducing global methane emissions by at least 30% from 2020 levels by 2030. 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.[677] The GMP marks 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. As of February 2023, 150 countries including the European Union have joined the GMP,[678] representing approximately 70% of the global economy and nearly half of anthropogenic emissions.[679]

Successful implementation of the GMP would reduce warming by at least 0.2 °C by 2050.[680] Achieving the GMP emissions-reduction target would keep the planet on a pathway consistent with staying within 1.5 °C, according to the *Global Methane Assessment*.[681] This is roughly equivalent to a 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.[682]

At COP26, 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."[683] The Glasgow Climate Pact, also agreed to at COP26, also explicitly mentions methane and non-CO_2 GHGs. The Pact "invites Parties to consider further actions to reduce by 2030 non-carbon dioxide greenhouse gas emissions, including methane."[684]

At the U.S.-ASEAN Special Summit in Washington, D.C., 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."[685]

In their 27 May 2022 communiqué, G7 Climate, Energy, and Environment Ministers re-affirmed their commitment to the GMP and noted the importance of responding "to the current crisis, in a manner consistent with our climate objectives and without creating lock-in effects."[686] In June 2022, G7 Leaders reaffirmed their commitment to the GMP.[687]

In June 2022, the U.S., EU, and 11 other countries launched the GMP Energy Pathway, which includes $59 million in funding to support methane reductions in the oil and gas sector.[688] The funding includes $4 million to support the World Bank Global Gas Flaring Reduction Partnership, $5.5 million to support the Global Methane Initiative, 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.

GMP Energy Pathway developments that took place during COP27 in November 2022 include the following:[689]

- The United States, European Union, Japan, Canada, Norway, Singapore, and the United Kingdom 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.[690] 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.

- The World Bank Global Gas Flaring Reduction Partnership announced the launch of the 2023 phase of its trust fund, with plans to become the Global Flaring and Methane Reduction (GFMR) Partnership to address methane emissions across the oil and gas value chain.

Also at COP27, GMP countries launched the GMP Food and Agriculture Pathway and Waste Pathway.[691] The Food and Agriculture Pathway will leverage up to $400 million to help smallholder farmers transition diary systems to lower emission, climate-resilient pathways[692] and raise $70 million for a new Enteric Methane Research and Development Accelerator.[693] 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.

Also launched at COP27, the GMP Waste Pathway will scale up subnational action on waste methane[694] and establish a Food Waste Management Accelerator to develop mitigation projects.[695] 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.

Other funding announcements at COP27 include a $3.5 million seed grant for further financing for 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.[696] Prior to COP27, the U.S. announced a $5 million grant to the African

Development Bank to fund methane abatement across Africa[697] 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.[698]

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 GMP lays the foundation for more concrete, emergency methane abatement, including in the form of a global methane agreement that 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),[699] 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.[700] Methane is the last remaining major ozone precursor not explicitly controlled under the Gothenburg Protocol, as currently amended.[701]

Including methane in LRTAP is an active area of discussion and should acknowledge and reinforce efforts, including through UNECE's existing collaboration with the CCAC, to develop a global methane agreement on an emergency basis. 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.[702]

Several LRTAP subsidiary bodies are studying methane emissions, including modelling impacts of methane emissions from outside the region on ozone levels in the UNECE region.[703] LRTAP and its eight protocols[704] 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;[705] a robust scientific body that monitors whether Parties are on track to meet their targets;[706] and a dual reporting system that requires Parties to report their annual pollutant emissions and progress in implementing their national strategies.[707] 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* GMP. LRTAP Parties are members of UNECE.[708] 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[709] 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.[710] The objectives of the Gothenburg Protocol include control and reduction of emissions of sulphur, 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.[711] Methane is a major source for tropospheric ozone and contributes to background ozone levels globally.[712] Although methane is recognized as an ozone precursor in the Gothenburg Protocol,[713] 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.[714] 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.[715] This review also includes how methane emissions reductions may be better achieved through a future and instrument.[716]

- *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 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.[717] The LRTAP Gothenburg Protocol Review Group, established under the Working Group on Strategies and Review (WGSR) pursuant to decision 2020/2,[718] 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.[719] 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.[720] 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.[721] 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,[722] and the feasibility of adopting control technology among its priorities.[723] Options being considered for methane action under the Convention range from developing guidance documents on best practices for emissions reduction to adopting national methane emission reduction targets.[724] At an informal meeting of the Heads of Delegation (HoD) to the WGSR held in September 2022, HoDs differed in their preferences for methane control measures within the Protocol but expressed that "voluntary measures and awareness-raising activities could be a first step forward, likely to be generally supported."[725] The HoDs recommended that the WGSR continue discussions on appropriate policy mechanisms to address methane as an ozone precursor and to present their findings at the 43rd Executive Body meeting.[726]

Taking these into consideration and recognizing that controlling methane calls for urgent action, Parties to LRTAP should consider both rapidly moving to include methane within existing mechanisms and calling for an emergency agreement to account for the global nature of methane emissions and impacts.

C. U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s

The U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s, announced at COP26 on 10 November 2021, 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,"[727] including additional measures to reduce methane emissions. China agreed to develop a "comprehensive and ambitious National Action Plan" to achieve methane emissions control and reductions in the 2020s.[728] 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,[729] and to establish a Working Group on Enhancing Climate Action in the 2020s to address the climate crisis, which would meet regularly.[730]

China's announcement of a National Action Plan on methane to reduce methane emissions in the 2020s is a significant step towards achieving the objectives of the GMP, although China has yet to formally join. Notwithstanding, as a result of the U.S.-China Joint Declaration, activities that GMP countries undertake will no doubt help inform China's methane mitigation policy and technical solutions. 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.[731]

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.[732] 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.[733] More recently, China's Ministry of Ecology and Environment (MEE) announced progress that helps lay the foundation for a National Action Plan on methane. During its January 2023 press conference, 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.[734]

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 from the IPCC 1.5 °C Special Report, AR6, and the *Global Methane Assessment*."[735] There already is a strong and evolving foundation for negotiating such an agreement. 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 foundation includes the *Global Methane Assessment*, the GMP; AR6 WGI; an appetite among key leaders for multilateralism to solve unprecedented global challenges and keep democracy alive; strong methane-mitigation policy and technical achievements at the international, national, and subnational levels; improved measuring and monitoring capabilities; and public and private collaborations over the past decade.

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

The Montreal Protocol on Substances that Deplete the Ozone Layer (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.[736]

The Montreal Protocol has several features that 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.[737] 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."[738] This principle is implemented by giving developing-country Parties a grace period, often five or ten years, before requiring them to phase out or phase down a controlled substance.[739] 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.[740] 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.[741] 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)[742] and the Technology and Economic Assessment Panel (TEAP).[743] 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.[744]

The Montreal Protocol was preceded by an underlying framework treaty, the Vienna Convention for the Protection of the Ozone Layer.[745] 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, including crises involving food security and energy. Nonetheless, a similar 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,[746] while also addressing research and development of strategies to remove methane from the atmosphere to counter natural emissions.[747]

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 terms means that speed must become the key factor in the selection of climate solutions,[748] to quickly limit warming, slow self-reinforcing feedbacks, avoid tipping points, and protect the most vulnerable people and ecosystems.[749] The United Nations Environment Programme, the IPCC,[750] the CCAC,[751] and the Arctic Council[752] have all contributed to this scientific understanding. The IPCC's Working Group II report (AR6 WGII) underscores the dire consequences of further delays in global action and the urgency of slowing warming in the near term.[753] 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.[754]

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. This foundation includes:

- **International commitments and recognitions involving critical methane action.** For instance, over 180 of 197 Parties under the Paris Agreement mention methane in their NDCs.[755] The U.S. and EU anchored support for the GMP at the leadership level during the Major Economies Forum on Energy and Climate in September 2021.[756] In June 2022, the U.S., EU, and 11 other countries launched the GMP Energy Pathway, which includes funding to support methane reductions in the oil and gas sector. In November 2022, the U.S. and EU launched the GMP Food and Agriculture Pathway and Waste Pathway to advance methane mitigation in the agriculture and waste sectors. The GMP includes 150 participants as of February 2023,[757] with developing countries such as Argentina, Ghana, Indonesia, Iraq, and Mexico, among the earliest supporters.[758] 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.[759] The European Union has committed to reduce all greenhouse gas emissions by 55% by 2030[760] and the European Commission has emphasized the need for unified, global action on methane.[761] 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.[762] International Monetary Fund 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."[763] And the CCAC is actively strengthening global understanding and ambition for methane control though initiatives such as its Methane Flagship.[764]

- **Bilateral and national commitments and actions on methane mitigation.** For instance, the U.S. and China, in their *Joint Glasgow Declaration on Enhancing Climate Action in the 2020s*, demonstrated the capability of economic and political rivals to find common ground on methane mitigation.[765] China subsequently announced its own workplan on how to address methane emissions [766] and commenced work on methane emissions data analysis and monitoring methodologies.[767] 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.[768] Canada[769] and Mexico,[770] as additional examples, have established regulations for energy-sector methane emissions, and joined the U.S. in pledging to enhance cooperation.[771] Nigeria stands out as the first African country to regulate its energy-sector methane emissions.[772]

- **Subnational efforts inspiring national measures.** These include regulations in U.S. states such as California,[773] New Mexico[774] and Colorado,[775] and in Canadian provinces such as British Columbia.[776] Climate-focused initiatives such as the C40 Cities network[777] and Under2 Coalition[778] have united subnational entities around the world in addressing methane emissions.

- **Methane measurement and monitoring initiatives.** The Carbon Mapper satellite program[779] and International Methane Emissions Observatory[780] are already informing global understanding of the levels of methane emissions contributing to the climate emergency. These initiatives and the technologies, described in **Section 8**, are essential to understanding whether the world is on track to meet existing commitments. They also provide critical information needed for successful and robust accountability and enforcement mechanisms in a global methane agreement.

- **And 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 include, in addition to the CCAC initiatives, the Global Methane Initiative,[781] the Oil and Gas Climate Initiative,[782] and methane emissions mitigation performance-rating initiatives such as MiQ[783] and the Natural Gas Sustainability Initiative.[784]

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 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, including crises involving food security and energy. This work can and should start immediately. This includes strengthening or creating within an organization such as the CCAC, which has been proposed as the Secretariat for the GMP, scientific, technical assessment, financial, and capacity-building organizations similar to those associated with the Montreal Protocol.[785] This could build upon existing commitments under the CCAC. For example, Ministers and Leaders of the CCAC have noted in the Sharm el-Sheikh Communiqué that they "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."[786] The creation of a methane control regime based on this successful template would help ensure that it lives up to its mandate.[787]

iv. *Building upon the existing strong scientific, technical, and policy foundation and CCAC organisations, 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,[788] and in March 2022, UNEP launched negotiations with the ambition of completing a global agreement to address plastic pollution two years later, in 2024.[789]

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

It is essential to secure the appropriate funding and finance 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. It is important to note that 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.

Already, 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 GMP.[790] The philanthropies committed to quickly deploy grants and ensure that funding is flexible.[791] As a result, the *Global Methane Hub* was launched in March 2022 and 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 GMP by meaningfully investing in methane reduction solutions."[792]

Notably, however, methane mitigation solutions remain severely underfunded.[793] A first-of-its-kind assessment of the landscape of methane mitigation finance 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.[794] 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, despite emitting 82% of anthropogenic methane.[795]

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

1) Ensure the availability of finance mechanisms for projects that reduce methane emissions from fossil fuel, waste, and agriculture.

2) Promote an evaluation of climate risk that includes climate tipping points and feedbacks.[796]

3) Avoid investments that will precipitate climate tipping points and are not aligned with keeping global temperature under 1.5 °C in the next decade.

4) Introduce GWP_{20} in climate impact evaluation to more accurately value near-term temperature impacts of action to reduce methane and other SLCPs.

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 .[797] The EBRD already finances green projects in large methane-emitting sectors, including energy and agribusiness.[798] 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.[799] The European Investment Bank and Green Climate Fund also committed to providing technical assistance and project finance to support the GMP .[800]

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.[801] 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."[802]

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.[803]

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."[804] 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.

A. The Resilience and Sustainability Trust

On 2 August 2021, The Board of Governors of the International Monetary Fund (IMF) approved the anticipated general allocation of $456 billion worth of Special Drawing Rights (SDR) (equivalent to US$605 billion).[805] While this was a historic accomplishment by the IMF under the direction of the IMF'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.[806]

On 13 October 2021, at the G20 meeting in Rome, world leaders issued the Leaders' Declaration requiring the IMF 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."[807] 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.[808] The RST will 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*.[809]

As of February 2023, 13 countries have pledged the equivalent of US$37 billion on SDRs to the RST.[810] Rwanda and Barbados received approval from the IMF Executive Board of Directors to receive additional SDRs through the RST for climate, but it remains to be seen how the RST can really contribute to helping the climate emergency by 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."[811] 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."[812]

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. 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.

The IMF's Board of Directors agreed to an interim review to take stock of the initial experience and revisit the set of qualifying structural challenges at around 18 months after its operationalization.[813] This presents an opportunity for the Board of Directors to implement any institutional RST reform needed to strengthen its implementation to finance the goal set through the GMP.

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.[814] 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.[815] The IMF will work with the World Bank and regional multilateral development banks to develop policy priorities and conditionality. RST measures will be informed and consistent with country diagnostics developed by both the IMF and the World Bank relevant to the RST's purposes.[816] An important way to strengthen countries' COB is to promote investments and policies to stop methane leakages which waste energy.

About three quarters of IMF's membership will be eligible for RST financing, including low-income countries, developing and vulnerable small states, and lower middle-income countries.[817] Access will be capped at SDR 1 billion. The loans will have a 20-year maturity and a 10.5-year grace period.

The RST resources will be mobilized based on voluntary contributions from members.[818] It will be ready to commence lending operations once it achieves a critical mass of resources from a broad base of contributors and when robust financial systems and processes are in place, which is anticipated to occur by the end of the year.[819] Its estimated total resource needs is SDR 33 billion (equivalent to US$45 billion).

The proposed framework to establish the RST does not specifically mention methane emissions mitigation among the projects that could benefit from RST financing. However, the language in the proposal 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.

In particular, 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 sets up the RST to reduce climate risk, the IMF must keep climate science as the core of its efforts. 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. Through its mandate, the RST could incorporate the goal of reducing climate risk to prospective balance of payments stability by cutting the rate of warming in half in the next decade. It is noteworthy that IMF staff published a paper on *How to Cut Methane Emissions*, specifically calling for a global agreement on a methane pricing.[820]

The U.S. Congress approved a contribution of US$20 million to the Poverty Reduction and Growth Trust or the Resilience and Sustainability Trust.[821] On 18 August 2022, China announced its willingness to rechannel US$10 billion of its SDRs to "IMF's two Trusts" and direct its contributions to Africa.[822]

B. The 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."[823] 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.[824]

The latest IPCC reports offer an opportunity for the WBG to review its Climate Action Plan (2021–2025) and realign its portfolio 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.[825]

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.[826]

In 2012, the G8 agreed to commission the WBG to evaluate innovative pay-for-performance mechanisms to address methane.[827] A report by the Methane Finance Study Group supported the establishment of a methane facility.[828] 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.[829] 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.[830] The three auctions allocated up to US$54 million, resulting in abatement of up to 20.6 million metric tons of CO_2eq (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 U.S..[831] The GMP might provide an opportunity to further explore this kind of finance mechanism.

The International Finance Corporation finances methane mitigation projects. For example, on 29 July 2022, International Finance Corporation disclosed its funding for 24 landfill gas-to-energy project that will be implemented in 10 provinces in China.[832] The project is estimated to reduce about 3.4 $mtCO_2e$ of GHG through methane capture.[833] 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.[834] However, the International Finance Corporation could do more and update its Performance Standards on Environment and Social Sustainability and its Definitions and Metrics on Climate Related Activities 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.

In addition, the Multilateral Investment Guarantee Agency, a WBG member that provides long-maturity guarantees,[835] 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.

C. The World Bank 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."[836] One of the key tools of this collaboration is the World Bank's Country Climate and Development Report (CCDR), which would potentially be complemented with other reports like the Climate Change Policy Assessments (CCPAs) and Climate Macroeconomic Assessments Programs (CMAPs).[837]

The World Bank launched a CCDR at COP26 and currently includes Brazil, Nepal, Honduras, Morocco, Angola, Burkina Faso, Chad, Mali, Mauritania, Niger, and Vietnam.[838] Most of these countries have signed on the GMP and are CCAC partners that requested support to develop their action plans to reduce methane. The World Bank is also a partner of the CCAC. This provides an opportunity to promote the link between the work of the World Bank on the CCDRs and the GMP goal. The World Bank could support CCDR countries to consider methane mitigation in the CCDR work. If methane mitigation is included in the CCDR RST investment strategy will be more easily aligned with the Global Methane Pledge, as the IMF expects to "[d]raw significantly on the CCDR, if available, for climate-related RST reform measures."[839]

At COP27, the World Bank hosted an event titled "It's Time to Sprint: Targeting Methane Emissions."[840] While the World Bank has extensive experience on high methane emission sectors, it remains to be seen how the Bank is going to ramp up support to its clients' countries to substantially reduce methane emissions and help remain under 1.5 °C.

D. A global financial strategy to tackle the climate emergency

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."[841]

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.[842]

The proposal includes a design of the $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 attend the climate emergency, must prioritize methane emissions reductions.

In 2022, Barbados hosted the Bridgetown Initiative with key stakeholders and developed the Bridgetown Agenda.[843] While the Bridgetown Agenda does not mention methane specifically, if implemented, it might present an important opportunity for methane mitigation within the global finance system.

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 GMP and related commitments represent important steps along the way to a global agreement. In the meantime, immediate action is needed to require a progressively lower methane emissions rate from providers of "replacement methane gas" in response to changes in countries' methane gas imports. 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. 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
ARPA-E	Advanced Research Projects Agency–Energy
ASEAN	Association of Southeast Asian Nations
BLM	Bureau of Land Management
BUR	Biennial Update Report
CATF	Clean Air Task Force
CAP	Common Agriculture Policy
CBM	Coal Bed Methane
CCAC	Climate & Clean Air Coalition
CCDR	Country Climate and Development Reports
CCPA	Climate Change Policy Assessment
CH_4	methane
CIL	Coal India Limited
CMAP	Climate Macroeconomic Assessments Program
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)
DFC	United States International Development Finance Corporation
EBRD	European Bank for Reconstruction and Development
EDF	Environmental Defense Fund
EMIT	Earth Surface Mineral Dust Source
EPA	Environmental Protection Agency
ESG	Environmental, Social, and Governance framework
EXIM	Export–Import Bank of the United States
GCF	Green Climate Fund
GFMR	Global Flaring and Methane Reduction
GGFR	Global Gas Flaring Reduction Partnership

GHG	Greenhouse gas
GMI	Global Methane Initiative
GMP	Global Methane Pledge
Gothenberg 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
IMEO	International Methane Emissions Observatory
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
Kigali Amendment	Kigali Amendment to the Montreal Protocol (Kigali, Rwanda) (2016)
LDAR	Leak Detection and Repair
LNG	Liquified natural gas
LRTAP	Convention on Long-Range Transboundary Air Pollution
MARS	Methane Alert and Response System
MEE	China Ministry of Ecology and Environment
MLF	Multilateral Fund of the Montreal Protocol
Montreal Protocol	Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal, Canada) (1987)
MRV	measurement, reporting, and verification
Mt	Metric ton
N_2O	nitrous oxide
NDC	Nationally Determined Contribution
NGSI	Natural Gas Sustainability Initiative
O_3	tropospheric ozone
OCI+	Oil Climate Index Plus
OGCI	Oil & Gas Climate Initiative
OGMP	Oil & Gas Methane Partnership

PAF	Pilot Auction Facility for Methane and Climate Change Mitigation
PEMEX	Petroleos Mexicanos
PIPES Act	Protecting Our Infrastructure of Pipelines and Enhancing Safety Act (United States) (2020)
ppb	parts per billion
REMEDY	Reducing Emissions of Methane Every Day of the Year
RMI	Rocky Mountain Institute
RST	Resilience and Sustainability Trust
SAP	Scientific Assessment Panel
SDR	Special Drawing Rights
SLCP	short-lived climate pollutant
SO_2	sulphur dioxide
TEAP	Technology and Economic Assessment Panel
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USTDA	United States Trade and Development Agency
WBG	World Bank Group
WGI	Working Group I contribution to the IPCC Sixth Assessment Report on the *Physical Science Basis* (2021)
WGII	Working Group II contribution to the IPCC Sixth Assessment Report on *Impacts, Adaptation, and Vulnerability* (2022)
WGIII	Working Group III contribution to the IPCC Sixth Assessment Report on *Mitigation of Climate Change* (2022)
WGSR	Working Group on Strategies and Review

References

[1] 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}").

[2] 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, 6-8 ("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}"; "Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).").

[3] 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.").

[4] 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): e2123536119, 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."; "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)."). *See also* 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 ("Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (SI Appendix, Fig. S2A) suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050... 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)."); *and* 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.), 6-6 ("Over time scales of 10 to 20 years, the global temperature response to a year's worth of current emissions of SLCFs is at least as large as that due to a year's worth of CO_2 emissions (*high confidence*).").

[5] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254, 262 ("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)."; "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, 184–185 ("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).").

[6] 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.").

[7] 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.

[8] 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℃ 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 and 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).

[9] UNITED STATESDepartment of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 2 February 2023); Lan X., Thoning K. W., & Dlugokencky E. J. (2022) *Trends in globally-averaged CH_4, N_2O, and SF_6 determined from NOAA Global Monitoring Laboratory measurements*, Version 2023-01. *Referenced in* 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(1) (15 and 18 ppb,(2) 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* 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."); National Oceanic and Atmospheric Administration (7 April 2022) *Increase in atmospheric methane set another record during 2021* ("NOAA's preliminary analysis showed the annual increase in atmospheric methane during 2021 was 17 parts per billion (ppb), the largest annual increase recorded since systematic measurements began in 1983. The increase during 2020 was 15.3 ppb. Atmospheric methane levels averaged 1,895.7 ppb during 2021, or around 162% greater than pre-industrial levels."); *and* 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.").

[10] 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)").

[11] 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; *and* Hansen J., Sato M., & Ruedy R. (12 January 2023) *Global Temperature in 2022*, Columbia University ("The already long La Nina is unlikely to continue, tropical neutral conditions are expected by Northern Hemisphere spring, with continued warming as the year progresses.

Thus, 2023 should be notably warmer than 2022 and global temperature in 2024 is likely to reach +1.4-1.5°C, as our first Faustian payment of approximately +0.15°C is due.”).

[12] 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): eabn7950, 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).”); *and* 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.”).

[13] 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, SPM-13 (“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.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*).”).

[14] 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.”).

[15] 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): 054042, 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.").

[16] 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}").

[17] 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}").

[18] 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}").").

[19] 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)"). *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 ("According to our analysis, five industries could take actions that would have a significant impact on methane emissions, reducing annual methane emissions by 20 percent by 2030 and by 46 percent by 2050. This impact could be achieved largely with established technologies and at a reasonable cost: 90 percent of these reductions could come at a cost of less than $25 per metric ton of carbon dioxide equivalent (tCO_2e).").

[20] 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): 054042, 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.").

[21] 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)").

[22] 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.").

[23] 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.").

[24] 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.").

[25] 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.").

[26] 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.").

[27] 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.").

[28] 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.").

[29] 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.").

[30] 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).").

[31] 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*).").

[32] 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.").

[33] 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)").

[34] 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): e2123536119, 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.").

[35] 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.").

[36] 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 %).").

[37] 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.").

[38] 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.").

[39] 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.").

[40] 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 %).").

[41] 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): 20200440, 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 ± 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): nwab200, 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 $\delta^{13}C$-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.").

[42] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 20200454, 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): 20210104, 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*.").

[43] 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, 561 ("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* 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).").

[44] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 024019, 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.

[45] Limiting warming to 1.5 °C with little or no overshoot requires reducing global methane emissions by 34% [21–57%, range from modelled scenarios] in 2030 compared to 2019 levels, which is consistent with achieving and exceeding the *Global Methane Pledge* collective target. *See* 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}").

[46] 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.").

[47] 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).").

[48] 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).").

[49] Based upon IGSD's research involving the UNFCCC NDC Registry, as of 23 August 2022, 184 NDCs directly reference methane. Of these, 28 NDCs include quantitative sectoral or economy-wide methane-reduction targets. *See* IGSD NDC tracker. *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; 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.

[50] For a list of Global Methane Pledge participants, *see* https://www.globalmethanepledge.org/ - pledges.

[51] 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."). *See also* International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 19 ("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.").

[52] 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.

[53] *See* UNITED STATESDepartment of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 2 February 2023); *and* Lan X., Thoning K. W., & Dlugokencky E. J. (2022) *Trends in globally-averaged CH_4, N_2O, and SF_6 determined from NOAA Global Monitoring Laboratory measurements*, Version 2023-01; *referenced in* 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(1) (15 and 18 ppb,(2) 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* 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.").

[54] United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 25 January 2023). *See also* 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.").

[55] White House (18 September 2021) *Joint US-EU Press Release on the Global Methane Pledge*, Statements and Releases ("Methane is a potent greenhouse gas and, according to the latest report of the Intergovernmental Panel on Climate Change, accounts for about half of the 1.0 degree Celsius net rise in global average temperature since the pre-industrial era. Rapidly reducing methane emissions is complementary to action on carbon dioxide and other greenhouse gases, and is regarded as the single most effective strategy to reduce global warming in the near term and keep the goal of limiting warming to 1.5 degrees Celsius within reach.").

[56] 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.").

[57] 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.), 6-47 ("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}.).

[58] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 17, 21 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years."; "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.”).

[59] 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.”).

[60] 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): biab079, 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.”).

[61] 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): eabn7950, 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).”).

[62] 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.”).

[63] 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).

[64] 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).").

[65] 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) selfperpetuating 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): eabn7950, 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.").

[66] 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.").

[67] 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.”).

[68] 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).”).

[69] 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.”).

[70] 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): e2123536119, 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.”); 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.”); *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.").

[71] 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, 6-8 ("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}"; "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.").

[72] 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}").

[73] 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): 1919, 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).").

[74] 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.").

[75] 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.").

[76] 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.").

[77] 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.").

[78] 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.").

[79] 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).

[80] 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.").

[81] 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.").

[82] 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.").

[83] 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.").

[84] 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.").

[85] 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).”).

[86] 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.”).

[87] 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.”).

[88] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT SUMMARY FOR POLICYMAKERS, The global monetized benefits for all market and non-market impacts are approximately US$ 4 300 per tonne of methane reduced1. When accounting for these benefits nearly 85 per cent of the targeted measures have benefits that outweigh the net costs. The benefits of the annually avoided premature deaths.”).

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

[90] 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, 6-8 (“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}”; “Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).”).

[91] 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.”).

[92] 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.).

[93] 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.").

[94] 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): eaay1052, 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.").

[95] 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 ¶47 (March 19, 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).'").

[96] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 024019, 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.

[97] 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.").

[98] 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.

[99] 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): 044023, 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).").

[100] 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".").

[101] 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): 068002, 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.

[102] 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*).").

[103] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11: 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.").

[104] 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.").

[105] 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; *and* McGuire B. (12 September 2022) *Why we should forget about the 1.5C global heating target*, THE GUARDIAN; *and* Hansen J., Sato M., & Ruedy R. (12 January 2023) *Global Temperature in 2022* ("The already long La Nina is unlikely to continue, tropical neutral conditions are expected by Northern Hemisphere spring, with continued warming as the year progresses. Thus, 2023 should be notably warmer than 2022 and global temperature in 2024 is likely to reach +1.4-1.5°C, as our first Faustian payment of approximately +0.15°C is due.").

[106] 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.").

[107] 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*).").

[108] 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)").

[109] 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.").

[110] 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.").

[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: 592–595.

[112] 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): eabn7950, 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).").

[113] 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): eabn7950, 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.").

[114] 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.").

[115] 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, 5 ("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 ± 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."; "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.

[116] 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.").

[117] 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): e2108146119, 1–9, 2, 3 ("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)."; "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.").

[118] 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): e2123536119, 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*, NATURE 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.").

[119] 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 Sulphur dioxide (SO_2) contributes –0.49 °C (–0.10 to –0.93 °C) to observed warming in 2010–2019 relative to 1850–1900).

[120] 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, Addendum "Methods" ("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."; "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): 04407, 1–11.

[121] 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): e2123536119, 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).").

[122] 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, 6-8 ("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}"; "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.").

[123] 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.").

[124] 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): 054042, 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.").

[125] 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}").

[126] 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) {3.3, 3.5, Box 3.4, Cross-Chapter Box 3 in Chapter 3, AR6 WG I SPM D1.8}").

[127] 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}").

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

[129] 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, 6-8 ("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}"; "Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).").

[130] 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.").

[131] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 239, 246 ("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)."; "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.").

[132] 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): 054042, 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).").

[133] 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.").

[134] 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): 044001, 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.”).

[135] 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.”).

[136] 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.”).

[137] 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.”).

[138] 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 %).”).

[139] 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.”).

[140] 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).").

[141] 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.").

[142] 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): 20200440, 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): nwab200, 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, 129 ("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). The increase in atmospheric."; "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).").

[143] 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): 413–14; *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): 094003.

[144] 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.").

[145] 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): 025004, 1–21, 7–8 (Table 2 and Supplementary material tab "World"). *See also* International Energy Agency (2022) GLOBAL METHANE TRACKER, 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.").

[146] 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.").

[147] 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.").

[148] 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.").

[149] 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.").

[150] 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.").

[151] 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.").

[152] 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.").

[153] 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."); *and* 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.").

[154] 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.").

[155] 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.").

[156] 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* EMBER (31 January 2023) *European Electricity Review 2023*, 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.").

[157] 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.").

[158] 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.").

[159] 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).").

[160] 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.").

[161] 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): 025004, 1–21, 7–8 (Table 2) and Supplementary material tab "World".

[162] 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).").

[163] 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).").

[164] 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.).

[165] 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): 025004, 1–21, 7–8 (Table 2) and Supplementary material tab "World".

[166] 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.").

[167] 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): 025004, 1–21.

[168] 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): eabn9683, 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.").

[169] 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.").

[170] 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)").

[171] 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.").

[172] 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)").

[173]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.").

[174] 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.").

[175] 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): 025004, 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.

[176] *See* Solar Impulse Foundation, *Solutions Explorer*.

[177] 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.").

[178] 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.").

[179] International Energy Agency (2022) GLOBAL METHANE TRACKER 2022, 25 ("The cost effectiveness of abatement measures vary by country, depending on the prevailing emissions sources, capital and labour costs, and natural gas prices. We estimate that it is technically possible to avoid over 70% of today's methane emissions from global oil and gas operations. Based on average natural gas prices over the past five years, over 40% of methane emissions from oil and gas operations could be avoided at no net cost as the outlays for the abatement measures are less than the market value of the additional gas that is captured. Based on the elevated natural gas prices seen in 2021, almost all of the options to reduce emissions from oil and gas operations worldwide could be avoided implemented at no net cost."). *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%.").

[180] 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.").

[181] 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): 054042, 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.").

[182] 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.").

[183] 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.").

[184] *See e.g.,* 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.").

[185] 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.").

[186] 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%.").

[187] 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.").

[188] 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.

[189] 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.").

[190] 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., 1–14, 10, 11 ("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."; "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)."). *See also* Proville J., & Roberts K. (2022) *Creating data to support communities on the front lines of oil and gas production in the US*, ENVIRONMENTAL DEFENSE FUND.

[191] 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.").

[192] 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.").

[193] 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.").

[194] 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.

[195] 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.").

[196] 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."; "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).").

[197] 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.

[198] 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.").

[199] 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.").

[200] 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.").

[201] 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 ("I n 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.").

[202] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 107 ("Coal mining: flooding abandoned mines.").

[203] 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.").

[204] 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).").

[205] 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)").

[206] 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.").

[207] 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): 025004, 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).").

[208] 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].").

[209] 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.").

[210] Agrovive Biologicals (30 May 2022) *Announcement: New In-Plant Inoculants Lower Methane Emissions* ("Corn silage from these early on-farm trials was sent to Fermentrics Technologies, an independent fermentation laboratory for potential methane reduction analysis. Their four-step analysis process supports a greater than 30% methane reduction. The final percent reduction will be released when the fourth analysis is completed later this summer. Other studies are underway that could demonstrate even more impressive results. Dairy One - a DFA aligned cooperative - Agrovive Biologicals and other interested parties have contracted with Cornell University to do a seed-to-lagoon agronomic, nutritional and economic study. Results are expected in fall 2022. A large, multi-farm study is being initiated by a leading dairy cooperative and their producer patrons by applying 'Leaf2Rumen' Inoculant to 100,000 plus acres of corn for silage this June. During June 2022 South Dakota State University will be launching a beef cow feeding study to evaluate animal performance and measure methane and greenhouse gas emissions.").

[211] Vijn S., *et al.* (2020) *Key Considerations for the Use of Seaweed to Reduce Enteric Methane Emissions from Cattle*. FRONT. VET. SCI. 7(597430): 1–9, 2 ("Feeding livestock many seaweeds—also known as red, green or brown marine macroalgae—has been shown to reduce methane production, but with highly variable results (9–12). For example, *in vitro* analysis suggested that the tropical/subtropical red seaweed *Asparagopsis taxiformis* can reduce methane production by 95% when added to feed at a 5% organic matter inclusion rate... Kinley et al. (14) reported that inclusion of *A. taxiformis* at 0.10 and 0.20% of dietary dry matter over a 90 day period decreased methane production in steers up to 40 and 98%, and produced weight gain improvements of 24 and 17 kg, respectively, relative to control steers."). *See also* Kinley R. D., Martinez-Fernandez G., Matthews M. K., de Nys, R., Magnusson M., Tomkins N. W. (2020) *Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed*, J. CLEAN. PROD. 259(120836): 1–10, 2 ("A rumen *in vitro* study screened 20 different macroalgae species and *Asparagopsis taxiformis* was identified as the primary candidate for further investigation (Machado et al., 2014). Subsequent *in vitro* work to determine optimum inclusion rates for ruminants has demonstrated no negative impact on fermentation with 99% decrease in CH_4 (Kinley et al., 2016a). Validation of the *in vitro* work was demonstrated *in vivo* with a clear inclusion level response effect and decrease of 80% CH_4 production in sheep (Li et al., 2018). Further validation of the capability of *Asparagopsis in vitro* (Roque et al., 2019a; Kinley et al., 2016b) and *in vivo* as a functional feed ingredient for lactating dairy cattle demonstrated CH_4 decrease of 67% (Roque et al., 2019b)."); Abbott D. W., *et al.* (2020) *Seaweed and Seaweed Bioactives for Mitigation of Enteric Methane: Challenges and Opportunities*, ANIMALS 10(2432): 1–28, 2, 5 ("Recently, researchers concluded that commercial production of the red seaweed *A. taxiformis* could create new economies due to the fact that addition of small quantities of this seaweed in the diet of ruminant animals reduced CH_4 emissions by up to 98% when included at 0.2% of dry matter intake of steer diets [**14**]."; "The greatest CH_4 mitigation potential was observed for the red seaweed *A. taxiformis* with almost complete inhibition in vitro with inclusion levels up to 16.7% of the organic matter (OM). *A. taxiformis* was highly effective in decreasing the production of CH_4 with a reduction of 99% at doses as low as 2% OM [**45**,**46**,**47**,**48**]."); *and* Roque B. M., Venegas M., Kinley R. D., de Nys R., Duarte T. L., Yang X., & Kebreab E. (2021) *Red Seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane over 80% in beef steers*, PLOS ONE 16(3): 1–20, 7–9 ("Steers fed low forage TMR and supplemented with A. taxiformis reduced CH_4 production, yield, and intensity by 72.4 and 81.9%, 69.8 and 80.0%, and 67.5 and 82.6% for Low and High treatments, respectively. Additionally, H_2 production, yield, and intensity increased by 419 and 618%, 503 and 649%, and 566 and 559% for the Low and High treatments, respectively. No significant differences were found in CO_2 production, yield, or intensity in any of the three diets.").

[212] 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.”).

[213] Rumin8 (18 July 2022) *Rumin8 Attracts Domestic and International Climate Fund Investors – Aware Super Sentient WA Growth Fund and Prelude Ventures* (“Rumin8’s lead product replicates the methane reductions of red seaweed (Asparagopsis), but instead of harvesting from the marine ecosystem, the plant’s methane busting bioactive is manufactured and transformed into a scalable, stable feed supplement in Rumin8’s quality-controlled laboratories. … Rumin8 recently concluded highly encouraging sheep trials which demonstrated methane reductions of up to 95 per cent, with no residues detected in 80 independently analysed samples.”). *See also* Algae Planet (2 June 2022) *Rumin8 Copies Asparagopsis in Lab*.

[214] 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.”). *See also* Bryce E. (20 September 2021) *Kowbucha, seaweed, vaccines: the race to reduce cows’ methane emissions*, GUARDIAN (“There are dozens more livestock methane interventions under development, according to a recent assessment co-authored by Ermias Kebreab. But only a handful – including Bovaer and Zelp – have reached the market. Even here, there’s still fine-tuning to be done. For instance Bovaer needs to be constantly in the rumen to work, meaning it may be less practical for free-ranging cattle whose feeding is less controlled (van Nieuwland said DSM is working to develop slow-release 3-NOP to help with this).”).

[215] 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.”). *See also* 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.”).

[216] 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...”).

[217] 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.").

[218] 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* 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, 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)."); 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(1393): 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(4988): 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.").

[219] 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).").

[220] 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, 25 ("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."; "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*, PENN STATE.

[221] 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; *and* Sainato M. (4 February 2022) *California subsidies for dairy cows' biogas are lose-lose, campaigners say*, THE GUARDIAN.

[222] Bakkaloglu S., Cooper J., & Hawkes A. (2022) *Methane emissions along biomethane and biogas supply chains are underestimated*, ONE EARTH 5(6): 724–736, 726, 730 ("Although emissions from the biomethane supply chain are

comparable to oil and natural-gas production in terms of Tg CH_4 year^{-1}, the production-normalized emission rate is considerably higher. This could be due to a variety of factors, including poorly managed production facilities; a lack of attention to the biomethane industry resulting in lower investments for modernization, operation, and monitoring; and employment of highly skilled plant operators when compared with oil and natural gas. In addition, poor design and management of feedstock and digestate storage units as well as a limited interest in infrastructure emissions may result in higher emission rates compared with the amount of gas produced. Because oil and natural-gas supply chains have been primarily operated by large companies for decades, they have invested more in leak detection and repair. On the other hand, given the growth in biomethane generation due to national decarbonization strategies, more urgent efforts are also needed for the biomethane supply chain to address not only CH_4 emissions but also the sustainability of biomethane."; "The synthesis of available data here showed that this leads to lower direct CH_4 emissions than the oil and natural-gas supply chain but much higher CH_4 loss rates than the oil and natural-gas supply chain. This conclusion is pertinent in the context of global efforts to mitigate CH_4 emissions, which to date largely focuses on natural-gas supply chains.").

[223] Staggs B. (16 August 2022) *California cows are leaving the state and that won't help global warming*, DAILY BULLETIN ("But while half of those reductions have come from dairies changing the ways they process cow manure, the other half has come because California simply is losing cows. And when cows are moved, global methane emissions don't actually drop. They just shift, or "leak," into another state, where lighter regulations mean the greenhouse problems likely will get worse.").

[224] United States Environmental Protection Agency (2019) *GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION 2015-2050*, EPA-430-R-19-010, 56 ("The analysis considers six enteric fermentation CH_4 abatement measures: improved feed conversion efficiency, antibiotics, bovine somatotropin (bST), propionate precursors, antimethanogen vaccines, and intensive grazing. 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. For example, the average annual operation and maintenance cost for antibiotics ranges from $4 to $9 per head. Likewise, intensive grazing can save farmers up to $180 annually while reducing emissions by 9 $MtCO_2e$ at break-even prices below $0/$tCO_2e$.").

[225] 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.").

[226] 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, 7–8 ("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.").

[227] 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, 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.").

[228] Kim M., Masaki T., Ikuta K., Iwamoto E., Nishihara K., Hirai M., Uemoto Y., Terada F., & Roh S. (2022) *Physiological responses and adaptations to high methane production in Japanese Black cattle*, SCI. REP. 12(11154): 1–14, 1 ("In this study, using enteric methane emissions, we investigated the metabolic characteristics of Japanese Black cattle. Their methane emissions were measured at early (age 13 months), middle (20 months), and late fattening phases (28 months). Cattle with the highest and lowest methane emissions were selected based on the residual methane emission values, and their liver transcriptome, blood metabolites, hormones, and rumen fermentation characteristics were analyzed. Blood β-hydroxybutyric acid and insulin levels were high, whereas blood amino acid levels were low in cattle with high methane emissions. Further, propionate and butyrate levels differed depending on the enteric methane emissions. Hepatic genes, such as *SERPINI2*, *SLC7A5*, *ATP6*, and *RRAD*, which were related to amino acid transport and glucose metabolism, were upregulated or downregulated during the late fattening phase. The above mentioned metabolites and liver transcriptomes could be used to evaluate enteric methanogenesis in Japanese Black cattle."); *discussed in* Sexton C. (31 July 2022) *Study reveals features of cattle with high methane emissions*, EARTH.COM.

[229] 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.").

[230] 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 parasitised 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).").

[231] 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): e2111294119, 1– 10, 3 ("Decreasing grass maturity decreased CH_4I_M (13%, 7 to 18%, n = 6), did not affect feed intake, but increased milk yield (9%, 1 to

18%, *n* = 6). Furthermore, it improved fiber digestibility (15%, 9 to 21%, *n* = 9), which can potentially decrease manure CH_4 emissions (22).").

[232] 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 CO2e 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 CO2e 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.").

[233] 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.: 1–23, 1 ("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.").

[234] Palangi V., Taghizadeh A., Abachi S., & Lackner M. (2022) *Strategies to Mitigate Enteric Methane Emissions in Ruminants: A Review,* SUSTAINABILITY 14(20): 13229, 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.").

[235] 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). Currently, most countries in Africa rely on the Intergovernmental Panel on Climate Change (IPCC) tier 1 methodology to estimate their livestock-based emissions. However, detailed, and precise activity data are lacking, and accurate estimates of natural resource use and environmental impact by livestock in Africa, particularly SSA are scarce.").

[236] 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. 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. Adoption of modern reproductive management technologies, targeting increased conception rates, increased fecundity (in swine and small ruminants) and reduced embryo loss also provide a significant opportunity to reduce GHG emissions from the livestock sector, with appropriate attention to animal welfare considerations. We estimated that these improved animal management practices could reduce emissions in the livestock sector by 0.2 $GtCO_2e\ yr^{-1}$ by 2050.").

[237] 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): e786–e796, e794 ("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]").

[238] O'Hara Y. (15 December 2017) *Vaccine to reduce methane from cows could be '5 to 7 years away'*, NEW ZEALAND HERALD ("However, DairyNZ and the dairy industry, including Fonterra, are looking at ways of mitigating that production as part of the Dairy Action for Climate Change framework, launched earlier this year. DairyNZ's senior adviser and policy analyst Kara Lok said AgResearch was working on the methane inhibitor vaccine, and it was one of several studies under way.").

[239] 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, 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.").

[240] 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): 025004, 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 ("Rice paddies: 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 species." (Listed under "Targeted Measures")); Project Drawdown, *Technical Summary: Improved Rice Production* (*last visited* 5 February 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, White Paper, 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).").

[241] 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): 025004, 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).").

[242] 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.").

[243] Climate & Clean Air Coalition, *Paddy rice production* (*last visited* 5 February 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* 5 February 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.").

[244] 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, 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.").

[245] 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.").

[246] 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, 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.").

[247] 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.").

[248] California Air Resources Board, *Rice Cultivation Projects* (*last visited* 5 February 2023).

[249] 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.").

[250] Romero-Briones A. (19 April 2022) *The Future of Agriculture in a Warming World Panel*, Speech.

[251] 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.'").

[252] 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.").

[253] 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(18140): 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 (CH4) 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.").

[254] 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.").

[255] 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(720646): 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.").

[256] *See* Number 8 Bio (*last visited* 5 February 2023).

[257] 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.

[258] Good Food Institute, *Defining alternative proteins* (*last visited* 26 January 2023) ("Alternative proteins are proteins produced from plants or animal cells, or by way of fermentation. These innovative foods are designed to taste the same as or better than conventional animal products while costing the same or less. Compared to conventionally produced proteins, alternative proteins require fewer inputs, such as land and water, and generate far fewer negative externalities, such as greenhouse gas emissions and pollution. Some of these products are available to consumers today, including numerous plant-based and fermentation-derived options. Others, such as cultivated meats, remain primarily in development."). See also Purvis N. & Friedrich B. (8 October 2022) *Plant-based proteins are too expensive: Here's how to level the playing field with meat*, FOREIGN POLICY.

[259] 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).").

[260] N2–Applied, *N2 Solution* (*last visited* 5 February 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.").

[261] 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* 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, 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)."); 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): 1393, 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."); Yang S., Xiao Y., Sun X., Ding J., Jiang Z., & Xu J. (2019) *Biochar improved rice yield and mitigated CH_4 and N_2O emissions from paddy field under controlled irrigation in the Taihu Lake Region of China*, ATMOS. ENVIRON. 200: 69–77, 69 ("These results suggest that 20 and 40 t ha−1 biochar can be utilized under controlled irrigation not only for mitigation of CH_4 and N_2O emission but also to increase rice yield, soil fertility and irrigation water productivity. Therefore, the combination of biochar amendment and controlled irrigation might be a good option for mitigating greenhouse gases emission and realizing the sustainable utilization of soil and water resources of paddy fields in the Taihu Lake Region of China."); *and* 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.").

[262] 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.").

[263] 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.").

[264] 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): e2202338119, 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.").

[265] 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.").

[266] 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.").

[267] 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.").

[268] United States Environmental Protection Agency, *Basic information about landfill gas* (*last visited* 5 February 2023).

[269] 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.").

[270] 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)).

[271] 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*.

[272] 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.").

[273] 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.").

[274] 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.").

[275] 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(110397): 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.").

[276] 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: 6−73, 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}).").

[277] 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.").

[278] 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.").

[279] 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.").

[280] 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).").

[281] 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.").

[282] 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.").

[283] 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.").

[284] 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.").

[285] 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.").

[286] 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.").

[287] 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).

[288] 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): 054012, 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.").

[289] 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): eabn9683, 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.

[290] 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* ("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.").

[291] 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(00050): 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.'").

[292] 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.").

[293] 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): 025004, 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.").

[294] 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(1): 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.").

[295] 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): 20200440, 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.").

[296] 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* U.S. Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 2 February 2023); 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).

[297] 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, 481 ("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)."; "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.").

[298] 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* 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.").

[299] 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: 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., Abbott B.W., Commane R., Ernakovich J., Euskirchen E., Hugelius G., Grosse G.,

Jones M., Koven C., Leshyk V., Lawrence D., Loranty M.M., Mauritz M., Olefeldt D., Natali S., Rodenhizer H., Salmon V., Schädel C., Strauss J., Treat C., & Turetsky M. (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47(1): 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).").

[300] Rehder Z., Kleinen T., Kutzbach L., Stepanenko V., Langer M., & Brovkin V. (13 January 2023) *Simulated methane emissions from Arctic ponds are highly sensitive to warming*, BIOGEOSCI. DISCUSS. (*preprint*), 2 ("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."). 21 ("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): 094006. 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.").

[301] 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.

[302] 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.").

[303] 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, 5 ("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."; "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., & Boesch H. (17 June 2022) *Methane emissions responsible for record-breaking atmospheric methane growth rates in 2020 and 2021*, ATMOS. CHEM. PHYS. (*preprint*), 1–23, 5 ("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 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., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (27 June 2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ESSOAR (*preprint*), 1–14, 7–8 ("Africa shows an increase of 15 Tga^{-1} in methane emissions from 2019 to 2020. 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 TAMSAT (http://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, 2022]. Flooding in 2020 was widespread, affecting 50% more East Africans than in 2019 [BBC, 2020].").

[304] Gulev S. K., Thorne P. W., Ahn J., Dentener F. J., Domingues C. M., Gerland S., Gong D., Kaufman D. S., Nnamchi H. C., Quaas J., Rivera J. A., Sathyendranath S., Smith S. L., Trewin B., von Schuckmann K., & Vose R. S. (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.").

[305] 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): e2201871119, 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.").

[306] 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: Oxford, United Kingdom; *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.

[307] 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, 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 26estabilization 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.”).

[308] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 20200454, 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): 20210104, 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 0.03Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of *E*.").

[309] 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, 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.").

[310] 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: 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.").

[311] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379: 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.").

[312] 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): 20210104, 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.").

[313] 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): 20210104, 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.").

[314] 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): 20210104, 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.").

[315] 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): 20210104, 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.").

[316] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 20200454, 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.").

[317] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 20200454, 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.").

[318] 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* 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)."). 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. T. R. SOC. A 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].).

[319] 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).

[320] 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.

[321] 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").

[322] Yoon S., Carey J. N., & Semrau J. D. (2009) *Feasibility of atmospheric methane removal using methanotrophic biotrickling filters*, APPL. MICROBIOL. BIOTECHNOL. 83: 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: 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.").

[323] 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* Yang S., Xiao Y., Sun X., Ding J., Jiang Z., & Xu J. (2019) *Biochar improved rice yield and mitigated CH_4 and N_2O emissions from paddy field under controlled irrigation in the Taihu Lake Region of China*, ATMOS. ENVIRON. 200: 69–77, 69 ("These results suggest that 20 and 40 t ha^{-1} biochar can be utilized under controlled irrigation not only for mitigation of CH_4 and N_2O emission but also to increase rice yield, soil fertility and irrigation water productivity. Therefore, the combination of biochar amendment and controlled irrigation might be a good option for mitigating greenhouse gases emission and realizing the sustainable utilization of soil and water resources of paddy fields in the Taihu Lake Region of China.").

[324] 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): 1803, 1–13, 1, 8 ("In this context, a real-scale trial was performed to measure the ability of the commercial additive SOP LAGOON to reduce carbon-based greenhouse gas (GHG) emissions from liquid manure over approximately 4 months. Gas emissions were measured at a commercial dairy farm from two slurry tanks, one treated with the abovementioned product (SL) and the other used as the untreated control (UNT). 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."; "The results of this work show an improved mitigation capacity of SOP LAGOON at scale than that previously measured [30,31], both for CH_4 and CO_2. The duration of the monitoring in this study was much longer than the previous works (5 months vs. 26 days or 1 week, respectively, for [30,31]). The experiment was performed in a commercial dairy, with pre-existing manure tanks, as opposed to the two preliminary works where the emissions were measured from manure in 220 L barrels. The analysis of the chemical characteristics of the liquid manure in both UNT and SL does not show remarkable differences between the treatments or throughout the test dates. The values are similar to what Martínez-Suller et al. [36] found and are consistent with regular dairy farm practices, where the feed quality and composition do not vary significantly over the year.").

[325] 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): 1393, 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.").

[326] Jackson R. B., Saunois M., Bousquet P., Canadell J. G., Poulter B., Stavert A. R., Bergamaschi P., Niwa Y., Segers A., & Tsuruta A. (2020) *Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources*, ENVIRON. RES. LETT. 15(7): 071002, 1–7, 6 ("Increased emissions from both the agriculture and waste sector and the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner *et al* 2019), atmospheric chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.").

[327] International Energy Agency (2021) DRIVING DOWN METHANE LEAKS FROM THE OIL AND GAS INDUSTRY: A REGULATORY ROADMAP AND TOOLKIT.

[328] 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.

[329] 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.").

[330] 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.

[331] 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.").

[332] 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.").

[333] 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.").

[334] United States Bureau of Land Management (18 November 2016) *Waste Prevention, Production Subject to Royalties, and Resource Conservation*, FED. REG. 87: 73588–73620, 73589 ("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.").

[335] 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.").

[336] United States Securities and Exchange Commission (2022) *The Enhancement and Standardization of Climate-Related Disclosures for Investors*, 87 FED. REG. 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").").

[337] 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.").

[338] 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.").

[339] 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.").

[340] United States Department of Energy (30 March 2022) *Repurposing Fossil Energy Assets Workshop*.

[341] 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.39 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.").

[342] 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.").

[343] *See* United States Environmental Protection Agency, *Livestock Anaerobic Digester Database* (*last visited* 5 February 2023) (Tracking anaerobic digester projects in the U.S.); *and* United States Environmental Protection Agency, *LMOP Landfill and Project Database* (*last visited* 5 February 2023) (Tracking U.S. landfills, including candidates for landfill gas energy projects.).

[344] 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.").

[345] United States Environmental Protection Agency, *United States 2030 Food Loss and Waste Reduction Goal* (*last visited* 5 February 2023) ("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.").

[346] United States Environmental Protection Agency, *About the Landfill Methane Outreach Program* (*last visited* 5 February 2023) ("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.").

[347] United States Environmental Protection Agency, *Coal Mine Methane – What EPA is Doing* (*last visited* 5 February 2023) ("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.”).

348 United States Environmental Protection Agency, *What EPA is Doing: AgSTAR* (*last visited* 5 February 2023) (“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.”).

349 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.”). ***See also*** 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....”).

350 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).”).

351 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.").

[352] 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").

[353] *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.

[354] 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.").

[355] 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]").

[356] 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.").

[357] 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...").

[358] 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.").

[359] 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 other17 wise available, there is appropriated to the Administrator 18 for fiscal year 2022, out of any money in the Treasury 19 not otherwise appropriated, $700,000,000, to remain 20 available until September 30, 2028, for activities described 21 in paragraphs (1) through (4) of subsection (a) at marginal conventional wells.").

[360] *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."); *and* 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.").

[361] 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.").

[362] 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.").

[363] 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.

[364] White House (10 January 2023) *Declaration of North America (DNA)*, Press Release ("We will continue to implement and build on commitments from the 2021 North American Leaders' Summit on climate mitigation, adaptation, and resilience, while renewing our focus on reducing methane emissions from all sources, with a new focus on waste methane.").

[365] 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.").

[366] 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* ("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.").

[367] 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.").

[368] 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;").

[369] 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.").

[370] 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.").

[371] 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.”).

[372] 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”).

[373] Venting and flaring of natural gas, N.M. CODE R. Pt. 19.15.27 (2022). *See also* YCC Team (31 May 2021) *New Mexico imposes strict rule to prevent venting, flaring of natural gas*, YALE CLIMATE CONNECTIONS (“The state recently passed a new rule that requires oil producers to capture waste natural gas. ‘The rule will lead to a 98% gas capture in the oil and gas sector by 2026,’ says Sarah Cottrell Propst, cabinet secretary of the New Mexico Energy, Minerals, and Natural Resources Department.”); 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*, In the Matter of Proposed New Regulation, 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). *Compare with* McDevitt, R. (14 June 2022) *Pennsylvania drops a major source of methane from new rule to limit emissions*, STATE IMPACT PENNSYLVANIA (“Pennsylvania’s environmental regulator is moving forward with a pared-down version of its rule to curb harmful emissions from existing oil and gas sites as it faces a federal deadline. The Environmental Protection Agency does not distinguish between shallower conventional oil and gas wells and deeper, fracked unconventional wells. Pennsylvania does. The Department of Environmental Protection had been developing a rule to limit emissions of volatile organic compounds and methane from both types of wells. But it dropped the conventional wells from the final rule before presenting it to the Environmental Quality Board Tuesday. . . . In December, DEP projected that the rule for both types of well sites would prevent more than 11,000 tons of VOCs per year and more than 213,000 tons of methane annually. The rule for only unconventional sites projects reductions of 2,864 tons of VOCs per year and more than 45,000 tons per year of methane. That’s about an 80 percent difference.”).

[374] Oil and Gas Sector – Ozone Precursor Pollutants, N.M. CODE R. Pt. 20.2.50 (2022). *See also* Office of the Governor (28 July 2022) *New Mexico’s nationally leading oil and gas emissions rule becomes law*, Press Release (“A nationally leading rule over the oil and gas industry that will cut harmful air emissions by 260 million pounds is now state law – a fulfillment of one of Gov. Michelle Lujan Grisham’s first commitments made in office. The rule, which was developed with input from over 520 stakeholders representing industry, environmental groups and the public, was published in the state register this week.”).

[375] There are currently 23 states, plus Puerto Rico, who have joined the U.S. Climate Alliance, and American Samoa has indicated that it has joined the alliance. *See* United States Climate Alliance, *Governors* (*last visited* 5 February 2023); *and* Radio New Zealand (12 October 2017) *American Samoa joins US climate change Alliance*.

[376] *See* 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*, 11 (“Significant additional opportunities exist to cut methane emissions quickly and cost effectively across the U.S. Capturing the full potential of expected reduction opportunities, as described in Appendix A, could reduce methane emissions by 40-50 percent below current levels in the U.S. Climate Alliance. Existing and emerging strategies and technologies can achieve these reductions by 2030.”).

[377] 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*, 11 (“There is an opportunity for the U.S. Climate Alliance to help fulfill the commitment by the U.S., Canada, and Mexico to implement federal regulations on new and

existing sources in the oil and gas sector to reduce methane emissions by 40-45 percent below 2012 levels by 2025."). In 2016, the U.S., Canada, and Mexico committed to reducing methane emissions in the oil and gas sector by 40–45% by 2025 (compared to 2012 levels).

[378] 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.").

[379] 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. . . . Promising technologies are also emerging that may cut methane emissions from enteric fermentation by 30 percent or more (Appendix 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* Ross E. G., Peterson C. B., Carrazco A. V., Werth S. J., Zhao Y., Pan Y., DePeters E. J., Fadel J. G., Chiodini M. E., Poggianella L., & Mitloehner F. M. (2020) *Effect of SOP "STAR COW" on Enteric Gaseous Emissions and Dairy Cattle Performance*, SUSTAINABILITY 12(24): 10250, 1–12, 1 ("The aim of this study was to investigate the efficacy of the commercial feed additive SOP STAR COW (SOP) to reduce enteric emissions from dairy cows and to assess potential impacts on milk production. ... SOP-treated cows over time showed a reduction in CH_4 of 20.4% from day 14 to day 42 ($p = 0.014$), while protein % of the milk was increased (+4.9% from day 0 to day 14 ($p = 0.036$) and +6.5% from day 0 to day 42 ($p = 0.002$)).").

[380] 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... 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* 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 (*claiming* that additives treating liquid manure of dairy cows, made from agricultural gypsum processed with proprietary technology [SOP LAGOON], showed significant reductions of climate emissions from waste slurry, eliminating ammonia and N_2O, and significantly reducing CH_4 and CO_2. "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 [Day 4] when the emission peaks were recorded.").

[381] United States Composting Council, *State Regulations* (*last visited* 5 February 2023) (States with yard debris bans: Arkansas, Connecticut, Delaware, Florida, Georgia, Illinois, Indiana, Iowa, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nebraska, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, South Carolina, South Dakota, Vermont, West Virginia, Wisconsin. States with food scrap collection mandates or aggressive legislation for keeping out of landfills: California, Connecticut, Massachusetts, Montana, Rhode Island, Vermont).

[382] University of California Berkeley, Center for Law, Energy & the Environment, *Methane Protocols for Reducing Emissions* (*last visited* 5 February 2023) ("Project Climate and CLEE are developing frameworks for methane emission reduction at the sub-national jurisdiction level for each of the main sources of anthropogenic methane: fossil fuels,

agriculture, and waste. The frameworks are designed to engage sub-national governments in commitments to a jurisdiction-appropriate level of emission reduction action through inventories, baselines, target-setting, policy implementation, and information-sharing. The goal is to achieve the highest level possible of commitment to aggressive methane emission reduction with sufficient flexibility to include all relevant governments and sectors. Participation in the frameworks will then facilitate iterative policy and technology development to continually raise the bar on emission reduction.").

383 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.").

384 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.").

385 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.").

386 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.").

387 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.").

[388] Vasconcellos R. B. (4 August 2022) *Energy Is Up on U.S.-Brazil Relations* ("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.").

[389] 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).

[390] 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.").

[391] 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.").

[392] United States Environmental Protection Agency (4 January 2022) *Map of US Coal Mine Methane Current Projects and Potential Opportunities* (*See* mapping tool on U.S. Coal Mine Methane).

[393] 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).

[394] United States Energy Information Administration (*last updated* 29 July 2022) *U.S. Coalbed Methane Production* (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.).

[395] Natural Resources Defense Council (March 2022) REGENERATIVE AGRICULTURE: *FARM POLICY FOR THE 21ST CENTURY*, 1–54, 7, 19 ("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."; "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*.

[396] 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.").

[397] Commission Regulation 2021/1119, 2021 O.J.L. (243) Article 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.").

[398] 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.").

[399] 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.").

[400] 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.").

[401] 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%'").

[402] 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.").

[403] European Environment Agency, *EEA greenhouse gases – data viewer* (*last visited* 5 February 2023) (Data through 2020).

[404] 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%.").

[405] 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.").

[406] 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*.

[407] 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.").

[408] 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).

[409] 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 & Art. 15 ("[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.**"; "Venting shall be prohibited except in the circumstances provided for this Article. Routine flaring shall be prohibited.") (emphasis in original).

[410] 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 & Art. 10 ("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...."; "~~*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).

[411] 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).

[412] 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).

[413] 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. 26 ("1. On the basis of the inventory referred to in Article 25, Member States shall develop and implement a mitigation plan to address methane emissions from **closed and** abandoned **underground** coal mines **where operations have ceased since** … **[50 years prior to the date of entry into force of this Regulation]**.... 2. Venting and flaring from equipment referred to in Article 25(2) shall be prohibited from 1 January 2030, unless utilisation or mitigation is not technically feasible or risks endangering environmental safety, ~~*or safety of operations or personnel*~~ **human safety, including that of the personnel, or public health.** In such a situation, as part of the reporting obligations set out in Article 25, mine operators or Member States shall demonstrate the necessity to opt for venting or flaring instead of utilisation or mitigation.")(emphasis in original).

[414] 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).

[415] 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).

[416] 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).

[417] 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.").

[418] Mohlin K., Piebalgs A., & Olczak M. (2021) *Designing an EU methane performance standard for natural gas*, European University Institute ("A methane performance standard could take the form of a mandatory requirement that all natural gas sold on the EU internal market meets a benchmark upstream emission intensity value equivalent to 0.2%."). *See also* Brower D. (19 July 2021) *US gas exporters face EU methane curbs after carbon tax reprieve*, FINANCIAL TIMES.

[419] 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.").

[420] 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(**46**), 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).

[421] 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.").

[422] Eurostat (2021) *Energy production and imports* ("Between 2009 and 2019, some variations were noticed on the energy dependency rate: a maximum of 60.7 % was registered in 2019, while 53.9 % was the lowest dependency registered in 2013. Looking in more detail, the highest rates in 2019 were recorded for crude oil (96.8 %) and for natural gas (89.7 %), while the latest rate available for solid fossil fuels was 44 %.") (*See* Table 3 for breakdown by source.).

[423] 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 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.'").

[424] Environmental Investigation Agency (19 December 2022) *European Council votes on the EU Methane Regulation – but it's a big miss for people and the planet* (*last visited* 1 February 2023) ("A first version of the text for a new EU regulation to clamp down on methane emissions is "devoid of substance", according to EIA Climate campaigners. O'Dowd said: "The text in its current, diluted form would mean leaving aside any meaningful measures that could actually help the EU's goal to reduce its greenhouse gas emissions by 55 per cent.").

[425] European Parliament Legislative Observatory. *2021/0423(COD) Methane emissions reduction in the energy sector* (*last visited* 1 February 2023) (*see* section on Forecasts showing the indicative plenary sitting date scheduled on 29/03/2023).

[426] Council fo the European Union (7 April 2022) *The ordinary legislative procedure* (*last visited* 1 February 2023) ("General approach - a political agreement at Council level that may be adopted pending first reading position of the Parliament").

[427] Council of the European Union (19 December 2022) *Member States agree on new rules to slash methane emissions*, Press Release ("The Council reached an agreement (general approach) on a proposal to track and reduce methane emissions in the energy sector. The text is the first of its kind and a crucial contribution to climate action, as methane is the second most important greenhouse gas following carbon dioxide.").

[428] 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.").

[429] 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).").

[430] 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.").

[431] 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;").

[432] European Parliament (13 December 2022) *Deal reached on new carbon leakage instrument to raise global climate ambition*, Press Releases ("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.").

[433] 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.").

[434] 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.").

[435] European Commission (8 March 2022) *REPowerEU: Joint European Action for more affordable, secure and sustainable energy*, 52022DC0108, 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.").

[436] 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.").

[437] 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.").

[438] 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.").

[439] White House (8 May 2022) *G7 Leaders' Statement*, Statements and Releases ("a. 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.").

[440] 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.).

[441] 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.").

[442] 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.").

[443] 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.").

[444] 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.").

[445] 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.").

[446] Ocko I. B. & Hamburg S. P. (2022) *Climate consequences of hydrogen leakage*, ATMOS. CHEM. PHYS. 22(14): 9349–9368, 9362, 9367 ("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."; "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.

[447] Warwick N., Griffiths P., Archibald A., & Pyle J. (2022) *Atmospheric implications of increased hydrogen use*, UK Met Office, 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).").

[448] Government of Canada (2021) *Canada's 2021 Nationally Determined Contribution under the Paris Agreement*, 1, 26 ("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."; "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.").

[449] 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.").

[450] 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.").

[451] 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.").

[452] Government of Canada (10 November 2022) *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.").

[453] Government of Canada (10 November 2022) *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.").

[454] Government of Canada (10 November 2022) *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.").

[455] *See* 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; 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; Government of Canada (2020) *Saskatchewan equivalency with federal methane regulations: emissions reduction estimation*.

[456] 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 ("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 $MtCH_4$).").

[457] 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.").

[458] 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.").

[459] 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.").

[460] 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.").

[461] 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.").

[462] 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.").

[463] 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”).

[464] 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.”).

[465] 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;”).

[466] 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.

[467] United States Department of State (17 November 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Releases (“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.”).

[468] 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.”).

[469] 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).

[470] 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).

[471] 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).

[472] 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(112461): 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.").

[473] 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): 024019, 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.

474 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.").

475 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.").

476 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.").

477 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.

478 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).").

479 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*, 163 ("The main GHG emissions from the agriculture sector are methane from livestock's enteric fermentation and rice cultivation and nitrous oxide from manure

management and agriculture soil. The Agriculture sector represented 14 per cent of the total GHG emissions (4,07,821 $GgCO_2e$) in 2016, a decrease of 2.25 per cent since 2014.”).

480 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.”).

481 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.”).

482 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).”).

483 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 (“**3.7.9 Mission for Integrated Development of Horticulture (MIDH)** 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.... **3.7.10 Balanced ration for livestock** 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.... **3.7.11 Bypass Proteins for animals** 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. **3.7.12 Mitigation reduction due to various activities** 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.”).

484 Government of India, Ministry of New and Renewable Energy, *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.”); Government

of India, Ministry of Drinking Water & Sanitation (30 April 2018) *Swachh Bharat Mission launches GOBAR-DHAN to promote wealth and energy from waste* ("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.").

[485] 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): 105435, 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, regula- tions, 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 demonstra- tion 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].").

[486] 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.").

[487] Government of India, Ministry of Petroleum and Natural Gas (2021) ANNUAL REPORT 2020–21.

[488] 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).").

[489] Government of India, National Data Repository (*last updated* 22 April 2021) Directorate General of Hydrocarbons, Ministry of Petroleum and Natural Gas, *Coal Bed Methane* (Table listing awarded CBM blocks).

[490] Ministry of Environment, Forest and Climate Change, Government of India (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).

[491] *See generally* India Coal Mine Methane / Coal Bed Methane Clearinghouse.

[492] 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.").

[493] 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).").

494 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 Tranch of auction for commercial mining was launched by Ministry of Coal on 25.03.2021. In the second Tranche, a total of 67 coal mines.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.").

495 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.").

496 Ministry of Environment, Forest and Climate Change, Government of India (2021) INDIA: THIRD BIENNIAL UPDATE RPORT 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 mning operations, and 54 per cent from oil and natural gas production and handling systems.").

497 United States Environmental Protection Agency (*last updated* 2022) *Non-CO_2 Greenhouse Gas Data Tool*, Data Tool. 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).

498 Ministry of Environment, Forest and Climate Change, Government of India (2021) INDIA: THIRD BIENNIAL UPDATE RPORT TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 22 ("Fugitive methane emissions have registered a decrease of 2 per cent between 2014 nad 2016, mainly due to a relative reduction in underground mining activities.").

499 Ministry of Environment, Forest and Climate Change, Government of India (2021) INDIA: THIRD BIENNIAL UPDATE RPORT 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 Boad with designated EF IDs 122973 – 122975 for underground mining and 124920 – 124921 for surface mining (IPCC, 2020)").

500 Ministry of Environment, Forest and Climate Change, Government of India (2021) INDIA: THIRD BIENNIAL UPDATE RPORT 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)").

501 Coal India Limited (2021) COAL INDIA LIMITED ESG REPORT FY 2020 – 2021, 12 ("Our ESG Commitments: 1) Low-Carbon Coal… Adopting clean coal technolgoies such as: coal gasificiation; coal-to liquid; coal min methane; coal bed methane; and coal washeries").

502 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.").

[503] 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* ("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.").

[504] 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).

[505] People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, submission to the Secretariat of 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-CO_2 greenhouse gases (GHGs) incorporated into China's updated NDCs.).

[506] People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, submission to the Secretariat of UNFCCC. (28 October 2021) China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy, submission to the Secretariat of 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-CO_2 greenhouse gases (GHGs) incorporated into China's updated NDCs.).

[507] People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, 2, 40,submission to the Secretariat of UNFCCC.

[508] (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.).

[509] China State Council (28 December 2021) 14th Five-Year Comprehensive Work Plan on Energy Conservation and Emission Reduction ["十四五"节能减排综合工作方案] (hyperlink to original Chinese).

[510] Carbon Monitoring and Assessment Pilot Work Plan [碳监测评估试点工作方案](Promulgated by the General Office of China Ministry of Ecology and Environment, Sept. 12, 2021; effective Sept. 12, 2021) (hyperlink to original Chinese).

[511] 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.”).

[512] 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).

[513] 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* Emission Standard of Coal-bed Methane / Coal Mine Gas (Trial) [煤层气（煤矿瓦斯）排放标准（暂行）] (Promulgated by China Ministry of Environmental Protection (now “Ministry of Ecology and Environment”) and the General Administration of Quality Supervision, Inspection and Quarantine, April 2, 2008; effective July 1, 2008) (hyperlink to original Chinese).

[514] 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] (promulgated by Central Committee of the Chinese Communist Party and the State Council, Sept. 22, 2021; effective Sept. 22, 2021) (hyperlink to original Chinese).

[515] National Energy Administration (5 August 2022) Summary of the Reply to Proposal No. 02646 of the Fifth Session of the 13th National Committee of the Chinese People's Political Consultative Conference [关于政协十三届全国委员会第五次会议第 02646 号提案的答复复文摘要] (hyperlink to original Chinese).

[516] National Energy Administration (5 August 2022) Summary of the Reply to Proposal No. 02646 of the Fifth Session of the 13th National Committee of the Chinese People's Political Consultative Conference [关于政协十三届全国委员会第五次会议第 02646 号提案的答复复文摘要] (hyperlink to original Chinese).

[517] National Energy Administration (5 August 2022) Summary of the Reply to Proposal No. 02646 of the Fifth Session of the 13th National Committee of the Chinese People's Political Consultative Conference [关于政协十三届全国委员会第五次会议第 02646 号提案的答复复文摘要] (hyperlink to original Chinese).

[518] 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] (promulgated by the Central Committee of the Chinese Communist Party and the State Council, Sept. 22, 2021; effective Sept. 22, 2021) (hyperlink to original Chinese).

[519] 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] (promulgated by the Central Committee of the Chinese Communist Party and the State Council, Nov. 2, 2021; effective Nov. 2, 2021) (hyperlink to original Chinese).

[520] China State Council (28 December 2021) 14th Five-Year Comprehensive Work Plan on Energy Conservation and Emission Reduction [“十四五”节能减排综合工作方案] (hyperlink to original Chinese).

[521] China State Council (28 December 2021) 14th Five-Year Comprehensive Work Plan on Energy Conservation and Emission Reduction [“十四五”节能减排综合工作方案] (hyperlink to original Chinese).

[522] (28 October 2021) *China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy*, 13, submission to the Secretariat of UNFCCC. *See also* 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] (promulgated by Central Committee of the Chinese Communist Party and China

State Council, October 22, 2021; effective October 22, 2021) (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.").

523 (28 October 2021) China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy, 9, submission to the Secretariat of UNFCCC. *See also* Action Plan for Achieving Carbon Peaking Before 2030 [2030 年前碳达峰行动方案] (promulgated by China State Council, October 24, 2021; effective October 24, 2021) (hyperlink to original Chinese).

524 People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, 52,submission to the Secretariat of UNFCCC.

525 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").

526 Action Plan for Achieving Carbon Peaking Before 2030 [2030 年前碳达峰行动方案] (promulgated by China State Council, Oct. 24, 2021; effective Oct. 24, 2021) (link to original Chinese).

527 Opinions on Accelerating the Resource Utilization of Livestock and Poultry Farming Waste [关于加快推进畜禽养殖废弃物资源化利用的意见] (promulgated by the General Office of China State Council, May 31, 2017; effective May 31, 2017) (hyperlink to original Chinese).

528 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] (promulgated by The Central Committee of the Chinese Communist Party and the State Council, Nov. 2, 2021; effective Nov. 2, 2021) (hyperlink to original Chinese).

529 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] (promulgated by The Central Committee of the Chinese Communist Party and the State Council, Nov. 2, 2021; effective Nov. 2, 2021) (hyperlink to original Chinese).

530 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](promulgated by the General Office of the Central Committee of the Communist Party of China and General Office of the State Council, 2017) (hyperlink to original Chinese).

531 Action Plan for Achieving Carbon Peaking Before 2030 [2030 年前碳达峰行动方案] (promulgated by China State Council, October 24, 2021; effective October 24, 2021) (hyperlink to original Chinese). *See also* China National Development and Reform Commission (19 September 2014) National Plan to Address Climate Change (2014-2020) [国家应对气候变化规划（2014-2020 年）] (hyperlink to original Chinese).

[532] 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.").

[533] 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).

[534] 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).

[535] 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] (promulgated by The Central Committee of the Chinese Communist Party and the State Council, Nov. 2, 2021; effective Nov. 2, 2021) (hyperlink to original Chinese).

[536] 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).

[537] Implementation Plan for Carbon Peaking in Urban and Rural Development [城乡建设领域碳达峰实施方案], 5, (promulgated by China Ministry of Housing and Urban-Rural Development and National Development and Reform Commission, June 30, 2022; effective June 30, 2022) (hyperlink to original Chinese).

[538] 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).

[539] Action Plan for Achieving Carbon Peaking Before 2030 [2030 年前碳达峰行动方案] (promulgated by China State Council, October 24, 2021; effective October 24, 2021) (hyperlink to original Chinese).

[540] 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).

[541] 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).

[542] 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).

[543] 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).

[544] 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.").

[545] 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).

[546] Ainger J. & Dlouhy J. A. (17 November 2022) *China Has Plan to Curb Methane Emissions in Sign of Progress* BLOOMBERG GREEN ("China said it has developed a draft plan to curb methane emissions, even as it stopped short of joining a global pledge to reduce the potent greenhouse gas. 'We're in the process of getting approval to the draft action plan, which we have already finished,' China's climate envoy Xie Zhenhua said at the COP27 climate summit in Egypt. China is hoping to seek cooperation on the issue, Xie added… Xie's announcement came during a ministerial meeting of countries that have enrolled in the Global Methane Pledge, an initiative that was first advanced by the US and EU at last year's climate summit in Glasgow. One-hundred fifty countries have now joined the pledge to collectively cut methane emissions 30% by 2030 -- an achievement US Special Presidential Envoy for Climate John Kerry called 'an extraordinary step forward.').

[547] 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.").

[548] Wang F., Maksyutov S., Janardanan R., Tsuruta A., Ito A., Morino I., Yoshida Y., Tohjima Y., Kaiser J. W., Lan X., Zhang Y., Mammarella I., Lavric J. V., Matsunaga T. (2022) *Atmospheric observations suggest methane emissions in north-eastern China growing with natural gas use*, SCI. REP. 12(18487): 1–9, 3 ("Anthropogenic CH_4 emission is about 90% of the total CH_4 emission in China[31,34]. Figure 3 shows the relative contributions of major CH_4 emission sources in China and related productions percentage in the four regions analysed in this study using data from EDGAR v5 and China National Statistic Yearbook[18]. The major anthropogenic emission sources are solid fuel (31%), rice production (24%), waste (18%), and livestock (15%). NE is the most energy production region producing 55, 77, and 40% of Chinese national coal, oil, and natural gas each year, followed by NW which produces 29, 14, and 23% of Chinese national coal, oil and natural gas each year. 77% of rice is produced in SE and 21% in NE. The total volume of collected municipal solid waste and wastewater discharged are mainly in SE (60%) and NE (35%) due to its large population in SE (58% of national population) and NE (36% of national population). Ruminant population spreads in the four regions with 33% in NE, 31% in NW, 26% in SE, and 10% in TP.").

[549] International Energy Agency, *Methane Tracker Data Explorer* (*last visited* 5 February 2023).

[550] 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.").

[551] Global Methane Initiative, *Methane Emissions Data* (*last visited* 5 February 2023).

[552] 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.").

[553] 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.").

[554] 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.").

[555] 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.").

[556] 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.

[557] 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.").

[558] UN 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.").

[559] Global Gas Flaring Reduction Partnership (2022) *2022 Global Gas Flaring Tracker Report*, 6–7 ("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.").

[560] 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.").

[561] Iraq (2021) *Nationally Determined Contributions of Iraq*, 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 لتقليل إنبعاثات الميثان وتجنب "تنفيس" الغاز (venting) عن طريق التصميم الجيد، بما في ذلك عن طريق إسترجاع الغاز وإعادة تدويره. - إجراء برامج للكشف الدوري لتسربات غاز الميثان في منشآت النفط والغاز لغرض القيام بإصلاحها (LDAR) بالتعاون مع الشركاء الدوليين (التحالف العالمي للميثان-GMA) وشركات النفط والغاز العاملة في العراق. - استخدام الدورات المركبة في زيادة انتاج الطاقة الكهربائية - تغيير نوع الوقود السائل الى 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 الـLPG 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 ("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.").

[562] 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.")

[563] Middle East Monitor (21 October 2022) *Iraq prepares law to support waste-to-energy projects* (*last visited* 24 January 2023) ("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.").

[564] 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.").

[565] 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*.

[566] 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 ested 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 Federa 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.

[567] Government of the Federal Republic of Nigeria (2021) Climate Change Act, 2021, 4, 25–26 ("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[.]"; "In this Act - … "greenhouse gases" or "GHG" means the consituents 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…").

[568] Government of the Federal Republic of Nigeria, Federal Ministry of Petroleum Resources (2017) NATIONAL GAS POLICY: NIGERIAN GOVERNMENT POLICY AND ACTIONS.

[569] Government of the Federal Republic of Nigeria (2018) NATIONAL ACTION PLAN TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS (SLCPS).

[570] Government of the Federal Republic of Nigeria, Federal Ministry of Environment, Department of Climate Change (2021) NATIONAL CLIMATE CHANGE POLICY FOR NIGERIA 2021-2030.

[571] 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. *See also* additional climate policies and guidance on the Federal Ministry of Environment's *Department of Climate Change* web site, accessible *here*.

[572] Government of the Federal Republic of Nigeria (2018) *Flare Gas (Prevention of Waste and Pollution) Regulations*.

[573] Government of the Federal Republic of Nigeria (17 August 2021) *Petroleum Industry Act, 2021*.

[574] Government of the Federal Republic of Nigeria (2020) Draft Gas Flaring (Prohibition and Punishment) Bill, 2020.

[575] Government of the Federal Republic of Nigeria, Upstream Petroleum Regulatory Commission (November 2022) *Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria*.

[576] Global Gas Flaring Reduction Partnership (2022) 2022 GLOBAL GAS FLARING TRACKER REPORT, World Bank, 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.").

[577] Global Gas Flaring Reduction Partnership (2022) 2022 GLOBAL GAS FLARING TRACKER REPORT, World Bank, 11 ("Promising Reductions… Nigeria: 2021 Flare volume rank 7th; 2012 – 2021 31% reduction in flaring").

[578] 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.").

[579] 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.").

[580] 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 provide an excellent summary of key targets and include a 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* ("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.").

[581] Government of the Federal Republic of Nigeria, Upstream Petroleum Regulatory Commission (November 2022) *Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria*. *See also* Clean Air Task Force (11 November 2022) *Nigeria announces rule to reduce methane emissions from the oil and gas sector* ("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.").

[582] 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)).

[583] 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 ($NOx_{)}$ would also be reduced by 35% and 65%, respectively.").

[584] 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.").

[585] 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.").

[586] 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.

[587] 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.").

[588] 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.").

[589] Explore mitigation amounts and impacts at: http://shindellgroup.rc.duke.edu/apps/methane/.

[590] 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).").

[591] *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.").

[592] Climate and 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.").

[593] Climate and 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.").

[594] Climate and 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.").

[595] Climate and 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]").

[596] 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").

[597] AIM For Climate, *Partners* (*last visited* 26 January 2023) (List of partners).

[598] 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.").

[599] 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.").

[600] World Bank, *Global Gas Flaring Reduction Partnership (GGFR), About the Partnership* (*last visited* 25 January 2023).

[601] *See e.g.*, World Bank, *Global Gas Flaring Reduction Partnership (GGFR), About the Partnership* (*last visited* 5 February 2023).

[602] 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.").

[603] World Bank, *Zero Routine Flaring by 2030, Initiative Endorsers* (*last visited* 5 February 2023) (List of endorsers).

[604] 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.").

[605] Race to Resilience, *The Breakthrough Agenda* (*last visited* 25 January 2023) ("To keep that 1.5°C target alive we must halve global emissions by 2030 and reach global net zero emissions by the middle of the century. Key to achieving this will be the Breakthrough Agenda, launched by a coalition of 45 world leaders, whose countries collectively represent over 70% of global GDP, at the COP26 World Leaders' Summit."; "At COP27, countries responded to these recommendations with a package of 28 Priority Actions to decarbonise the power, road transport, steel, hydrogen, and agriculture sectors in line with the goals of the Paris Agreement. In agriculture, the actions also address climate adaptation, environmental protection and food security. This international plan for sectoral decarbonisation includes action to align on standards to favour low-carbon alternatives, coordinate government procurement to stimulate demand, and scale up production through support for finance, demonstration projects and R&D.").

[606] 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").

[607] 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.").

[608] 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").

[609] 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.").

[610] 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.").

[611] 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.").

[612] 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.").

[613] 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.").

[614] 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.")

[615] 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.").

[616] 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.").

[617] 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.").

[618] 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.").

[619] 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.").

[620] 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.").

[621] The World Biogas Summit, *2021 Programme* (*last visited* 5 February 2023).

[622] Methane Guiding Principles, *The Methane Guiding Principles* (*last visited* 5 February 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....").

[623] Methane Guiding Principles, *Oil and Gas Sector Toolkit for the Global Methane Pledge* (*last visited* 5 February 2023) ("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.").

[624] *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.

[625] 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.").

[626] 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.").

[627] 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.").

[628] MiQ (2022) *Main Document – Onshore Production v1.0*, 15 (Table 2).

[629] Project Canary, *About [Project Canary]* (*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*.

[630] Project Canary, *Emissions Management* (*last visited* 3 February 2023).

[631] 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.").

[632] Project Canary, *Environmental Assessments* (*last visited* 3 February 2023).

[633] Project Canary and 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).

[634] Project Canary, *Emissions Management* (*last visited* 3 February 2023). *See also* 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.).

[635] 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.").

[636] 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.").

[637] 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.

[638] 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.").

[639] 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).

[640] 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.").

[641] 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.").

[642] Carbon Mapper Data Portal (*last visited* 4 February 2023).

[643] 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).

[644] 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**.").

[645] 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.").

[646] 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.").

[647] 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.").

[648] 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.").

[649] 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.").

[650] MethaneSAT, *About MethaneSAT* (*last visited* 5 February 2023) ("MethaneSAT will locate and measure methane emissions from oil and gas operations almost anywhere on Earth, producing quantitative data that will enable both companies and countries to identify, manage, and reduce their methane emissions, slowing the rate at which our planet is warming. Other satellites can either identify emissions across large geographic areas or measure them at predetermined locations. MethaneSAT will do both. It will cover a 200-kilometer (124-mile) view path, passing over target regions every few days. Along with a wide field of view, the instrument will provide highly sensitive, high-resolution methane measurements.").

[651] MethaneSAT (13 January 2021) *MethaneSAT picks SpaceX as launch provider for mission to protect Earth's climate*, Press Release ("The nonprofit MethaneSAT LLC announced today that it has signed a contract with SpaceX to deliver its new satellite into orbit aboard a Falcon 9 rocket. Now under construction after completing an intensive design process, the MethaneSAT instrument is on schedule for a launch window that opens October 1, 2022.").

[652] spaceQ (9 September 2019) *GHGSat Signs Data Agreement with the Canadia 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.").

[653] 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.").

[654] BBC (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.

[655] 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): eabn9683, 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.

[656] 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.").

[657] 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.").

[658] 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.").

[659] 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.").

[660] 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.").

[661] 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.").

[662] 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.").

[663] *See generally* UNEP IMEO (2021) AN EYE ON METHANE: INTERNATIONAL METHANE EMISSIONS OBSERVATORY 2021 REPORT; *and* UNEP IMEP (2022) AN EYE ON METHANE: INTERNATIONAL METHANE EMISSIONS OBSERVATORY 2022 REPORT.

[664] 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).

[665] 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.

[666] 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.").

[667] 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.'").

[668] National Aeronotics 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.").

[669] 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.").

[670] National Aeronotics 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.").

[671] 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.").

[672] 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 (The Intergovernmental Panel on Climate Change (IPCC) Working Group I

contribution to the Sixth Assessment Report (AR6) 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*).").

673 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.").

674 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.").

675 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.").

676 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.").

677 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.").

678 For a list of Global Methane Pledge participants, *see* https://www.globalmethanepledge.org/#pledges.

679 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.").

680 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.").

[681] 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).").

[682] 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.").

[683] (8 November 2021) *LIVE: President Obama delivers a speech at COP26 climate summit in Glasgow, Scotland*, YAHOO FINANCE, YouTube (from 23:12–23:19).

[684] (13 November 2021) Parties to the Paris Agreement, Decision -/CP.26 ¶19, *Glasgow Climate Pact Advance unedited version*.

[685] 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.").

[686] 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.”).

[687] G7 (28 June 2022) *G7 Leaders’ Communiqué*.

[688] 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.”).

[689] 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).

[690] European Commission (11 November 2022) *Joint Declaration from Energy Importers and Exporters*.

[691] 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.”).

[692] 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, **approved** $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.”).

[693] 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.").

[694] 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.").

[695] 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.").

[696] 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, **approved** $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 **announced** 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.").

[697] 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.").

[698] 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.").

[699] (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.").

[700] (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.").

[701] (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.").

[702] 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).")

[703] 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.

[704] *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.").

[705] 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.").

[706] 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.").

[707] (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.").

[708] 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).

[709] 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.").

[710] (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.").

[711] (*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....").

[712] 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).").

[713] (*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").

[714] 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.").

[715] 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;").

[716] 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?").

[717] 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.").

[718] 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;").

[719] 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.").

[720] 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.").

[721] 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).").

[722] 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;").

[723] 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 costeffectiveness 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.").

[724] LRTAP Gothenburg Protocol Review Group (27 September 2022) *Technical information for the review of the Gothenburg Protocol*, ECE/EB.AIR/2022/5, ¶ 77 ("Options range in ambition and are split amongst four themes: status quo, new measures/commitments, information-based and voluntary-based. The options include: (a) Maintaining current activities and taking no additional action (status quo); (b) Supporting the Global Methane Pledge; (c) Adopting national emission reduction targets or optimized national/regional CH_4 reduction commitments; (d) CH_4-specific emission limit values for certain activities; (e) Compiling, reviewing and improving CH4 emissions information; (f) Setting minimum requirements for monitoring and reporting of data; (g) Developing guidance documents and/or a report on recommendations for CH_4 emission reduction measures or best practices.").

[725] Engleryd, A. & Spranger, T. (September 2022) *Chairs Report: Outcomes of the informal meeting of the Heads of Delegations to the Working Group on Strategies and Review*, 4 ("Policy action" was defined in different ways: some definitely see the urgent need to reduce ozone precursor emissions including methane including in the UNECE region, while others would define policy action as any agreement between Parties on taking action, including keeping the status quo. Voluntary measures and awareness-raising activities could be a first step forward, likely to be generally supported.").

[726] Engleryd, A. & Spranger, T. (September 2022) *Chairs Report: Outcomes of the informal meeting of the Heads of Delegations to the Working Group on Strategies and Review*, 4 ("WGSR should add to their workplan to undertake continued discussions on the appropriate policy mechanisms by which to achieve methane reductions for the purposes of reducing ozone. . . . It was recommended that Executive Body at its 42nd session should task WGSR with further

discussing policy options and present the result to the Executive Body at its 43rd session. It was further recommended to establish a drafting group assisting the WGSR. This group could also develop options on how to deal with technical annexes and guidance documents (see session E).").

727 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.").

728 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.").

729 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.").

730 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.").

731 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.).

732 The World Bank (8 November 2022) *It's Time to Sprint: Targeting Methane Emissions* (COP27 Side Event). 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).

733 The World Bank (8 November 2022) *It's Time to Sprint: Targeting Methane Emissions* (COP27 Side Event).

734 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.").

[735] 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 . . . .'").

[736] 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.").

[737] (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. and Murphy A. (16 December 2022) "A global methane agreement can prevent climate chaos" in *Opportunities beyond CO_2 for climate mitigation*, ONE EARTH.

[738] (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* UN 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) UN 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.").

[739] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989).

[740] 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.").

[741] 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.").

[742] 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.").

[743] 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.").

[744] 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.").

[745] (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.").

[746] 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.").

[747] 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.").

[748] 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.").

[749] 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}"); 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): eabn7950, 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.").

[750] *See* 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.).

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

[752] 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).

[753] 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, SPM-13 ("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.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*).").

[754] 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.").

[755] Based upon IGSD's research involving the UNFCCC NDC Registry, 184 NDCs directly reference methane. Of these, 32 NDCs include quantitative sectoral or economy-wide methane-reduction targets. *See* IGSD NDC tracker (*last updated* 25 January 2023).

[756] 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.”).

[757] For a list of Global Methane Pledge participants, *see* https://www.globalmethanepledge.org/#pledges.

[758] 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”).

[759] 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.”).

[760] (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.”).

[761] 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.”).

[762] *See* (*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 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;”).

[763] Ian Parry, Simon Black, Danielle Minnett, Victor Mulonas, and Nate Vernon, International Monetary Fund Staff Climate Note (October 2022) *How to Cut Methane Emissions,* 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.").

[764] 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.").

[765] 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.").

[766] Institute for Governance & Sustainable Development (25 November 2021) *China Announces Next Steps on Methane Emissions Control During the 14th Five-Year Period*, Press Release ("China's Ministry of Ecology and Environment (MEE) announced next steps for methane emissions control during the 14th Five-Year period (2021-2025), at its monthly press conference in November 2021. These steps are intended to support China's targets for achieving net-zero emissions of all greenhouse gases (GHGs) by 2060 and implement the U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s.").

[767] 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.").

[768] 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.").

[769] 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.").

[770] 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.

[771] 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* 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.").

[772] 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*.

[773] *See, e.g.*, Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities, Cal. Code Regs. Tit. 17, §§ 95665–95677.

[774] 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).

[775] 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).

[776] 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.").

[777] 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.").

[778] 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.").

[779] 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.").

[780] 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.").

[781] 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.").

[782] 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.").

[783] 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.").

[784] 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.").

[785] *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.").

[786] Climate & Clean Air Coalition (15 November 2022) *Sharm el-Sheikh Communiqué*.

[787] *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.

[788] 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.").

[789] 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....").

[790] 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.*").

[791] 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.*").

[792] 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.").

[793] 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.").

[794] 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, 11 ("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)."; "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 99 136–49.

[795] 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, 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."; "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.").

[796] Dietz S., Rising J., Stoerk T., & Wagner G. (2021) *Economic impacts of tipping points in the climate system*, PROC. NAT. ACAD. SCI. 118(34): e2103081118, 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%.").

[797] 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.'").

[798] 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.").

[799] Renaud-Basso O. (2 November 2021) *Launch of Global Methane Pledge*, Speech ("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.").

[800] 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.").

[801] 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.”).

[802] 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.”).

[803] 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*.

[804] 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)).

[805] As of 1 September 2022, the SDR exchange rate of reference was 0.768104 SDR per USD.

[806] 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.”).

[807] 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.”).

[808] 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.").

[809] 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.").

[810] International Monetary Fund (12 October 2022) *IMF Managing Director Kristalina Georgieva Announces Operationalization of the Resilience and Sustainability Trust (RST) to Help Vulnerable Countries Meet Long-Term Challenges*, Press Release ("This first round of RST resources represents just over half of the total of current RST pledges of SDR 29 billion (US$ 37 billion) from 13 countries.").

[811] 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.")

[812] 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").

[813] International Monetary Fund (18 April 2022) *IMF Executive Board Approves Establishment of the Resilience and Sustainability Trust*, Press Release ("Directors endorsed the governance structure of the RST… They also agreed to an interim review to take stock of the initial experience and revisit the set of qualifying structural challenges at around 18 months after its operationalization. Directors looked forward to receiving regular updates on the adequacy of RST resources with the possibility to adopt contingency measures at that time, typically near the end of each financial year, and on an ad hoc basis if warranted.").

[814] 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.").

[815] 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.”).

[816] 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.”).

[817] 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.”).

[818] International Monetary Fund (11 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 67 (“1. The RST is a loan-based trust administered by the IMF, with a financial structure broadly similar to that of the PRGT. In particular, and similar to the PRGT, RST resources would be mobilized based on voluntary contributions from members, including those wishing to channel SDRs for the benefit of low-income and vulnerable middle-income members.”).

[819] International Monetary Fund (18 April 2022) *IMF Executive Board Approves Establishment of the Resilience and Sustainability Trust*, Press Release (“The RST will stand ready to commence lending operations once a critical mass of resources from a broad base of contributors is achieved and once sufficiently robust financial systems and processes are in place, which is anticipated to occur by the end of the year. Fundraising toward the estimated total resource needs of about SDR 33 billion (equivalent to US$45 billion) will be initiated immediately.”).

[820] Parry I. W. H., Black S., Minnett D. N., Mylonas V., & Vernon N. (2022) How to Cut Methane Emissions, IMF Staff Climate Note 2022/008, 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.”).

[821] 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.”).

[822] Yi W. (18 August 2022) *The Eighth Ministerial Conference of the Forum on China-Africa Cooperation*, Speech (“We are prepared to, through the IMF’s two Trusts, re-channel 10 billion US dollars of its SDR to Africa, and encourage the IMF to direct China’s contributions to Africa.”).

[823] 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.")).

[824] 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.").

[825] 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.").

[826] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 024019, 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 $GTP_{1.5\ °C} = 41$.").

[827] 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.").

[828] 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.").

[829] Pilot Auction Facility, *About the PAF* (*last visited* 5 February 2023) ("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..").

[830] Pilot Auction Facility, *About the PAF* (*last visited* 5 February 2023) ("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.").

[831] The 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* 5 February 2023).

[832] 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[.]").

[833] 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.").

[834] International Finance Corporation (2022) *Green Bond Framework*, 5–8 (*see* table of activities that are "potentially eligible for IFC Green Bond finance").

[835] 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.").

[836] International Monetary Fund (18 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 63-66.

[837] 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).").

[838] World Bank Group (November 2021) *COP26 Climate Brief: Country Climate and Development Reports (CCDRs).*

[839] International Monetary Fund (11 April 2022) *Proposal to Establish a Resilience and Sustainability Trust*, 66 ("Draw significantly on the CCDR, if available, and any Fund CD or other diagnostics for climaterelated RST reform measures.").

[840] World Bank Group (8 November 2021) It's Time to Sprint: Targeting Methane Emissions, COP27 Side Event, Sharm El-Sheikh, Egypt.

[841] Austin S. (1 November 2021) *Prime Minister Mottley: Closing of Gaps Required*, Barbados Government Information Service.

[842] Austin S. (1 November 2021) *Prime Minister Mottley: Closing of Gaps Required*, Barbados Government Information Service.

[843] (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.