Manual sobre la Reducción del Metano:
La Mejor Estrategia para Frenar el Calentamiento en la Década de 2030

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Acerca del Institute for Governance & Sustainable Development

La misión de la IGSD es aumentar la resiliencia acelerando las medidas de mitigación del cambio climático para frenar el calentamiento a corto plazo y las retroalimentaciones climáticas que se refuerzan a sí mismas, evitar puntos críticos de inflexión catastróficos para el clima y la sociedad y limitar la temperatura mundial a 1,5 °C,—o al menos mantener controlado este límite de seguridad respecto de dicha temperatura.

Las últimas investigaciones del IGSD muestran que la descarbonización por sí sola no basta para frenar el calentamiento a corto plazo y mantenernos por debajo de 1,5 ºC o incluso del límite más peligroso de 2 ºC. También concluyen que la estrategia más rápida y eficaz es combinar los esfuerzos acelerados para reducir a cero las emisiones de dióxido de carbono (CO_2) de la descarbonización del sistema energético, *con* el sprint para reducir rápidamente los supercontaminantes climáticos distintos del CO_2 y proteger los sumideros de carbono. Los supercontaminantes climáticos incluyen cuatro contaminantes climáticos de vida corta (CCVC)—metano (CH_4), hollín negro, ozono troposférico (O_3) e hidrofluorocarbonos (HFC)—así como el óxido nitroso (N_2O) de vida más larga.

Combinar el *sprint* de la mitigación rápida con los esfuerzos acelerados de la descarbonización ayudaría a abordar las cuestiones éticas de la equidad intra e intergeneracional, concediendo a las sociedades el tiempo que necesitan para adaptarse urgentemente a los cambios inevitables y crear resiliencia. Los últimos datos científicos sugieren que la ventana para superar el límite de seguridad de 1,5 °C podría cerrarse tan pronto como a principios de la década de 2030, por lo que esta es la década decisiva para actuar con rapidez para frenar el calentamiento. La teoría de la acción del IGSD se basa en la urgencia de responder rápida y eficazmente para evitar daños irreversibles en el sistema climático con consecuencias catastróficas para todos.

La forma más rápida de reducir el calentamiento a corto plazo en la próxima década es reducir los CCVC. Dado que sólo duran en la atmósfera por un plazo que va de días a 15 años; su reducción evitará el 90% del calentamiento previsto en una década. Las estrategias dirigidas a reducir los CCVC pueden evitar cuatro veces más calentamiento en 2050 que las dirigidas únicamente al CO_2. La reducción de los HFC puede evitar casi 0,1 °C de calentamiento para el 2050 y hasta 0,5 °C a finales de siglo. El calendario inicial de reducción progresiva de la Enmienda de Kigali al Protocolo de Montreal abarcará alrededor del 90% de este objetivo. Los esfuerzos paralelos para mejorar la eficiencia energética de los aparatos de aire acondicionado y otros aparatos de refrigeración durante la eliminación progresiva de los HFC pueden duplicar los beneficios climáticos en 2050. La reducción de las emisiones de metano puede evitar casi 0,3 °C en la década de 2040, con la posibilidad de evitar un calentamiento significativo gracias a las tecnologías emergentes para eliminar el metano atmosférico más rápidamente que su ciclo natural.

Al combinar el *sprint* de mitigación rápida con los esfuerzos acelerados para lograr la descarbonización se reduciría a la mitad la tasa de calentamiento global de 2030 a 2050, se frenaría el ritmo de calentamiento una o dos décadas antes que mediante la descarbonización por sí sola, y se haría posible que el mundo mantuviera controlado el límite de seguridad de 1,5 °C. También se reduciría en dos tercios la tasa de calentamiento del Ártico. Esto ayudaría a frenar las retroalimentaciones climáticas que se refuerzan a sí mismas en el Ártico, y así evitar, o al menos retrasar, la serie de puntos críticos de inflexión proyectados si se superasen los 1,5 °C. Reducir los riesgos climáticos y no sobrepasar los límites para lograr la adaptación es fundamental para aumentar la resiliencia.

El enfoque del IGSD para una mitigación rápida abarca los ámbitos de la ciencia, el derecho, la política y la financiación climática. El IGSD trabaja a escala mundial, regional, nacional y subnacional.

Acerca del Centro de Derechos Humanos y Ambiente

El Centro de Derechos Humanos y Ambiente (CEDHA), creado en 1999 en Argentina, y constituido en los Estados Unidos en 2015, es una organización no gubernamental sin fines de lucro cuyo objetivo es construir una relación más armoniosa entre el ambiente y las personas. Su trabajo se centra en mejorar el acceso a la justicia de víctimas de violaciones de derechos humanos como consecuencia de la degradación ambiental o a causa de la gestión no sustentable de los recursos naturales, y prevenir futuras violaciones. Para ello impulsa la generación de políticas públicas que promuevan el desarrollo social y ambientalmente sustentable e incluyente a través de la participación comunitaria, el litigio de interés público, el fortalecimiento de instituciones democráticas y la capacitación de actores clave.

Hace más de dos décadas que CEDHA trabaja para proteger y para defender a personas y comunidades afectadas por la degradación ambiental y para promover políticas públicas sustentables, basadas en la ciencia y orientadas a la protección de los derechos humanos.

Las actividades programáticas de CEDHA incluyen iniciativas para asistir a revertir el cambio climático y promover una transición energética justa. CEDHA focaliza sus efuerzos en reducir emisiones de Contaminantes Climáticos de Corta Vida tales como el carbón negro, el metano y los HFCs, con el fin de bajar la tasa de calentamiento global y evitar soprepasar puntos de no retorno. CEDHA ha sido una de las organizaciones pioneras en promover la protección de glaciares blancos , glaciares de roca y el ambiente periglacial por su valor como reservas hídricas y reguladores de cuencas. Asimismo nuestro equipo trabaja para abordar los impactos sociales y ambientales del de la minería incluyendo gas y petróleo, para reducir las emisiones de carbono en la producción de ladrillos, promover la transición energética justa incluyendo en el triángulo de litio y fortalecer la responsabilidad legal empresaria en materia de derechos humanos y cambio climático.

Nuestra labor transcurre a nivel local e internacional, y ha sido reconocida por nuestros colegas y por organizaciones internacionales, tales como el Sierra Club quien otorgó a CEDHA su más distinguido premio internacional (el Earth Care Award) y por el prestigioso premio global el Sophie Prize, otorgado a Romina Picolotti, co-fundadora de CEDHA por su labor única en la promoción de los derechos humanos y la protección del ambiente.

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Resumen Ejecutivo

El *Manual sobre la Reducción del Metano* del IGSD brinda claridad a los responsables de políticas sobre las bases científicas de la mitigación del metano y explica las razones por las que es necesario emprender acciones urgentes; presenta las oportunidades de mitigación actuales y emergentes por cada sector; los esfuerzos nacionales, regionales e internacionales que pueden servir de base para la acción mundial de emergencia sobre el metano y enumera las iniciativas de financiación para garantizar el apoyo destinado a su rápida reducción. Este *Manual sobre el Metano* proporciona un razonamiento científico y político para que los responsables de políticas puedan lograr reducciones "grandes, rápidas y sostenidas" de las emisiones de metano que son necesarias para retrasar el calentamiento global a corto plazo[1] y limitar el riesgo de activar los puntos críticos de inflexión. El *Manual sobre el Metano* también justifica la necesidad de investigación y desarrollo de tecnologías para eliminar el metano de la atmosfera a gran escala.

El metano es un gas superpotente que calienta el planeta—una tonelada de gas metano tiene un poder de calentamiento 80 veces mayor que una tonelada de emisiones de dióxido de carbono en un período de 20 años. Si bien el metano es el foco del presente *Manual*, retrasar el calentamiento en el corto plazo también requiere profundas reducciones de otros "contaminantes climáticos de corta vida" (CCVC) similarmente potentes—como el hollín de carbono negro, los hidrofluorocarbonos (utilizados principalmente como refrigerantes) y el ozono troposférico, que son supercontaminantes climáticos con una vida media en la atmósfera inferior a 15 años[2]. Una reducción drástica de estos supercontaminantes también reducirá la acumulación de calor en los océanos que de otro modo seguirían contribuyendo al calentamiento por décadas o siglos, mucho después del ciclo de vida del contaminante en cuestión[3].

Si bien disminuir las emisiones de CO_2 a largo plazo seguirá siendo importante, reducir los supercontaminantes climáticos puede frenar el calentamiento una o dos décadas antes que las estrategias enfocadas exclusivamente en el CO_2, evitar entre dos y cinco veces más calentamiento que las reducciones de CO_2 en 2050[4], disminuir el calentamiento previsto en el Ártico en dos tercios y la tasa de calentamiento global a la mitad[5].

Los mensajes principales son:

- La contaminación por metano ya ha causado 0,51 °C de los 1,06 °C de calentamiento total observado (2010-2019) en comparación con la era preindustrial[6]. El calentamiento provocado por el metano seguirá aumentando si las emisiones de metano continúan creciendo, con un aumento del 30% de las emisiones antropogénicas previstas para 2050 según los escenarios de políticas actuales[7]. Las concentraciones atmosféricas de metano batieron récords en 2020 y 2021 con la tasa de aumento más rápida desde que se iniciaron los registros en 1983; los datos preliminares muestran que el metano superó las 1.900 partes por billón (ppb) por primera vez en septiembre de 2021 (
- **Recuadro** 1)[8].

- Si no se toman medidas rápidas para frenar el calentamiento, es probable que sobrepasemos el "límite de seguridad" de 1,5 °C al menos temporalmente a finales de esta década[9], con una probabilidad del 50-50 de que al menos durante el año 2026 se superen los 1,5 °C y una probabilidad del 10% de que la media en los cinco años comprendidos entre 2022 y 2026 se supere este umbral[10].

- Sobrepasar el límite de 1,5 °C aumenta el riesgo de que las retroalimentaciones que se refuerzan a sí mismas aceleren aún más el aumento de las temperaturas y desencadenen una cascada de puntos críticos de inflexión irreversibles en el sistema climático (**Recuadro 2**)[11].

- Más de 3.000 millones de personas viven en contextos vulnerables. Los impactos del calentamiento por encima de 1,5 °C suponen riesgos muy elevados e impactos potencialmente irreversibles para sistemas humanos y naturales únicos y amenazados, y aumentan el riesgo de fenómenos meteorológicos extremos[12].

- La *Evaluación Global del Metano* del Programa de las Naciones Unidas para el Medio Ambiente (PNUMA) y la Coalición Clima y Aire Limpio (CCAC, por sus siglas en inglés) confirma que la reducción de las emisiones de metano es la estrategia más rápida para evitar que el mundo se estrelle contra la barrera de 1,5°C[13]. Aplicar todas las medidas de mitigación del metano en esta década es la única forma conocida de evitar casi 0,3 °C de calentamiento para la década de 2040 y frenar el calentamiento en un 30%[14]. El *Sexto Informe de Evaluación* (IE6) del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC, por sus siglas en inglés) confirma que "una reducción grande, rápida y sostenida de las emisiones de metano" es clave para limitar el calentamiento a corto y largo plazo[15].

  - El Grupo de Trabajo III (WGIII, por sus siglas en inglés) del IE6 concluye además que "[l]as reducciones drásticas de las emisiones de GEI para 2030 y 2040, en particular las reducciones de las emisiones de metano, disminuyen el calentamiento máximo, reducen la probabilidad de sobrepasar los límites de calentamiento y conducen a una menor dependencia de emisiones netas negativas de CO_2 para revertir el calentamiento en la segunda mitad del siglo..... Debido a la corta vida del CH_4 en la atmósfera, la reducción drástica prevista de las emisiones de CH_4 hasta que se alcancen emisiones netas de CO_2 iguales a cero en las vías de mitigación modelizadas reduce efectivamente el pico de calentamiento global (*nivel de confianza alto*)"[16].

  - Para limitar el calentamiento a 1,5 °C sin sobrepaso o con un sobrepaso limitado, es necesario reducir las emisiones mundiales de metano de origen humano en un 34% en 2030 y en un 44% en 2040 con respecto a los niveles previstos para 2019, además de reducir las emisiones mundiales de CO_2 a la mitad en 2030 y en un 80% en 2040, así como reducir drásticamente otros contaminantes climáticos de vida corta y el óxido nitroso[17].

- Existe tecnología para reducir el 45% de las emisiones antropogénicas de metano para 2030 procedentes de la producción de energía, la agricultura y los desechos (**Cuadro 2**)[18]. Las medidas dirigidas específicamente a las fuentes de metano son esenciales, ya que las acciones de descarbonización más generales sólo pueden lograr el 30% de las reducciones de metano necesarias[19].

  - Aproximadamente el 60% de las medidas específicas disponibles tienen costos de mitigación bajos (definidos como inferiores a 21 dólares por tonelada de CO_2e para un Potencial de Calentamiento Global a 100 años (PCG_{100}) y a 7 dólares por tonelada de CO_2e para un Potencial de Calentamiento Global a 20 años (PCG_{20}), y algo más del

50% de ellas tienen costos negativos, es decir, que las medidas se amortizan por sí solas[20].

- En la producción de energía, el mayor potencial de mitigación se encuentra en el sector del petróleo y el gas[21]. En el sector de los residuos, la reducción y gestión de los residuos sólidos es el más prometedor[22]. Y en la agricultura, las medidas para reducir las emisiones de metano del ganado podrían tener el mayor impacto[23].

- La mitigación del metano también puede apoyar la creación de puestos de trabajo geográficamente diversos y bien remunerados[24].

- La aplicación exitosa del *Compromiso Mundial sobre el Metano* reduciría el calentamiento en al menos 0,2 °C para 2050[25] y mantendría al planeta en una trayectoria coherente con el objetivo de no superar los 1,5 °C, según la *Evaluación Global del Metano*[26]. El despliegue de todas las medidas disponibles y adicionales podría conducir a una reducción del 45% por debajo de los niveles de 2030 para alcanzar casi 0,3 °C de calentamiento evitado en la década de 2040[27].

- La reducción del metano también aumenta la resiliencia y promueve la justicia ambiental[28]. Al frenar el calentamiento a corto plazo y reducir los riesgos asociados, la mitigación del metano proporciona a las comunidades vulnerables al cambio climático más tiempo para adaptarse, mientras también disminuye la carga de adaptación de las mismas[29]. Además, como el metano se oxida en la atmósfera para formar ozono troposférico (también conocido como smog fotoquímico), las reducciones de metano reducen el daño ocasionado a la salud de la población y a los cultivos, apoyando la seguridad alimentaria[30].

  - Para estabilizar el clima, es esencial para lograr emisiones netas de CO_2 iguales a cero acelerando la transición hacia energías limpias. Además, durante el tiempo que dure una transición justa hacia una economía neta igual a cero, es esencial detener las fugas de metano para frenar el calentamiento y proteger la salud de las comunidades locales y la seguridad alimentaria[31].

  - La transición para dejar de producir combustibles fósiles no sólo reducirá el CO_2, sino también las emisiones de aerosoles refrigerantes. Los aerosoles refrigerantes se coemiten con el CO_2 cuando se queman combustibles fósiles que contienen azufre, como el carbón y el gasoil. A diferencia del CO_2, que permanece en la atmósfera durante décadas o siglos, estos aerosoles refrigerantes desaparecen de la atmósfera en cuestión de días o meses. La pérdida de este efecto de enfriamiento contrarrestará las reducciones del calentamiento procedentes de la descarbonización hasta 2050 aproximadamente, e incluso acelerará el calentamiento durante la primera década o más[32].

  - Por lo tanto, reducir el metano y otros contaminantes climáticos de vida corta también es clave para contrarrestar este aumento de la tasa de calentamiento a corto plazo[33].

- Del total de emisiones globales de metano (550-594 millones de toneladas métricas de metano, Mt CH_4 año^{-1}), entre el 50% y el 65% provienen de fuentes antropogénicas (336-376 Mt CH_4 año^{-1}) en tres sectores principales: producción de energía, agricultura y residuos[34]. La producción de energía representa alrededor del 35% de las emisiones antropogénicas de metano[35], la agricultura alrededor del 40%[36] y los residuos alrededor del 20%[37], con la quema de biomasa y los biocombustibles como fuentes menores.

- Alrededor del 35-50% de las emisiones globales de metano provienen de fuentes naturales[38]. Estas fuentes naturales incluyen los humedales tropicales, las turberas y el permafrost ártico, todos los cuales se están calentando y parecen estar aumentando las emisiones como parte de las retroalimentaciones del ciclo clima-carbono que se refuerzan a sí mismas[39]. Además de frenar la tasa de calentamiento para reducir las fuentes naturales de emisiones de metano, se está investigando la eliminación del metano atmosférico[40].

- Muchos gobiernos nacionales y subnacionales (incluidos los principales países emisores de metano y organizaciones regionales), así como iniciativas y asociaciones internacionales, ya están aplicando medidas obligatorias y voluntarias de mitigación del metano. Estos esfuerzos nacionales e iniciativas ascendentes refuerzan y expanden la acción y el liderazgo nacionales en materia de mitigación.

- Ya existen sistemas para medir y controlar las emisiones de metano y otros están en fase de desarrollo. Los sistemas satelitales están aumentando rápidamente nuestra comprensión sobre las principales fuentes emisoras, incluido un pequeño número de “ultraemisores” responsables del 8-12% de las emisiones globales de metano del sector del petróleo y el gas[41]. Estos sistemas de vigilancia, junto con una estrategia de responsabilidad y cumplimiento, serán esenciales para garantizar que el mundo se dirija en una trayectoria que garantice la máxima reducción de las emisiones de metano. Esto incluye fomentar el uso de métricas que reflejen mejor el impacto de las estrategias en la temperatura global para alcanzar el objetivo de 1,5 °C, como por ejemplo el potencial de calentamiento global a 20 años (PCG_{20}) para el metano y otros contaminantes climáticos de vida corta (

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- Recuadro 3) [42].

- Se necesitan fondos y financiación para apoyar a los gobiernos y organizaciones comprometidos con la rápida reducción del metano y la gobernanza asociada. Esto incluye la financiación disponible a través de instrumentos como el nuevo Fondo Fiduciario para la Resiliencia y la Sostenibilidad (FFRS) del Fondo Monetario Internacional (FMI) (véase la **Sección 11**).

- La acción multilateral para reducir rápidamente las emisiones de metano es fundamental. El metano es un gas de efecto invernadero bien mezclado, y su mitigación por parte de todos los países y territorios es el mejor medio para lograr reducciones rápidas y efectivas de las emisiones de metano. El *Compromiso Mundial sobre el Metano*, que establece el objetivo colectivo de reducir las emisiones mundiales de metano al menos un 30 % de aquí a 2030 con respecto a los niveles de 2020 es un paso importante para mantener el límite de seguridad de 1,5 °C a nuestro alcance[43]. No obstante, una fuerte acción y liderazgo a nivel nacional que no incluyan a determinados países y no garanticen la responsabilidad y el apoyo a los compromisos de mitigación del metano pueden no ser suficientes para lograr las reducciones de metano a la velocidad y escala necesarias con el fin de evitar impactos climáticos potencialmente catastróficos. Por lo tanto, los gobiernos deben basarse en el *Compromiso* o en acuerdos paralelos como la *Declaración Conjunta de Glasgow de Estados Unidos y China para Reforzar la Acción Climática en la Década de 2020* con el objeto de abrir la puerta a un acuerdo mundial sobre el metano. Esto incluye actuar de inmediato para exigir una tasa de emisiones de metano progresivamente más baja a los proveedores de “gas metano de sustitución” en respuesta a los cambios en el abastecimiento a medida que se reduce la disponibilidad de gas ruso.

1. Introducción

Acabar con la dependencia de los combustibles fósiles, incluido el gas fósil, mediante el cambio a energías limpias es esencial para proteger el clima y garantizar la paz y la seguridad. Pero durante el tiempo que se necesita para cambiar el sistema energético mundial hacia energías limpias, también es esencial reducir las emisiones de metano lo antes posible para hacer frente a la emergencia climática.

El metano (CH_4) es un gas superpotente que calienta el planeta, con un poder de calentamiento más de 80 veces superior al del dióxido de carbono en 20 años. Tal como ilustró recientemente el Financial Times, "[s]i pensamos que las emisiones de los combustibles fósiles están poniendo al mundo a hervir lentamente, el metano es un soplete que nos está cocinando hoy"[44]. El metano es también uno de los principales precursores del ozono troposférico, un contaminante atmosférico responsable de millones de muertes prematuras, de pérdidas de cosechas por un valor de miles de millones de dólares al año[45] y del debilitamiento de los sumideros de carbono[46]. Abordar la contaminación por metano frenará el calentamiento global, mejorará la salud, generará empleo, aumentará la seguridad alimentaria e incrementará las inversiones en los países en desarrollo. Más de 180 países hacen referencia directa a la mitigación del metano en sus contribuciones determinadas a nivel nacional (NDC, por sus siglas en inglés)[47]. En septiembre de 2022, 120 países y la Unión Europea se adhirieron al *Compromiso Mundial sobre el Metano*[48], que establece el objetivo colectivo de reducir las emisiones mundiales de metano al menos un 30 % de aquí a 2030 con respecto a los niveles de 2020, los cuales representan aproximadamente el 70% de la economía mundial y el 45% de las emisiones antropogénicas de metano[49].

La contaminación por metano ya ha causado 0,51 °C del calentamiento total observado entre 2010 y 2019 de 1,06 °C (0,88-1,21 °C), en comparación con la era preindustrial (

Recuadro 1)[50]. Y el calentamiento aumentará aún más si las emisiones de metano siguen creciendo. Las concentraciones atmosféricas de metano batieron récords en 2020 con la tasa de aumento más rápida desde que se iniciaron los registros en 1983[51]. Los datos preliminares muestran que el metano superó las 1.900 partes por billón (ppb) por primera vez en septiembre de 2021[52]. Tal como se señala en el anuncio conjunto de Estados Unidos y la UE en el marco del *Compromiso Mundial sobre el Metano*, "el metano es un potente gas de efecto invernadero [GEI] y, según el último informe del Grupo Intergubernamental de Expertos sobre el Cambio Climático, es responsable de aproximadamente la mitad del aumento neto de 1,0 °C de la temperatura media mundial desde la era preindustrial[53].

Recuadro 1. Contribución del metano al calentamiento actual

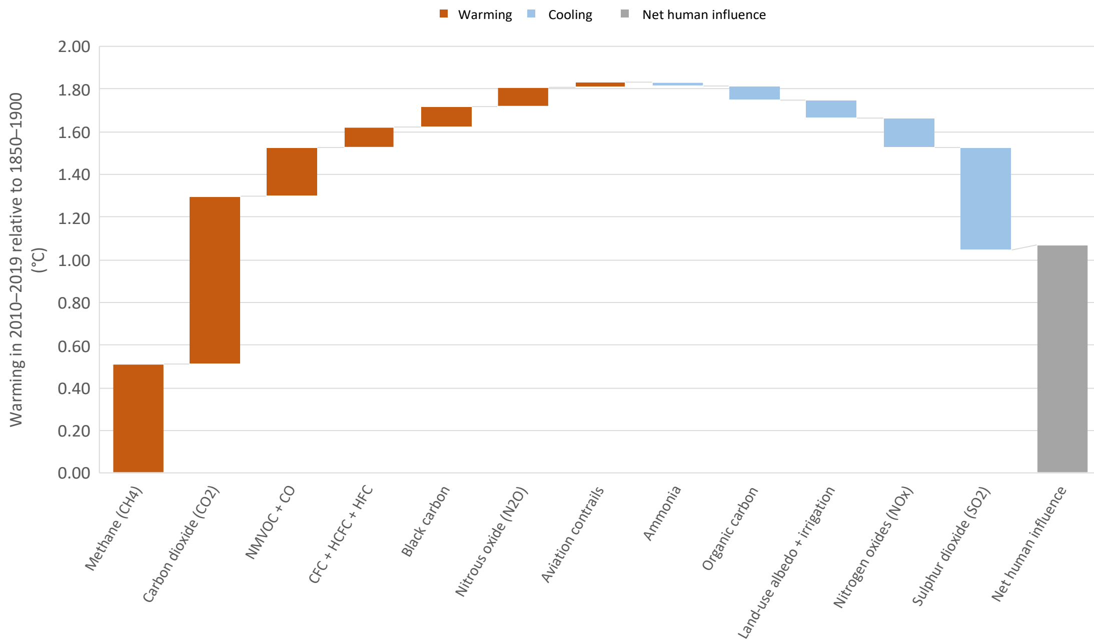
Según la Figura SPM.2c del IE6, la contaminación por metano causó 0,51 °C (0,29-0,84 °C) de calentamiento en el período de 2010-2019 en relación con 1850-1900, y el CO_2 causó 0,79 °C (0,52-1,25 °C) de calentamiento. El calentamiento antropogénico neto total actual era de aproximadamente 1,07 °C (0,8 a 1,3 °C) hasta 2019. Mientras que las emisiones de gases de efecto invernadero y de aerosoles de carbono negro contribuyen a un calentamiento de aproximadamente 1,8 °C, alrededor de 0,7 °C de este calentamiento está actualmente enmascarado debido al efecto refrigerante de los aerosoles reflectantes que se emiten principalmente junto con el CO_2 durante la combustión de carbón y gasoil. Este calentamiento neto evaluado de 1,07 °C está muy próximo al calentamiento observado de 1,06 °C (0,88 a 1,21 °C) según la Figura SPM.2a del IE6, adaptada en la **Figura 1**. Si se consideran únicamente las emisiones de gases de efecto invernadero y se excluyen otros contaminantes climáticos, como los aerosoles y los precursores de gases de efecto invernadero, el metano contribuye en torno al 30% del forzamiento radiativo antropogénico (aproximadamente 1,2 de 3,8 Watts por metro cuadrado, Wm^{-2}). El forzamiento radiativo del metano basado en las emisiones es de 1,2 (0,90 a 1,51) Wm^{-2} y tiene en cuenta el efecto directo de las emisiones de metano. También tiene en cuenta el forzamiento positivo indirecto derivado de la contribución de las emisiones de metano al aumento del ozono troposférico de fondo y del vapor de agua estratosférico[54].

Reducir las emisiones de metano es la mejor y más rápida estrategia para frenar el calentamiento y mantener 1,5 °C a nuestro alcance[55]. La *Evaluación Global del Metano* de la Coalición Clima y Aire Limpio (CCAC) y el Programa de las Naciones Unidas para el Medio Ambiente (PNUMA), dirigida por el Dr. Drew Shindell, concluye que las medidas de mitigación actualmente disponibles podrían reducir las emisiones de metano causadas por el hombre en un 45% para 2030, en comparación con los niveles previstos para 2030 sin introducción de cambios de la práctica actual (en inglés, *business as usual*), y evitar un calentamiento de casi 0,3 °C para la década de 2040[56].

Una mitigación rápida y enérgica del metano es fundamental porque la ventana para reducir el calentamiento lo suficiente como para frenar las retroalimentaciones que se refuerzan a sí mismas y evitar los puntos críticos de inflexión puede cerrarse a finales de esta década[57]. Muchas de estas retroalimentaciones están mostrando signos de activación, y hay pruebas de que nos estamos acercando o ya hemos cruzado múltiples puntos críticos de inflexión climáticos[58]. Se prevé que se produzcan seis puntos críticos de inflexión climáticos entre 1 °C de calentamiento y los 1,5 °C de calentamiento previstos para finales de la década, y otros once puntos críticos de inflexión entre 1,5 °C y 2 °C[59]. Las interacciones de efecto dominó entre estos sistemas plantean el riesgo de desencadenar una cascada mundial de puntos críticos de inflexión[60]. Además, es posible que se produzcan puntos críticos de inflexión aún no descubiertos debido a las limitaciones de los modelos actuales y a su exclusión en estos modelos de procesos, incluidos los relacionados con retroalimentaciones biogeoquímicas tales como el deshielo del permafrost[61].

Descarbonizar el sistema energético y lograr emisiones netas de CO_2 iguales a cero es crucial para estabilizar el clima y mantener las temperaturas por debajo de 1,5 °C a finales de este siglo[62]. Sin embargo, la eliminación gradual de los combustibles fósiles que emiten CO_2, como el carbón y el gasoil, también detiene las emisiones de aerosoles refrigerantes coemitidos, como el dióxido de azufre (SO_2)[63]. A diferencia del CO_2, que permanece en la atmósfera durante décadas o siglos, estos aerosoles refrigerantes desaparecen de la atmósfera en cuestión de días o meses. La pérdida de este efecto refrigerante contrarrestará las reducciones del calentamiento derivadas de la descarbonización hasta aproximadamente 2050 y *probablemente incluso acelerará el calentamiento durante la primera década o más*[64]. Tanto la *Evaluación Global del Metano* como el *Sexto Informe de Evaluación* (IE6) del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) destacan que "una reducción grande, rápida y sostenida del metano" es clave para contrarrestar este aumento del calentamiento en las próximas décadas[65]. Además, el IE6 concluye que la reducción de las emisiones de metano es clave para reducir eficazmente el pico de calentamiento y disminuir los costos del cambio climático a corto plazo, limitando la probabilidad de sobrepasar el umbral de 1,5 °C[66].

Figura 1. Contribuciones al calentamiento observado en 2010–2019 en relación con 1850–1900



Adaptado del Resumen para Responsables de Políticas, del Grupo Intergubernamental de Expertos sobre el Cambio Climático (2021) en CAMBIO CLIMÁTICO 2021: BASES FÍSICAS, *Contribución del Grupo de Trabajo I al Sexto Informe de Evaluación del Informe del Grupo Intergubernamental de Expertos sobre el Cambio Climático*, Masson-Delmotte V., *y otros* (eds.), Datos de la Figura SPM.2 (v20210809). *Véase también* NERC EDS Centre for Environmental Data Analysis (2021).

Además de provocar el calentamiento del planeta, el metano es también un importante precursor del ozono troposférico[67], que está relacionado con una importante morbilidad y mortalidad humanas[68] de tipo respiratorio y cardiovascular y con daños a los cultivos agrícolas (estimados en 63.000 millones de dólares anuales sólo en Asia Oriental)[69]. Los daños causados a las plantas por el aumento del ozono troposférico pueden reducir su capacidad de absorción de carbono y anular en parte el efecto de fertilización por carbono derivado del aumento de las concentraciones de CO_2, con un efecto potencialmente significativo sobre el forzamiento radiativo indirecto[70]. Un estudio reciente ha estimado en un 35% la contribución del metano a la carga actual de ozono troposférico[71]. Es probable que el metano desempeñe un papel más importante en la formación de ozono troposférico a medida que disminuyan las emisiones de otros precursores debido a los controles de la contaminación atmosférica[72]. La reducción de las emisiones mundiales de metano en un 45% para 2030 evitaría 255.000 muertes prematuras, 775.000 visitas hospitalarias relacionadas con el asma, 73.000 millones de horas de trabajo perdidas por el calor extremo y 26 millones de toneladas de pérdidas de cultivos en todo el mundo[73]. Eliminar todas las emisiones antropogénicas de metano podría evitar 690.000 muertes prematuras al año en 2050[74]. Cada tonelada de metano reducida genera 4.300 dólares en beneficios para la salud, la productividad y otros[75]. Además, las estrategias de mitigación del metano proporcionan mayores reducciones de costos y ganancias derivadas de la eficiencia en el sector privado, crean empleo, estimulan la innovación tecnológica y ayudan a reducir la vulnerabilidad climática de las comunidades más desfavorecidas.

El *Compromiso Mundial sobre el Metano* se lanzó formalmente a nivel de Jefes de Estado en el segmento de alto nivel de la 26ª Conferencia de las Partes (COP26) el 2 de noviembre de 2021[76]. Anteriormente, Estados Unidos y la Unión Europea anunciaron este *Compromiso* en el Foro de las

Principales Economías el 17 de septiembre de 2021[77]. El mismo compromete a los gobiernos a un objetivo colectivo mundial de reducción de las emisiones mundiales de metano en al menos un 30% con respecto a los niveles de 2020 para 2030. Los signatarios también se comprometen a avanzar hacia el uso de las metodologías de inventario de buenas prácticas del IPCC de más alto nivel para cuantificar las emisiones de metano, con especial atención a las fuentes de altas emisiones.

La aplicación con éxito del *Compromiso Mundial sobre el Metano* reduciría el calentamiento en al menos 0,2 °C para 2050[78] y mantendría al planeta en una trayectoria coherente con el mantenimiento dentro de los 1,5 °C, según la *Evaluación Global del Metano*[79]. El despliegue de todas las medidas disponibles y adicionales podría conducir a una reducción del 45% por debajo de los niveles de 2030 para alcanzar casi 0,3 °C de calentamiento evitado en la década de 2040[80].

El *Compromiso* marca la primera vez que los Jefes de Estado se comprometen a actuar con rapidez para reducir los supercontaminantes climáticos y alcanzar el objetivo de 1,5 °C de temperatura del Acuerdo de París. Este documento inicial crea conciencia sobre la oportunidad y la urgencia de frenar el calentamiento reduciendo el metano. También identifica los sectores implicados y el nivel de ambición necesario. Los gobiernos deben basarse en el *Compromiso* para abrir la puerta a un acuerdo mundial sobre el metano, que incluya actuar de inmediato para exigir una tasa de emisiones de metano progresivamente más baja a los proveedores de “gas metano de sustitución” en respuesta a los cambios en el abastecimiento a medida que se reduce la disponibilidad de gas ruso. Reducir el metano es nuestra mejor oportunidad para frenar rápidamente el calentamiento y evitar puntos críticos de inflexión que desencadenarían un calentamiento global devastador y harían mucho más difícil evitar una amenaza existencial para un planeta Tierra habitable[81] .

Aunque el presente *Manual* se centra en el metano, un contaminante climático de vida corta (CCVC), la reducción drástica de otros CCVC igualmente potentes—incluyendo el hollín o carbono negro, los hidrofluorocarbonos (HFC) y el ozono troposférico (del que el metano es uno de los principales precursores)—también es crucial para frenar el calentamiento a corto plazo[82]. Estas reducciones disminuirán la acumulación de calor en el océano que, de otro modo, seguiría contribuyendo al calentamiento durante décadas o siglos, mucho después de la vida útil del contaminante[83].

Recuadro 2. Retroalimentaciones autorrefozantes y puntos críticos de inflexión

El IE6 define una *retroalimentación climática* como "Interacción en la que una perturbación en una magnitud *climática* causa un cambio en una segunda magnitud, y el cambio en esta conduce, en última instancia, a un cambio añadido en la primera magnitud". Los ejemplos de retroalimentación climática del IE6 incluyen la retroalimentación del ciclo del carbono, a la retroalimentación de las nubes y la retroalimentación hielo-albedo, entre otros. El IE6 define un *punto de inflexión* como "Nivel de cambio en las propiedades de los sistemas más allá del cual el sistema se reorganiza, generalmente de forma abrupta, y no vuelve al estado inicial incluso aunque se reduzca el efecto de los causantes del cambio[84]". Algunas retroalimentaciones, como la retroalimentación hielo-albedo, se autorrefuerzan cuando el calentamiento inicial reduce el volumen y la extensión del hielo marino reflectante del Ártico en verano y expone la superficie más oscura del océano que absorbe más calor, calentando aún más y reduciendo el hielo marino. Los elementos clave del sistema climático tienen puntos críticos de inflexión que, una vez sobrepasados, obligan al sistema a cambiar, aunque este cambio pueda tardar cientos de años en producirse por completo, como en el caso del deshielo de la capa de hielo de Groenlandia[85]. Otros sistemas pueden inclinarse bruscamente. Un ejemplo sería el cambio de la biosfera terrestre de un sumidero neto de CO_2 a una fuente neta de CO_2 a medida que el calentamiento aumenta las tasas de respiración y disminuye las tasas de fotosíntesis[86].

Para consultar un debate más completo de las retroalimentaciones y puntos críticos de inflexión y las soluciones para una rápida mitigación, *véase* 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*.

Recuadro 3. Métricas de tiempo y temperatura del metano: utilizar el PCG_{20} es bueno, medir la temperatura es aún mejor!

Reducir los riesgos asociados con la aceleración del calentamiento exige estrategias de mitigación, como la reducción de las emisiones de metano, que pueden frenar el calentamiento a corto plazo. Evaluar cómo afectan las estrategias al calentamiento a corto plazo requiere considerar las emisiones individuales por contaminante en unidades de masa, tal como exigen las directrices de información de la Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC) y recomiendan los científicos en materia climática[87]. También es necesario tener en cuenta las coemisiones por fuente, ya que las políticas actúan sobre las fuentes y no sobre los contaminantes individuales.

Una opción ideal para evaluar el impacto sobre la temperatura es convertir las emisiones por fuente, en términos de contaminante y coemisiones en impactos sobre la temperatura, utilizando herramientas como la Herramienta de Evaluación de los Beneficios Ambientales y Sociales de la Reducción del Metano o la Herramienta para Medir la Trayectoria de la Temperatura de la CCAC. Alternativamente, cuando se comparan los impactos climáticos de los contaminantes climáticos de vida corta como el metano, utilizar el potencial de calentamiento global a 20 años (PCG_{20}) capta mejor el impacto del calentamiento a corto plazo que el PCG a 100 años (PCG_{100}), además de estar más alineado con el alcance del objetivo de 1,5 °C[88]. Aunque la CMNUCC exige actualmente el uso de la métrica PCG_{100} al notificar emisiones o absorciones agregadas, que infravalora sistemáticamente el impacto climático del metano, las Partes notificantes pueden utilizar además otras métricas, como el PCG_{20} o los potenciales absolutos de temperatura[89]. El IE6 ha actualizado las métricas para el metano de la siguiente manera: PCG_{20} es 81,2 y PCG_{100} es 27,9[90]. La **Cuadro 1** a continuación resume los valores de PCG para el metano de los informes del IPCC.

Cuadro 1. Valores de PCG para el metano de los informes del IPCC

		IE6	IE5		IE4	TIE	SIE
Metano (CH_4)	**PCG_{20}**	81,2	84	86*	72	62	56
	PCG_{100}	27,9	28	34*	25	23	21
Fósil CH_4	**PCG_{20}**	82,5 ± 25,8	85		--	--	--
	PCG_{100}	29,8 ± 11	30		--	--	--
No-fósil CH_4	**PCG_{20}**	80,8 ± 25,8	--		--	--	--
	PCG_{100}	27,2 ± 11	--		--	--	--

*con retroalimentación del ciclo de carbono. Todo el metano evaluado por el IE6 incluye la retroalimentación del ciclo de carbono.

IE6 = 2021 Sexto Informe de Evaluación WGI (Cuadro 7.SM.7; Cuadro 7.15); **IE5** = 2013 Quinto Informe de Evaluación WGI (Cuadro 8.A.1; Tablea 8.7); **IE4** = 2007 Cuarto Informe de Evaluación (Cuadro 2.14); **TIE** = 2001 Tercer Informe de Evaluación (Cuadro 6.7); **SIE** = 1995 Segundo Informe de Evaluación (Cuadro 2.9).

La mayoría de las métricas agregadas están diseñadas para compararse con el CO_2 de larga vida. Las métricas como la equivalencia de CO_2 en términos de PCG y PCG* se basan en relaciones matemáticas que pretenden hacer que CCVC como el metano sean comparables al impacto de calentamiento a largo plazo de las emisiones de CO_2[91]. Estas métricas agregadas suelen ignorar los contaminantes coemitidos con importantes impactos climáticos a corto plazo, como los aerosoles refrigerantes. La métrica PCG* intenta tomar en cuenta la vida más corta del metano diferenciando las emisiones históricas de los cambios en la tasa de emisiones[92]. Una de las críticas a este enfoque es que básicamente "excluye" las emisiones históricas, de modo que cuando es aplicada a la escala de emisores de metano regionales o individuales, las fuentes con emisiones históricas elevadas pueden acusar un PCG* negativo reduciendo su tasa de emisiones. Este ocurre incluso si sus emisiones en un año determinado son equivalentes a las de una nueva fuente sin emisiones históricas. Esto ha llevado a un uso incorrecto de estas métricas para afirmar que algunos sectores con grandes emisiones históricas y tasas de emisiones actuales estables o decrecientes han contribuido en menor medida al calentamiento global[93].

Por estas razones, el presente *Manual sobre el Metano* se basa en la convención de la *Evaluación Global del Metano* del PNUMA/CCAC al utilizar las métricas basadas en la masa, tales como el millón de toneladas métricas del metano ($MtCH_4$), y el impacto en la temperatura en lugar de las métricas de PCG.

2. La necesidad de actuar con rapidez: Ganar el *sprint* hasta el 2030 es fundamental para evitar una catástrofe climática

Cada aumento del calentamiento cuenta[94]. Ya estamos viviendo una situación de emergencia climática, con fenómenos extremos que se producen antes de lo previsto y con mayor gravedad. A medida que el ritmo de calentamiento se acelere, los récords de fenómenos extremos serán cada vez más frecuentes y peligrosos[95]. Tenemos como mucho hasta el final de esta década, y probablemente menos, para frenar drásticamente el calentamiento global o enfrentarnos a una amenaza existencial para un planeta Tierra habitable. El mundo podría llegar al límite de seguridad de 1,5 °C en 2030 debido al aumento de las emisiones, al descenso de la contaminación atmosférica por partículas que desenmascara el calentamiento existente y a la variabilidad natural del clima[96].

La rapidez debe convertirse en un factor clave en la selección de las soluciones climáticas, con el fin de limitar rápidamente el calentamiento, frenar las retroalimentaciones que se refuerzan a sí mismas, evitar los puntos críticos de inflexión y proteger a las personas y los ecosistemas más vulnerables. Por lo tanto, necesitamos "soluciones climáticas rápidas", es decir, medidas —incluidas las normas— que puedan empezar a aplicarse inicialmente en un plazo de dos a tres años, sustancialmente en un plazo de cinco a diez años y producir una respuesta climática en una o dos décadas[97]. Estas estrategias también son fundamentales para aumentar la resiliencia, otorgando a las comunidades más tiempo para adaptarse al calentamiento global y reduciendo la cantidad de adaptación necesaria[98].

La comunidad científica no ha comunicado adecuadamente la necesidad de actuar con rapidez. Tal como señalaron Yangyang Xu, V. Ramanathan David Victor en su Comentario de la publicación *Nature*[99],

> "[El Informe Especial del IPCC sobre 1,5 °C] subestima otro hecho alarmante: el calentamiento global se está acelerando. Tres tendencias —el aumento de las emisiones, la disminución de la contaminación atmosférica [que está reduciendo rápidamente las partículas de sulfato reflectantes que enmascaran el calentamiento] y los ciclos climáticos naturales— se combinarán en los próximos 20 años para hacer que el cambio climático sea más rápido y furioso de lo previsto. En nuestra opinión, es muy probable que superemos el nivel de 1,5 °C en 2030, y no en 2040 como se prevé en el informe especial ..... La comunidad que elaboran modelos climáticos no se ha ocupado lo suficiente de los cambios rápidos que más preocupan a los responsables de políticas, prefiriendo centrarse en tendencias y equilibrios a más largo plazo".

A. El impacto actual sobre el clima es malo, y lo peor está por venir: el riesgo de ciclos de retroalimentaciones que se refuerzan a sí mismas y puntos críticos de inflexión

El calentamiento rápido a corto plazo amenaza con acelerar un círculo vicioso —de retroalimentaciones que se refuerzan a sí mismas donde el planeta comienza a calentarse en un escenario de "Tierra invernadero". Estos mecanismos de retroalimentación podrían desencadenar una cascada de puntos críticos de inflexión en efecto dominó en el Ártico y en otros lugares, muchos de ellos irreversibles y potencialmente catastróficos[100]. Esto podría conducir a un calentamiento incontrolable, convirtiéndose en la fuerza dominante que regulará el sistema climático[101].

Un prestigioso grupo de científicos sobre clima, en su Comentario de 2019 de la publicación de *Nature* titulada *Climate Tipping Points—Too Risky to Bet Against*, explican que "la emergencia más clara se presentaría si nos aproximáramos a una cascada global de puntos críticos de inflexión" y que dichos "efectos en cascada puedan tornarse comunes"[102].

Los datos de la última revisión de las retroalimentaciones y los puntos críticos de inflexión sugieren que ya nos encontramos en un estado de emergencia planetaria en el que tanto el riesgo como la urgencia de la emergencia son agudos. Con un calentamiento de aproximadamente 1,1 °C, existe un riesgo no desdeñable de que ya se hayan superado uno o varios puntos críticos de inflexión relativos a la criosfera[103]. Las mejores estimaciones indican que los umbrales críticos para la capa de hielo de Groenlandia, la capa de hielo de la Antártida occidental, los corales de aguas cálidas y el deshielo abrupto del permafrost se producen en torno a ~1,5 °C. Limitar el calentamiento por debajo de 2 °C y la duración del calentamiento por encima de 1,5 °C puede evitar el colapso de los mantos de hielo[104]. El deshielo del manto de hielo de Groenlandia es el factor que más contribuye al aumento del nivel del mar[105], y ya se ha previsto que perderá 110 trillones de toneladas de hielo para finales de siglo, lo que elevaría el nivel del mar en casi 30 centímetros[106]. Retrasar la acción aumenta el riesgo de cruzar uno o más umbrales de temperatura[107] y somete al planeta a fenómenos meteorológicos y climáticos extremos que suponen una amenaza existencial para la civilización[108].

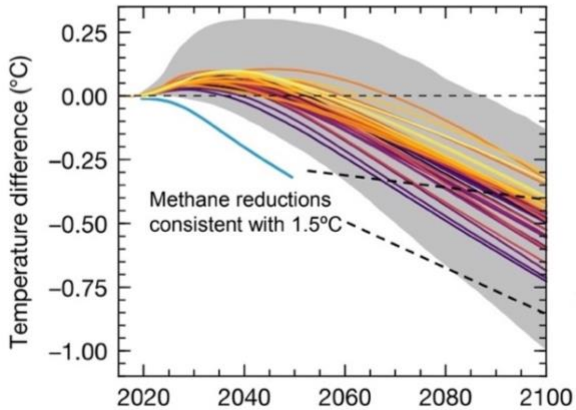
B. Reducir la quema de combustibles fósiles es esencial, pero no frena el calentamiento a corto plazo

Descarbonizar el sistema energético y lograr emisiones netas de CO_2 iguales a cero es fundamental para estabilizar el clima y mantener las temperaturas por debajo de 1,5 °C a finales de este siglo, pero reducir el CO_2 por sí solo no basta para alcanzar este objetivo[109]. De hecho, reducir la quema de combustibles fósiles como el carbón y el gasoil también reduce los aerosoles refrigerantes coemitidos, principalmente en forma de sulfatos y nitratos. Los aerosoles refrigerantes coemitidos son partículas reflectantes que actualmente enmascaran un calentamiento de aproximadamente 0,5 C[110]. Mientras que el CO_2 acumulado en la atmósfera seguirá provocando calentamiento durante décadas o siglos, estos aerosoles refrigerantes se desprenden de la atmósfera en cuestión de días o meses, y este desenmascaramiento de los aerosoles servirá para compensar las reducciones del calentamiento derivadas de la descarbonización hasta aproximadamente 2050 e incluso añadirá calentamiento durante la primera década o más **Figura 2**)[111]. Incluso sin tener en cuenta el calentamiento derivado de la reducción de los aerosoles refrigerantes, alcanzar el máximo de emisiones de CO_2 en 2030 y la neutralidad de carbono en la década de 2060 sólo evitaría un calentamiento de 0,1C en 2050[112], aunque los beneficios de esta estrategia se acumularán rápidamente desde 2060 hasta finales de siglo.

El IE6 confirma que la transición de los combustibles fósiles a las energías limpias está desenmascarando un calentamiento oculto de hasta 0,5 °C que anula los beneficios de enfriamiento de la descarbonización hasta 2050 aproximadamente, lo que subraya la importancia de reducir los supercontaminantes climáticos distintos del CO_2:

> "La mitigación sostenida del metano, dondequiera que se produzca, se destaca como una opción que combina ganancias a corto y largo plazo en la temperatura de la superficie (*nivel de confianza alto*) y conduce a beneficios en la calidad del aire mediante la reducción de los niveles de ozono en superficie a nivel global (*nivel de confianza alto*).... La mitigación adicional [del metano] y [del carbono negro] contribuiría a compensar el calentamiento adicional asociado a las reducciones [del dióxido de azufre] que acompañarían a la descarbonización (*nivel de confianza alto*"[113].

Figura 2. Reducciones del Metano comparadas con las respuestas de la temperatura media global en superficie a los cambios en las emisiones relacionadas con los combustibles fósiles (CO_2 + SO_2)



Fuente: Shindell D. (25 de mayo de 2021) *Benefits and Costs of Methane Mitigation*, Presentación en la Reunión del Grupo de Trabajo de la CCAC. *Updating* Figure 3d de Shindell D. y Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411.

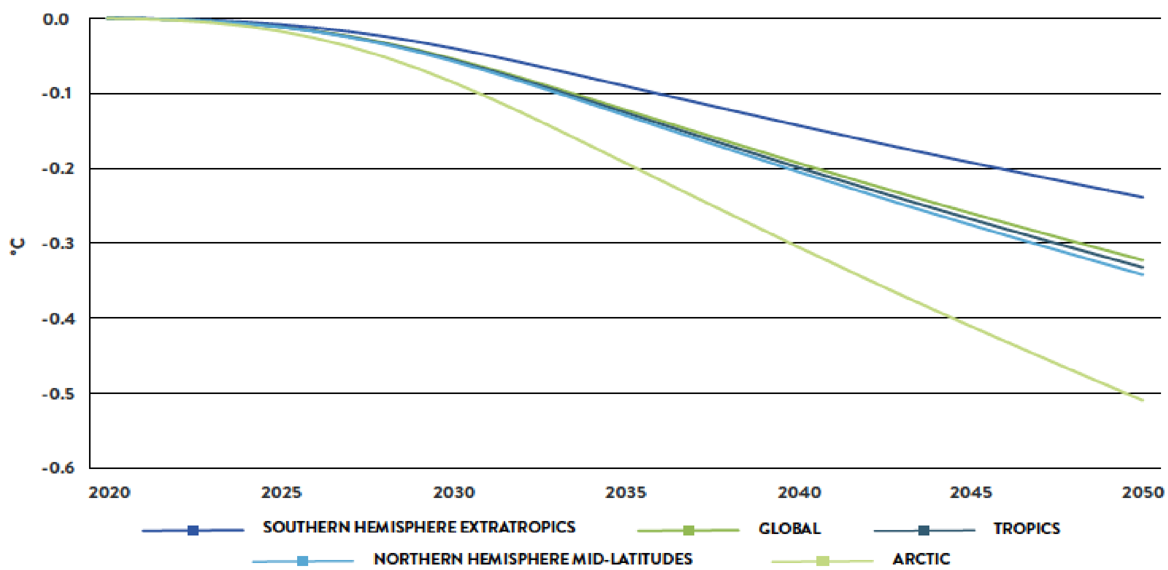
3. Reducir las emisiones de metano es la mejor manera de frenar el cambio climático a corto plazo

La *Evaluación Global del Metano* confirma que reducir las emisiones de metano es la estrategia más rápida para limitar el calentamiento durante los próximos 20 años[114]. Llevar a cabo todas las medidas de mitigación del metano en esta década es la única forma conocida de evitar casi 0,3 °C de calentamiento para la década de 2040 y frenar el calentamiento en un 30%[115]. El IE6 confirma que "una reducción grande, rápida y sostenida del metano" es clave para limitar el calentamiento a corto y largo plazo[116]. Además, el informe más reciente del IPCC sobre soluciones climáticas, elaborado por el Grupo de Trabajo III (IE6 del WGIII), refuerza la idea de que la reducción drástica y rápida de las emisiones de metano es esencial para limitar el calentamiento a corto plazo y evitar que el calentamiento máximo supere los 1,5 °C[117]. Para limitar el calentamiento a 1,5 °C sin sobrepasar o sobrepasando muy poco el límite, es necesario reducir las emisiones un 34% por debajo de los niveles de 2019 en 2030 y un 44% por debajo de los niveles de 2019 en 2040[118].

A. Aplicar todas las medidas disponibles de mitigación del metano es la única forma plausible de limitar el calentamiento en los próximos 20 años

La *Evaluación Global del Metano* estima que las estrategias para reducir las emisiones de metano en un 40–45% para el 2030 podrían evitar aproximadamente 0,3 °C para la década de 2040, y 0,5 °C en el Ártico para 2050, un 60% más que la media global (**Figura 3**)[119]. Esto es coherente con el IE6, que confirmó que la reducción del metano (en un 35% o más) junto con otros CCVC podría frenar el calentamiento global en 0,2 °C (0,1-0,4 °C) en 2040[120]. Los niveles actuales de emisión de metano sitúan las temperaturas medias mundiales en una trayectoria que superará el límite de seguridad de 1,5 °C, y las emisiones antropogénicas de metano representan aproximadamente un tercio del aumento de la temperatura[121]. La *Evaluación Integrada del Carbono Negro y el Ozono Troposférico* de 2011 calcula que la plena aplicación de medidas dirigidas al metano y al carbono negro podría reducir la tasa de calentamiento global a la mitad y reducir el calentamiento del Ártico en dos tercios[122]. La implementación de todas las medidas de mitigación del metano disponibles reduciría la tasa de calentamiento global en un 30% a mediados de siglo[123]. Si se eliminaran todas las emisiones antropogénicas de metano, los niveles de este gas en superficie podrían descender por debajo de los niveles preindustriales en 15 años[124].

Figura 3. Respuesta de la temperatura a la reducción del metano entre 2020 y 2050 basada en niveles de mitigación coherentes con escenarios de 1,5 °C

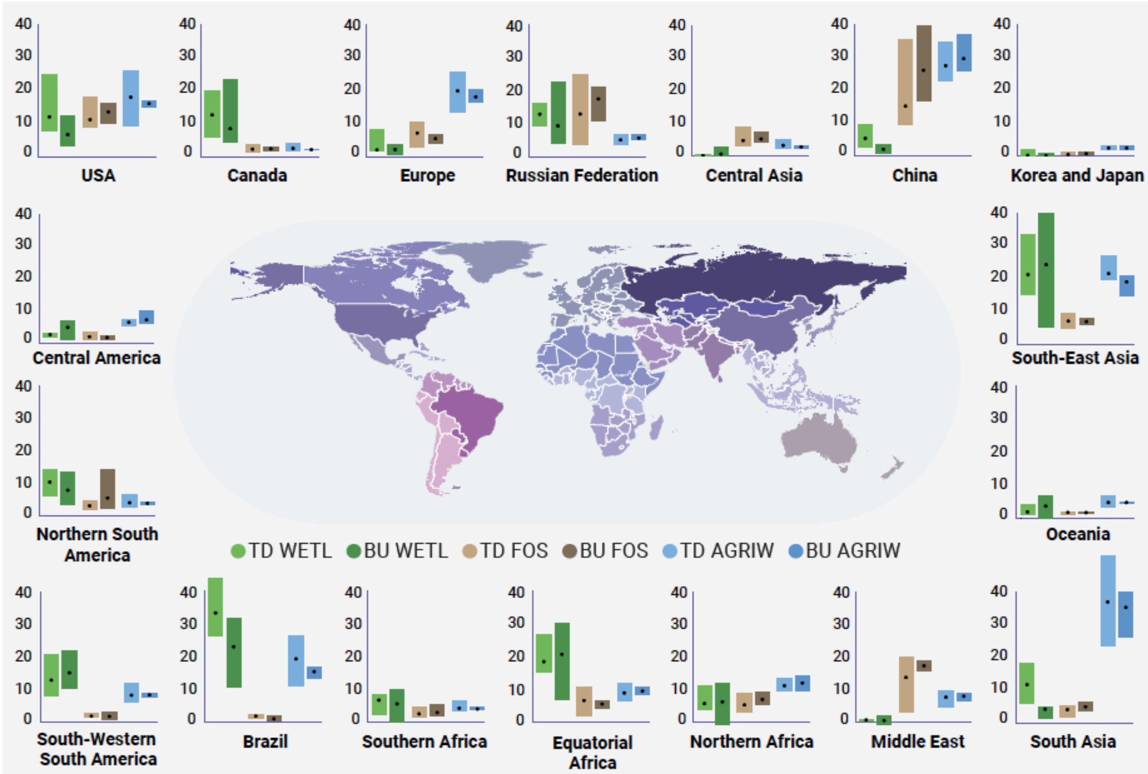


Fuente: Programa de Naciones Unidas para el Medio Ambiente y Coalición Clima y Aire Limpio (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, Figura 5.1. *Nota*: Además de las respuestas medias globales, se proporcionan valores para las zonas extratropicales del hemisferio sur (90–28 °S), los trópicos (28 °S–28 °N), y las latitudes medias del hemisferio norte (28–60 °N) y el Ártico (60–90 °N).

Una reducción rápida de las emisiones de metano también podría reducir el riesgo de deshielo del hielo marino del Ártico durante el verano[125]. Si el hielo marino del Ártico en verano desapareciera durante los meses de sol, como podría ocurrir ya a mediados de siglo[126], se produciría un calentamiento equivalente a 1.000 billones de toneladas de CO_2[127].

En resumen, debido a la larga vida del CO_2 y al desenmascaramiento del calentamiento asociado a la descarbonización, reducir el metano junto con el resto de los CCVC es la única forma plausible de limitar el calentamiento en los próximos 20 años[128].

Figura 4. Emisiones medias de metano para 2008–17 en $MtCH_4$ por año para 18 regiones



continentales

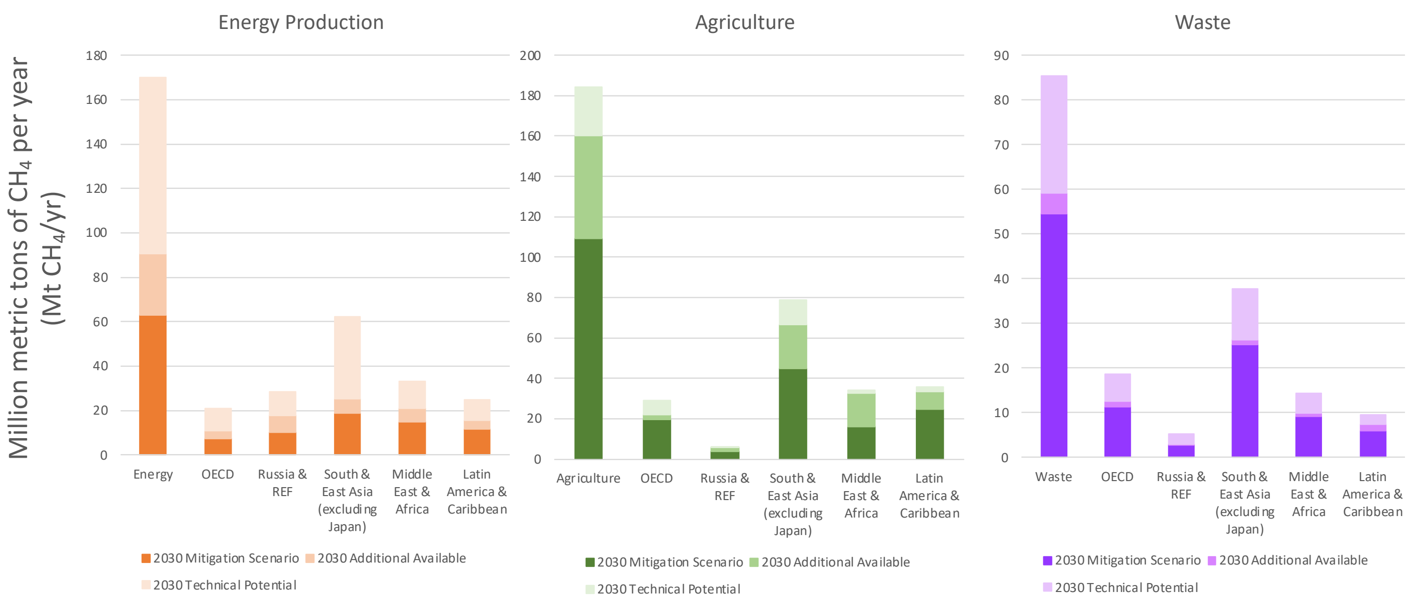
Fuente: Programa de Naciones Unidas para el Medio Ambiente (2021) INFORME SOBRE LA BRECHA DE EMISIONES 2021: LA CALEFACCIÓN ESTÁ ENCENDIDA – UN MUNDO DE PROMESAS AÚN POR CUMPLIRSE, Figura 6.1. *Nota*: Se muestran las emisiones de tres categorías principales: humedales (WETL), combustibles fósiles (FOS) y agricultura y residuos (AGRIW). Las barras de colores representan el intervalo mínimo y máximo de las estimaciones disponibles a partir de los enfoques descendente (TD) y ascendente (BU). Los puntos negros muestran la media de cada enfoque (basada en la serie de datos Saunois et al. 2020). Los colores del mapa indican únicamente las regiones.

B. Fuentes antropogénicas de las emisiones globales de metano

La actividad humana es responsable de aproximadamente el 60% (las estimaciones oscilan entre el 50 y el 65%) del total de las emisiones globales de metano[129]. Tres sectores son los principales responsables de la generación antropogénica de emisiones de metano: la producción de energía (~35%), la agricultura (~40%) y los residuos (~20%), con diferencias regionales e incertezas en las estimaciones que se muestran en la **Figura 4**[130]. En comparación, la quema de biomasa y los biocombustibles son fuentes menores[131]. Las medidas de mitigación actualmente disponibles podrían reducir las emisiones de estos sectores en unas 180 millones de toneladas métricas de metano al año (Mt/año), aproximadamente un 45%, para 2030 (**Figura 5**). De esas reducciones, unas 75 Mt (aproximadamente el 60%) podrían reducirse sin costo o con un costo bajo (menos de 600 dólares por tonelada de metano reducida, o unos 21 dólares por tonelada de CO_2 equivalente utilizando un potencial de calentamiento global a 100 años de 28) (

Recuadro 3)[132]. Aunque las emisiones antropogénicas son probablemente la causa principal del aumento de los niveles de metano en la atmósfera durante las últimas dos décadas, las fuentes naturales de metano parecen estar aumentando las emisiones como parte de las retroalimentaciones de los humedales y el permafrost[133]. Se están llevando a cabo importantes investigaciones sobre la eliminación del metano de la atmósfera, como se explica en la **Sección 5**.

Figura 5. Emisiones indicativas de referencia en 2030 y potencial de mitigación de las medidas técnicas y adicionales coherentes con una trayectoria de 15 °C



Fuente: 2030 Business As Usual Scenarios (limited climate policy; SSP3-7.0) *adaptado de* 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. Los potenciales técnicos en 2030 son adaptados de la reducción máxima en: Agencia de Protección Ambiental (2019) *Non-CO_2 Greenhouse Gas Emission Projections and Mitigation: 2010-2050*. Las medidas adicionales son la diferencia entre los potenciales técnicos y el escenario de mitigación coherente de 1,5 °C (SSP1-1.9) *de* 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. El sector de la producción de energía representa alrededor del 35% de las emisiones atmosféricas de metano

Alrededor del 35% de las emisiones antropogénicas de metano proceden de actividades de producción de energía relacionadas con el petróleo, el gas y el carbón[134]. Las emisiones en 2020 se estiman en cerca de 130 $MtCH_4$ a nivel mundial, de las cuales unas 80 $MtCH_4$ proceden del petróleo y el gas y 40 Mt del carbón, y la Agencia Internacional de la Energía (AIE) calculó un aumento del 5% de estas emisiones en 2021[135]. Cada combustible es responsable de aproximadamente un tercio de las emisiones de metano asociadas con la producción de energía[136]. La mayor parte de las emisiones del petróleo y el gas proceden de la extracción en tierra, seguida de actividades posteriores como el refinado y la distribución[137]. Estas emisiones incluyen tanto las fugas accidentales como el venteo intencional de metano. Si se tienen en cuenta estas fugas y las emisiones fugitivas (gas que se escapa durante el proceso de perforación, extracción y transporte)[138], las emisiones de metano del sector de la producción de energía son aproximadamente un 70% superiores a las de los datos comunicados[139].

Hay que tener en cuenta, sin embargo, que estas estimaciones excluyen las emisiones probablemente significativas de las minas de carbón abandonadas y de los pozos de petróleo y gas[140].

El metano se produce de forma natural en las minas de carbón. De ahí que deban adoptarse numerosas medidas, incluidas las mencionadas en la **Sección 6**, para garantizar la seguridad de los trabajadores. Las emisiones proceden de minas subterráneas activas, minas abandonadas que siguen filtrando metano y algunas minas de superficie[141]. Un análisis reciente de las emisiones de las minas de carbón de Australia, incluidas las minas de superficie, reveló que las emisiones de metano se habían subestimado considerablemente en los informes oficiales[142]. A pesar de la disminución de la producción de carbón, se prevé que el metano procedente del carbón siga siendo un foco importante de los esfuerzos de mitigación, ya que, en ausencia de intervención, las emisiones de las minas abandonadas aumentarán a medida que se abandonen más minas[143]. La AIE estima que las emisiones de metano de las minas de carbón en funcionamiento en 2020 tuvieron un mayor impacto a corto plazo sobre el clima que las emisiones combinadas de CO_2 de la Unión Europea, y que la generación de electricidad a partir del carbón tendría que reducirse en un 75% de aquí a 2030 para limitar el calentamiento a 1,5 °C[144]. Además, las olas de calor extremo y el cambio para sustituir el gas ruso en Europa están haciendo que la demanda de carbón en 2022 vaya camino de alcanzar el récord anual de 2013 y de establecer un nuevo máximo histórico en 2023[145].

ii. *El sector de la agricultura representa alrededor del 40% de las emisiones antropogénicas de metano*

La agricultura representa en torno al 40% de las emisiones antropogénicas, y las emisiones antropogénicas suponen el 60% de las emisiones totales de metano. Estas emisiones agrícolas proceden principalmente de la ganadería y el cultivo del arroz[146]. La mayor contribución dentro de la agricultura procede del ganado vacuno, ovino y otros rumiantes que generan metano a través de sus procesos de digestión (fermentación entérica)[147], siendo el ganado vacuno responsable del 77% de estas emisiones[148]. Las prácticas actuales de gestión del estiércol, especialmente en el caso del ganado porcino y vacuno, también liberan metano[149]. Las emisiones en 2020 se estiman en aproximadamente 117 $MtCH_4$ procedentes de la ganadería y la gestión del estiércol[150].

Los campos inundados utilizados para el cultivo de arroz son otra fuente importante de metano, especialmente en regiones con una elevada producción de arroz[151]. En Asia, el cultivo de arroz aporta alrededor del 20% de las emisiones de metano de la región[152]. Se calcula que en 2020 el cultivo mundial de arroz emitió aproximadamente 30 $MtCH_4$[153].

iii. *El sector de los residuos representa alrededor del 20% de las emisiones antropogénicas de metano*

Del 60% de las emisiones mundiales de metano procedentes de fuentes antropogénicas, aproximadamente el 20% de estas emisiones antropogénicas procede del sector de los residuos[154]. Este sector incluye tanto los vertederos como el tratamiento de aguas residuales. La descomposición de los residuos orgánicos produce metano. Las emisiones del sector de los residuos en 2017 se estimaron en aproximadamente 68 $MtCH_4$[155]. Sin embargo, es probable que los métodos tradicionales sigan subestimando las emisiones de los vertederos. Un reciente estudio multisatélite reveló que las emisiones de metano a nivel de ciudad en Buenos Aires, Delhi, Lahore y Mumbai eran entre 1,4 y 2,6 veces mayores con respecto a lo estimado, y que las emisiones de los vertederos contribuían a entre el 6 y el 50% de dichas emisiones[156].

En la actualidad, se calcula que se generan anualmente 2.000 millones de toneladas métricas de residuos sólidos urbanos en todo el mundo, y se espera que esta cantidad aumente un 70% hasta alcanzar los 3.400 millones de toneladas en 2050[157].

4. Existen tecnologías para reducir casi la mitad de las emisiones antropogénicas de metano procedentes de los sectores de la producción de energía, los residuos y la agricultura

Según la CCAC, las medidas actualmente disponibles podrían reducir las emisiones antropogénicas de metano procedentes de los sectores de producción de energía, residuos y agricultura en un 45% para 2030[158]. Las medidas dirigidas específicamente a las fuentes de metano son esenciales, ya que las medidas de descarbonización más amplias sólo pueden lograr el 30% de las reducciones de metano necesarias[159]. Aproximadamente el 60% de las medidas específicas disponibles tienen bajos costos de mitigación (menos de 21 dólares por tonelada de CO_2e para un PCG_{100} y 7 dólares por tonelada de CO_2e para un PCG_{20}), y algo más del 50% de ellas tienen costos negativos, es decir, que las medidas se amortizan por sí solas[160]. La mitigación del metano también puede crear puestos de trabajo geográficamente diversos y bien remunerados[161].

El **Cuadro 2** resume las medidas técnicas y adicionales de control de las emisiones de metano por sectores. Existen muchas recopilaciones de soluciones y costos basados en la tecnología, como los informes del Instituto International para el Análisis de Sistemas Aplicados, la Agencia Internacional de la Energía, la Agencia de Protección Ambiental de Estados Unidos, McKinsey y otros[162]. Varios grupos rastrean y evalúan enfoques novedosos e innovadores, como la recopilación de la Fundación Solar Impulse de más de 1.000 soluciones eficientes, limpias y rentables para el medio ambiente[163].

Cuadro 2. Medidas de control de las emisiones por sector

Controles Técnicos		
Combustibles Fósiles	**Residuos**	**Agricultura**
Petróleo y gas: detección y reparación de fugas (LDAR) de manera ascendente y descendente.	**Residuos sólidos municipales:** compostaje; separación en la fuente con reciclado/reutilización; sin vertido de residuos orgánicos; uso de biocoberturas; tratamiento con recuperación de energía o recolección de gas de vertedero.	**Ganado vacuno, ovino y otros rumiantes mediante la fermentación entérica:** cambio en la alimentación y suplementos; cría para mejorar la productividad y la salud/fertilidad de los animales.
Petróleo y gas: captura de purgas; recuperación y utilización del gas venteado con unidades de recuperación de vapores y émbolos de pozo; instalación de antorchas.	**Residuos sólidos industriales:** reciclado y tratamiento con recuperación de energía; sin vertido de residuos orgánicos.	**Rumiantes y porcinos mediante la gestión del estiércol:** tratamiento en digestores de biogás; reducción del tiempo de almacenamiento del estiércol; mejora de la cobertura del almacenamiento del estiércol; mejora de los sistemas de alojamiento y corrales; acidificación del estiércol.
Petróleo y gas por dispositivos existentes: sustituir las bombas de gas a presión y los controladores por sistemas eléctricos o de aire; sustituir los dispositivos neumáticos accionados a gas y los motores de gasolina o gasoil	**Aguas residuales residenciales:** mejora del tratamiento primario para convertirlo en tratamiento anaerobio secundario/terciario con recuperación y utilización de biogás. Plantas de tratamiento de	**Cultivo de arroz:** Mejora del manejo del agua o el arroz de humedal de inundación/drenaje alternativo; siembra húmeda directa; adición de fosfoyeso y sulfato para inhibir la

por motores eléctricos; sustituir anticipadamente los dispositivos por versiones de menor liberación; sustituir las juntas o varillas de los compresores; tapar los pozos no utilizados.	aguas residuales en lugar de letrinas y eliminación.	metanogénesis; compostaje de paja de arroz; uso de híbridos alternativos.
Minería de carbón: desgasificación previa a la extracción; oxidación del metano del aire con ventilación mejorada. Inundación de minas abandonadas.	**Aguas residuales industriales:** mejora del tratamiento para realizarlo en dos etapas, es decir, un tratamiento anaeróbico con recuperación de biogás seguido de un tratamiento aeróbico.	**Quema de los residuos agrícolas:** aplicación y cumplimiento de las prohibiciones existentes.
Cambios de Comportamiento y Tecnológicos		
Combustibles Fósiles	**Residuos**	**Agricultura**
Cambio de combustibles fósiles por renovables/nucleares.	Reducción del desperdicio de alimentos.	Reducción de la pérdida de cosechas y del desperdicio de alimentos.
Gestión de la demanda energética.		Cambio en la dieta.
Mejora de la eficiencia energética.		
Fijación de precios de las emisiones.	Fijación de precios de las emisiones.	Fijación de precios de las emisiones.

Adaptado del Programa de Naciones Unidas para el Medio Ambiente y la Coalición Clima y Aire Limpio (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*, 107 (Cuadro 4.1 Medidas de control de las emisiones incluidas en al menos uno de los análisis de mitigación).

A. Sector de la producción de energía

El mayor potencial para mitigar las emisiones de metano procedentes de la producción de energía se encuentra en el sector del petróleo y el gas, donde el potencial de mitigación es de 29-57 $MtCH_4$/año[164]. La AIE identificó vías para lograr reducciones del 75% en el sector de la producción de energía, tal como se requiere en la Hoja de Ruta de la AIE para lograr Emisiones netas cero para 2050[165], con un 40-50% de las medidas sin costo neto a los precios medios del gas de los últimos cinco años; casi todas las opciones de mitigación de las operaciones de petróleo y gas en todo el mundo podrían aplicarse sin costo neto a los precios de 2021[166]. Si se hubieran capturado y comercializado las fugas de metano de las operaciones con combustibles fósiles en 2021, los 180 billones de metros cúbicos adicionales de gas habrían sido equivalentes a todo el gas utilizado en el sector eléctrico europeo y habrían aliviado considerablemente la presión sobre los precios[167]. La AIE calcula que si todos los países alcanzaran una intensidad de emisiones de metano (emisiones por unidad de producción) similar a la de Noruega, las emisiones de metano procedentes de las operaciones de petróleo y gas se reducirían en más de un 90%[168].

Las medidas para hacer frente a las fugas[169] y reducir la quema en antorcha y el venteo[170] de metano son fundamentales para reducir las emisiones en el sector del petróleo y el gas[171]. Estas medidas incluyen la intensificación de los programas de detección y reparación de fugas (LDAR, por sus siglas en inglés) y la sustitución de los dispositivos con fugas y los equipos más antiguos por equipos modernos de bajas emisiones[172]. La *Clean Air Task Force* (CATF, por sus siglas en inglés) afirma que prohibir el venteo de gas natural en los pozos petrolíferos puede reducir las emisiones en un 95%[173]. La Asociación Mundial para la Reducción de la Quema de Gas del Banco Mundial calcula que en 2021 se desperdiciaron 144 billones de metros cúbicos (bmc) de gas, una cantidad que si se capturara, podría abastecer de energía a toda la región de África subsahariana[174]. Según un análisis de Ceres y la CATF, en 2020, los 100 principales productores de petróleo y gas de Estados Unidos contribuyeron al 74% de las emisiones de metano y al 77% de las emisiones de GEI notificadas, encabezados por Hilcorp Energy, Exxon Mobil, Occidental Petroleum y ConocoPhillips[175]. Este análisis confirmó que las operaciones de equipos relacionados con la quema en antorcha y el venteo son un factor determinante en la intensidad de las emisiones, ya que los controladores neumáticos representan el 62% de las emisiones de metano notificadas y la quema en antorcha y el venteo de gas representan el 58% del total de emisiones de GEI notificadas en la cuenca de Williston[176].

La reducción de las emisiones fugitivas de metano y contaminantes atmosféricos asociados es también una cuestión de justicia ambiental. Por ejemplo, más de 18 millones de personas en Estados Unidos viven a menos de una milla de pozos y son grupos desproporcionadamente marginados; también se ha constatado que el desempleo cerca de los pozos es de 4 a 12 veces superior a la media nacional[177]. Los esfuerzos para el taponamiento y desmantelamiento de los millones de pozos de petróleo y gas abandonados e inactivos reducirían aún más las emisiones al tiempo que crearían puestos de trabajo, incluso en las zonas más afectadas por la transición energética[178].

Para reducir las emisiones de metano del sector del petróleo y el gas, es fundamental actualizar y mejorar el monitoreo de las emisiones de metano para identificar los puntos calientes y los superemisores. Esto es especialmente importante si se tiene en cuenta que es probable que las emisiones de metano de este sector sean significativamente superiores a las estimadas actualmente, sobre todo cuando las estimaciones se basan en métodos de inventario que utilizan factores de emisión[179]. Un estudio aéreo de la cuenca del Pérmico, en Nuevo México, estimó emisiones 6,5 veces superiores a las de un inventario basado en factores de emisión[180]. Nuevos datos obtenidos por satélite revelaron una cantidad significativa de fugas de metano procedentes de las mayores minas de carbón de Australia, lo que hace temer una "gran subestimación en la información facilitada sobre las emisiones de metano en el inventario nacional"[181]. Los satélites también han observado más de 1.800 "ultraemisores" entre 2019 y 2020, principalmente asociados con el sector de producción de petróleo y gas, con una contribución total de emisiones equivalente al 8 al 12% (alrededor de 8 millones de toneladas métricas de metano por año) de las emisiones mundiales de metano de producción de petróleo y gas[182]. Teniendo en cuenta las observaciones por satélite y las intensidades de las emisiones a escala, la AIE calcula que las emisiones del sector energético fueron un 70% superiores a las comunicadas oficialmente[183]. Investigadores del Rocky Mountain Institute (RMI, por sus siglas en inglés), la Universidad de Stanford, la Universidad de Calgary y Koomey Analytics desarrollaron la herramienta *Oil and Climate Index Plus* (OCI+) que determinó que los yacimientos de petróleo y gas más perjudiciales para el clima se encontraban en el yacimiento ruso de Astrakhanskoye, en la cuenca sur del Caspio de Turkmenistán y en la cuenca estadounidense de Permian, en Texas[184]. Las actividades de monitoreo del metano se tratan con más detalle en la **Sección 8**.

Además de las reducciones en el sector del petróleo y el gas, las medidas para reducir las emisiones de la minería de carbón pueden proporcionar una mitigación de 12-25 $MtCH_4$/año[185]. La AIE calcula que la eliminación del cuartil de minas de carbón en funcionamiento con peores resultados eliminaría unas 25 MtCH4[186]. Los principales métodos para reducir las emisiones de las minas de carbón subterráneas activas son la oxidación del metano del aire de ventilación y la recuperación y utilización del metano mediante la desgasificación previa a la explotación[187]. Aunque el metano puede recuperarse antes de que comiencen las operaciones mineras, el metano expulsado de las minas (metano del aire de ventilación) es diluido y, por lo tanto, más caro de utilizar[188]. Además, dado que las minas abandonadas siguen filtrando metano, la CCAC recomienda la inundación de las minas de carbón abandonadas para eliminar estas emisiones[189]. En algunas situaciones, el metano de las minas abandonadas puede recuperarse y utilizarse antes de que se produzca la inundación[190].

La reducción de las emisiones de metano procedentes del sector de la producción de energía tiene importantes beneficios climáticos y económicos. La transición a las energías renovables y el tratamiento del metano procedente de instalaciones de combustibles fósiles abandonadas[191] son esenciales para reducir las emisiones de metano en las próximas décadas[192].

B. Sector de la agricultura

El sector agrícola puede proporcionar una mitigación de 4-42 MtCH_4/año procedentes del subsector ganadero y de 6-9 MtCH_4/año procedentes del cultivo del arroz[193]. Las medidas para reducir las emisiones del ganado comprenden mejorar la alimentación y la gestión del estiércol en las granjas y reducir el metano generado por unidad de productividad animal, al tiempo que se reduce el número de cabezas de ganado (**Cuadro 3**). Se están desarrollando planes de cría y nuevas tecnologías, incluidos aditivos para piensos y estiércol, para mejorar la salud y la productividad del ganado, gestionar la fermentación entérica y reducir las emisiones procedentes del estiércol[194]. El éxito de estas estrategias debe considerarse tanto en términos de reducción del metano como de los impactos medioambientales relacionados con el uso de la tierra y los fertilizantes para piensos y las emisiones asociadas[195], así como de los posibles incentivos perversos hacia la consolidación e industrialización continua de los sectores cárnico y lácteo[196].

Dos aditivos alimentarios prometedores que han demostrado reducir las emisiones entéricas de metano son las algas marinas, concretamente un tipo de alga roja (*Asparagopsis taxiformis*), y el inhibidor de metano 3-nitrooxipropanol (3-NOP, comercializado como Bovaer®). Además, se ha demostrado que algunos inoculantes bacterianos diseñados para mejorar el crecimiento y el rendimiento de las plantas disminuyen la producción de metano cuando se utilizan en el ensilado del ganado, y se están realizando estudios adicionales para verificar este efecto[197]. Los científicos siguen comprobando que la inclusión de algas marinas en la dieta del ganado puede reducir significativamente las emisiones de metano[198]. En mayo de 2022, el Departamento de Alimentos y Agricultura de California aprobó el uso comercial del aditivo de algas marinas Brominata, de Blue Ocean Barns, como ayuda digestiva para el ganado lechero[199]. Esta fue la primera vez que un organismo regulador de Estados Unidos aprobaba el uso de algas marinas para la digestión del ganado. Los aditivos de algas se enfrentan a problemas de escala, ya que la *Asparagopsis* aún no se ha cultivado en laboratorio; sin embargo, los esfuerzos de empresas, como Rumin8, están avanzando en el aislamiento de los compuestos bioactivos que suprimen la metanogénesis en el ganado[200]. En septiembre de 2021, Brasil y Chile concedieron la autorización de comercialización a Bovaer® para su uso en rumiantes[201]. Tras la aprobación en febrero de 2022, se espera que el aditivo para piensos Bovaer® salga al mercado en la Unión Europea en el transcurso de ese año, con programas piloto a gran escala previstos[202]. Un estudio de 2021 dirigido por Princeton y Cornell recomienda realizar estudios plurianuales sobre Bovaer® y las algas rojas para observar los efectos sostenidos, incluidos los efectos potencialmente negativos para el ganado y la salud humana (es decir, las concentraciones de bromoformo en las algas rojas), la eficiencia y los flujos de producción de los aditivos[203]. A pesar de ello, los productos de ganado alimentado con algas rojas ya se venden en los supermercados suecos[204].

Los aditivos para el estiércol, como el biocarbón (carbono negro producido a partir de la pirólisis de biomasa), los ácidos, la paja o la tecnología SOP basada en sulfato cálcico dihidratado (yeso) pueden reducir las emisiones de metano y otros contaminantes como el amoníaco[205]. Las emisiones de estiércol también pueden abordarse mediante la digestión anaeróbica —una tecnología que convierte los residuos orgánicos en biogás y digestato rico en nutrientes que puede utilizarse para la aplicación de fertilizantes[206]— y opciones de gestión alternativas (es decir, la separación de los lodos en componentes sólidos y líquidos, y la retirada rápida del estiércol de los establos), pero deben evaluarse en función de las características de la explotación[207]. La promoción de productos de biogás de digestión anaeróbica debe evaluarse en función de las preocupaciones en materia de justicia climática y medioambiental, que implican un posible aumento de los olores y la contaminación, así como su relación con la ampliación de las infraestructuras de combustibles fósiles[208]. Además, las instalaciones de producción de biogás tienden a tener altos índices de pérdida de metano debido a un diseño, gestión y mantenimiento deficientes, según un estudio reciente[209]. Otra preocupación que suscita la aplicación de estas medidas a través de regulaciones es que puedan producirse "fugas" de emisiones de metano en regiones vecinas donde las restricciones a las operaciones ganaderas puedan ser menos estrictas (por ejemplo, en escenarios en los que los rebaños de California se trasladen a otros estados con normativas lácteas más laxas)[210].

Reducir la intensidad de metano por unidad de productividad del ganado puede limitar las emisiones de metano al requerir menos ganado para producir la misma cantidad de leche o carne[211]. La mejora de la digestibilidad de los piensos, la gestión del pastoreo, las estrategias de cría y los sistemas forrajeros pueden aumentar la eficiencia de los animales[212]. Al mejorar la digestibilidad de los piensos reduciendo la lignina, las vacas pueden consumir más pienso y producir más leche/carne, reduciendo las emisiones de metano por producto[213]. La cría y selección de genes que aumenten la productividad y reduzcan las emisiones es otra estrategia que los ganaderos pueden adaptar a sus necesidades[214]. Esta investigación tiene un enfoque limitado y es cada vez más selectiva. En Japón actualmente se estudia el ganado negro para determinar las características metabólicas que producen metano y cómo suprimirlo en esta raza concreta[215]. Garantizar niveles elevados de salud animal reduce la necesidad de sustituir animales enfermos y poco productivos (lo que disminuye la intensidad de las emisiones de metano)[216] y, en algunos casos, reduce directamente las emisiones de metano[217]. Estas soluciones podrían tener repercusiones significativas para los países de África y los países en desarrollo con menor productividad ganadera[218].

Disminuir el número de cabezas de ganado es otra estrategia para reducir el metano, especialmente cuando aumenta la productividad[219]. Un cambio hacia un menor consumo de carne, especialmente en regiones con un consumo de carne superior a la media, es un ejemplo de cambio de comportamiento que reduciría las emisiones de metano procedentes del ganado al disminuir el número de cabezas y las emisiones asociadas al uso de la tierra, junto con beneficios colaterales para la salud[220].

Los investigadores también están estudiando otras estrategias innovadoras, como una vacuna antimetano para el ganado[221]. Sin embargo, hasta la fecha las vacunas sólo han demostrado efectos a corto plazo, y podría llevar décadas desarrollar vacunas más permanentes que mitiguen el metano[222].

Cuadro 3. Principales tecnologías emergentes de mitigación para el metano procedente del ganado, su aplicabilidad y principales limitaciones en los distintos sistemas, reducción relativa de emisiones, impacto en el desempeño animal, potencial de mitigación global estimado, incluidas las limitaciones para su adopción, y calendario y nivel de confianza en su disponibilidad comercial

Tecnología	Aplicabilidad	Limitación Principal	Reducción Relativa de Emisiones†	Impacto en el desempeño animal	Potencial de Mitigación en 2050‡	Disponibilidad Comercial General§
		Modificación del Rumen				
Inhibidores de CH_4 [a,b]	 *	costo, aprobación regulatoria	30%	Efecto nulo/limitado[b]	0,8	2025 (*alta*)
		costo	20–30%		5–8	2030 (*media*)
Vacuna para el CH_4[a]		"Investigación y Desarrollo sostenidos, servicios veterinarios, costo"[b]	30% (asumido)[a]	--	11–28	2050 (*media*)
Sumidero de electrones de nitrato[b]		Efecto sobre las emisiones de óxido nitroso entérico y del estiércol, costo, posibles efectos negativos sobre la salud animal	15%	Efecto neutro: menor ingesta & mayor rendimiento lácteo	No evaluado	--
Algas marinas[a]	 *	"Producción a escala mundial, costo, toxicología, regulación y aceptación en el mercado"[a]	20–50%	desconocido[b]	0,5–1	2030 (*pruebas insuficientes para determinar el nivel de confianza*)
					1–10	
		Formulación de la Dieta				
Forrajes tánicos[b]		Efecto sobre el CH_4 del estiércol, disminución de la palatabilidad y del consumo de pienso	10%	Efecto nulo/limitado[b]	No evaluado	--
Inclusión de aceites/semillas oleaginosas y grasas[b]		Efecto sobre el CH_4 del estiércol, costo, efecto sobre las emisiones anteriores	14–15%	Efecto negativo (altos niveles de inclusión)[b]	No evaluado	--
Disminución de la relación forraje-concentrado en la dieta[b]		Riesgo de enfermedades, competencia entre pienso y alimento	9% (intensidad)	Efecto positivo: mayor aumento de peso & rendimiento lácteo [b]	No evaluado	--
		Gestión de Animales y Piensos				
Aumento del nivel de alimentación[b]		Efecto sobre el CH_4 del estiércol	17% (intensidad)	Efecto positivo: mayor aumento de peso & digestibilidad[b]	No evaluado	--
Disminución de la madurez de la hierba[b]		Efecto sobre el N_2O del estiércol	13% (intensidad)	Efecto positivo: aumento del rendimienteo lácteo & digestibilidad[b]	No evaluado	--
Cría con bajas emisiones [b]		Programa de cría	1% anual, 15% máximo	Efecto positivo limitado [b]	2–9	Ovino: 2030 (*alta*) Vacuno: 2035 (*media*)

 Sistemas Feedlot y Mixtos  Sistemas de Pastoreo

** sistemas de pastoreo intensivo[a]*
† absoluto salvo indicación contraria
‡ en Mt CH_4 año^{-1}
§ nivel de confianza

Adaptado de [a] Reisinger A., Clark H., Cowie A. L., Emmet-Booth J., Gonzalez Fischer C., Herrero M., Howden M. y 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; *y*
[b] Arndt C., *y otros* (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. La reducción relativa de emisiones se evalúan como CH_4 por unidad de ingesta de materia seca del pienso, g kg^{-1}.

En el caso de los arrozales, la mejora de la gestión del agua, la alternancia entre inundación y drenaje del arroz de humedal, la siembra directa y la mejora del rendimiento pueden reducir mucho las emisiones[223]. La principal estrategia de mitigación consiste en reducir el tiempo de inundación de los campos[224], pero hay que tener en cuenta el aumento de las emisiones de óxido nitroso (N_2O)—otro potente gas de efecto invernadero—[225]. Los expertos estiman que la alternancia entre el humedecimiento y el secado de los campos (frente a la inundación continua durante la temporada de cultivo) podría reducir las emisiones de metano hasta en un 48%[226]. El aumento del rendimiento puede mejorarse mediante la mejora genética de los cultivos (para seleccionar las especies más productivas) y las modificaciones del biocarbón[227], así como la mecanización de lo que de otro modo sería un trabajo manual[228]. Searchinger y otros (2021) estiman que por cada 1% de aumento en el rendimiento del arroz, las emisiones de metano se reducen en un 1%[229]. Además de ofrecer mitigación del metano, el cultivo selectivo de arroz también puede brindar beneficios adaptativos, como el aumento de la productividad en zonas que se enfrentarán a peores condiciones de sequía en un clima cambiante[230]. Algunas estrategias descriptas anteriormente pueden ser elegibles para recibir beneficios a través de programas regulatorios establecidos, como el Protocolo de Compensación de Cumplimiento de la Junta de Recursos del Aire de California[231].

Una amplia variedad de investigaciones innovadoras busca reducir las emisiones de metano del sector agrícola. Ejemplos exitosos de investigación en pequeños ensayos o basados en las enseñanzas Indígenas[232] que pueden reducir las emisiones de metano son, entre otros: la agricultura regenerativa (por ejemplo, silvopastura, agroecología[233] y pastoreo solar[234]); aplicación de escarabajos peloteros[235] o lombrices (vermafiltración)[236] al estiércol vacuno; uso de levadura de cerveza para suprimir el metano entérico al tiempo que se promueve el crecimiento animal[237]; modificación genética de la levadura para inhibir la actividad metanogénica en el rumen[238]; el uso de Crispr, o tecnología de edición genética, para cultivar microbios del suelo en laboratorios con el fin de comprender mejor las interacciones del suelo que producen metano en los arrozales[239]; el uso del metano capturado como alimento para peces[240]; el uso de electricidad para convertir los residuos ganaderos en abono[241] y la introducción de determinados aditivos y procesos en las lagunas de tratamiento del estiércol[242]. Estas soluciones, excluyendo las que tienen su origen en prácticas Indígenas, están aún en pañales y todavía no se han evaluado formalmente. No obstante, se trata de posibilidades interesantes para el futuro de la reducción del metano en la agricultura.

Como se describe en la **Sección 8** sobre sistemas de monitoreo (incluida la integración de satélites y datos), la mejora de los sistemas de monitoreo de los sectores agrícolas será fundamental para evaluar el impacto de estos métodos innovadores. Por ejemplo, las emisiones de metano procedentes del ganado se han observado por primera vez en el valle californiano de San Joaquín a través de GHGSat[243]. Además, los algoritmos de aprendizaje automático son cada vez más rápidos a la hora de estimar las emisiones de GEI (incluido el N_2O, que hasta ahora era difícil de cuantificar) a partir de interacciones complejas en el suelo[244]. Seguir mejorando los sistemas de observación del metano, especialmente en sectores difíciles de cuantificar como la agricultura, será esencial en los esfuerzos de monitoreo una vez que se hayan implementado estas soluciones. *Véanse*, en la **Sección 8**, ejemplos de herramientas de observación aérea, lanzadas o a punto de lanzarse, que pueden ser especialmente pertinentes para monitorear el metano procedente de la agricultura.

C. Sector de los residuos

El sector de los residuos puede proporcionar una mitigación de 29-36 MtCH_4/año[245]. La mitigación de los residuos sólidos constituye la mayor parte del potencial de reducción de este sector[246]. Los operadores de vertederos pueden capturar y convertir en energía el metano emitido por los vertederos existentes[247]. La recolección del gas de vertedero requiere la construcción de equipos costosos (pozos de extracción y tuberías en el interior del vertedero)[248] y un funcionamiento continuado; sin embargo, la producción de un producto de biogás apto para el uso energético reporta beneficios económicos[249]. En su caso, McKinsey estima que la máxima oportunidad técnica para la inclusión de tecnología de captura puede conducir a una reducción de 4,50Mt CH_4/año en 2030[250]. Como alternativa a la combustión, la cual puede contribuir a la contaminación atmosférica, el gas de vertedero puede generar electricidad mediante pilas de combustible[251]. Además, están surgiendo mejoras en la captura del gas metano de los vertederos para optimizar dicha captura minimizando las necesidades de infraestructuras y la frecuente intervención humana[252]. Esta tecnología debe evaluarse en función de cada vertedero, ya que las necesidades de infraestructura pueden hacer que el desarrollo de la captura de gas de vertedero sea más costoso.

Los alimentos desechados y otros residuos orgánicos liberan metano al descomponerse en los vertederos en condiciones de poco oxígeno (anaeróbicas). La desviación de residuos orgánicos de los vertederos puede reducir significativamente las emisiones de metano[253]. Los programas para reducir el desperdicio de alimentos pueden disminuir las emisiones de metano tanto del sector de los residuos como del agrícola[254]. Esto puede incluir la promoción de estrategias para gestionar la exposición al calor extremo y aumentar el acceso a la refrigeración por parte de los productores agrícolas a pequeña escala con el fin de reducir el desperdicio de alimentos debido al adelanto de las cosechas provocado por un clima más cálido[255]. En el caso de los residuos orgánicos ya presentes en un vertedero, las cubiertas biológicamente activas o biocubiertas, compuestas por residuos verdes/compost, limitan las emisiones de metano estimulando la oxidación microbiana del metano[256]. Los índices de oxidación del metano varían en función del tipo de vertedero, la ubicación y la composición/espesor de la biocubierta, pero el uso de cubiertas biológicas puede dar resultados impresionantes: los estudios han arrojado mejoras de más del 60%, y en algunos casos de casi el 80%[257], en la oxidación del metano[258]. Las cubiertas biológicas pueden utilizarse en vertederos inactivos como tecnología de control de las emisiones de metano restantes tras el cierre[259]. Debido a su costo relativamente bajo (en comparación con la recolección de gases de vertedero), a su sencilla aplicabilidad técnica[260] y a su posible vida útil de 6-7 años con una disminución limitada de su rendimiento[261], pueden ser una solución para reducir las emisiones de metano en vertederos explotados en países de ingresos bajos con una capacidad de gestión limitada[262]. Las cubiertas biológicas también han demostrado su eficacia en jurisdicciones desarrolladas, como Dinamarca, donde se emplea simultáneamente la tecnología de captura de gases de vertedero para optimizar la reducción de metano[263]. También se ha comprobado que las medidas de mitigación de olores están relacionadas con la reducción de las emisiones de metano[264]. Si se combinan con una mejor gestión de los vertederos, estas medidas podrían reducir las emisiones de los vertederos de Estados Unidos en un 50% para 2030[265].

La teledetección aérea es una opción probada para el monitoreo del metano en vertederos que tiene más probabilidades de cuantificar con precisión las emisiones que son difíciles de captar en los modelos tradicionales. En particular, la teledetección aérea es más flexible con respecto a los cambios de infraestructura de los vertederos y puede identificar tendencias importantes en las emisiones que podrían conducir a nuevas estrategias de mitigación[266]. Datos recientes obtenidos por satélite han revelado que las emisiones de los vertederos de Buenos Aires, Delhi, Lahore y Mumbai han sido subestimados en los cálculos habituales de los inventarios de emisiones[267]. Las estimaciones y el monitoreo de las emisiones de metano de los vertederos también podrían mejorarse al incorporar los factores específicos a cada sitio y las cualidades de la cubierta del suelo en las estimaciones de los modelos[268].

En el caso de las aguas residuales, McKinsey calcula que las medidas de mitigación podrían reducir las emisiones en un 27% para 2030 y en un 77% para 2050[269]. Los métodos para lograr esta reducción de las emisiones incluyen la mejora del tratamiento de las aguas residuales mediante la modernización de los procesos, las infraestructuras y la tecnología[270].

5. Fuentes naturales de metano e investigaciones emergentes sobre la eliminación del metano atmosférico y la prevención de su formación

Las fuentes naturales de metano representan aproximadamente el 40% (35-50%) de las emisiones e incluyen los humedales y otros sistemas de agua dulce, el deshielo del permafrost, las filtraciones geológicas, los animales salvajes y las fuentes oceánicas, incluidos los hidratos de metano del fondo marino[271]. Se prevé que algunas de estas fuentes naturales aumenten y actúen como retroalimentadores autorreforzantes del calentamiento provocado por el hombre. Mientras que la retroalimentación del metano del permafrost está bien establecida, aunque mal delimitada[272], se han sugerido nuevas retroalimentaciones para explicar la reciente aceleración de la concentración atmosférica de metano. Se trata de una combinación de retroalimentaciones positivas reforzadas debidas a las interacciones entre la temperatura de la superficie, las emisiones de los humedales y los incendios forestales, así como a la reducción de la eliminación de metano a través de retroalimentaciones negativas de radicales hidroxilos[273]. Además, según estudios recientes, las fuentes de los humedales tropicales podrían explicar más del 80% del rápido aumento de las concentraciones atmosféricas de metano entre 2010 y 2019, lo que podría ser el resultado de una retroalimentación entre el calentamiento y la fuerza del dipolo del Océano Índico y las precipitaciones sobre África Oriental[274]. Sin embargo, el informe del Grupo de Trabajo I del IPCC (IE6 del WGI) otorga un *nivel de confianza bajo* a la tendencia multidecadal del dipolo del Océano Índico debido a la escasez de datos anteriores a la década de 1960[275].

Otra preocupación es el riesgo de que el calentamiento de las aguas oceánicas desestabilice los hidratos de metano del fondo marino. Tal desestabilización se produjo probablemente en la costa de Guinea hace 125.000 años, durante el anterior período interglacial, y los registros de los núcleos de hielo sugieren que se liberó a la atmósfera una cantidad suficiente de metano como para afectar a las concentraciones de CO_2 y CH_4[276]. Con un Ártico que se calienta rápidamente, el lecho marino poco profundo de la plataforma ártica de Siberia Oriental plantea importantes preocupaciones debido a su potencial para acelerar otros impactos del calentamiento global[277]. La liberación de hidratos de metano terrestres a medida que los glaciares retroceden podría amplificar aún más la retroalimentación del permafrost[278].

Se está investigando cuál es el mejor enfoque para eliminar el metano atmosférico[279]. Esta estrategia podría ser vital para combatir el metano procedente de fuentes naturales[280]. Estas fuentes incluyen el calentamiento de los humedales tropicales y árticos y las turberas que parecen estar emitiendo más metano como parte de una retroalimentación que se refuerza a sí misma entre el clima y el ciclo del carbono[281]. El IE6 del WGI estima que la liberación de metano procedente del deshielo del permafrost podría alcanzar los 4.100 millones de toneladas hasta 2.100 con los compromisos climáticos actuales[282].

Un estudio de modelización dirigido por la Universidad de Stanford calcula que la eliminación de las emisiones de metano causadas por el hombre en unos tres años reduciría el calentamiento en 0,21 °C[283]. Dos posibles categorías de estrategias de eliminación de metano son la oxidación catalítica[284] y la oxidación microbiana mejorada[285].

Se están explorando muchas estrategias y tecnologías dentro de cada categoría. Recientemente, un grupo de investigación del Instituto Tecnológico de Massachusetts (MIT, por sus siglas en inglés) identificó un material arcilloso capaz de oxidar los niveles atmosféricos de metano a temperaturas relativamente bajas[286]. Otro ejemplo son los aerosoles de sales de hierro que se han propuesto como un mecanismo rentable para oxidar el metano atmosférico[287]. Se han realizado experimentos con filtros que contienen microbios comedores de metano para procesar metano relativamente concentrado, como el que se encuentra en las minas de carbón y sobre los vertederos y las lagunas de estiércol[288].

Las alternativas a la eliminación del metano pueden incluir medidas para evitar su formación natural. Estudios preliminares sugieren que el uso de aditivos como el biocarbón (carbono negro producido a partir de la pirólisis de biomasa), ácidos, paja o tecnología basada en sulfato cálcico dihidratado (yeso) podría reducir las emisiones de metano procedentes de lagunas de estiércol, arrozales y otras fuentes antropogénicas de metano[289]. Podrían aplicarse métodos similares a fuentes naturales y seminaturales, como humedales y embalses.

Para más información, *véase* Institute for Governance & Sustainable Development (2022) METHANE REMOVAL: *R&D needed for removing methane from the atmosphere*, Nota Informativa.

6. Los principales países emisores están aplicando y deben reforzar las medidas de mitigación del metano

Los gobiernos nacionales y subnacionales están desarrollando y aplicando cada vez más políticas e iniciativas de mitigación del metano. Sin embargo, estas medidas deben ampliarse y reforzarse para lograr las reducciones de metano necesarias a corto plazo[290]. Los gobiernos pueden reforzar las políticas de mitigación del metano aplicando al máximo las tecnologías, leyes y estructuras de gobernanza ya disponibles y estudiando formas de ampliar la mitigación del metano a través de otras vías disponibles. La AIE ha elaborado una Hoja de ruta y un Paquete de Herramientas Regulatorias para la Reducción de las Fugas de Metano en la Industria del Petróleo y el Gas[291]. La base de datos de políticas de la IEA incluye las políticas de reducción de metano de sus países miembros en todo el mundo. A continuación se describen ejemplos de medidas específicas de mitigación del metano en Estados Unidos, la Unión Europea, Canadá, México, India, China, Brasil e Irak. También cabe destacar la finalización de las regulaciones de Colombia en febrero de 2022, que la convierte en el primer país de Sudamérica en regular las emisiones procedentes del petróleo y el gas[292].

A. Estados Unidos

Estados Unidos se fijó el objetivo de alcanzar emisiones netas de gases de efecto invernadero iguales a cero a más tardar en 2050, con un objetivo intermedio de alcanzar, en 2030, una reducción del 50-52% respecto a los niveles de emisiones de gases de efecto invernadero de 2005[293]. En noviembre de 2021, la Casa Blanca publicó el *Plan de Reducción de Emisiones de Metano de Estados Unidos*, una iniciativa de todo el gobierno y un modelo para adoptar un enfoque sectorial para reducir las emisiones de metano[294]. Como parte del Plan, la Agencia de Protección Ambiental (EPA, por sus siglas en inglés) propuso una serie de regulaciones en virtud de la Ley de Aire Limpio para establecer requisitos de control de emisiones más estrictos para las operaciones de gas y petróleo en forma de límites a la fuga y el venteo para las emisiones de metano procedentes de fuentes de petróleo y gas nuevas y existentes[295]. La EPA calcula que, si se aprueban, las regulaciones reducirán 41 millones de toneladas de metano hasta 2035[296]. La Oficina de Gestión de Tierras también ha restablecido normas para evitar los residuos procedentes del venteo, la quema en antorcha y las fugas producto de la explotación de petróleo y gas en tierras federales, que se prevé que reduzcan las emisiones de metano en un 35% con respecto a la línea de base de 2014[297]. Además, el Departamento de Transporte está ultimando normas para reducir las fugas en todo el sistema de gasoductos[298]. Sin embargo, los informes indican que la administración Biden está aprobando más permisos de perforación en terrenos públicos que las administraciones anteriores[299].

El 31 de enero de 2022, la administración Biden anunció los próximos pasos del Plan de Reducción de Emisiones de Metano de Estados Unidos, empezando por la asignación de 1.150 millones de dólares a los Estados para que limpien los pozos de petróleo y gas abandonados[300]. Los siguientes pasos de este Plan incluyen la aplicación de la Ley de Protección de Nuestra Infraestructura de Oleoductos y Aumento de la Seguridad (PIPES, por sus siglas en inglés) para garantizar que los operadores de oleoductos minimicen las fugas de metano, haciendo hincapié en los actuales esfuerzos de investigación e inversiones para reducir el metano procedente del ganado, y asignando 11.300 millones de dólares en financiación para la recuperación de tierras de minas abandonadas y 1.000 millones de dólares para la modernización de oleoductos de gas natural. Como parte del Plan, la administración Biden anunció la creación de un grupo interinstitucional para coordinar la medición, monitoreo, notificación y verificación del metano, y convocó un taller para las comunidades del sector de la energía sobre la reutilización de las infraestructuras de combustibles fósiles[301].

El *Plan de Reducción de Emisiones de Metano de Estados Unidos* también incluye regulaciones y programas para reducir el metano procedente de otras fuentes[302]. La EPA está aplicando normas y requisitos actualizados de reducción de emisiones para los vertederos municipales de residuos sólidos (originalmente se estimaba que reducirían las emisiones de metano en más de 300.000 toneladas métricas de metano al año)[303]. La EPA también está realizando un seguimiento de otros muchos esfuerzos para reducir el metano, incluidos los proyectos de digestores anaeróbicos de ganado y de captura de gases de vertedero[304].

En agosto de 2022, el Departamento de Energía de Estados Unidos anunció una financiación de hasta 32 millones de dólares para la investigación y el desarrollo de tecnologías de monitoreo, medición y otras tecnologías de mitigación para detectar y reducir las emisiones de metano en el sector del petróleo y el gas[305].

Además, el gobierno federal está gestionando una serie de iniciativas voluntarias que incentivan la reducción de metano y proporcionan apoyo técnico para reducir estas emisiones. Entre ellas se incluyen el *Food Waste Challenge* (Desafío para reducir el desperdicio de alimentos) con el fin de reducir el desperdicio de alimentos en un 50% para 2030[306], el *Landfill Methane Outreach Program* (Programa de divulgación del metano de vertedero) que promueve la captura y el uso del gas de vertedero[307], el *Coalbed Methane Outreach Program* (Programa de divulgación del metano en capas de carbón) que promueve el uso del metano de las minas de carbón[308] y el Programa *AgStar* que pretende reducir las emisiones de metano de los residuos ganaderos[309]. El Departamento de Agricultura de Estados Unidos también ha anunciado una financiación de 1.000 millones de dólares en concepto de *Partnerships for Climate-Smart Commodities* (Asociaciones para materias primas climáticamente inteligentes) para fomentar la aplicación de prácticas inteligentes en términos climáticos, incluidas las prácticas que mitigan las emisiones de metano, como la gestión del estiércol, la gestión de los piensos para reducir las emisiones entéricas y el humedecimiento y secado alternativos de los arrozales[310].

El 2 de diciembre de 2021, la Agencia de Proyectos de Investigación Avanzada–Energía (ARPA-E, por sus siglas en inglés) del Departamento de Energía anunció 12 seleccionados que recibirán un total de 35 millones de dólares en subvenciones para reducir las emisiones de metano de los sectores del petróleo, el gas y el carbón. Estos proyectos incluyen la investigación sobre la reducción de las emisiones de metano de los motores de gas natural, las antorchas de gas y los pozos de las minas de carbón[311]. Según la ARPA-E, estas tres fuentes contribuyen a al menos el 10% de las emisiones antropogénicas de metano de Estados Unidos[312]. Al desarrollar el programa REMEDY (Reducción del metano todos los días del año), la ARPA-E reconoció la necesidad de seguir investigando sobre la captura de metano del aire en paralelo a los esfuerzos para capturar CO_2[313]. En julio de 2022, el presupuesto de ARPA-E se duplicó gracias a la Ley CHIPS y Ciencia[314].

Como parte de la Ley de Inversión en Infraestructura y Empleos promulgada en noviembre de 2021, el gobierno de Estados Unidos está distribuyendo subvenciones para impulsar la acción climática. El Departamento de Energía distribuirá casi 11.000 millones de dólares en subvenciones para minas abandonadas entre los Estados y tribus eligibles a lo largo de 15 años[315]. Se alienta a los Estados con minas no recuperadas incluidas en la Base de Datos de Oportunidades de Minas de Carbón con Metano de la EPA a dar prioridad a la recuperación de dichas minas, eliminando las emisiones de metano “en la mayor medida posible”[316]. El Departamento de Agricultura también está invirtiendo 10 millones de dólares en un Programa Piloto de Bioproductos para “avanzar en el desarrollo de bioproductos competitivos en términos de costos y con beneficios medioambientales en comparación con los productos tradicionales”[317], incluidos los productos con menor huella de carbono[318].

La Ley de Reducción de la Inflación de 2022, aprobada en agosto, destina casi 370.000 millones de dólares de financiación para el clima, incluidos 1.550 millones para controlar y reducir las emisiones de petróleo y gas[319]. La ley incluye un Programa de Reducción de Emisiones de Metano con una tasa de residuos de metano de hasta 1.500 dólares por tonelada de metano para 2026[320], y aumenta las tasas de regalías para el petróleo y el gas extraído de tierras y aguas federales, incluidas las tasas sobre el gas que se pierde de forma evitable por la quema en antorcha o el venteo en casos que no son de emergencia[321]. La Ley destinará unos 20.000 millones de dólares en los próximos cuatro años a subvenciones para la conservación de la agricultura, que darán prioridad a las cuestiones climáticas, incluida la mitigación del metano[322]. Se calcula que esta ley reducirá para 2030 las emisiones de gases de efecto invernadero de Estados Unidos un 40% por debajo de los niveles de 2005[323].

Mientras tanto, la Ley CHIPS y Ciencia de 2022 también amplió la financiación para la investigación sobre el clima y los sistemas terrestres, incluyendo un Centro de Mediciones, Normas e Información sobre Gases de Efecto Invernadero[324].

Recuadro 4. Los gobiernos subnacionales demuestran su liderazgo en la mitigación del metano

Los estados de Estados Unidos también están trabajando para reducir las emisiones de metano en el sector del petróleo y el gas. California estableció el objetivo legislativo de reducir las emisiones de metano en un 40% para 2030[325]. En 2014, Colorado aprobó las primeras regulaciones sobre metano del país, que obliga a las empresas del sector de la energía a reducir las emisiones de metano de las instalaciones de petróleo y gas natural nuevas y existentes. Colorado sigue reforzando sus regulaciones sobre petróleo y gas, prohibiendo las prácticas de rutina de quema y venteo en 2020[326]. En la Cumbre de las Américas de junio de 2022, California dio a conocer el Compromiso Climático de California, que incluye una propuesta presupuestaria para sanear pozos petrolíferos inactivos (200 millones de dólares) y lanzar satélites de detección de metano (100 millones de dólares)[327]. En 2021, Colorado adoptó normas para reducir las emisiones de metano de los controladores neumáticos[328]. Nuevo México hizo lo propio, promulgando normas estrictas para el sector del petróleo y el gas, y prohibiendo también todas las prácticas de rutina de quemas y venteo[329]. Se espera que una norma más reciente de Nuevo México reduzca aún más las emisiones[330].

Los miembros de la Alianza del Clima de Estados Unidos, que incluye a los gobiernos de 24 Estados y a Puerto Rico, se han propuesto reducir las emisiones de metano en todos los sectores entre un 40 y un 50% para 2030[331]. Este objetivo incluye la reducción de las emisiones del sector energético en un 40-45% para 2025[332], y del sector de los residuos en un 40-50% para 2030[333]. Los miembros también tienen previsto reducir las emisiones de metano del sector agrícola, incluida la reducción de emisiones de la fermentación entérica en un 30%[334], y hasta un 70% de la gestión del estiércol, para 2030[335]. Además, los Estados y municipios han promulgado políticas que prohíben o desvían los residuos orgánicos de los vertederos y pretenden reducir el desperdicio de alimentos[336].

Las instituciones de investigación y de otros ámbitos también están desarrollando herramientas para las jurisdicciones subnacionales, como los marcos de protocolos sectoriales para la reducción de las emisiones de metano, que involucran a los gobiernos en acciones como inventarios, bases de referencia, establecimiento de objetivos, aplicación de políticas e intercambio de información[337].

La Alianza del Clima, la Energía Limpia y el Medio Ambiente de América del Norte creada por Estados Unidos, Canadá y México en 2016 ha acordado reducir las emisiones de metano del sector del petróleo y el gas en un 40-45% para 2025[338]. Los socios se comprometieron a desarrollar e implementar regulaciones federales para reducir las emisiones de las nuevas fuentes existentes en el sector del petróleo y el gas, así como a desarrollar e implementar estrategias nacionales de reducción de metano para sectores clave lo antes posible, incluyendo los sectores de gas y petróleo, la agricultura y la gestión de residuos y alimentos[339]. *Véanse* las subsecciones a continuación sobre las medidas de Canadá y México para cumplir con este objetivo. En julio de 2022, Estados Unidos y México se comprometieron juntos a "abordar las emisiones de metano procedentes del petróleo y el gas y de otros sectores"[340]. Además, Estados Unidos es Parte del Convenio sobre la Contaminación Atmosférica Transfronteriza a Gran Distancia (LRTAP, por sus siglas en inglés), que está examinando los impactos del metano en la formación de ozono, el cual se analiza con más detalle en la **Sección 10**[341].

En respuesta al impacto de la actual invasión rusa de Ucrania en la energía a nivel mundial, la Casa Blanca acordó ayudar a la transición de la UE para abordar su dependencia del gas ruso, intentando garantizar envíos adicionales de 15 bmc de gas natural licuado (GNL) en 2022, además de "mantener un ambiente regulatorio propicio" con respecto al desarrollo de nuevas capacidades de exportación de gas natural licuado. Sin embargo, también acordó "emprender esfuerzos para reducir la intensidad de gases de efecto invernadero de todas las nuevas infraestructuras de GNL y gasoductos asociados"[342]. La Comisión Federal Reguladora de la Energía también dio marcha atrás en una nueva política de evaluación del impacto climático de las emisiones de los gasoductos[343]. Esto destaca la importancia de tomar medidas inmediatas para exigir reducciones progresivas de las tasas de emisión de metano procedentes del "gas metano de sustitución" suministrado en respuesta a los cambios en las importaciones de gas metano de los países, teniendo en cuenta los compromisos asumidos en el marco del *Compromiso Mundial sobre el Metano*[344].

El 12 de mayo de 2022, los líderes de Estados Unidos y de la Asociación de Naciones del Sudeste Asiático (ASEAN, por sus siglas en inglés) acordaron, en la Cumbre Especial celebrada entre Estados Unidos y ASEAN en Washington, D.C., aumentar su ambición colectiva para, entre otras cosas, reducir las emisiones de metano. La hoja informativa de la Cumbre Especial indica:

> "Estados Unidos se ha comprometido a trabajar con las naciones del Sudeste Asiático para reducir las emisiones de metano de la región. Estados Unidos acogió con satisfacción la adhesión de Indonesia, Vietnam, Malasia, Filipinas y Singapur al Compromiso Mundial sobre el Metano en la COP-26, y estamos acelerando la asistencia técnica, los recursos financieros y el desarrollo de proyectos para la mitigación del metano en los países del Compromiso Mundial sobre el Metano, incluso a través de la EPA, la USTDA [Agencia de Comercio y Desarrollo de Estados Unidos], la DFC [Corporación Financiera de Desarrollo] y el EXIM [Banco de Exportación e Importación], así como el recientemente creado Global Methane Hub, un fondo filantrópico que puede apoyar las prioridades de mitigación del metano en la región[345]".

Estados Unidos también tiene acuerdos de colaboración con Brasil en materia de energía. El Foro de Energía entre Estados Unidos y Brasil es un mecanismo para que los dos gobiernos intercambien conocimientos técnicos, regulatorios y políticos, incluida la gestión del carbono y el metano[346]. En agosto de 2022, Estados Unidos y Brasil lanzaron el Diálogo de la Industria de Energía Limpia, un foro bilateral liderado por el sector privado y la industria para promover la energía limpia, incluyendo la eólica marina y el hidrógeno limpio[347]. En la **Sección 6.G.** también puede encontrarse una descripción de estos avances.

La industria estadounidense del petróleo y el gas ha fundado múltiples iniciativas relacionadas con las emisiones de metano. La *Environmental Partnership* es una asociación de 97 empresas estadounidenses de petróleo y gas natural concebida para mejorar los resultados medioambientales mediante el intercambio de información, incluidas las mejores prácticas en materia de LDAR, quema en antorcha y otras tecnologías[348]. La *ONE Future Coalition* es una asociación de 50 empresas de gas natural con el objetivo colectivo de reducir las emisiones de metano en toda la cadena de valor del gas natural a un 1% o menos para 2025[349]. La *Natural Gas Sustainability Initiative*, lanzada por Edison Electric Institute, American Gas Association y otras organizaciones del sector, publicó un protocolo para informar sobre la intensidad de las emisiones de metano[350].

En el sector del carbón, la EPA de Estados Unidos documentó 53 proyectos actuales de recuperación de metano de minas de carbón y perfila oportunidades de proyectos en otras minas emisoras de gas[351]. La EPA estimó en 2019 que los proyectos de recuperación en algunas de las minas más gaseosas estaban capturando u oxidando más de 700.000 toneladas de metano al año[352]. Sin embargo, la producción global de metano de las minas de carbón se ha reducido a la mitad desde 2008, pasando de aproximadamente 57 bmc en 2008 a 23 bmc en 2020[353].

B. Unión Europea

La Unión Europea aborda el metano en sus políticas y trabaja para reforzarlas. La Legislación Europea sobre el Clima incluye un objetivo vinculante para que Europa logre la neutralidad climática de aquí a 2050, con un objetivo provisional de reducir todas las emisiones de gases de efecto invernadero en un 55% para 2030, con respecto a los niveles de 1990[354]. La Comisión Europea presentó una estrategia sobre el metano en octubre de 2020 y señaló que el objetivo del 55% requeriría que la Unión Europea redujera las emisiones de metano en un 35-37% para 2030[355]. Además, la estrategia sobre el metano da prioridad a garantizar un sistema de medición y notificación más preciso de las emisiones del sector privado[356].

En julio de 2021, la Comisión Europea adoptó una serie de propuestas, conocidas como el paquete de medidas "Objetivo 55", que permitirían alcanzar el objetivo de reducir las emisiones netas de gases de efecto invernadero en al menos un 55 % de aquí a 2030[357]. El paquete de medidas "Objetivo 55" aumentaría la ambición de los sectores no cubiertos por el Régimen de Comercio de Derechos de Emisión, como la gestión de residuos, la construcción y la agricultura, incrementando el objetivo global de reducción de emisiones del 30% al 40%[358]. El paquete también modificaría el Reglamento de la UE sobre el Uso de la Tierra, el Cambio de Uso de la Tierra y Silvicultura para incluir las emisiones distintas del CO_2, incluido el metano, de aquí a 2031[359]. Más de la mitad de las emisiones nacionales de metano de la Unión Europea se producen en el sector agrícola[360], mientras que la mayor parte de las emisiones de metano procedentes del uso de la energía se producen en el exterior[361]. Algunos analistas han llegado a la conclusión de que la Unión Europea no logrará grandes reducciones de las emisiones nacionales de metano sin "políticas que impulsen la adopción de medidas técnicas y de comportamiento en el sector agrícola-ganadero"[362].

En diciembre de 2021, la Comisión propuso un reglamento y una directiva[363] basadas en una combinación energética propuesta para 2050 en la que el biogás, el biometano, el hidrógeno renovable e hipocarbónico (véase el **Recuadro 5**) y el metano sintético representarían dos tercios de los combustibles gaseosos, y el resto provendría del gas fósil acompañado de la captura y el almacenamiento de carbono (una reducción del 95% del gas fósil en 2021). La directiva propone limitar la vigencia de los contratos de gas natural a largo plazo más allá de 2049[364].

El reglamento propuesto exige a los operadores de petróleo y gas que informen sobre las emisiones de metano a nivel de fuente, incluida la introducción progresiva de mediciones directas y mediciones in situ de los activos no explotados[365]. El reglamento también exige a los operadores que establezcan programas de detección y reparación de fugas (LDAR, por sus siglas en inglés) y prohíban el venteo y la quema en antorcha rutinarios[366]. Las inspecciones reglamentarias y la información del Observatorio Internacional de Emisiones de Metano verificarían el cumplimiento de este reglamento[367].

Además, los reglamentos propuestos exigirían que los Estados miembros hicieran un inventario público de los pozos de petróleo y gas inactivos. También exigirían que los Estados miembros u otras partes responsables controlasen las emisiones de metano y elaborasen planes de mitigación para la reparación, recuperación y taponamiento permanente[368]. El reglamento también obligaría a los Estados miembros a elaborar un inventario público de las minas de carbón cerradas y abandonadas, y exigiría a los Estados miembros con jurisdicción sobre las minas abandonadas y a los operadores de minas cerradas que controlen y notifiquen las concentraciones de metano en las minas cerradas o abandonadas en los últimos 50 años[369]. Además, el reglamento propuesto exige planes de mitigación y prohíbe el venteo y la quema en antorcha innecesarios[370].

El reglamento propuesto también especifica que las minas de carbón subterráneas y las estaciones de drenaje realicen mediciones continuas de las emisiones, mientras que las minas de superficie deberán emplear factores de emisión específicos del yacimiento para cuantificar las emisiones[371]. Las minas subterráneas y de superficie calculan las emisiones posteriores a la extracción basándose en los factores pertinentes y notifican todas las emisiones a los organismos reguladores[372]. A las minas subterráneas se les prohibiría el venteo y la quema en antorcha rutinarios y se les exigiría que informaran de los casos de quema en antorcha[373].

Asimismo, el reglamento propuesto no incluía objetivos de reducción específicos y vinculantes[374]. La Unión Europea había considerado la posibilidad de establecer requisitos de intensidad de metano para el gas importado[375], pero tales requisitos aún no figuran en ninguna propuesta oficial. En su lugar, la Unión Europea reiteró un llamamiento a la transparencia y remitió el asunto a la Agencia de Cooperación de los Reguladores de la Energía y al Comité de Responsables Europeos de Reglamentación de Valores[376]. El reglamento propuesto requeriría que los importadores de la UE presenten información adicional sobre los esfuerzos de mitigación de metano de los exportadores y productores, y establezcan una Base de Datos de Transparencia sobre el Metano y una herramienta de seguimiento mundial del metano[377]. En 2019, la Unión Europea importó casi el 90% de su gas natural, principalmente de Rusia[378]. Un reglamento de julio de 2022 permitió, polémicamente, la certificación, en circunstancias limitadas, de parte del gas natural bajo la taxonomía de inversión sostenible de la UE[379].

La Directiva de Vertederos de la UE obliga a los Estados miembros a separar los residuos biodegradables y establece el objetivo de verter solo el 10 % de los residuos sólidos municipales para 2035[380]. Los requisitos para que se desvíen los residuos orgánicos ayudaron a lograr un descenso del 47% en las emisiones de los vertederos de la UE entre 1990 y 2017[381].

Además, la Comisión Económica de las Naciones Unidas para Europa (CEPE) está estudiando el papel del metano como precursor de la formación de ozono en la región de la CEPE como parte de su trabajo en el marco del LRTAP[382]. La región de la CEPE incluye a toda Europa, así como a países de Norteamérica, Asia Central y Asia Occidental. Para más información, *véase* la **Sección 10**.

Antes de la invasión rusa de Ucrania en febrero de 2022, la Unión Europea importaba de Rusia más del 40% de su consumo total de gas[383]. La Unión Europea ha respondido a esta cambiante situación geopolítica anunciando la aceleración de su transición para dejar de utilizar la energía fósil[384]. El 23 de marzo de 2022, la Comisión Europea presentó una propuesta legislativa para aumentar sus niveles de almacenamiento de gas en un 80% para noviembre de 2022[385]. Además, emitió un comunicado en el que declaraba sus planes para formar un Grupo de Trabajo sobre Compras Comunes de Gas que "preparará el terreno para asociaciones energéticas con proveedores clave de GNL, gas e hidrógeno en el Mediterráneo, África, Oriente Medio y Estados Unidos"[386]. El 25 de marzo de 2022, la Casa Blanca y la Comisión Europea sobre Seguridad Energética Europea anunciaron que garantizarían procedimientos regulatorios expeditivos para las infraestructuras de GNL, pero también hicieron hincapié en sus esfuerzos por reducir la intensidad de las emisiones de dichas infraestructuras[387]. En particular, el 8 de mayo de 2022, el G7 se comprometió a "eliminar gradualmente nuestra dependencia de la energía rusa, incluida la eliminación progresiva o la prohibición de la importación de petróleo ruso", pero no mencionó específicamente el gas[388].

La Comunicación Conjunta sobre el Compromiso Energético Exterior de la UE, publicada el 18 de mayo de 2022, expone los esfuerzos actuales y los planes futuros de la región para diversificar su suministro energético. Esto incluye asociaciones para aumentar las importaciones de gas natural licuado de otros países, como Egipto, Israel, Japón y Corea[389], y un compromiso para "garantizar que los suministros adicionales de gas procedentes de los proveedores de gas existentes y nuevos se combinen con medidas específicas para solucionar las fugas de metano, el venteo y la combustión en antorcha" [390]. Desde entonces, la Unión Europea ha firmado memorandos de entendimiento sobre cooperación energética con Israel, Egipto y Azerbaiyán, destinados a "permitir un suministro estable de gas natural a la UE que sea coherente con los objetivos de descarbonización a largo plazo y se base en el principio de fijación de precios orientada al mercado"[391]. La Unión Europea no especifica ninguna intención de promulgar reglamentos para controlar las emisiones de metano procedentes de las importaciones de energía, pero aumentará el apoyo para desarrollar un mercado mundial del hidrógeno, empezando por asociaciones con "con países socios fiables para garantizar unas relaciones comerciales y de inversión abiertas y no distorsionadas en el ámbito de los combustibles renovables y con bajas emisiones de carbono"[392]. Además, dará prioridad al ahorro y la eficiencia energéticos, con el objetivo de lograr una reducción del 5 % de la demanda de petróleo y gas a corto plazo[393].

Recuadro 5. Riesgos y beneficios climáticos limitados del cambio al hidrógeno

El hidrógeno se propone como alternativa energética limpia, especialmente para sectores difíciles de descarbonizar como la industria pesada, el transporte marítimo y la aviación. Los beneficios climáticos del hidrógeno como sustituto de los combustibles fósiles dependen de varios factores: 1) la fuente de la energía utilizada para generar el hidrógeno y sus emisiones y el grado de captura de carbono en el caso del "hidrógeno azul"; 2) la tasa de fuga de metano si se utiliza como fuente de hidrógeno o fuente de energía, con tasas de fuga de metano incluso bajas, del 1,54%, que dan lugar a emisiones de GEI más altas que la quema de gas natural para obtener energía[394]; y 3) la tasa de fuga del propio hidrógeno, que puede contribuir al calentamiento al prolongar la vida útil del metano y otros GEI. Las estimaciones preliminares sugieren que una tasa de fuga de hidrógeno del 10% en un escenario de alto despliegue podría causar al menos 0,1°C de calentamiento, lo que podría compensar el calentamiento evitado en 2050 por el despliegue de todas las opciones de mitigación del metano rentables actualmente a nivel mundial[395]. Una fuga elevada de hidrógeno combinada con crecientes emisiones de metano podrían añadir hasta 0,4 °C de calentamiento[396].

C. Canadá

Canadá se comprometió a reducir las emisiones en un 40-45% por debajo de los niveles de 2005 para 2030, incluida una reducción del 40-45% de las emisiones de metano procedentes del sector del petróleo y el gas, y alcanzar las emisiones netas cero para 2050[397]. Como parte de su participación en el *Compromiso Mundial sobre el Metano*, Canadá pretende reducir las emisiones de metano procedentes del petróleo y el gas en un 75%[398]. Las regulaciones canadienses vigentes abarcan las instalaciones de petróleo y gas nuevas y existentes, e incluyen requisitos más estrictos de detección y reparación de fugas y, cuando se apliquen plenamente, límites cuantitativos al venteo de gas natural[399]. El gobierno anunció en abril que tenía previsto publicar nuevas directivas sobre los proyectos de petróleo y gas[400].

En cuanto a los vertederos, Canadá se comprometió a aumentar el número de vertederos que recolecten y capturen eficazmente el metano[401]. El gobierno federal de Canadá trabaja con los gobiernos provinciales y locales para concientizar sobre los residuos alimentarios y las opciones de eliminación con el objetivo de reducir la cantidad de residuos orgánicos que se depositan en vertederos[402]. A su vez, los gobiernos locales y provinciales desarrollaron objetivos[403], planes[404] e incentivos fiscales[405] para reducir el desperdicio de alimentos.

Además, el gobierno federal está poniendo en marcha programas para incentivar la agricultura climáticamente inteligente y la reducción de las emisiones de GEI del sector agrícola. El programa de Soluciones Climáticas Agrícolas invierte en soluciones climáticas naturales, como el aumento del almacenamiento de carbono en las granjas[406]. El Programa de Tecnología Agrícola Limpia apoya las reducciones de metano en el sector agrícola invirtiendo en energía verde y tecnologías que utilicen el estiércol y otros residuos como fuente de energía[407].

En febrero de 2021, Canadá y Estados Unidos declararon un "compromiso compartido para reducir las emisiones de metano procedentes del petróleo y del gas con el fin de proteger la salud pública y el medio ambiente, guiado por los mejores conocimientos científicos"[408]. Además, Canadá es Parte del Convenio LRTAP, que está examinando los impactos del metano en la formación de ozono, como se explica con más detalle en la **Sección 10**[409].

D. México

Además de los objetivos relativos al metano derivados de la Alianza del Clima, Energía Limpia y Medio Ambiente de América del Norte conformada en 2016, México publicó una normativa integral para la reducción de las emisiones de metano en el sector del petróleo y el gas que reconoce el potencial de reducir las emisiones de este sector hasta en un 75% para 2025[410]. Estas disposiciones incluyen normas para la detección y reparación trimestral de fugas, el uso de sistemas de recuperación de vapores para capturar el gas, el paso a la neumática de bajo y cero sangrado, y prácticas con menos desperdicios. México también se adhirió al *Compromiso Mundial sobre el Metano*.

Las contribuciones previstas y determinadas a nivel nacional (NDC, por sus siglas en inglés) para México en virtud del Acuerdo de París incluyen objetivos para reducir las fugas de metano, el venteo y la combustión controlada en un 25% y para utilizar la recuperación de metano en los vertederos municipales y plantas de tratamiento de agua[411]. Estos objetivos forman parte de su compromiso de reducir las emisiones de GEI en al menos un 22% y hasta un 36% por debajo del escenario proyectado si no se introdujeran cambios para 2030[412]. La actualización de la NDC de México para 2020 confirma este compromiso e incluye una mención a la posible implementación de una Política de Reducción de las Emisiones de Metano[413].

Una de las prioridades para la reducción del metano en México es mejorar el monitoreo de las emisiones de metano con el fin de elaborar informes precisos. Por ejemplo, recientes mediciones por satélite han revelado que las emisiones de origen antropogénico son un 45% superiores a las estimadas en el inventario nacional de GEI, y que la mayor discrepancia entre las emisiones inferidas y las estimadas procede del sector del petróleo y el gas[414]. Otro estudio dirigido por el Fondo de Defensa del Medio Ambiente (EDF, por sus siglas en inglés) concluyó que las fugas de metano de las instalaciones de procesamiento en tierra eran 10 veces superiores a las notificadas, mientras que las emisiones de las instalaciones de procesamiento en alta mar eran un 90% inferiores a las notificadas. Según el EDF, esta conclusión sugiere que el gas de alta mar se conducía a tierra, donde posteriormente se quemaba o se filtraba. Se descubrió que las emisiones de una sola instalación que recibía gas de alta mar equivalían a la mitad del consumo residencial de gas de México[415].

El Presidente de México, Andrés Manuel López Obrador, y otros funcionarios mexicanos se reunieron el 9 de febrero de 2022 con el Enviado Especial Presidencial para el Clima, John Kerry, para continuar el diálogo entre Estados Unidos y México sobre la colaboración climática y acciones en torno a la energía limpia. Durante esta visita, las dos partes acordaron que el enfoque político de sus acciones "incluirá el control de las emisiones de metano provenientes del combustóleo y el gas, los desechos y la agricultura", entre otras áreas[416]. En julio de 2022, Estados Unidos y México se comprometieron a "abordar las emisiones de metano procedentes del petróleo y el gas y de otros sectores”, y a que Estados Unidos coopere con México y Pemex en un plan para eliminar la quema y venteo rutinarios[417]. Los satélites detectaron recientemente grandes columnas de metano procedentes de una plataforma petrolífera en alta mar en uno de los principales yacimientos petrolíferos de México, lo que pone de relieve la urgencia de abordar estas emisiones[418].

E. India

Según el tercer Informe Bienal de Actualización de la India para la CMNUCC, el metano representó 19,5 millones de toneladas (409 $MtCO_2e$, utilizando el PCG_{100} de 21 según el informe de la India), o el 14,43% de las emisiones totales de GEI de la India en 2016[419]. También según este Informe, las principales emisiones de GEI de la India procedentes del sector agrícola son el metano procedente de la fermentación entérica del ganado y del cultivo de arroz[420].

India trabaja para reducir las emisiones de metano en el sector agrícola. Dos métodos de cultivo de arroz en este país tienen por objeto reducir el uso de agua y las emisiones de metano: el sistema de intensificación del arroz y el arroz de siembra directa. El sistema de intensificación del arroz se utiliza en 24 de los 28 estados de la India[421], y el cultivo con el método de siembra directa se está implantando en casi 100.000 hectáreas de tierra[422]. India también está cambiando las tierras dedicadas al cultivo de arroz por otros cultivos que requieren menos agua y permiten así reducir las emisiones de metano[423]. Además, está aplicando métodos, incluidos aditivos para piensos, que aumentan la productividad de los animales productores de leche y reducen las emisiones de GEI[424]. India también ha puesto en marcha dos programas dedicados al biogás, denominados *Galvanising Organic Bio-Agro Resources* (Gobar-Dhan) y *New National Biogas and Organic Manure*[425].

Se calcula que la cantidad de metano en las capas de carbón de la India es de 91,8 billones de pies cúbicos repartidos en 11 estados[426]. Además, India ha identificado 233,30 billones de pies cúbicos de gas/petróleo de esquisto, cuya comercialización puede aumentar drásticamente las emisiones de metano[427].

En julio de 1997, el gobierno indio formuló su política *Coal Bed Methane* (política sobre el metano en las capas de carbón, CBM por sus siglas en inglés) para aprovechar su potencial y reducir las emisiones de metano procedentes de la minería de carbón. Gracias a esta política, el CBM es convertido en gas natural en virtud de las disposiciones de la Ley de Yacimientos Petrolíferos (Regulación y Desarrollo) de 1948 y de las Normas sobre Petróleo y Gas Natural de 1959 del Ministerio de Petróleo y Gas Natural de la India[428]. Para aprovechar el potencial del CBM, se han ofrecido a las empresas bloques productores de metano en capas del carbón mediante licitaciones competitivas. Hasta ahora, India ha adjudicado 30 bloques de CBM en cuatro rondas de licitaciones a empresas nacionales, privadas y mixtas[429].

La estrategia de la India para reducir las emisiones de metano del sector energético parece centrarse en la transición a las energías renovables y la mejora de la eficiencia energética[430]. En la India, se han debatido y planificado eventos de intercambio, capacitación y proyectos sobre el metano de las minas de carbón y el metano en las capas de carbón[431]. Se está desarrollando un proyecto de drenaje previo en una mina subterránea[432] y se han realizado estudios para determinar la viabilidad de otros proyectos sobre la reducción del metano de las minas de carbón[433].

Un acontecimiento de mayo de 2022 con posibles implicancias en la mitigación del metano es el anuncio de que tres autoridades ministeriales—el Ministerio de Ciencias de la Tierra, el Departamento de Ciencia y Tecnología y el Ministerio de Medio Ambiente, Bosques y Cambio Climático—

formarán un consorcio para “trabajar de forma cohesiva en la acción climática y en el cumplimiento de las Contribuciones Determinadas a Nivel Nacional de la India en virtud del Acuerdo de París”[434].

F. China

El 22 de septiembre de 2020, en la Asamblea General de la ONU, China anunció su objetivo de alcanzar la neutralidad de carbono antes de 2060[435]. Este objetivo a largo plazo abarca todos los GEI, incluido el metano. A corto plazo, el Proyecto del 14º Plan Quinquenal (2021-2025) de China para el Desarrollo Económico y Social Nacional y los Objetivos a Largo Plazo hasta el Año 2035 establece que China “reforzará el control de otros GEI como el metano, los HFC y los perfluorocarburos (PFC)" [436]. La destacada referencia al metano en este Plan otorga a los ministerios y organismos nacionales de China autoridad para incluir requisitos detallados sobre el metano en su 14to plan quinquenal de implementación para el período 2021-2025.

El 28 de octubre de 2021, China presentó a la Secretaría de la CMNUCC su NDC actualizada[437] y su Estrategia de Desarrollo a Medio Siglo, y a Largo Plazo, con Bajas Emisiones de Gases de Efecto Invernadero (Estrategia de Medio Siglo)[438]. En la NDC actualizada, China incorporó su objetivo de aumentar la cuota de los combustibles no fósiles en el consumo de energía primaria hasta alrededor del 25% en 2030 y señaló que ya se han gastado fondos en un importante proyecto, denominado “Desarrollo de grandes yacimientos de petróleo y gas y del metano en las capas del carbón”[439]. En su Estrategia de Medio Siglo, China incluyó su objetivo de seguir aumentando el porcentaje de combustibles no fósiles hasta más del 80% para 2060[440]. Tanto la NDC actualizada como la Estrategia de Mitad de Siglo enumeran acciones políticas para la reducción de las emisiones de metano. Además, con el fin de apoyar la consecución de los objetivos en materia de combustibles no fósiles y promover el despliegue de energías renovables, el 14to Plan Quinquenal de Trabajo Integral sobre la Conservación de la Energía y la Reducción de las Emisiones de China establece que la energía renovable no se contabilizará en los límites totales de consumo de energía para las localidades durante el período del 14to Plan Quinquenal (2021-2025)[441].

Para el sector de las minas de carbón, los objetivos de China incluyen: “para 2020, el volumen de extracción del metano de las capas de carbón (gas de las minas de carbón) alcanzará los 24 bmc, dentro de los cuales la producción de metano de las capas de carbón en tierra alcanzará los 10 bmc con una tasa de utilización superior al 90%; y la extracción de gas de las minas de carbón alcanzará los 14 bmc con una tasa de utilización superior al 50%”[442]. En una conferencia de prensa del Consejo de Estado celebrada el 27 de abril de 2021, el Ministerio de Ecología y Medio Ambiente anunció un plan para revisar las normas de emisión del metano de las capas de carbón y del gas de las minas de carbón[443]. Además, las directivas políticas de China sobre la neutralidad del carbono incluyen la ampliación del desarrollo y la utilización del metano en las capas de carbón[444]. Además, China anunció un plan para controlar estrictamente el aumento del consumo de carbón entre 2021 y 2025, y reducirlo gradualmente entre 2026 y 2030[445]. China también anunció objetivos subnacionales clave con implicancias para las emisiones de metano. Entre ellos se incluyen la reducción del consumo de carbón en Pekín, Tianjin, Hebei y las zonas circundantes en un 10% aproximadamente, la reducción del consumo de carbón en la región del Delta del Río Yangtsé en un 5% aproximadamente y el logro de un crecimiento negativo del consumo de carbón en la región de la Llanura de Fenwei para 2025[446].

En cuanto al sector del petróleo y el gas, China se ha fijado el objetivo de alcanzar el pico y la meseta de consumo de petróleo entre 2026 y 2030[447]. También pretende alcanzar el punto máximo de consumo de petróleo utilizado en el transporte terrestre en 2030[448]. Las NDC actualizadas de China incorporan acciones para reducir las emisiones de metano en este sector, incluso mediante el despliegue de tecnologías para la recuperación del gas asociado[449]. El 13º Plan Quinquenal de Desarrollo del Gas Natural de China (2016) incluye la promoción de tecnologías de recuperación del gas asociado a los yacimientos petrolíferos, el refuerzo de la detección de fugas de gas natural y la reducción de las emisiones fugitivas de GEI. La Alianza de Metano de Gas y Petróleo de China, una asociación de siete empresas chinas, se ha comprometido a reducir la intensidad media de las emisiones de metano de las empresas en la producción de gas natural por debajo del 0,25% para 2025, y a cooperar y compartir experiencias técnicas sobre el control de las emisiones de metano, incluidos los sistemas LDAR y de recuperación de gas[450]. También se espera que los esfuerzos de China para promover un transporte ecológico y limpio reduzcan el consumo de petróleo y contribuyan a mitigar las emisiones de metano. Ejemplos de los principales objetivos en el sector del transporte son aumentar el transporte impulsado por nuevas energías y energías limpias hasta aproximadamente el 40% [del total de transporte nuevo] por año en 2030 y lograr una tasa de despliegue no inferior al 70% para el transporte ecológico en ciudades con una población de un millón de habitantes o más en 2030[451].

En el sector agrícola, en 2017 China estableció el objetivo de lograr la "reutilización integral" de más del 75% del estiércol de la cría de ganado y aves de corral para 2020[452]. En 2021 elevó este objetivo a más del 80% del estiércol de ganado y aves de corral en todo el país para 2025[453]. China también aumentará la eficiencia de los fertilizantes y pesticidas químicos hasta el 43% para 2025[454], lo que también puede tener implicancias en la reducción de las emisiones de metano. Asimismo, está dando prioridad a las medidas de control de las emisiones agrícolas, incluyendo la promoción de plantas de arroz de bajas emisiones y alto rendimiento, la mejora de las técnicas agrícolas, el fomento del uso de fertilizantes orgánicos, la regulación del uso de fertilizantes químicos y pesticidas y el avance en el uso integral de la paja de los cultivos[455]. Además, la CCAC está colaborando con China para, entre otras cosas, investigar y desarrollar estrategias eficaces de mitigación del metano "como el control minucioso del agua, los fertilizantes, los antibióticos y el tipo de pienso, que no sólo pueden reducir las emisiones sino también aumentar la producción agrícola"[456].

En el sector de los residuos, China se ha fijado objetivos como alcanzar, de aquí a 2025, el 90% de eliminación inocua de los lodos urbanos[457], el 25% de utilización de los recursos de aguas residuales en las ciudades con escasez de agua a nivel de prefectura y superior[458], y el 40% de tratamiento de las aguas residuales domésticas en las zonas rurales[459]. Además, para 2030, la tasa media nacional de utilización de agua reciclada urbana aumentará hasta el 30%[460]. Asimismo, China se comprometió a aumentar la reutilización de los residuos domésticos urbanos hasta aproximadamente el 60% en 2025 y el 65% en 2030[461]. Este país también está promoviendo el reciclaje y la reutilización de los residuos sólidos industriales con el objetivo de aumentar la tasa de reutilización global de los residuos sólidos industriales a granel hasta el 57% en 2025[462]. Además, China anunció un plan para construir 100 ciudades con cero residuos para 2025[463]. La construcción de ciudades con cero residuos contribuirá a reducir las emisiones de metano gracias a las mejoras previstas en la eliminación de residuos sólidos en fuentes industriales, la reducción de vertederos de residuos domésticos, la gestión y reutilización de residuos ganaderos y el control de la aplicación de fertilizantes químicos y pesticidas[464].

Además de las políticas y objetivos nacionales de reducción de emisiones de metano descriptos anteriormente, China ha tomado una serie de medidas para mitigar el impacto climático y otros impactos ambientales de sus inversiones en el extranjero. Entre ellas figuran el compromiso de dejar de construir nuevas centrales eléctricas de carbón[465] y la publicación de directrices gubernamentales que recomiendan a las empresas chinas cumplir las normas internacionales vigentes o las propias de China si el país receptor de la inversión china 1) carece de normas medioambientales aplicables a la inversión y al proyecto en cuestión; o 2) cuenta con normas medioambientales para la inversión o el proyecto en cuestión que son inferiores a las normas internacionales vigentes o a las que se aplican a dichas inversiones y proyectos en China[466].

G. Brasil

Brasil es el quinto mayor emisor de metano del mundo[467], debido a su industria ganadera, que representa el 14% del rebaño bovino mundial[468]. Las emisiones totales de metano de Brasil ascendieron a aproximadamente 400 $MtCO_2e$ en 2020, de las cuales ~285 $MtCO_2e$ proceden únicamente del sector ganadero[469].

Brasil es signatario del *Compromiso Mundial sobre el Metano*. Para cumplir con sus obligaciones en el *Compromiso* y la CMNUCC, Brasil promulgó un decreto que creó la Estrategia Federal para Incentivar el Uso Sostenible del Biogás y el Biometano[470]. El decreto establece directrices para incentivar el desarrollo de mercados de carbono, el uso del biometano como fuente de energía renovable y de combustible, y la inversión en investigación científico-tecnológica[471]. Además, proporciona una lista no exhaustiva de residuos urbanos y rurales que pueden utilizarse para producir biogás y biometano, incluidos los residuos depositados en vertederos.

La Estrategia Federal, que incluye el Programa Metano Cero, introducirá créditos de metano en los mecanismos de mercado existentes[472]. Los créditos de metano que representan toneladas de metano no emitidas generarán ingresos adicionales para los proyectos de biogás y biometano. Antes del Programa Metano Cero, Brasil fomentaba el desarrollo de biocombustibles a través de RenovaBio, un mercado regulado de créditos de descarbonización que obliga a las empresas distribuidoras de combustibles fósiles a cumplir sus objetivos invirtiendo en empresas de biocombustibles[473].

En 2019, Estados Unidos y Brasil lanzaron el Foro de Energía entre Estados Unidos y Brasil como un mecanismo de cooperación en la gestión del carbono y el metano, la energía nuclear civil, las energías renovables, la eficiencia energética y la modernización de la red de suministro eléctrico. En su segunda reunión ministerial de 2022, los dos gobiernos acordaron "intercambiar experiencias en la gestión del carbono y el metano, y el secuestro y almacenamiento de carbono"[474]. Más recientemente, en agosto de 2022, Estados Unidos y Brasil también pusieron en marcha el Diálogo de la Industria de la Energía Limpia para colaborar en materia de energías renovables y combustibles sostenibles, incluida la energía eólica marina y el hidrógeno limpio[475].

H. Irak

El sector del petróleo y el gas de Irak contribuye en gran medida a las emisiones de metano, que representan aproximadamente el 9 % de las emisiones mundiales de metano del sector en 2019[476]. Irak también ha estado entre los 10 países que más han quemado en los últimos 10 años[477].

En 2020, Irak anunció que su Ministerio de Salud y su Ministerio de Medio Ambiente y Petróleo crearían un grupo de trabajo técnico interministerial para estudiar la naturaleza y la magnitud de las emisiones de metano del sector del petróleo y el gas del país[478]. Desde entonces, Irak ha incluido el metano en su NDC, se ha unido a la Asociación de la Coalición Clima y Aire sobre el Petróleo y Gas Metano y ha firmado el *Compromiso Mundial sobre el Metano*[479]. En 2022, el Ministerio de Medio Ambiente de Irak anunció que está trabajando con la Asociación Mundial para la Reducción de la Quema de Gas del Banco Mundial para desarrollar su hoja de ruta con el objetivo de quema cero en la producción de petróleo y gas para 2030[480].

7. La colaboración internacional es fundamental para combatir las emisiones de metano

Organizaciones e iniciativas públicas y privadas de todo el mundo, como las que se describen brevemente a continuación (y el *Global Methane Hub*), están colaborando en la mitigación del metano. Su colaboración es fundamental para fortalecer el consenso que apoye la acción contra el metano, incluso a nivel bilateral y multilateral. Las iniciativas que evalúan el rendimiento del metano pueden ser una parte cada vez más importante de esta colaboración a medida que el mundo se adapta a los cambios en el suministro mundial de gas natural y se centra en evaluar la intensidad de metano de los volúmenes de gas disponibles y el rendimiento asociado de los productores.

i. Organizaciones e iniciativas cuasi-gubernamentales

- *La Coalición Clima y Aire Limpio para Reducir los Contaminantes Climáticos de Vida Corta*

La Coalición Clima y Aire Limpio (CCAC, por sus siglas en inglés) facilita la mitigación del metano y el intercambio de información a todos los niveles, incluso mediante la publicación de los principales datos científicos. La CCAC es una asociación voluntaria con más de 70 socios estatales y regionales, y un número similar de socios no estatales[481]. Se ha propuesto que la CCAC actúe como Secretaría del *Compromiso Mundial sobre el Metano*. Esta coalición ayuda a los países a desarrollar planes para reducir los CCVC[482]. También ayuda a los países a aumentar la ambición de los objetivos de reducción de los CCVC que notifican en sus NDC bajo el Acuerdo de París. Aumentar el apoyo y la financiación de la CCAC reforzaría el intercambio de información y el apoyo técnico a los países, lo que conduciría a un aumento concertado de la ambición. Esto podría incluir una mayor ambición en relación con los informes sobre el metano en el marco de la Asociación CCAC sobre el Petróleo y Gas Metano, que se describe más adelante bajo el título ***Iniciativas impulsadas por la industria***. Esto también podría incluir la coordinación del apoyo a las "Oficinas Nacionales de Metano" y otras estructuras de mitigación del metano, adoptando el enfoque de fortalecimiento institucional que ha sido "un factor importante en el éxito" de los países en desarrollo para alcanzar los objetivos del Protocolo de Montreal (véase la **Sección 11**)[483].

El 9 de noviembre de 2021, la reunión Ministerial de la CCAC puso en marcha la Iniciativa Emblemática sobre el Metano, cuyos objetivos "a partir de 2022, serán fomentar y reforzar los compromisos de alto nivel para reducir el metano, acelerar y fomentar la concienciación, apoyar la planificación y la ejecución de estrategias, mejorar las herramientas y el análisis para apoyar las medidas y aumentar la financiación"[484].

Los esfuerzos de la CCAC que dieron lugar a la *Evaluación Global del Metano* aumentaron la concienciación y la atención política sobre las oportunidades de la reducción del metano. Además de la *Evaluación Global del Metano*, el trabajo de la CCAC, con el grupo del Dr. Shindell en la Universidad de Duke, dio como resultado una herramienta en línea de acceso público para la mitigación del metano[485]. La CCAC planea mejorar esta herramienta para facilitar su utilización, incluyendo la actualización continua de las emisiones de metano y las métricas existentes para cuantificar los beneficios colaterales. Esto permitirá obtener una visión general a nivel nacional de las medidas pertinentes y los beneficios colaterales relacionados, incluida la creación de empleo.

La CCAC también planea desarrollar un *Rastreador Mundial de Políticas/Aplicación del Metano* con el fin de registrar y cuantificar los avances hacia la aplicación de medidas, políticas y normativas relacionadas con el metano. Además, esta coalición alberga tres centros que trabajarán con gobiernos y otras partes interesadas en los sectores de la agricultura, los residuos y el petróleo y el gas. En particular, la CEPE se unió a la CCAC en 2015 con el objetivo de contribuir al trabajo de esta última mediante el intercambio de experiencias, conocimientos y mejores prácticas, incluso con respecto al Protocolo enmendado de la CEPE para luchar contra la acidificación, la eutrofización y el ozono troposférico (Protocolo de Gotemburgo) del Convenio LRTAP[486]. Esta relación puede ayudar a informar los esfuerzos para desarrollar un acuerdo mundial sobre el metano con carácter de urgencia. El Convenio LRTAP y el Protocolo de Gotemburgo se tratan más adelante, en la **Sección 10**.

En septiembre de 2022, la CCAC y la Iniciativa Mundial del Metano (GMI, por sus siglas en inglés) convocaron un Foro Mundial sobre Metano, Clima y Aire Limpio con el objetivo de reunir a responsables de políticas, líderes industriales, expertos técnicos e investigadores de todo el mundo[487]. En el mismo se debatieron las posibilidades de proteger el clima y mejorar la calidad del aire, con especial atención al metano. El evento formó parte de la Reunión Anual de la CCAC para 2022 e incluye actualizaciones sobre esfuerzos internacionales como el *Compromiso Mundial sobre el Metano*, el Observatorio Internacional de Emisiones de Metano, el *Global Methane Hub* y la Vía Energética del Compromiso Mundial sobre el Metano.

- *Misión de Innovación Agrícola para el Clima*

La Misión de Innovación Agrícola para el Clima (AIM4C, por sus siglas en inglés), creada conjuntamente por Estados Unidos y Emiratos Árabes Unidos, es una iniciativa para aumentar la financiación y la participación en la agricultura climáticamente inteligente y la innovación de los sistemas alimentarios en los próximos cinco años. Los "sprints de innovación" de la AIM4C guiarán a los participantes para abordar objetivos específicos utilizando financiación coordinada. Dos sprints de innovación que tienen relación directa con la mitigación del metano son la "*Greener Cattle Initiative: Addressing Enteric Methane Emissions*" y "*Satellite monitoring of quantity and quality of available biomass in pastoral livestock systems*"[488]. Más de 70 países y organizaciones se han asociado a esta iniciativa[489].

- *Foro de Productores Neto Cero*

En abril de 2021, Canadá, Noruega, Qatar, Arabia Saudita y Estados Unidos anunciaron su intención de crear el Foro de Productores Neto Cero (en inglés, *Net-Zero Producers Forum*). El Foro "desarrollaría estrategias pragmáticas de emisiones netas cero, incluida la reducción del metano, el avance del enfoque de la economía circular del carbono, el desarrollo y despliegue de tecnologías de energía limpia y de captura y almacenamiento de carbono, la diversificación de la dependencia de los ingresos procedentes de los hidrocarburos y otras medidas acordes con las circunstancias nacionales de cada país"[490].

- *Asociación Mundial para la Reducción de la Quema de Gas del Banco Mundial*

La Asociación Mundial para la Reducción de la Quema de Gas del Banco Mundial es un fondo fiduciario de múltiples donantes compuesto por 17 gobiernos, 13 compañías petroleras y 3 organizaciones multilaterales. La GGFR desarrolla programas para la reducción de la quema de gas específicos a cada país, realiza investigaciones, comparte las mejores prácticas, crea conciencia, garantiza compromisos globales para acabar con la quema rutinaria que provoca emisiones de metano y avanza en la medición y la notificación de la quema[491]. Estados Unidos tiene previsto reincorporarse a la GGFR[492]. Esta Asociación busca compromisos con la iniciativa *Zero Routine Flaring* de aquí a 2030. Los gobiernos y las empresas que participan en la Iniciativa del Banco Mundial "Eliminación de la quema regular de gas para 2030" se comprometen a poner fin a la quema rutinaria para 2030[493].

34 gobiernos, 53 empresas de petróleo y gas y 15 organizaciones de desarrollo apoyan la Iniciativa[494]. En colaboración con la *Oil and Gas Climate Initiative* y el Payne Institute (Facultad de Minería de Colorado), el GGFR está desarrollando un Herramienta de Seguimiento de la Quema de Gas, una plataforma en línea que ofrecerá un seguimiento en tiempo real de la quema de gas en todo el mundo.

El informe de la Herramienta de Seguimiento de la Quema de Gas de 2022 reveló que diez países representan el 75% de toda la quema de gas y el 50% de la producción mundial de petróleo: "Siete de los 10 países que más gas queman han mantenido esta posición de forma constante durante los últimos 10 años: Rusia, Irak, Irán, Estados Unidos, Venezuela, Argelia y Nigeria. Los tres restantes (México, Libia y China) han registrado aumentos significativos en los últimos años"[495].

- *La Iniciativa Global de Residuos 50 para 2050*

Egipto realizó el lanzamiento de la Iniciativa Global de Residuos 50 para 2050 en la COP27 celebrada en Sharm El-Sheikh en noviembre de 2022. Esta Iniciativa identifica posibles vínculos entre los residuos y el metano. Asimismo, en una sesión organizada en el marco de la COP27 anunció la creación de un "África verde", que incluye el objetivo de reducir los residuos en un 50% en los países africanos[496].

La Iniciativa Global de Residuos estima que el sector de los residuos contribuye en un 20% a las emisiones mundiales de metano[497]. Las emisiones de metano procedentes del vertido de residuos sólidos alcanzaron alrededor de 1,3 $MtCH_4$ en 2010, y se prevé que aumentarán aún más si no mejoran las prácticas de gestión de residuos[498]. La Iniciativa Global de Residuos desarrollará una plataforma para asociaciones y proyectos sobre mitigación y adaptación y apoyará la transferencia de conocimientos e innovación de infraestructuras para la gestión de residuos[499].

ii. Iniciativas impulsadas por la industria

- *Iniciativa Mundial del Metano*

La Iniciativa Mundial del Metano (GMI, por sus siglas en inglés) es una asociación público-privada que abarca los tres sectores principales (producción de energía, agricultura y residuos) y promueve la captura y el uso del metano[500]. Facilita el intercambio de información y asistencia técnica a nivel internacional. La GMI incluye a 45 países que representan alrededor del 70% de las emisiones antropogénicas de metano del mundo, entre ellos Estados Unidos, Canadá, Argentina, Brasil, Rusia, China, India y Australia[501]. Según su sitio web, los proyectos de la GMI han reducido más de 500 $MtCO_2e$ desde 2004[502].

- *Asociación Petróleo y Gas Metano*

La Asociación Petróleo y Gas Metano (OGMP, por sus siglas en ingles), una iniciativa de la CCAC (con el PNUMA, la Comisión Europea y EDF) avanza en la notificación de las emisiones de metano, entre otros, mediante el marco de notificación OGMP 2.0. Este Marco exige a las empresas que informen sobre las emisiones de metano procedentes de fuentes que intervienen en toda la cadena de valor del petróleo y el gas, con el objetivo de reducir las emisiones entre un 50 y un 75% para 2030[503]. La Unión Europea pretende basarse en este Marco para desarrollar sus requisitos de medición, notificación y verificación para el sector energético[504].

- *Iniciativa Climática Petróleo y Gas*

La Iniciativa Climática de Petróleo y Gas (OGCI, por sus siglas en inglés) es una iniciativa liderada por los CEO de las empresas que son miembro y por medio de la cual acuerdan una serie de compromisos y principios. En particular, los miembros de la OGCI se comprometen, de aquí a 2025, a que la intensidad media colectiva de emisiones de metano procedente de las operaciones agregadas de extracción de petróleo y gas se sitúe muy por debajo del 0,20%, a partir de una base de referencia de 2017 del 0,30%. También se comprometen, entre otras cosas, a reducir la intensidad total de carbono de las actividades de exploración y producción de 23 kg de GEI por barril de petróleo o gas en 2017 a 17 kg en 2025 y a apoyar expresamente el objetivo de quema rutinaria cero para 2030[505].

- *Asociación Mundial de Biogás*

La Asociación Mundial de Biogás actúa como una asociación comercial mundial para los sectores industriales del biogás, los gases de vertedero y la digestión anaeróbica[506]. La Asociación proporciona a sus miembros publicaciones como el Directorio Mundial de la Industria del Biogás, datos sobre la magnitud y el crecimiento de los mercados mundiales del biogás y varios análisis que demuestran el potencial ambiental y económico de la industria[507]. La Asociación organiza la Cumbre Mundial del Biogás, que en 2021 se centró en la mitigación del metano[508].

- *Los Principios Rectores del Metano*

Los 24 signatarios de los Principios Rectores del Metano (en inglés, *Methane Guiding Principles*) de la industria del petróleo y el gas se han comprometido a informar públicamente sobre cómo están cumpliendo la intención de cinco principios, incluida la reducción continua de las emisiones de metano, la mejora de la exactitud de los datos sobre emisiones y el aumento de la transparencia. El compromiso de reducir las emisiones de metano incluye la aplicación de programas LDAR y la reducción de las emisiones fugitivas y por venteo. El grupo también ha publicado un conjunto de herramientas para los responsables políticos.

Los 24 signatarios de los Principios Rectores del Metano de la industria del petróleo y el gas se han comprometido a informar públicamente sobre cómo están cumpliendo con los cinco principios, incluida la reducción continua de las emisiones de metano, la mejora de la exactitud de los datos sobre dichas emisiones y el aumento de la transparencia[509]. El compromiso de reducir las emisiones de metano incluye la aplicación de programas LDAR y la reducción de las emisiones fugitivas y por venteo. El grupo también ha publicado un conjunto de herramientas para los responsables de políticas[510].

ii. Iniciativas de calificación del desempeño

- *MiQ*

RMI y SYSTEMIQ crearon MiQ, una organización independiente sin fines de lucro. MiQ desarrolló un sistema de certificación basado en la intensidad de metano que califica los volúmenes de gas natural producidos y el rendimiento de los productores. La intención es crear un mercado de gas natural diferenciado para incentivar a los productores a reducir las emisiones de metano del sector del petróleo y el gas[511].

- *Iniciativa para la Sostenibilidad del Gas Natural*

La Iniciativa para la Sostenibilidad del Gas Natural (*Gas Sustainability Initiative*, NGSI, por sus siglas en inglés) desarrolló el Protocolo de Intensidad de las Emisiones de Metano de (*NGSI Methane*

Emissions Intensity Protocol) como un enfoque voluntario para que las empresas calculen la intensidad de sus emisiones de metano[512].

8. Los sistemas de monitoreo añaden transparencia y responsabilidad

En la actualidad, las emisiones de metano se calculan sobre la base de una serie de regímenes y protocolos de notificación existentes, como la CMNUCC, la *Global Reporting Initiative* (GRI) y los programas nacionales de notificación. Los sistemas cada vez más sofisticados de medición y monitoreo de las emisiones de metano añadirán transparencia y responsabilidad a los esfuerzos mundiales de reducción del metano. En concreto, estos sistemas serán esenciales para garantizar que el mundo se dirige en la dirección correcta para alcanzar reducciones del 30% (o más) en las emisiones de metano necesarias para frenar el calentamiento del planeta a corto plazo, tal y como apela el *Compromiso Mundial sobre el Metano*. Los sistemas de monitoreo ayudan a proporcionar información crucial que el público puede utilizar para exigir responsabilidades a las empresas y los países[513].

Los sistemas de monitoreo incluyen satélites y tecnologías de sobrevuelo desde aviones desplegados para identificar con mayor exactitud los puntos de origen de las emisiones de las infraestructuras, y dispositivos manuales de vigilancia con luz infrarroja y de otro tipo utilizados sobre el terreno para localizar la maquinaria emisora.

La rápida mejora de las tecnologías de detección de metano y análisis de datos está impulsando un auge de las empresas privadas dedicadas al monitoreo y análisis de datos[514]. A continuación figura una lista no exhaustiva de iniciativas destinadas a mejorar el monitoreo y la responsabilidad de las emisiones de metano. Estos ejemplos sugieren cómo una combinación de servicios de monitoreo públicos y privados podría ofrecer un "sistema de sistemas" para las empresas, los entes reguladores, los investigadores y los ciudadanos interesados en el seguimiento y la mitigación de las emisiones de metano[515].

Entre las iniciativas de medición y monitoreo del metano se incluyen las siguientes:

- *Carbon Mapper*

En abril de 2021, Carbon Mapper, Inc., una organización sin fines de lucro financiada con fondos filantrópicos, anunció un plan para lanzar una constelación de satélites con el fin de localizar las emisiones de metano, en colaboración con el Estado de California, el Laboratorio de Propulsión a Chorro de la NASA, Planet, la Universidad de Arizona, la Universidad Estatal de Arizona, High Tide Foundation y RMI[516]. Los dos primeros satélites están en fase de desarrollo y se lanzarán en 2023. El desarrollo de una constelación multisatélite operativa comenzará en 2025[517]. Además, Carbon Mapper está elaborando un portal de datos en colaboración con la Junta de Recursos del Aire de California para poner los datos a disposición del público.

- *Copernicus*

Copernicus es el programa de observación de la Tierra de la UE que proporciona servicios de información con datos procedentes de sistemas de observación por satélite e *in situ* (no espaciales)[518]. La Comisión Europea gestiona el servicio de vigilancia Copernicus y ejecuta el programa en colaboración con los Estados miembros, agencias y centros europeos[519]. Además de recabar información de sistemas *in situ*, la Unión Europea pondrá en órbita una constelación de unos 20 satélites antes de 2030[520]. De los seis servicios de información, el Servicio de Vigilancia Atmosférica[521], el Servicio de Vigilancia Terrestre[522] y el Servicio de Cambio Climático de

Copernicus[523] están estrechamente relacionados con el monitoreo del metano. Todos estos servicios de información son de libre acceso para todos.

- *MethaneSAT del Fondo de Defensa Ambiental*

El MethaneSAT del Fondo de Defensa Ambiental (EDF, por sus siglas en inglés) planea lanzar un nuevo satélite para realizar un monitoreo periódico de las operaciones mundiales de petróleo y gas, incluida la identificación de emisiones de metano en grandes áreas geográficas y la medición de emisiones en lugares predeterminados[524]. En enero de 2021, MethaneSAT celebró un contrato con SpaceX para la puesta en órbita de su nuevo satélite dedicado al metano, prevista para el 1 de octubre de 2022[525]. Una vez lanzado, MethaneSAT transmitirá sus datos en línea sin costo alguno para los usuarios no comerciales.

- *GHGSat*

GHGSat, empresa mundial de monitoreo de emisiones, firmó en 2019 un memorando de intenciones con la Agencia Espacial Canadiense y la Agencia Espacial Europea[526]. GHGSat colaborará con el Observatorio Internacional de Emisiones de Metano proporcionando datos gratuitos sobre las emisiones de metano captadas desde sus satélites[527]. El 4 de mayo de 2022, GHGSat compartió sus primeros hallazgos utilizando tecnología satelital sobre las emisiones de metano del ganado de una granja en Joaquin Valley, California[528]. Más recientemente, en agosto de 2022, GHGSat detectó emisiones de vertederos en Buenos Aires, Delhi, Lahore y Mumbai, descubriendo que los vertederos contribuyen entre un 6 y un 50% de las emisiones declaradas a nivel urbano[529].

- *La Iniciativa del Metano y el Proyecto de Metodología de Medición del Metano del Foro Internacional de Energía*

La Iniciativa del Metano del Foro Internacional de Energía (IEF, por sus siglas en inglés) desarrollará una metodología de medición de las emisiones de metano que permita normalizar la recolección de datos[530]. El proyecto de metodología de medición del metano pretende ayudar a los Estados miembros del IEF a elaborar planes creíbles de reducción del metano en el sector energético basados en los mejores datos disponibles sobre las emisiones de metano[531].

- *El Observatorio Internacional de Emisiones de Metano*

Presentado el 31 de octubre de 2021 en la Cumbre del G20, el Observatorio Internacional de Emisiones de Metano (IMEO, por sus siglas en inglés) es una iniciativa del PNUMA con el apoyo de la Comisión Europea y de otros gobiernos que integrará los datos de las emisiones de metano obtenidos de múltiples fuentes en una base de datos congruente que describirá el nivel de confianza en cada elemento de datos[532]. El IMEO se centrará inicialmente en el sector energético y más adelante se extenderá a los residuos y la agricultura[533]. Además, el IMEO desempeñará un papel importante en la aplicación del *Compromiso Mundial sobre el Metano*, ayudando a los países a priorizar sus acciones y monitoreando los compromisos[534]. El PNUMA alberga al IMEO, con una financiación pública de 100 millones de euros a lo largo de cinco años (incluida la financiación de la Comisión Europea como miembro fundador)[535]. El Observatorio se coordinará estrechamente con la CCAC, entre otras organizaciones, incluso en lo relativo a la incorporación y el análisis de los datos del OGMP 2.0, mencionado en la **Sección 7**[536]. En 2021, el IMEO publicó su primer informe, *An Eye on Methane*, en el que se describen los avances del OGMP 2.0 y los retos pendientes en el monitoreo y la medición del metano.

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

Investigadores de RMI, la Universidad de Stanford, la Universidad de Calgary y Koomey Analytics desarrollaron la herramienta *Oil and Climate Index Plus* (OCI+) como respuesta a la poca claridad de los informes sobre las emisiones de GEI que realiza el sector del petróleo y el gas[537]. El OCI+ presenta una evaluación completa del ciclo de vida de las emisiones de GEI provocadas por la mitad de la producción mundial de petróleo y gas. La herramienta OCI+ y el informe que la acompaña concluyen que las emisiones más significativas de los combustibles fósiles se producen no sólo en el punto de combustión, sino también en la boca del pozo y durante el procesamiento, el refinado y el transporte[538]. El informe también menciona la reducción del metano como "la máxima prioridad para el sector del petróleo y el gas"[539].

9. Crear una estrategia de responsabilidad y cumplimiento utilizando sistemas sólidos de monitoreo de las emisiones

Como se ha comentado en la **Sección 8**, los sistemas de monitoreo de emisiones añaden transparencia y responsabilidad a los esfuerzos de reducción. Las tecnologías que sustentan estos sistemas están a listas para revolucionar la información disponible al hacer visibles emisiones que antes eran invisibles para el público, los organismos reguladores y los propietarios y operadores de fuentes de metano de todos los sectores. Estos sistemas de monitoreo, cuando se combinan con una estrategia de responsabilidad y cumplimiento, serán esenciales para garantizar que el mundo se encamine hacia la máxima reducción de las emisiones de metano.

Mecanismos eficaces de responsabilidad y respuesta para abordar las fuentes de emisiones incluirían varios componentes. En el nivel más básico, se encuentra: 1) un ejercicio de inventario por el total de emisiones, sectores y ubicación; 2) el nivel de referencia de las emisiones por jurisdicción; 3) el objetivo de reducción por el total de emisiones y sectores; y 4) monitoreo y notificación, proporcionando total transparencia. Además, estos componentes incluyen las capacidades de 1) identificar y alertar a las organizaciones responsables de los activos emisores; 2) dar a conocer las emisiones a los organismos reguladores responsables y 3) garantizar que los datos de las emisiones estén disponibles de forma accesible y oportuna para los organismos de control de la sociedad civil, los medios de comunicación y las comunidades afectadas.

Una estrategia eficaz de responsabilidad y cumplimiento debe incorporar mecanismos de "zanahoria" (incentivos) y "palo" (por ejemplo, mecanismos regulatorios, "hacer públicos los nombres de los infractores"). La estrategia debe abarcar a los operadores de fuentes de metano, a los organismos gubernamentales responsables, incluidos los fiscales, y a la sociedad civil, incluidas las comunidades afectadas. Además, también deben identificarse soluciones para abordar las emisiones detectadas y conectar a los operadores con la capacidad técnica y los recursos financieros necesarios, según proceda. Asimismo, resulta necesario crear capacidades que reflejen la formación y otros incentivos adecuados para las partes interesadas implicadas en los aspectos de la estrategia relacionados con la responsabilidad. Entre ellos se encuentran los operadores de fuentes de emisión, las agencias reguladoras, las agencias de calificación de riesgo financiero y los organismos de vigilancia.

Una estrategia de responsabilidad podría contener varios componentes, los cuales incluyen:

1) Un mapa de activos y un inventario de fuentes de metano con coordenadas geoespaciales que permitan la identificación detallada de las fuentes y los contactos correspondientes para los operadores;
2) Una "guía telefónica" de los agentes de control correspondientes a cada punto de emisión (federal, estatal, local, sector privado, etc.) en base a la ubicación y el tipo de activo;
3) Un mecanismo para acceder a los datos sobre emisiones procedentes de los sistemas de monitoreo y convertirlos rápidamente en formatos utilizables por los actores responsables; y
4) Una red de coordinación y comunicación de los actores de la sociedad civil por región, país y jurisdicción subnacional donde las emisiones sean significativas, con el fin de reforzar la capacidad colectiva de la sociedad civil para actuar a medida que surjan los datos sobre las emisiones.

A nivel gubernamental, podrían establecerse Oficinas Nacionales de Metano que asumieran la responsabilidad de elaborar y mantener inventarios de emisiones y de identificar y monitorear los principales puntos de origen de las mismas. Estas Oficinas también servirían de enlace con los organismos subnacionales correspondientes para crear sistemas eficaces de rendición de cuentas, establecer procedimientos e identificar especialistas y otras partes interesadas en las que se pueda confiar para que ayuden a desplegar acciones y sistemas de rendición de cuentas. Estas Oficinas se organizarían regionalmente, y también a nivel subnacional, para fomentar la cooperación y el intercambio de información y las estrategias de mitigación.

Un componente clave para incentivar las acciones de mitigación es que las fuentes de emisiones de metano identificadas tengan acceso a tecnologías y financiación para aplicar las soluciones de mitigación. Un Grupo de Evaluación Tecnológica y Económica (inspirado en el Grupo de Evaluación Tecnológica y Económica del Protocolo de Montreal) y una Herramienta de Seguimiento del Metano (albergado por la CCAC) podrían evaluar y recomendar soluciones tecnológicas de forma periódica para fomentar la innovación continua y el apoyo a la aplicación de las mejores prácticas.

10. Los esfuerzos internacionales, incluido el Compromiso Mundial sobre el Metano, están catalizando otras acciones bilaterales y multilaterales para frenar el metano

Las emisiones de metano procedentes de cualquier fuente y en cualquier lugar afectan al clima mundial, así como a la salud pública y al medio ambiente, ya que el metano es un gas de efecto invernadero bien mezclado y contribuye a aumentar la contaminación de fondo por ozono troposférico. La mitigación del metano por parte de todos y cada uno de los países es, por lo tanto, el mejor medio para lograr una reducción rápida y eficaz de las emisiones de metano en cualquier lugar que se produzcan[540].

Además del *Compromiso Mundial sobre el Metano*, los esfuerzos bilaterales y regionales conexos sientan las bases para la celebración de un acuerdo mundial sobre el metano, que encuentra su inspiración en el exitoso Protocolo de Montreal de 1987. El Protocolo de Montreal no sólo ha resuelto la primera gran amenaza para la atmósfera global al poner el ozono estratosférico en vías de recuperación para 2065, sino que también ha hecho más por evitar el calentamiento global más que cualquier otro acuerdo[541], evitando una cantidad de calentamiento que, de otro modo, habría igualado o incluso superado el calentamiento que el CO^2 está causando en la actualidad[542].

El Protocolo de Montreal ofrece una estructura arquitectónica útil para adoptar un enfoque sectorial que pueda incluirse dentro de un acuerdo internacional, lo cual se analiza más adelante. Además, se están llevando a cabo otros debates sobre el metano en el marco del *Compromiso Mundial sobre el Metano*, el Protocolo de Gotemburgo del Convenio sobre la Contaminación Atmosférica Transfronteriza a Gran Distancia y la Declaración Conjunta de Glasgow de Estados Unidos y China para Reforzar la Acción Climática en la década de 2020.

A. El Compromiso Mundial sobre el Metano y el Pacto Climático de Glasgow

El *Compromiso Mundial sobre el Metano* se lanzó formalmente a nivel de Jefes de Estado en el segmento de alto nivel de la COP26 el 2 de noviembre de 2021 en Glasgow[543]. Estados Unidos y la Unión Europea anunciaron por primera vez este *Compromiso* en el Foro de las Principales Economías el 17 de septiembre de 2021[544]. El mismo compromete a los gobiernos a un objetivo colectivo mundial de reducción de las emisiones mundiales de metano en al menos un 30% con respecto a los niveles de 2020 para 2030. Los signatarios también se comprometen a avanzar hacia el uso de las metodologías de inventario de buenas prácticas del IPCC de más alto nivel para cuantificar las emisiones de metano, con especial atención a las fuentes de altas emisiones[545]. La aplicación con éxito del *Compromiso Mundial sobre el Metano* reduciría el calentamiento en al menos 0,2 °C para 2050[546]. Para septiembre de 2022, 120 países y la Unión Europea se habían adherido al *Compromiso*[547], quienes representan aproximadamente el 70% de la economía mundial y casi la mitad de las emisiones antropogénicas[548]. En la COP26, el expresidente de Estados Unidos Barack Obama recordó a los asistentes que "frenar las emisiones de metano es actualmente la forma más rápida y eficaz de limitar el calentamiento"[549].

En la Cumbre Especial entre Estados Unidos y la ASEAN celebrada en Washington, D.C., el 12 de mayo de 2022, Estados Unidos se comprometió a "acelerar la asistencia técnica, los recursos financieros y el desarrollo de proyectos para la mitigación del metano en los países del *Compromiso Mundial sobre el Metano*, incluso a través de la EPA, la USTDA [Agencia de Comercio y Desarrollo de Estados Unidos], la DFC [Corporación Financiera de Desarrollo] y el EXIM [Banco de Exportación e Importación], así como el recientemente creado *Global Methane Hub*"[550].

Alcanzar el objetivo de reducción de emisiones establecido en el *Compromiso Mundial sobre el Metano* mantendría al planeta en una vía coherente con el objetivo de no superar los 1,5 °C, según la *Evaluación Global del Metano*[551]. Esto equivale aproximadamente a una reducción del 35% por debajo de los niveles previstos para 2030. El despliegue de todas las medidas disponibles y adicionales podría conducir a una reducción del 45% por debajo de los niveles de 2030 para alcanzar casi 0,3 °C de calentamiento evitado en la década de 2040[552].

Es la primera vez que los Jefes de Estado se comprometen, en el marco de un *Compromiso* como el antes mencionado, a actuar con celeridad para reducir los supercontaminantes climáticos y alcanzar el objetivo de 1,5 °C de temperatura del Acuerdo de París. El Pacto de Glasgow para el Clima, acordado en la COP26, también menciona explícitamente el metano y los GEI distintos del CO^2. El Pacto "invita a las Partes a considerar nuevas medidas para reducir para 2030 las emisiones de gases de efecto invernadero distintos del dióxido de carbono, incluido el metano[.]"[553] En su comunicado del 27 de mayo de 2022, los Ministros de Clima, Energía y Medio Ambiente del G7 reafirmaron su adhesión al *Compromiso Mundial sobre el Metano* y señalaron la importancia de responder "a la crisis actual, de manera coherente con nuestros objetivos climáticos y sin crear efectos de bloqueo"[554].

En junio de 2022, Estados Unidos, la Unión Europea y otros 11 países pusieron en marcha la Vía Energética del Compromiso Mundial sobre el Metano, que incluye 59 millones de dólares en financiación para apoyar la reducción de metano en el sector del petróleo y el gas[555]. La financiación incluye 4 millones de dólares para apoyar la Asociación Mundial para la Reducción de la Quema de Gas del Banco Mundial, 5,5 millones de dólares para apoyar la Iniciativa Global del Metano, hasta 9,5 millones de dólares del Observatorio Internacional de Emisiones de Metano del PNUMA para apoyar las evaluaciones científicas de las emisiones de metano y el potencial de mitigación, y hasta 40 millones de dólares anuales del *Global Methane Hub* filantrópico para apoyar la mitigación del metano en el sector de la energía fósil.

Estos compromisos iniciales, así como los que se describen a continuación, aumentan la conciencia sobre la oportunidad de frenar el calentamiento reduciendo el metano, los sectores implicados y el nivel de ambición necesario. Los gobiernos deberían basarse en el *Compromiso* y en la Vía Energética del *Compromiso* para abrir la puerta a un acuerdo mundial sobre el metano, incluyendo la actuación inmediata para exigir una tasa de emisiones de metano progresivamente más baja a los proveedores de "gas metano de sustitución" en respuesta a los cambios en el abastecimiento energético.

B. Medidas relativas al metano en virtud del Protocolo de Gotemburgo del Convenio sobre la Contaminación Atmosférica Transfronteriza a Gran Distancia

El *Compromiso Mundial sobre el Metano* sienta las bases para abordar la emergencia de una reducción más concreta del metano, incluso en forma de un acuerdo mundial sobre el metano que se inspire en modelos de éxito como el Convenio de la CEPE de las Naciones Unidas sobre la Contaminación Atmosférica Transfronteriza a Gran Distancia (LRTAP) y su Protocolo de 1999 para reducir la acidificación, la eutrofización y el ozono troposférico (Protocolo de Gotemburgo)[556], que se describen a continuación.

El LRTAP es un marco de tratado regional entre Europa, América del Norte, Rusia y los países del antiguo bloque del Este para reducir la contaminación atmosférica transfronteriza y comprender la ciencia relacionada[557]. El metano es el último de los principales precursores del ozono que no está explícitamente controlado por el Protocolo de Gotemburgo, en su versión actual[558].

Incluir el metano en el LRTAP es un tema de debate activo y debería reconocer y reforzar los esfuerzos, incluso a través de la colaboración existente de la CEPE con la CCAC, para desarrollar un acuerdo mundial sobre el metano con carácter de urgencia. La CEPE se unió a la CCAC en 2015 con el objetivo de contribuir al trabajo de esta última a través del intercambio de experiencias, conocimientos y mejores prácticas, incluso en lo que respecta al Protocolo de Gotemburgo[559].

Varios órganos subsidiarios del LRTAP están estudiando las emisiones de metano, incluida la modelización de los efectos de las emisiones de metano procedentes de fuera de la región sobre los niveles de ozono en la región de la CEPE[560]. El LRTAP y sus ocho protocolos[561] reflejan una serie de innovaciones que pueden beneficiar el desarrollo de un acuerdo mundial sobre el metano. Entre ellas se encuentran: la adopción de un enfoque basado en la tecnología que incorpore medidas nacionales para reducir los contaminantes[562]; un sólido organismo científico que supervise si las Partes van en la dirección correcta para cumplir sus objetivos[563] y un sistema dual de notificación que exige a las Partes que informen de sus emisiones anuales de contaminantes y de los avances en la aplicación de sus estrategias nacionales[564]. Estos mecanismos de políticas reconocen, incorporan y supervisan los esfuerzos nacionales existentes para el control de las emisiones de contaminantes atmosféricos. A la hora de desarrollar un mecanismo mundial de control de las emisiones de metano, valdrá la pena tener en cuenta los beneficios de las innovaciones del LRTAP al momento de determinar la mejor manera de reconocer las medidas existentes de los países para controlar el metano.

Si bien el LRTAP podría ser un mecanismo regional valioso para establecer controles vinculantes del metano, otras consideraciones de dicho convenio desde una perspectiva global incluyen:

- *Las Partes del LRTAP provienen de América del Norte, Europa y Asia Central y Occidental y no incluyen a varios países con emisiones significativas de metano o países en desarrollo que apoyan el Compromiso Mundial sobre el Metano*. Las Partes del LRTAP son miembros de la CEPE[565]. No todas las Partes del LRTAP son también Partes de los protocolos adicionales de dicho convenio. Por ejemplo, Rusia es Parte del LRTAP pero no del Protocolo de Gotemburgo. Las Partes del LRTAP no incluyen a los principales países emisores de metano[566], como Brasil, China, India e Irán, ni a otros países del mundo en desarrollo que participan en el Compromiso Mundial sobre el Metano, como Argentina, Ghana, Indonesia, Irak, México, Nigeria y Pakistán.

- *El metano es objeto de debate activo, pero en este momento no está controlado por el LRTAP ni por ninguno de sus protocolos.* El LRTAP controla los contaminantes que contribuyen a la contaminación atmosférica transfronteriza. Ocho protocolos aclaran las obligaciones de las Partes en relación con contaminantes y actividades específicas. El Protocolo más reciente, y el más importante en torno al metano, es el Protocolo de Gotemburgo, que entró en vigor en 2005[567]. Los objetivos del Protocolo de Gotemburgo incluyen el control y la reducción de las emisiones de azufre, óxidos de nitrógeno, amoníaco, compuestos orgánicos volátiles (distintos del metano) y partículas causadas por actividades antropogénicas que puedan tener efectos nocivos para la salud humana y el medio ambiente, los ecosistemas naturales, los materiales, los cultivos y el clima a corto y largo plazo, debido, entre otras cosas, al ozono troposférico derivado del transporte a gran distancia de los contaminantes cubiertos[568]. El metano es una fuente importante de ozono troposférico y contribuye a los niveles de ozono de fondo en todo el mundo[569]. Aunque el metano está reconocido como precursor del ozono en el Protocolo de Gotemburgo[570], actualmente no es un contaminante controlado.

- *La CEPE sigue centrándose en el papel del metano como precursor del ozono y en cómo las emisiones de metano procedentes de fuera de la CEPE afectan a la formación de ozono dentro de la CEPE.* La CEPE reconoce que el aumento mundial de las emisiones de metano procede en gran parte de países de fuera de la región de la CEPE (o de la CEPE)[571]. La misma revisa las fuentes de las emisiones mundiales de metano, enfocándose en cómo las emisiones de las regiones no pertenecientes a la CEPE afectan al transporte y la formación de ozono dentro de la CEPE[572]. Esta revisión también incluye cómo mejorar las reducciones de las emisiones de metano a través de un futuro instrumento[573].

- *Es posible que sea necesario acelerar el proceso del LRTAP para formalizar los controles vinculantes referentes al metano con el fin de apoyar la reducción de las emisiones de metano con carácter de urgencia, al tiempo que se brindan oportunidades para la contribución, la colaboración y el apoyo a los controles mundiales de dichas emisiones*. Desde 2018, varios órganos subsidiarios del LRTAP han estado considerando emprender el trabajo relacionado con el metano. En septiembre de 2021, un Informe de Progreso Conjunto concluyó que el metano es el principal causante del aumento de los niveles de ozono de fondo, y que el sector de los residuos en Europa y el sector del petróleo y el gas en Europa del Este, Asia y Estados Unidos tienen el mayor potencial de reducción en esas regiones[574]. La finalización de la investigación sobre las mejores técnicas disponibles para la reducción de las emisiones y la contribución de las medidas climáticas a dicha reducción está prevista para la primavera de

2022[575], y la finalización de la Revisión para diciembre de 2022[576]. El Proyecto de Informe sobre la Revisión del Protocolo de Gotemburgo reconoce que es necesario centrarse en mayor medida en el metano, ya que desempeña un papel clave en la sinergia entre la contaminación atmosférica y los esfuerzos de mitigación relativos al clima[577]. En su 41º período de sesiones en diciembre de 2021, el Órgano Ejecutivo "acordó incluir el metano en su análisis para la revisión del Protocolo [de Gotemburgo]"[578]. Durante su 60º período de sesiones, el Grupo de Trabajo sobre Estrategias y Revisión (WGSR, por sus siglas en inglés) tomó nota de una lista no exhaustiva de opciones para abordar el metano, que incluyen el establecimiento de compromisos nacionales de reducción de emisiones y/o el establecimiento de objetivos sectoriales de emisiones[579]. Además, el WGSR debatió las opciones para abordar el metano en un futuro instrumento, incluido el posible vínculo con otros organismos como el Foro de Cooperación Internacional sobre Contaminación Atmosférica[580] y la Iniciativa Global del Metano[581]. En 2022-2023, otro grupo de trabajo llevará a cabo un examen de la respuesta regional del ozono a las reducciones mundiales del metano[582].

Teniendo esto en cuenta y reconociendo que controlar del metano requiere una acción urgente, las Partes del LRTAP deberían considerar dos cosas importantes: incorporar rápidamente el metano dentro de los mecanismos existentes y apelar a un acuerdo de emergencia para tener en cuenta la naturaleza global de las emisiones y los impactos del metano.

C. Declaración Conjunta de Glasgow de Estados Unidos y China para Reforzar la Acción Climática en la década de 2020

La Declaración Conjunta de Glasgow de Estados Unidos y China para reforzar la acción climática en la década de 2020, anunciada en la COP26 el 10 de noviembre de 2021, compromete a las dos mayores economías y emisores de contaminantes climáticos a abordar conjuntamente la crisis climática mediante "acciones aceleradas en la década crítica de 2020"[583], incluidas medidas adicionales para reducir las emisiones de metano. China acordó desarrollar un "Plan de Acción Nacional exhaustivo y ambicioso" para lograr el control y la reducción de las emisiones de metano en la década de 2020[584]. Ambos países también se comprometieron a "cooperar para mejorar la medición de las emisiones de metano", a reunirse durante el primer semestre de 2022 para centrarse en cuestiones de medición y mitigación del metano[585] y a establecer un Grupo de Trabajo para Reforzar la Acción Climática en la década de 2020 para hacer frente a la crisis climática, el cual se reuniría periódicamente[586].

El anuncio por parte de China de un Plan de Acción Nacional para reducir las emisiones de metano en la década de 2020 es un paso importante hacia la consecución de los objetivos del *Compromiso Mundial sobre el Metano*, aunque China aún no se ha adherido formalmente al mismo. No obstante, como resultado de la Declaración Conjunta de Estados Unidos y China, las actividades que emprendan los países de dicho instrumento sin duda ayudarán a informar las políticas de mitigación y las soluciones técnicas de China con respecto al metano. También resulta importante que tanto las NDC actualizadas como la Estrategia de Medio Siglo de China enumeran acciones políticas para la reducción de GEI distintos del CO_2, incluido el metano[587].

D. Un Acuerdo Mundial sobre el Metano para Abordar la Emergencia Climática y Promover la Paz y la Seguridad

En vísperas de la COP26 de Glasgow, el Parlamento Europeo pidió a la Comisión y a los Estados miembros que "negocien un acuerdo mundial vinculante sobre la mitigación del metano en la reunión de la COP 26 que se celebrará en Glasgow, en consonancia con las trayectorias modelizadas que limitan el calentamiento global a 1,5 °C del Informe Especial del IPCC, el IE6 y la *Evaluación Global del Metano*"[588]. Ya existe una base sólida y evolutiva para negociar un acuerdo de este tipo. Esto incluye actuar de inmediato para negociar una tasa de emisiones de metano progresivamente más baja por parte de los proveedores de "gas metano de sustitución" en respuesta a los cambios en el abastecimiento a medida que se reduce la disponibilidad de gas ruso. La base está conformada por la *Evaluación Global del Metano*, el *Compromiso Mundial sobre el Metano*; el IE6 del WGI; la voluntad de los principales líderes en pos del multilateralismo para resolver los desafíos globales sin precedentes y mantener viva la democracia; una sólida política de mitigación del metano y logros técnicos a nivel internacional, nacional y subnacional; mejores capacidades de medición y seguimiento y colaboraciones públicas y privadas durante la última década.

i. El Protocolo Montreal brinda inspiración y un modelo para el acuerdo mundial sobre el metano

El Protocolo Relativo a las Sustancias que Agotan la Capa de Ozono (Protocolo de Montreal) sirve de inspiración y modelo para un acuerdo mundial obligatorio sobre el metano centrado en un sector determinado. Este Protocolo está ampliamente considerado como el acuerdo ambiental más exitoso del mundo, ya que no sólo ha puesto la capa de ozono estratosférico en vías de recuperación para 2065, sino que también ha evitado un calentamiento global al menos igual al provocado actualmente por las emisiones de CO_2[589].

El Protocolo de Montreal presenta varias características que contribuyen al éxito de un acuerdo mundial sobre el metano, aunque es posible que sea necesario adoptar un enfoque diferente en el caso del metano asociado a la producción y el consumo de combustibles fósiles[590]. En primer lugar, el tratado impone obligaciones obligatorias a todas las Partes, tanto a las de los países desarrollados como a las de los países en desarrollo. Al mismo tiempo, aplica el principio de "responsabilidades comunes pero diferenciadas y capacidades respectivas"[591]. Este principio se aplica concediendo a las Partes que son países en desarrollo un período de gracia, a menudo de cinco o diez años, antes de exigirles que eliminen o reduzcan progresivamente una sustancia controlada[592]. El Protocolo también se aplica a través de un mecanismo de financiación específico, el Fondo Multilateral, por el que los países desarrollados asumen los "costos adicionales acordados" en que incurran los países en desarrollo al eliminar o reducir gradualmente las sustancias controladas[593]. Además del apoyo financiero a las tecnologías de sustitución, el Protocolo de Montreal proporciona ayuda financiera para reforzar las Unidades Nacionales del Ozono que funcionan en cada una de las 147 Partes que son países en desarrollo[594]. La oficina OzonAction del PNUMA también ofrece formación y capacitación de manera periódica a las Partes representantes de países en desarrollo, ampliando la acción y la concienciación sobre la importancia de lograr la mitigación del agotamiento de la capa de ozono y del cambio climático en el marco del Protocolo de Montreal.

Otras características importantes del Protocolo de Montreal son sus grupos de evaluación, en particular el Grupo de Evaluación Científica (SAP, por sus siglas en inglés)[595] y el Grupo de Evaluación Tecnológica y Económica (GETE)[596]. El SAP evalúa el estado de agotamiento de la capa de ozono y la ciencia atmosférica pertinente. El GETE examina las tecnologías y los aspectos **económicos** de las alternativas a las sustancias químicas que se están eliminando, reuniendo a expertos de la industria, el gobierno y el mundo académico para encontrar soluciones e informar de forma independiente sin censura gubernamental[597].

El Protocolo de Montreal fue precedido por un acuerdo marco subyacente, el Convenio de Viena para la Protección de la Capa de Ozono[598]. Una estrategia que involucre el desarrollo de un acuerdo mundial sobre el metano debería contemplar y anticipar una rápida priorización y aceleración de las acciones para hacer frente a las crisis, incluidas las relacionadas con la seguridad alimentaria y la energía. No obstante, una estructura similar de marco-protocolo podría ser adecuada para un tratado mundial sobre el metano: un acuerdo marco seguido de una serie de protocolos sobre los sectores de energía, residuos y agricultura[599], al tiempo que promueva la investigación y el desarrollo de estrategias para eliminar el metano de la atmósfera y contrarrestar así las emisiones naturales[600].

ii. Ya existen las bases científicas, políticas y técnicas para la negociación de un acuerdo mundial sobre el metano inspirado en el Protocolo de Montreal

La urgencia de frenar el calentamiento a corto plazo implica que la velocidad en la selección de las soluciones climáticas debe convertirse en el factor más importante[601] con el fin de limitar rápidamente el calentamiento, frenar las retroalimentaciones que se refuerzan a sí mismas, evitar los puntos críticos de inflexión y proteger a las personas y los ecosistemas más vulnerables[602]. El Programa de las Naciones Unidas para el Medio Ambiente, el IPCC[603], la CCAC[604] y el Consejo Ártico[605] han contribuido a esta comprensión científica. El sexto informe de evaluación del Grupo de Trabajo II del IPCC (IE6 del WGII) destaca una seria advertencias sobre las consecuencias de un mayor retraso en la puesta en marcha de la acción mundial y la urgencia de frenar el calentamiento a corto plazo[606]. La *Evaluación Global del Metano* confirma que reducir las emisiones de metano es la estrategia de mitigación más rápida y la única plausible para limitar el calentamiento en las próximas dos décadas[607].

En respuesta a este llamado a la acción, los gobiernos, las organizaciones y las iniciativas de colaboración de todos los niveles han creado una sólida base política y técnica para el control mundial del metano. Esta base incluye:

- **El compromiso y reconocimiento internacional que implica acciones cruciales para reducir el metano.** Por ejemplo, más de 180 de las 197 Partes del Acuerdo de París hacen referencia al metano en sus NDC[608]. Estados Unidos y la Unión Europea afianzaron su apoyo al *Compromiso Mundial sobre el Metano* a nivel de los principales líderes durante el Foro de las Principales Economías sobre Energía y Clima celebrado en septiembre de 2021[609]. En junio de 2022, Estados Unidos, la UE y otros 11 países lanzaron la Vía Energética del *Compromiso*, que incluye la concesión de financiación para apoyar las reducciones de metano en el sector del petróleo y el gas. En septiembre de 2022, este acuerdo ya contaba con 121 participantes[610], entre los que se encontraban países en desarrollo como Argentina, Ghana, Indonesia, Irak y México como algunos de los primeros partidarios[611]. El G20 ha reconocido que el metano es "una de las formas más rápidas, factibles y rentables de limitar el cambio climático y su impacto" y ha acordado promover la cooperación y la transparencia[612]. La Unión Europea se ha comprometido a reducir todas las emisiones de gases de efecto invernadero en un 55% para 2030[613] y la Comisión Europea ha hecho hincapié en la necesidad de una acción unificada y global sobre el metano[614]. Las Partes de la Comisión Económica del LRTAP—y en particular del Protocolo de Gotemburgo—están llevando a cabo un proceso para formalizar la mitigación vinculante del metano, a la vez que ofrecen oportunidades de contribución, colaboración y apoyo a los controles mundiales del metano[615]. Y la CCAC está reforzando activamente el proceso de comprensión y el nivel de ambición a nivel global para el control del metano a través de proyectos como la Iniciativa Emblemática sobre el Metano (*Methane Flagship*)[616].

- **Compromisos y acciones bilaterales y nacionales para la mitigación del metano.** Por ejemplo, Estados Unidos y China, en su *Declaración Conjunta de Glasgow para Reforzar la Acción Climática en la Década de 2020*, demostraron la capacidad de estos dos rivales económicos y políticos para encontrar un terreno común en la mitigación del metano[617]. China anunció posteriormente sus propios planes de control de las emisiones de metano[618]. Estas iniciativas políticas y la creciente emergencia climática subrayan la importancia de la cooperación, incluso en tiempos de crisis política,—y de cierta competencia que fomente la ambición—entre los campeones de la mitigación del metano en China y otros países[619]. Canadá[620] y México[621], por ejemplo, han promulgado regulaciones para las emisiones de metano del sector energético y se han sumado a Estados Unidos en el compromiso de aumentar la cooperación[622].

- **Esfuerzos subnacionales que inspiran medidas nacionales.** Estos esfuerzos incluyen regulaciones de algunos estados de Estados Unidos como California[623], Nuevo México[624] y Colorado[625], y de provincias canadienses como Columbia Británica[626]. Iniciativas centradas en el clima como C40 Cities network[627] y la Coalición Under2[628] han unido a entidades subnacionales de todo el mundo para hacer frente a las emisiones de metano.

- **Iniciativas de Medición y Monitoreo del Metano.** El programa satelital Carbon Mapper[629] y el Observatorio Internacional de Emisiones de Metano[630] ya están contribuyendo a la comprensión global de los niveles de emisiones de metano que contribuyen a la emergencia climática. Estas iniciativas y las tecnologías que se describen en la **Sección 8** son esenciales para saber si el mundo se dirige en la dirección correcta para cumplir con los compromisos existentes. También proporcionan información crítica necesaria para el éxito y la solidez de la rendición de cuentas y los mecanismos de aplicación en el marco de un acuerdo mundial sobre el metano.

- **Iniciativas de colaboración público-privada en todos los niveles sobre la mitigación del metano**. Estos esfuerzos, que se analizan con mayor profundidad en la **Sección 7**, están reforzando la concienciación sobre las medidas efectivas de mitigación del metano que deben sustentar un acuerdo mundial exitoso sobre el metano. Entre ellas se incluyen, además de las iniciativas de la CCAC, la Iniciativa Global del Metano[631], la Iniciativa Climática de Petróleo y Gas[632] y las iniciativas de calificación del rendimiento en la mitigación de las emisiones de metano como MiQ[633] y la Iniciativa para la Sostenibilidad del Gas Natural[634].

Esta base científica, técnica y política, sumada a la inspiración del Protocolo de Montreal, proporciona la comprensión, la ambición, los ejemplos y las soluciones necesarias para desarrollar un acuerdo mundial sobre el metano.

iii. La creación y el fortalecimiento de las organizaciones necesarias para apoyar un acuerdo mundial sobre el metano pueden y deben comenzar inmediatamente en el marco de la CCAC

Con la rapidez como factor clave para las soluciones climáticas, el trabajo en las organizaciones que eventualmente apoyarán un acuerdo mundial sobre el metano no debe esperar al inicio de las negociaciones. La emergencia climática y su impacto no tienen análogos en la historia de la humanidad. Por lo tanto, la estrategia para desarrollar un acuerdo de este tipo debe contemplar y anticipar la rápida priorización y aceleración de la acción para hacer frente a las crisis, incluidas las relacionadas con la seguridad alimentaria y la energía. Este trabajo puede y debe comenzar inmediatamente. Esto incluye reforzar o crear, dentro de una organización como la CCAC que ha sido propuesta como la Secretaría del *Compromiso Mundial sobre el Metano*, organizaciones científicas, de evaluación técnica, financieras y de creación de capacidades similares a las establecidas en el Protocolo de Montreal[635]. La creación de un régimen de control del metano basado en este exitoso modelo ayudaría a garantizar el cumplimiento de su mandato[636].

iv. Basándose en las sólidas bases científicas, técnicas y políticas existentes y de las organizaciones de la CCAC, las negociaciones de un acuerdo mundial sobre el metano deberían comenzar a nivel de los Jefes de Estado

Basándose en las sólidas bases ya existentes, utilizando el Protocolo de Montreal como inspiración y modelo y empleando organizaciones desarrolladas en el seno de una organización como la CCAC, debería lanzarse un acuerdo mundial sobre el metano a nivel de los Jefes de Estado. Las negociaciones para el acuerdo deberían celebrarse con una velocidad sin precedentes. El Protocolo de Montreal se negoció en sólo nueve meses[637] y, en marzo de 2022, el PNUMA inició las negociaciones con la ambición de concluir un acuerdo mundial para hacer frente a la contaminación por plásticos dos años después, en 2024[638].

11. Las organizaciones financieras y filantrópicas pueden proporcionar un apoyo financiero fundamental para alcanzar objetivos y acciones ambiciosas contra el metano

Será fundamental conseguir los fondos y la financiación adecuados para apoyar a los gobiernos y a las organizaciones comprometidas con la rápida reducción del metano. Las organizaciones filantrópicas privadas, los bancos multilaterales, los gobiernos y otras partes interesadas del sector financiero juegan un papel importante a la hora de posibilitar una rápida mitigación del metano para responder a la emergencia climática.

Más de 20 organizaciones filantrópicas importantes ya se han comprometido a destinar más de 328 millones de dólares para apoyar los esfuerzos encaminados a reducir drásticamente las emisiones de metano, incluidos los esfuerzos diplomáticos basados en el *Compromiso Mundial sobre el Metano*[639]. Estas organizaciones también se comprometieron a conceder subvenciones rápidamente y a garantizar la flexibilidad de la financiación[640]. Como resultado, en marzo de 2022, se lanzó el *Global Methane Hub* que “apoyará y sostendrá la acción de la sociedad civil, los gobiernos y la industria privada, incluso en los más de 100 países que han firmado el *Compromiso* invirtiendo significativamente en soluciones para la reducción de metano”[641].

Sin embargo, cabe destacar que las soluciones de mitigación del metano siguen estando escasamente financiadas[642]. Una evaluación pionera del panorama de financiación para la mitigación del metano registró alrededor de 11.600 millones de dólares en inversiones anuales durante 2019 y 2020, apenas el 2% de la financiación climática total registrada (financiación pública para el desarrollo y financiación privada relacionada con el clima, excluida la filantropía), y 10 veces menos que los 119.000 millones de dólares necesarios cada año hasta 2050 en base al costo de las medidas de mitigación fácilmente disponibles coherentes con un escenario de calentamiento de 2 °C[643]. Entre los sectores que reciben financiación, el sector de los residuos representa alrededor del 66% de la financiación para la reducción, mientras que los sectores de la agricultura y la energía reciben conjuntamente alrededor del 33% de la financiación disponible, a pesar de emitir el 82% del metano antropogénico[644].

Al más alto nivel, los bancos multilaterales de desarrollo pueden apoyar a los países para que alcancen al menos un 30% de la reducción de las emisiones de metano, en consonancia con el *Compromiso Mundial sobre el Metano* y la *Evaluación Global del Metano*, incluso a través de las siguientes acciones:

1) Garantizar la disponibilidad de mecanismos de financiación para proyectos que reduzcan las emisiones de metano procedentes de los combustibles fósiles, los residuos y la agricultura.
2) Promover una evaluación del riesgo climático que incluya los puntos críticos de inflexión y las retroalimentaciones en materia climática[645].
3) Evitar inversiones que precipiten los puntos críticos de inflexión y que no estén alineadas con el objetivo de mantener la temperatura global por debajo de 1,5 °C en la próxima década.
4) Introducir PCG_{20} en la evaluación sobre el impacto climático para valorar más precisamente el impacto a corto plazo en la temperatura de las acciones para reducir el metano y otros CCVC.

Al tiempo que incorporan estas respuestas de emergencia climática en los procesos bancarios, las instituciones financieras multilaterales pueden basarse inmediatamente en sus compromisos existentes para ayudar a los países a invertir en la reducción del metano. Por ejemplo, el Banco Europeo de Reconstrucción y Desarrollo (BERD) respaldó el *Compromiso Mundial sobre el Metano*[646]. El BERD ya financia proyectos verdes en sectores que provocan altas emisiones de metano, como la energía y el agronegocio[647]. En la presentación de dicho *compromiso*, el BERD se comprometió a ayudar a sus países de operación en sus esfuerzos para reducir el metano, incluso a través de la asistencia técnica y la financiación de proyectos para la reducción de metano[648]. El Banco Europeo de Inversiones y el Fondo Verde para el Clima también se comprometieron a proporcionar asistencia técnica y financiación con el objeto de apoyar el *Compromiso*[649].

También será importante que los gobiernos donantes brinden apoyo financiero, incluso a través de un mecanismo específico similar al Fondo Multilateral del Protocolo de Montreal. El apoyo del Fondo Multilateral al "fortalecimiento institucional" de las unidades nacionales del ozono en los países en desarrollo "está reconocido como un factor importante para el éxito de [los países en desarrollo] en el cumplimiento de las medidas de control del Protocolo de Montreal"[650]. Un modelo similar para apoyar una red de "Oficinas Nacionales de Metano" podría capacitar rápidamente a los gobiernos para que puedan evaluar y actuar sobre las oportunidades de mitigación del metano en todos los sectores y países, incluyendo el desarrollo de líneas de base de las emisiones de metano, el seguimiento y el inventario de los emisores, la educación sobre el metano, la aplicación de planes de acción nacionales sobre el metano y la facilitación del vínculo con la financiación mundial y otros fondos importantes para la mitigación del metano.

A. El Fondo Fiduciario para la Resiliencia y la Sostenibilidad

El 2 de agosto de 2021, la Junta de Gobernadores del Fondo Monetario Internacional (FMI) aprobó la asignación general anticipada de Derechos Especiales de Giro (DEG) por un valor de $456.000 millones (equivalentes a 605.000 millones de dólares)[651]. Aunque se trata de un logro histórico del FMI bajo la dirección de su Directora Gerente, Kristalina Georgieva, la gran mayoría de los DEG se destinan a países de renta alta debido al sistema de cuotas del Fondo. Reconociendo esta deficiencia, los líderes del G7 se comprometieron a redirigir $100.000 millones de DEG a los países más necesitados de recursos para hacer frente a la pandemia del COVID-19 y para estabilizar sus economías y emprender una recuperación ecológica y global que esté en consonancia con los objetivos compartidos en materia de desarrollo y clima[652].

El 13 de octubre de 2021, en la reunión del G20 celebrada en Roma, los líderes mundiales emitieron la Declaración de los Líderes, en la que solicitaban al FMI la creación de un Fondo Fiduciario para la Resiliencia y la Sostenibilidad (FFRS). En esta Declaración, los Líderes del G20 detallaron que el FFRS "proporcionaría financiación asequible a largo plazo para ayudar a los países de renta baja.... y a los países vulnerables de renta media a reducir los riesgos para la estabilidad prospectiva de balanza de pagos, incluidos los derivados de pandemias y del cambio climático"[653]. Esta fue la primera vez que los Jefes de Estado del G20 pidieron al FMI que cumpla una función en la reducción de los riesgos económicos provocados por el cambio climático.

El Directorio Ejecutivo del FMI aprobó la creación del FFRS el 13 de abril de 2022[654]. Este Fondo complementará el actual conjunto de instrumentos de préstamo de dicho fondo, que se centra en los retos estructurales a más largo plazo, como el cambio climático y la preparación para enfrentar las pandemias. Su objetivo es mejorar la resiliencia y la sostenibilidad económicas mediante: 1) el apoyo de la reforma de políticas para reducir los riesgos macrocríticos asociados con los retos estructurales a más largo plazo; y 2) la ampliación del espacio de políticas y los colchones financieros para mitigar los riesgos derivados de dichos retos estructurales a más largo plazo—contribuyendo así a la *estabilidad prospectiva de balanza de pagos*[655].

El FMI reconoce que el cambio climático es un reto estructural a largo plazo que hará a los países más propensos a sufrir graves problemas relativos a la balanza de pagos debido al aumento de la probabilidad y el impacto de futuras perturbaciones y el menoscabo de las perspectivas de crecimiento[656]. El FFRS puede financiar, entre otras cosas, los costos de las inversiones públicas y/o privadas relacionadas con el clima, como la rehabilitación energética de los edificios existentes, los costos relacionados con la transición a las tecnologías verdes y los costos de compensación de las políticas destinadas a garantizar una transición justa, como la prestación de asistencia social mientras los gobiernos retiran las subvenciones al carbono[657]. El FMI colaborará con el Banco Mundial y los bancos multilaterales de desarrollo regionales para establecer las prioridades políticas y la condicionalidad. Las medidas del FFRS se basarán y serán coherentes con los diagnósticos de país elaborados tanto por el FMI como por el Banco Mundial en relación con los objetivos del FFRS[658].

Alrededor de las tres cuartas partes de los miembros del FMI podrán postularse para recibir la financiación del FFRS, incluidos los países de renta baja, los pequeños Estados en desarrollo y vulnerables y los países de renta media baja[659]. El límite de acceso será de 1.000 millones de DEG. Los préstamos tendrán un plazo de vencimiento de 20 años y un período de gracia de 10 años y medio.

Los recursos del FFRS se movilizarán a partir de las contribuciones voluntarias de sus miembros[660]. Estará listo para iniciar operaciones de préstamo una vez que alcance una masa crítica de recursos procedentes de una amplia base de contribuyentes y cuando se hayan implantado sistemas y procesos financieros sólidos, lo que se prevé que ocurra a finales de 2022[661]. Sus necesidades totales de recursos se estiman en 33.000 millones de DEG (equivalentes a 45.000 millones de dólares).

El marco propuesto para establecer el FFRS no menciona específicamente la mitigación de las emisiones de metano entre los proyectos que podrían beneficiarse de la financiación de este Fondo. Sin embargo, el texto de la propuesta es lo suficientemente amplio como para abarcar la acción contra el metano. Debería alentarse al FMI y a sus miembros, con la orientación del Banco Mundial, a destinar fondos a la reforma de políticas dirigidas a la mitigación de las emisiones de metano.

En particular, el FFRS podría proporcionar apoyo financiero a los países en sus esfuerzos por reducir el metano y crear las condiciones de mercado para la inversión del sector privado en este sentido. Por ejemplo, el FFRS podría incluir la posibilidad de asignar DEG a países de renta media que tengan la capacidad de catalizar financiación de bajo costo para aplicar el *Compromiso Mundial sobre el Metano*. El FFRS también debería mejorar la capacidad de los países de renta media para movilizar financiación a más largo plazo para transiciones justas en sectores con altas emisiones de metano. Estos aspectos de diseño deben realizarse sin aumentar la carga de la deuda del receptor del DEG.

A medida que el FMI establece el FFRS para reducir el riesgo climático, debe mantener la ciencia climática como el núcleo de sus esfuerzos. El diseño, la implementación y la medición del éxito del FFRS deben guiarse por los últimos avances científicos sobre la emergencia climática, el riesgo climático y la trayectoria hacia una zona climáticamente segura, incluida la mitigación rápida y a corto plazo del metano. A través de su mandato, el FFRS podría incorporar el objetivo de reducir el riesgo climático para la estabilidad prospectiva de balanza de pagos reduciendo la tasa de calentamiento a la mitad en la próxima década.

El Congreso de Estados Unidos ha propuesto aportar 21 millones de dólares al Fondo Fiduciario para el Crecimiento y la Lucha contra la Pobreza o al Fondo Fiduciario para la Resiliencia y la Sostenibilidad[662]. El 18 de agosto de 2022, China anunció su voluntad de recanalizar 10.000 millones de dólares de sus DEG a "los dos fondos fiduciarios del FMI" y dirigir sus contribuciones a África[663]. El FMI espera poner en funcionamiento el FFRS en octubre de 2022[664].

B. El Grupo del Banco Mundial

El Grupo del Banco Mundial (GBM) es el mayor proveedor de financiación climática para los países en desarrollo. En 2018, el GBM anunció una nueva serie de objetivos relacionados con el clima para el período comprendido entre 2021 y 2025, "con el que duplica las inversiones en el actual período de cinco años para llevarlas hasta unos USD 200.000 millones a fin de apoyar a los países para que adopten medidas de gran envergadura en materia de cambio climático"[665]. Los 200.000 millones de dólares se componen de "alrededor de USD 100.000 millones en financiamiento directo del Banco Mundial, más aproximadamente USD 100.000 millones en financiamiento directo combinado" de la Corporación Financiera Internacional y el Organismo Multilateral de Garantía de Inversiones, así como de capital privado movilizado por el GBM[666].

Los últimos informes del IPCC ofrecen una oportunidad para que el GBM revise su Plan de Acción sobre el Cambio Climático (2021-2025) y realinee su cartera con el objetivo de mantener la temperatura en 1,5 °C conforme al l Acuerdo de París, centrándose en la emergencia climática, los puntos críticos de inflexión y los bucles de retroalimentación, y dando prioridad a las inversiones en estrategias de mitigación rápida dado que son esenciales para aumentar la resiliencia y reducir el riesgo climático[667].

El GBM también podría comenzar a incorporar la utilización de métricas que capturen el impacto a corto plazo del metano y de otros CCVC en la temperatura, tales como el PCG_{20}, en todo su trabajo de promoción de los mercados de carbono[668].

En 2012, el G8 acordó encargar al GBM que evaluara mecanismos innovadores de pago por desempeño para hacer frente al metano[669]. Un informe del Grupo de Estudio sobre el Financiamiento del Metano apoyó la creación de un mecanismo para el metano[670]. En su fase de diseño y desarrollo, el Mecanismo Piloto de Subasta para la Mitigación del Cambio Climático y la Reducción de las Emisiones de Metano (PAF, por sus siglas en inglés) contó con el apoyo de la *Coalición Clima y Aire Limpio*[671]. Este mecanismo completó tres subastas para asignar un precio garantizado para futuros créditos de carbono en forma de opción de venta negociable, dos para la reducción de las emisiones de metano del sector de los residuos y una para la reducción de las emisiones de óxido nitroso procedentes de la producción de ácido nítrico[672]. Las tres subastas asignaron hasta 54 millones de dólares, lo que se tradujo en una reducción de hasta 20,6 millones de toneladas métricas de CO_2eq (al utilizar el PCG_{100} se subestima el impacto climático del metano). Los principales contribuyentes al PAF fueron Alemania, Suecia, Suiza (a través de una contribución conjunta de la Secretaría de Estado de Economía y la Fundación Climate Cent) y Estados Unidos[673]. El *Compromiso Mundial sobre el Metano* podría brindar la oportunidad de seguir explorando este tipo de mecanismos de financiación.

La Corporación Financiera Internacional financia proyectos de mitigación del metano. Por ejemplo, el 29 de julio de 2022, hizo pública su financiación para 24 proyectos de conversión de gas de vertedero en energía que se llevarán a cabo en 10 provincias de China[674]. Se calcula que el proyecto reducirá unas 3,4 mtCO_2e de GEI mediante la captura de metano[675]. Su Programa de Bonos Verdes ofrece financiación para proyectos relacionados con la reducción del metano centrados en la ganadería, la acuicultura, la quema de gas y la conversión de residuos en energía, entre la lista de proyectos que pueden recibir financiación[676]. Sin embargo, la Corporación Financiera Internacional podría avanzar más y actualizar sus Normas de Desempeño sobre Sostenibilidad Ambiental y Social y sus Definiciones y Métricas para Actividades Relacionadas con el Clima utilizando los datos científicos más recientes sobre la emergencia climática, incorporando los puntos críticos de inflexión y los bucles de retroalimentación en su definición de riesgo climático para que su oferta de financiación se mantenga actualizada.

Además, el Organismo Multilateral de Garantía de Inversiones, miembro del GBM que ofrece garantías a largo plazo[677], puede apoyar la adopción rápida y permanente de soluciones para las emisiones de metano. Muchas de las acciones para reducir las emisiones de metano implican inversiones a largo plazo. Asimismo, este organismo podría elaborar un plan para ampliar su producto de optimización de capital con el objeto de apoyar una serie de préstamos para la mitigación del metano y desplegar una estrategia para atraer la asociación de bancos comerciales en proyectos clave.

C. Una estrategia de financiación mundial para hacer frente a la crisis climática

En la COP26, la Primera Ministra de Barbados, Mia Mottley, presentó un plan de financiación para hacer frente a la emergencia climática. La Primera Ministra Mottley, que también es Copresidenta del Comité de Desarrollo del Banco Mundial y del FMI, señaló que:

> "Los bancos centrales de los países más ricos han realizado $25 trillones de expansión cuantitativa en los últimos 13 años. $25 trillones. De ellos, en los últimos 18 meses, $9 trillones se destinaron a la lucha contra la pandemia. Si hubiéramos utilizado esos $25 trillones para comprar bonos con el fin de financiar la transición energética, o el cambio de alimentación, o de la manera en que nos transportamos, ahora, hoy, estaríamos logrando ese límite de 1,5 grados que es tan vital para nosotros"[678]. [La traducción al español nos pertenece]

La Primera Ministra Mottley propuso un aumento anual de DEG de $500.000 millones al año durante veinte años, que se depositarían en un fondo fiduciario para financiar la transición. Señaló que $500.000 millones son sólo el 2% de los $25 trillones que los bancos centrales de los países más ricos han comprometido en los últimos 13 años[679].

La propuesta incluye el diseño de un fondo fiduciario de $500.000 millones que operaría en base a un sistema de subastas para lograr una mayor mitigación climática y que incluiría al sector privado en sus criterios de elegibilidad. La Primera Ministra Mottley sigue abogando por la creación de este fondo fiduciario que, para hacer frente verdaderamente a la emergencia climática, debe dar prioridad a la reducción de las emisiones de metano.

12. Conclusión

Reducir las emisiones de metano es la mejor manera que conocemos de frenar el calentamiento global en los próximos 20 años. Alcanzar el objetivo de hasta 0,3 °C de calentamiento evitado para mantener el límite de 1,5°C dentro de nuestro alcance requiere crear mecanismos técnicos, financieros y de gobernanza. El *Compromiso Mundial sobre el Metano* y los objetivos relacionados representan pasos importantes para lograr un acuerdo mundial en esta materia. Mientras tanto, es necesario tomar medidas inmediatas para exigir a los proveedores de "gas metano de sustitución" una tasa de emisiones de metano progresivamente más baja en respuesta a los cambios en las importaciones de gas metano de los países. La mejora de los sistemas de control añaden transparencia, pero debe ir acompañada de una estrategia de responsabilidad y cumplimiento que incentive la reducción efectiva de las emisiones, conectando a los emisores con la capacidad técnica y financiera necesarias. El presente *Manual sobre el Metano* expone la urgencia, las oportunidades y los elementos clave para fundar una base sólida con el fin de elaborar un acuerdo mundial sobre el metano, que debería ser el objetivo final si deseamos frenar el calentamiento global durante esta década.

References

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[2] Naik V., *et al.* (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* Naik V., *et al.* (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] 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.

[7] 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.").

[8] 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."). *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."); *and* Pultarova T. (11 January 2022) *Satellites reveal record high methane concentrations despite reduction pledges*, SPACE.

[9] 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)").

[10] 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.

[11] 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.").

[12] 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., *et al.* (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*).").

[13] 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.").

[14] 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.").

[15] 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* Naik V., *et al.* (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}").

[16] 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., *et al.* (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}").

[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., *et al.* (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}")."").

[18] 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).").

[19] 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)").

[20] 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.").

[21] 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.").

[22] 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.").

[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] 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.").

[25] 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.").

[26] 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.").

[27] 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.").

[28] 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).").

[29] 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., *et al.* (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*).").

[30] 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* 31 August 2022) ("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.").

[31] 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)").

[32] 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.").

[33] 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* Naik V., *et al.* (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., *et al.* (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.").

[34] 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 %).").

[35] 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.").

[36] 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.").

[37] 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.").

[38] 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 %).").

[39] 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."). 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.").

[40] 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*.").

[41] 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).").

[42] 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.

[43] 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., *et al.* (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}").

[44] 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.").

[45] 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).").

[46] 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).").

[47] 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.

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

[49] 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.").

[50] 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.

[51] National Oceanic and Atmospheric Administration (7 April 2021) *Despite pandemic shutdowns, carbon dioxide and methane surged in 2020*, NOAA Research News ("NOAA's preliminary analysis showed the annual increase in atmospheric methane for 2020 was 14.7 parts per billion (ppb), which is the largest annual increase recorded since systematic measurements began in 1983.").

[52] 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.").

[53] 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.").

[54] Naik V., *et al.* (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.).

[55] 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.").

[56] 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.").

[57] 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.").

[58] 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).").

[59] Here we use "climate tipping points" to mean abrupt shifts, as in Drijfhout *et al*. (2015). Armstrong McKay *et al*. (2022) identify 16 "core" climate tipping points, with 6 likely to occur between 1.5°C and 2°C using the more restrictive definition of "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* 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."). *Compare with* 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."). *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., *et al.* (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).

[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, 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.").

[61] 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* 29 July 2022) ("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.").

[62] 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., *et al.* (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).").

[63] Naik V., *et al.* (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., *et al.* (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.").

[64] 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.").

[65] 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* Naik V., *et al.* (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.”).

[66] 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., *et al.* (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}”).

[67] 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).”).

[68] 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.”).

[69] 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.").

[70] 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.").

[71] 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.").

[72] 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.").

[73] 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).

[74] 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.").

[75] 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.").

[76] 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.").

[77] 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.").

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

[79] 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).").

[80] 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.").

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

[82] Naik V., *et al.* (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*).").

[83] 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.").

[84] 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.).

[85] 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.").

[86] 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.").

[87] 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).'").

[88] 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.

[89] 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.").

[90] Forster P., *et al.* (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.

[91] 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).").

[92] 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".").

[93] 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.

[94] 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*).").

[95] 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.").

[96] 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.").

[97] 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.").

[98] 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., *et al.* (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*).").

[99] 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)").

[100] 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.").

[101] 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.").

[102] 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.

[103] 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).”).

[104] 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.”).

[105] 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.”).

[106] 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.

[107] Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (22 April 2022) *Global warming overshoots increase risk of triggering climate tipping points and cascades*, NATURE (*preprint*), 1–31, 1, 11–12, 18 (“Climate tipping elements play a crucial role for the stability of the Earth system under human pressures and are potentially at risk of disintegrating within and partially even below the Paris temperature guardrails of 1.5-2.0°C above pre-industrial levels. However, current policies and actions make it very likely to, at least temporarily, transgress the Paris targets. This raises the question whether tipping points can still be avoided under such overshoot scenarios. Here, we investigate the associated risks for tipping under a range of temperature overshoot scenarios using a stylised network model of four interacting climate tipping elements: the Greenland and West Antarctic Ice Sheets, the Atlantic Meridional Overturning Circulation and the Amazon rainforest. Our results reveal that temporary overshoots can increase tipping risks by up to 72% compared to a soft landing without overshoots, even when the long-term equilibrium temperature stabilises within the Paris range.”).

[108] 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.”).

[109] 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.”).

[110] 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).

[111] 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.

[112] 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).").

[113] Naik V., *et al.* (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.").

[114] 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.").

[115] 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.").

[116] 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* Naik V., *et al.* (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}").

[117] 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., *et al.* (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}").

[118] 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., *et al.* (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 CH4 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}").

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

[120] Naik V., *et al.* (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*).").

[121] 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.").

[122] 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.").

[123] 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).").

[124] 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.").

[125] 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.").

[126] 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.").

[127] 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.").

[128] 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.").

[129] 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 %).").

[130] 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.").

[131] 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).").

[132] 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.").

[133] 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 $\delta^{13}C$-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).").

[134] 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.").

[135] 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.").

[136] 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.").

[137] 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.").

[138] 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.").

[139] 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.").

[140] 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.

[141] United States Environmental Protection Agency, *About Coal Mine Methane* (*last visited* 31 August 2022) ("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.").

[142] 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.").

[143] 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.").

[144] 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.").

[145] 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.").

[146] 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.").

[147] 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.").

[148] 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).").

[149] 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.").

[150] 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".

[151] 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).").

[152] 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.).

[153] 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".

[154] 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.").

[155] 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.

[156] 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.").

[157] 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.").

[158] 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)").

[159] 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)").

[160]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.").

[161] 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.").

[162] 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.

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

[164] 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.").

[165] 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.").

[166] 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%.").

[167] 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.").

[168] 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.").

[169] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 31 August 2022) ("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.").

[170] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 29 July 2022) (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.").

[171] *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.").

[172] 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* 31 August 2022) ("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.").

[173] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 31 August 2022) ("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%.").

[174] World Bank (5 May 2022) *Global Flaring and Venting Regulations* (*last visited* 31 August 2022) ("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.").

[175] 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.

[176] 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.").

[177] 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.

[178] 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.").

[179] 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.").

[180] 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.").

[181] 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.

[182] 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.").

[183] 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).").

[184] Rocky Mountain Institute, *Profiling Supply Chain Emissions* (*last visited* 29 July 2022) ("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.

[185] 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.").

[186] 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.").

[187] 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.").

[188] 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.").

[189] 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.").

[190] 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.").

[191] 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).").

[192] 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)").

[193] 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.").

[194] 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).").

[195] 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].").

[196] 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.").

[197] 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.”).

[198] 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.”).

[199] 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.”).

[200] 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*.

[201] 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).”).

[202] 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.”).

[203] 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...”).

[204] 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.”).

[205] 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.").

[206] Babiker M., *et al.* (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., *et al.* (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).").

[207] 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.

[208] 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.

[209] 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.").

[210] 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.").

[211] 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$.").

[212] 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.").

[213] 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.").

[214] 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.").

[215] 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.

[216] 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.").

[217] 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).").

[218] 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.").

[219] 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.").

[220] 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]").

[221] 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.").

[222] 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.").

[223] 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* 31 August 2022) ("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).").

[224] 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).").

[225] 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.").

[226] Climate & Clean Air Coalition, *Paddy rice production* (*last visited* 31 August 2022) ("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* 31 August 2022) ("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.").

[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, 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.").

[228] 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.").

[229] 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.").

[230] 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.").

[231] California Air Resources Board, *Rice Cultivation Projects* (*last visited* 29 July 2022).

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

[233] 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.'").

[234] 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.").

[235] 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.").

[236] 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.").

[237] 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.").

[238] *See* Number 8 Bio (*last visited* 29 July 2022).

[239] 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.

[240] 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).").

[241] N2–Applied, *N2 Solution* (*last visited* 31 August 2022) ("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.").

[242] 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.").

[243] 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.").

[244] 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.").

[245] 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.").

[246] 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.").

[247] 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.").

[248] United States Environmental Protection Agency, *Basic information about landfill gas* (*last visited* 29 July 2022).

[249] 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.").

[250] 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)).

[251] United States Environmental Protection Agency, *Basic information about landfill gas* (*last visited* 31 August 2022) ("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*.

[252] 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.").

[253] 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.").

[254] 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.").

[255] 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.").

[256] United Nations Climate Technology Centre & Network, *Biocovers of landfills* (*last visited* 31 August 2022) ("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.").

[257] 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.").

[258] 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.").

[259] 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).").

[260] United Nations Climate Technology Centre & Network, *Biocovers of landfills* (*last visited* 31 August 2022) ("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.").

[261] 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.").

[262] United Nations Climate Technology Centre & Network, *Biocovers of landfills* (*last visited* 31 August 2022) ("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.").

[263] 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.").

[264] 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.").

[265] 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.").

[266] 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.").

[267] 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.

[268] 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.'").

[269] 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.").

[270] 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.").

[271] 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).").

[272] 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* 29 July 2022) ("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.

[273] 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."). [Please double check term in green highlight]

[274] 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].").

[275] Gulev S. K., *et al*. (2021) *Chapter 2: Changing State of the Climate System*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 2-100 ("The role of decadal to multi-decadal variability has recently emerged as an important aspect of the IOD with many indications of the effects of Pacific Ocean processes on IOD variability through atmospheric and oceanic mechanisms (Dong et al., 2016; Jin et al., 2018; Krishnamurthy & Krishnamurthy, 2016; Zhou et al.,2017). . . Positive IOD events may have increased in frequency during the second half

of the 20th century (Abram et al., 2020a,b). Earlier observations of apparent changes in the frequency and / or magnitude of the IOD events are considered unreliable, particularly prior to the 1960s (Hernández et al., 2020). ... To summarize, there is *low confidence* in any multi-decadal IOD variability trend in the instrumental period due to data uncertainty especially before the 1960s... Neither the IOD nor the IOB have exhibited behaviour outside the range implied by proxy records (*low confidence*)."). *Compare with* Cheng C. & Redfern S. A. T. (2022) *Impact of interannual and multidecadal trends on methane-climate feedbacks and sensitivity*, NAT. COMMUN. 13(3592): 1–11, 7 ("The feedback sensitivity, in ppb $°C^{-1}$, before 1994 initially rises under positive feedback dominance, but declines subsequently and appears to stabilize around 200 ppb $°C^{-1}$ (Fig. 6a, b). This approximates ~0.08 W m^{-2} $°C^{-1}$ (ref. 70) which is about four times greater than the mean net feedback estimate given in IPCC AR6 (~0.05 positive feedback including permafrost and −0.03 negative feedback, giving ~0.02 W m^{-2} $°C^{-1}$) but agrees within uncertainty[7]. The difference could be largely due to the positive $\partial C_{CH4}(T\&Pr)/\partial t$ from negative feedbacks following the years or decades of positive feedback. In fact, several interannual peaks of sensitivity are due to the positive contributions of lowering GMST (i.e., negative feedbacks). If we breakdown our estimated sensitivity into positive and negative feedbacks, we estimate 0.05 + 0.03 W m^{-2} $°C^{-1}$ rather than 0.05 – 0.03 W m^{-2} $°C^{-1}$. Since the 200 ppb $°C_{-1}$ long-term sensitivity is even larger than the estimated absolute maximal instantaneous sensitivity in Eq. 5 (i.e., the calibration factor α in Eqs. 3–4) at 125 (ppb yr^{-1})/(°C yr^{-1}), the positive contributions from negative feedbacks should be viewed as lagged responses from earlier positive feedbacks due to nonlinearity. We note that the sensitivity is strongest in boreal and tropical regions (Fig. 6a) due to the positive feedbacks with wetland emissions.").

[276] 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.").

[277] 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.

[278] 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 27estabilization 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.").

[279] 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.").

[280] 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 %).").

[281] 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."). 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.").

282 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* 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.").

283 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.").

[284] 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.").

[285] 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.").

[286] 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.

[287] 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").

[288] 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.").

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

[290] 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.").

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

[292] 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.

[293] 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.”).

[294] 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.

[295] 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.”). The draft regulations were under review by the White House Office of Management and Budget as of 15 August 2022 and are expected to take effect for new and modified oil and gas operations in 2023 and for existing sources likely by 2026 after EPA approval of state implementation plans, *according to* Chemnick J. (30 August 2022) *The methane rule is under review. Here’s what it would do*, E&E NEWS (“While the EPA rule for new and modified oil and gas operations is likely to take effect next year, EPA’s guidelines for existing sources requires input from states in the form of a state implementation plan. Those must then be approved by EPA — or the agency must offer a federal alternative of its own. The process typically takes years. Schroeder said 2026 was a likely timeline for existing source rules to phase in, leaving a broad swath of onshore oil and gas sources to operate outside of EPA regulation until then.”).

[296] United States Environmental Protection Agency (2021) *EPA’s Proposal to Reduce Climate- and Health-Harming Pollution from the Oil and Natural Gas Industry: Overview*, 2 (“Reduce methane emissions by approximately 41 million tons through 2035, the equivalent of 920 million metric tons of carbon dioxide – more than the amount of carbon dioxide emitted in 2019 from all U.S. passenger cars and commercial aircraft combined. In 2030 alone, the proposed rule would reduce methane emissions from covered sources by an estimated 74 percent compared to emissions from those sources in 2005.”).

[297] United States Bureau of Land Management (18 November 2016) *Waste Prevention, Production Subject to Royalties, and Resource Conservation*, FED. REG. 81(223): 83008–83089, 83008, 83014 (Codified at 43 C.F.R. Parts 3100, 3160, and 3170) (“The BLM estimates that this rule would result in monetized benefits of $209–403 million per year (calculating the monetized emissions reductions using model averages of the social cost of methane with a 3 percent discount rate).162 We estimate that the rule would reduce methane emissions by 175,000– 180,000 tpy, which we estimate to be worth $189–247 million per year (this social benefit is included in the monetized benefit above). We estimate that the rule would reduce VOC emissions by 250,000–267,000 (this benefit is not monetized in our calculations).163 Overall, we predict the rule will reduce methane emissions by 35% from the 2014 estimates and reduce the flaring of associated gas by 49%, when the capture requirements are fully phased in.164”).

[298] 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.”).

[299] 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.").

[300] 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.").

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

[302] 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.").

[303] 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.").

[304] *See* United States Environmental Protection Agency, *Livestock Anaerobic Digester Database* (*last visited* 29 July 2022) (Tracking anaerobic digester projects in the U.S.); *and* United States Environmental Protection Agency, *LMOP Landfill and Project Database* (*last visited* 29 July 2022) (Tracking U.S. landfills, including candidates for landfill gas energy projects.).

[305] 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.").

[306] United States Environmental Protection Agency, *United States 2030 Food Loss and Waste Reduction Goal* (*last visited* 31 August 2022) ("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.").

[307] United States Environmental Protection Agency, *About the Landfill Methane Outreach Program* (*last visited* 31 August 2022) ("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.").

[308] United States Environmental Protection Agency, *Coal Mine Methane – What EPA is Doing* (*last visited* 31 August 2022) ("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.").

[309] United States Environmental Protection Agency, *What EPA is Doing: AgSTAR* (*last visited* 31 August 2022) ("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.").

[310] 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* 29 July 2022) ("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....").

[311] 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).").

[312] 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.").

[313] 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").

[314] *See* CHIPS and Science Act, Pub. L. No. 117-167 § 10771 (2022); U.S. 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.

[315] 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]").

[316] 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.").

[317] 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...").

[318] 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.").

[319] 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.").

[320] *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.").

[321] 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.").

[322] 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.").

[323] 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.

[324] 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.").

[325] 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.").

[326] 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.").

[327] 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* (*last visited* 31 August 2022) ("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.").

[328] 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").

[329] 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.").

[330] 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.").

[331] There are currently 24 states, plus Puerto Rico, who have joined the U.S. Climate Alliance. *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.").

[332] 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).

[333] 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.").

[334] 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 ($p = 0.002$))").

[335] 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.").

[336] United States Composting Council, *State Regulations* (*last visited* 29 July 2022) (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).

[337] University of California Berkeley, Center for Law, Energy & the Environment, *Methane Protocols for Reducing Emissions* (*last visited* 31 August 2022) ("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.").

[338] 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.").

[339] 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.").

[340] 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.").

[341] 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;").

[342] 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.").

[343] 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.").

[344] 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.").

[345] 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.").

[346] 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.").

[347] Vasconcellos R. B. (4 August 2022) *Energy Is Up on U.S.-Brazil Relations* (*last visited* 31 August 2022) ("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.").

[348] The Environmental Partnership, *Taking Action* (*last visited* 31 August 2022) ("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* 2 August 2022).

[349] ONE Future Coalition, *About Us* (*last visited* 31 August 2022) ("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.").

[350] 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.").

[351] 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).

[352] 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).

[353] 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.).

[354] 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.").

[355] 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.").

[356] 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.").

[357] 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.").

[358] 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%'").

[359] 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.").

[360] European Environment Agency, *EEA greenhouse gases – data viewer* (*last visited* 2 August 2022) (Data through 2020).

[361] 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%.").

[362] 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.").

[363] 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*.

[364] 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.").

[365] European Commission (15 December 2021) *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 ... [12 months from the date of entry into force of this Regulation], operators shall submit a report to the competent authorities containing source-level methane emissions estimated.... 3. By ... [36 months from the date of entry into force of this Regulation] and by 30 March every year thereafter, operators shall submit a report to the competent authorities containing direct measurements of source-level methane emissions for operated assets.... 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 containing direct measurements of source-level methane emissions for non-operated assets.... 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).").

[366] European Commission (15 December 2021) *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 to check the compliance of operators or mine operators with the requirements set out in 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, the International Methane Emissions Observatory shall be attributed a verification role with respect to methane emissions data....").

[367] European Commission (15 December 2021) *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 to be carried out in accordance with the requirements in this Article."; "Venting shall be prohibited except in the circumstances provided for this Article. Routine flaring shall be prohibited.").

[368] European Commission (15 December 2021) *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 inactive wells on their territory or under their jurisdiction.... 2. By [12 months from the date of entry into force of this Regulation], equipment for measurement of methane emissions shall be installed on all inactive wells. 3. Reports containing the measurements referred to in paragraph 2 shall be submitted to the competent authorities.... 4. The competent authorities shall make the reports set out in this Article available to the public and the Commission.... 5. 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.... 6. Member States shall develop and implement a mitigation plan to remediate, reclaim and permanently plug inactive wells located in their territory. Mitigation plans shall use the inventories referred to in paragraph 1 to determine priority for activities including: (a) remediating, reclaiming and permanently plugging wells; (b) reclaiming related access roads; (c) restoring land, water and habitat impacted by wells and the prior operations; (d) yearly checks to ensure plugged wells are no longer a source of methane emissions.").

[369] European Commission (15 December 2021) *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 ("Member States shall set up and make publicly available an inventory of all closed coal mines and abandoned coal mines in their territory or under their jurisdiction.... Methane concentration measurements shall be taken in accordance with appropriate scientific standards and at least on an hourly basis.... [M]easurement equipment shall be installed on all elements listed in point (v) of Part 1 of Annex VII 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].... Reports containing estimates of yearly source-level methane emissions data shall be submitted to the competent authorities....").

[370] European Commission (15 December 2021) *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 abandoned coal mines.... 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. 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.").

[371] European Commission (15 December 2021) *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 measurement and quantification on all exhaust ventilation shafts used by the mine operator.... 2. Drainage stations operators shall perform continuous measurements of volumes of 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. Mine operators shall estimate coal post-mining emissions using coal post-mining emission factors....").

[372] European Commission (15 December 2021) *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 measurement and quantification on all exhaust ventilation shafts used by the mine operator.... 2. Drainage stations operators shall perform continuous measurements of volumes of 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. Mine operators shall estimate coal post-mining emissions using coal post-mining emission factors....").

[373] European Commission (15 December 2021) *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 flaring 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...."); Art. 23 ("From [1 January 2025], drainage station operators shall notify the competent authorities of all venting and flaring events: (a) caused by an emergency or a malfunction, (b) occurring unavoidably due to maintenance of the drainage system.").

[374] 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.").

[375] 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.

[376] 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.").

[377] European Commission (15 December 2021) *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 31 December every year thereafter, importers shall provide the information set out in Annex VIII to the competent authorities of the importing Member State.... 2. By ... [12 months from the date of entry into force of the Regulation] and by 30 June 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), 18(4), 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.").

[378] 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.).

[379] 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.'").

[380] 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.").

[381] 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 (26).").

[381] 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 ("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.").

[382] 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;").

[383] 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.").

[384] 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.").

[385] 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.").

[386] 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.").

[387] 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.").

[388] 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.").

[389] 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.).

[390] 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.").

[391] 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.").

[392] 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.").

[393] 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.").

[394] 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.").

[395] 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.

[396] 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).").

[397] 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.").

[398] 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.").

[399] 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.").

[400] Environment and Climate Change Canada (6 April 2022) *Government of Canada to develop guidance for best-in-class new oil and gas projects and net-zero emissions requirements by 2050*, Press Release ("To remain competitive in a global market that is moving away from fossil fuels combustion to address climate change and enhance energy security, new Canadian oil production subject to federal impact assessment will have to meet even higher standards. New projects would have to deliver emissions performance—the amount of greenhouse gas pollution it takes to produce a barrel of oil or cubic metre of natural gas—that is best in class, and all future oil and gas projects would have to be net zero by 2050.").

[401] 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.").

[402] 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.").

[403] 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.").

[404] 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.").

[405] 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.").

[406] Agriculture and Agri-Food Canada, *Agricultural Climate Solutions* (*last visited* 31 August 2022) ("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.").

[407] Agriculture and Agri-Food Canada, *Agricultural Clean Technology Program: Adoption Stream: Applicant Guide* (*last visited* 31 August 2022) ("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").

[408] 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.").

[409] 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;").

[410] 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.

[411] Government of Mexico (2015) *Intended Nationally Determined Contribution*, 11 ("The energy and industry sectors intend to: ... 25% reduction in methane leaks, venting and controlled combustion... In the urban sector: ... methane recovery and use in municipal landfills and water treatment plans.").

[412] Government of Mexico (2015) *Intended Nationally Determined Contribution*, 22 ("Mexico is unconditionally committed to reduce its greenhouse gas (GHG) emissions by 22% and its black carbon emissions by 51% by 2030 compared to a baseline under a business-as-usual (BAU) scenario. In addition, conditional commitments would allow for increased emissions mitigation, reaching a target of up to 36% reduction of GHG emissions and 70% of black carbon emissions by 2030 compared to the BAU.").

[413] Government of Mexico, Ministry of Environment and Natural Resources (2020) *Nationally Determined Contribution: 2020 Update*, 27 ("A partir de procesos de consulta y de transversali- zación de la NDC, se han identificado ac- ciones que fomentarán la optimización de los procesos de los sistemas de refinación y procesamiento, así como la implemen-tación de la Política de Reducción de Emi- siones de Metano.") ("Based on consultation processes and the transversalities of the NDC, actions that will promote the optimization of the processes of the refining and processing systems have been identified, including the implementation of the Methane Emissions Reduction Policy.") (in Spanish).

[414] 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.").

[415] 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.

[416] 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.").

[417] 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.").

[418] 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.

[419] 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).").

[420] 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 $GgCO_2$e) in 2016, a decrease of 2.25 per cent since 2014.").

[421] 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.").

[422] 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 $MtCO_2$e in 2017- 18 and 2018-19.").

[423] 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).").

[424] 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 MtCO2 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.").

[425] Government of India, Ministry of New and Renewable Energy, *New National Biogas and Organic Manure Programme (NNBOMP)* (*last visited* 31 August 2022) ("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.").

[426] Government of India, Ministry of Petroleum and Natural Gas, *Unconventional Hydrocarbons* (*last visited* 29 July 2022) ("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.").

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

[428] Government of India, National Data Repository, Directorate General of Hydrocarbons, Ministry of Petroleum and Natural Gas, *Coal Bed Methane* (*last visited* 31 August 2022) ("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).").

[429] 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).

[430] 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).

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

[432] 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.").

[433] 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).").

[434] 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.").

[435] 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.").

[436] 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).

[437] 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.).

[438] 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.).

[439] 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.

[440] (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.).

[441] 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).

[442] 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).

[443] 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).

[444] 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).

[445] *See* People's Republic of China (2021) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, 3, submission to the Secretariat of UNFCCC; (28 October 2021) China's Mid-Century, Long-Term Low Greenhouse Gas Emission Development Strategy, 13, submission to the Secretariat of UNFCCC; *and* Institute for Governance & Sustainable Development (22 April 2021) *World leaders to US: "Welcome back to the fight. This time I know our side will win"*, Press Release ("President Xi Jinping, China: Stresses China's commitment to 'accept the Kigali Amendment to the Montreal Protocol' and 'to strengthen the control of non-CO_2 greenhouse gases'. And also to ';strictly control the growth of coal consumption during the 14th Five-Year period' [2021-2025] and 'gradually reduce coal consumption in the 15th Five-Year period' [2026-2030].").

[446] 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).

[447] (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.").

[448] (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).

[449] 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.

[450] 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").

[451] 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).

[452] 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).

[453] 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).

[454] 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).

[455] 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).

[456] 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.").

[457] 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).

[458] 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).

[459] 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).

[460] 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).

[461] 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).

[462] 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).

[463] 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] (Promulgated by 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, December 15, 2021) (hyperlink to original Chinese).

[464] 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] (Promulgated by 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, December 15, 2021) (hyperlink to original Chinese).

[465] 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.”).

[466] 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).

[467] International Energy Agency, *Methane Tracker Data Explorer* (*last visited* 31 August 2022).

[468] 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.").

[469] Global Methane Initiative, *Methane Emissions Data* (*last visited* 31 August 2022).

[470] 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.").

[471] 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.").

[472] 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.").

[473] 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.").

[474] 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.

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

[476] 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.").

[477] 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.").

[478] 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.").

[479] 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.").

[480] 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.")

[481] Climate & Clean Air Coalition, *Our Partners* (*last visited* 31 August 2022) ("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.").

[482] Climate & Clean Air Coalition, *National policy and planning support* (*last visited* 31 August 2022) ("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* 31 August 2022) ("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.").

[483] 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.

[484] 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.").

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

[486] 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).").

[487] *See* Global Methane, Climate and Clean Air Forum (*last visited* 31 August 2022) ("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.").

[488] AIM For Climate, *Innovation Sprints* (*last visited* 29 July 2022) (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").

[489] AIM For Climate, *Partners* (*last visited* 29 July 2022) (List of partners).

[490] 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.").

[491] *See e.g.*, World Bank, *Global Gas Flaring Reduction Partnership (GGFR), About the Partnership* (*last visited* 29 July 2022).

[492] United States Department of State (17 June 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Release ("The United States also intends to take the steps necessary to rejoin the World Bank Global Gas Flaring Reduction Partnership.").

[493] World Bank, *Zero Routine Flaring By 2030 (ZRF) Initiative* (*last visited* 31 August 2022) ("Launched in 2015, the ZRF Initiative commits governments and oil companies, to end routine flaring no later than 2030.").

[494] World Bank, *Zero Routine Flaring by 2030, Initiative Endorsers* (*last visited* 31 August 2022) (List of endorsers).

[495] 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.").

[496] 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.").

[497] 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").

[498] 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 CH4 for 2010) [17]. If deposited in managed landfills, waste can release significant amounts of CH4 into the atmosphere that could be avoided by installing proper LFG recovery systems.")

[499] 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").

[500] Global Methane Initiative, *About the Global Methane Initiative* (*last visited* 31 August 2022) ("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.").

[501] Global Methane Initiative, *Partner Countries* (*last visited* 31 August 2022) ("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.").

[502] Global Methane Initiative, *Overview of Accomplishments* (*last visited* 31 August 2022) ("Approximately 500 $MMTCO_2e$ emission reductions achieved through GMI projects since 2004").

[503] 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.").

[504] 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.").

[505] Oil and Gas Climate Initiative, *About Us* (*last visited* 31 August 2022) ("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.").

[506] World Biogas Association, *What is our mission?* (*last visited* 31 August 2022) ("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.").

[507] World Biogas Association, *Membership benefits* (*last visited* 31 August 2022) ("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.").

[508] The World Biogas Summit, *2021 Programme* (*last visited* 29 July 2022).

[509] Methane Guiding Principles, *The Methane Guiding Principles* (*last visited* 2 August 2022) ("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....").

[510] Methane Guiding Principles, *Oil and Gas Sector Toolkit for the Global Methane Pledge* (*last visited* 12 September 2022) ("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.").

[511] MiQ, *The Methane Mission* (*last visited* 31 August 2022) ("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.").

[512] American Gas Association, *Natural Gas Sustainability Initiative (NGSI)* (*last visited* 31 August 2022) ("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.").

[513] 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.

[514] 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.").

[515] 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).

[516] 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.").

[517] 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.").

[518] Copernicus, *About Copernicus* (*last visited* 31 August 2022) ("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**.").

[519] Copernicus, *About Copernicus* (*last visited* 31 August 2022) ("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.").

[520] Copernicus, *Copernicus in detail* (*last visited* 31 August 2022) ("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.").

[521] Copernicus, *Atmosphere* (*last visited* 31 August 2022) ("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.").

[522] Copernicus, *Land* (*last visited* 31 August 2022) ("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.").

[523] Copernicus, *Climate Change* (*last visited* 31 August 2022) ("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.").

[524] MethaneSAT, *About MethaneSAT* (*last visited* 31 August 2022) ("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.").

[525] 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.").

[526] 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.").

[527] 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.").

[528] 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.

[529] 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.

[530] International Energy Forum, *IEF Methane Initiative: Methane Measurement Methodology Project* (*last visited* 31 August 2022) (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.").

[531] International Energy Forum, *IEF Methane Initiative: Methane Measurement Methodology Project* (*last visited* 31 August 2022) ("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.").

[532] 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.").

[533] 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.").

[534] 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.").

[535] United Nations Environment Programme, *International Methane Emissions Observatory* (*last visited* 31 August 2022) ("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.").

[536] 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.").

[537] 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.

[538] 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.").

[539] 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.'").

[540] 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*).").

[541] 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.").

[542] 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.").

[543] 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.").

[544] 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.").

[545] 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.").

[546] 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.").

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

[548] 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.").

[549] (8 November 2021) *LIVE: President Obama delivers a speech at COP26 climate summit in Glasgow, Scotland*, YAHOO FINANCE, YouTube (from 23:12–23:19).

[550] 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.").

[551] 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).").

[552] 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.").

[553] (13 November 2021) Parties to the Paris Agreement, Decision -/CP.26 ¶19, *Glasgow Climate Pact Advance unedited version*.

[554] 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.").

[555] 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.").

[556] (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.").

[557] (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.").

[558] (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.").

[559] 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).")

[560] 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.

[561] *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.").

[562] 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.").

[563] 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.").

[564] (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.").

[565] 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* UNECE, *Member States and Member States Representatives* (*last visited* 29 July 2022).

[566] 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.").

[567] (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.").

[568] (*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....").

[569] 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).”).

[570] (*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”).

[571] 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.”).

[572] 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;”).

[573] 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?”).

[574] 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.”).

[575] 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 ¶ 16, Annex II (Setting out the work schedule for preparation of the Gothenburg Protocol review reports and specifying that the review should be concluded by December 2022).

[576] 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 ¶ 13, 14–15 (Annex I sets out the questions to subsidiary bodies of the Convention for the review of the Gothenburg Protocol and specifying that TFHTAP and MSC-W Review should be completed by Fall 2021 and that the TFIAM, TFTEI, TFRN, WGSR, and WGE review should be completed by Spring 2021 and Spring 2022).

[577] Executive Body (24 September 2021) *Draft report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, as amended in 2012*, ECE/EB.AIR/2021/4, at ¶ 96 ("To limit negative effects of air pollution on climate change, more focus is needed on reducing emissions of air pollutants that have a warming effect, such as BC and O_3 precursors. CH_4 reduction plays a key role in reaching synergetic effects, as CH_4 is both a greenhouse gas and an increasing determinant of O_3 formation.").

[578] Samuelsson E. (13 December 2021) *Change in the Air: Promising direction for Air Convention Protocol revision*, META, European Environmental Bureau ("Last week's meeting of the Air Convention agreed to include methane in its analysis for the revision of the Protocol, which is a promising first step for including methane in the protocol in the future.").

[579] Gothenburg Protocol Review Group (28 March 2022) *Potential options for addressing methane as an ozone precursor under the Air Convention Gothenburg Protocol Review*, Informal Document, 3–4 ("These options are provided for information only and are not exhaustive. These are not in priority order but rather presented as technical/data, reductions/abatement, and voluntary/capacity building. Each option could be stand-alone or used in combination or as a package. • Option 1: Compiling, reviewing and improving methane emissions information: issues include consistency/non-duplication of efforts with UNFCCC reporting, could result in creation of shareable database across MEAs *Considerations: Access to data for scientific and technical analysis; need for additional resources/expertise in the Convention* • Option 2: Minimum requirements for monitoring and reporting of data: issues could include requirements for leak detection, remote sensing. *Considerations: Access to data, verification of emission trends; potential for duplication of efforts* • Option 3: Adoption of national emission reduction targets/optimized national/regional methane reduction commitments: issues include binding or non-binding, national or collective using low-cost measures. *Considerations: First emission reduction commitment on methane, sets an example for other regions, may include a smaller number of countries; may reduce flexibility/cost-efficiency in implementing climate change targets addressing all GHGs (policies and measures)* • Option 4: Methane emission limit values for certain activities: issues include different requirements by sector; a new technical annex including emission limits & BAT, and guidance documents on best practices for major activities in certain sectors such as landfills, coal mining, oil and gas and agriculture. *Considerations: Guidance documents could be shared with other MEAs and initiatives; could incentivize/support and increase efficiency of biogas production and facilitate the uptake of renewable gases, technical annexes could be too stringent or result in barriers to implementation; key sources of CH4 differ between subregions of UNECE area: uniform requirements on all CH4 producing activities may be less cost-effective to achieve certain emission reductions* • Option 5: Voluntary programs (such as BACA): for example, agricultural best practices, consumer outreach, industry trade groups, behavioural and non-technical measures (could include guidance documents from Option 4) *Considerations: Could leverage resources with other initiatives with voluntary programs addressing methane and ozone, could duplicate efforts under GMI or CCAC; monitoring.* • Option 6: Capacity building programs, especially in Eastern Europe and Central Asia: supporting GMI, CCAC and coordination with the Forum (Task Force on International Cooperation on Air Pollution). *Considerations: Could apply resources directly to a country or a sector and achieve emission reductions more quickly; could leverage engagement mechanisms that are unique to UNECE, could overlap with existing efforts under GMI or CCAC (depending on how this is coordinated, this could be a pro or a con); may require additional resources (funding).*").

[580] Executive Body (2019) *Decision 2019/5 Establishment of the forum for international cooperation on air pollution* ("The Executive Body, Recognizing the importance of cooperation beyond the ECE region, Recalling the Long-term strategy for the Convention on Long-range Transboundary Air Pollution for 2020–2030 and beyond (decision 2018/5, annex), Recalling also that it agreed at its thirty-eighth session (Geneva, 10–14 December 2018) to establish a forum for collaboration on reducing air pollution (ECE/EB.AIR/142, para. 68 (b)), 1. Welcomes the establishment of the Forum in line with the proposal attached to the report of the Executive Body on its thirty-ninth session (see ECE/EB.AIR/144, Annex I);"). *See also* United Nations Economic Commission for Europe, *International Cooperation* (*last visited* 31 August 2022) ("The purpose of the forum is to provide a shared response to help address the threat to human health and ecosystems from air pollution. It also provides a platform for exchange and mutual learning and a repository of technical information.").

[581] Executive Body (24 September 2021) *Draft report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, as amended in 2012*, ECE/EB.AIR/2021/4, at ¶ 100 ("At its sixtieth session, the Working Group on Strategies and Review plans to discuss the need, best approach and potential options to address CH_4 in a future instrument: *e.g.*, if and how to include CH_4 in the Protocol, which emission sources to focus on, and how to link with the forum for international collaboration on air pollution, the United Nations Framework Convention on Climate Change and the Global Methane Initiative.").

[582] Task Force on Hemispheric Transport of Air Pollution (30 June 2021) *Report prepared by the Co-Chairs of the Task Force on Hemispheric Transport of Air Pollution*, ECE/EB.AIR/GE.1/2021/8−ECE/EB.AIR/WG.1/2021/19 at ¶ 12(a), ¶ 13(b)(i) ("The Task Force will continue implementation of the 2020–2021 workplan with a focus on: (a) Updating the Task Force contribution to the review of the Gothenburg Protocol taking into account insights from the Climate and Clean Air Coalition global methane assessment, ongoing tagging and shipping analyses and review of methane mitigation scenarios; Given the progress under the current workplan, the needs of the ongoing review of the Gothenburg Protocol and the science needs expressed in the Convention's Long-term strategy for 2020–2030 and beyond,[8] the contribution of the Task Force to the Convention's 2022–2023 workplan might be organized around three themes identified below that build on the current work. The Task Force leadership team invites discussion with the EMEP Steering Body on the prioritization of work in the following areas: (b) Global-regional model evaluation and intercomparison. Under this theme, the Task Force would continue to evaluate and intercompare global-regional models for ozone, particulate matter, mercury and POPs, with a focus on improving our confidence in estimating source-receptor relationships at intercontinental scales. Specifically, the Task Force might include organizing examinations of: (i) The regional ozone response to global methane reductions, working with the Meteorological Synthesizing Centre-West and the Task Force on Measurements and Modelling;").

[583] 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.").

[584] 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.").

[585] 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.").

[586] 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.").

[587] 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.).

[588] 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 . . . .'").

[589] 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.").

[590] (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.).

[591] (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.").

[592] (16 September 1987) Montreal Protocol on Substances that Deplete the Ozone Layer, 26 I.L.M. 1541 (entered into force 1 January 1989).

[593] 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.").

[594] United Nations Environment Programme, *National Ozone Officers' Capacity Building* (*last visited* 31 August 2022) ("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.").

[595] United Nations Environment ProgrammeOzone Secretariat, *Scientific Assessment Panel (SAP)* (*last visited* 31 August 2022) ("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.”).

[596] United Nations Environment Programme Ozone Secretariat, *Technical and Economic Assessment Panel* (*last visited* 31 August 2022) (“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.”).

[597] 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.”).

[598] (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.”).

[599] 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.”).

[600] 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.").

[601] 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.").

[602] 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., *et al.* (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.").

[603] *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., *et al.* (eds.).

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

[605] 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* 29 July 2022); Arctic Council, *Arctic Contaminants Action Program* (*last visited* 29 July 2022); *and* Arctic Council, *AMAP and the Arctic Council* (*last visited* 29 July 2022).

[606] 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., *et al.* (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*).").

[607] 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.").

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

[609] 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.").

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

[611] 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").

[612] 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.").

[613] (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.").

[614] 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.").

[615] *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;").

[616] 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.").

[617] 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.”).

[618] 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.”).

[619] 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.”).

[620] 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.”).

[621] 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.

[622] 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.”).

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

[624] 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).

[625] 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).

[626] 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.").

[627] C40 Cities, *Waste Management* (*last visited* 31 August 2022) ("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.").

[628] Climate Group, Under2 Coalition, *Methane Project* (*last visited* 31 August 2022) ("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.").

[629] 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.").

[630] 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.").

[631] Global Methane Initiative, *About the Global Methane Initiative* (*last visited* 31 August 2022) ("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.").

[632] Oil and Gas Climate Initiative, *About Us* (*last visited* 31 August 2022) ("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.").

[633] MiQ, *The Methane Mission* (*last visited* 31 August 2022) ("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.").

[634] American Gas Association, *Natural Gas Sustainability Initiative (NGSI)* (*last visited* 31 August 2022) ("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.").

[635] *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.").

[636] *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.

[637] 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.").

[638] 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....").

[639] 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*.").

[640] 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*.").

[641] 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.").

[642] 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.").

[643] 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.

[644] 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.").

[645] 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%.").

[646] 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.'").

[647] 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.").

[648] 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.").

[649] 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.").

[650] 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)).

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

[652] 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.").

[653] 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.").

[654] 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.").

[655] 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.").

[656] International Monetary Fund (11 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.").

[657] International Monetary Fund (11 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.").

[658] International Monetary Fund (11 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.").

[659] 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.").

[660] 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.").

[661] 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.").

[662] Department of State, Foreign Operations, and Related Programs Appropriations Act, 2023, S. 4662, 117th Cong., Title V ("For contribution to the Poverty Reduction and Growth Trust (PRGT) or to the proposed Resilience and Sustainability Trust (RST) of the International Monetary Fund (IMF) by the Secretary of the Treasury, $20,000,000, to remain available until September 30, 2031: *Provided*, That such funds shall be available to cover the cost, as defined in section 502 of the Congressional Budget Act of 1974, of loans made by the Secretary of the Treasury to the PRGT or the RST of the IMF: *Provided further*, That such funds shall be available to subsidize gross obligations for the principal amount of direct loans not to exceed $21,000,000,000 in the aggregate, and the Secretary of the Treasury is authorized to make such loans: *Provided further*, That the Exchange Stabilization Fund (ESF) and the financing account corresponding to transactions with the IMF are authorized to enter into such transactions as necessary to effectuate loans from resources held in the ESF to the PRGT or RST of the IMF.").

[663] 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.").

[664] Gold S. (18 April 2022) *IMF aims to operationalize new RST fund by October*, News ("The International Monetary Fund intends to operationalize its new Resilience and Sustainability Trust by October, and officials say they expect donors to announce significant contributions this week during the institution's yearly Spring Meetings.").

[665] 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.")).

[666] 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.").

[667] 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.").

[668] 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 $GTP_{1.5\,°C} = 41$.").

[669] 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.").

[670] 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.").

[671] Pilot Auction Facility, *About the PAF* (*last visited* 31 August 2022) ("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..").

[672] Pilot Auction Facility, *About the PAF* (*last visited* 31 August 2022) ("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.").

[673] 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* 29 July 2022).

[674] International Finance Corporation (2022) *New CWI Landfill Gas* (*last visited* 31 August 2022) ("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[.]").

[675] International Finance Corporation (2022) *New CWI Landfill Gas* (*last visited* 24 August 2022) ("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.").

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

[677] 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.”).

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

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