Methane emissions

Mitigation measures

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KEARNEY FORESIGHT | Energy Transition Institute

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About the FactBook: Methane emissions: mitigation measures

This FactBook highlights methane's outsized role in near-term climate change, contributing nearly 25% of global warming since pre-industrial times despite its short lifetime. It reviews uncertainties in measurement, advances in monitoring technologies, and the wide availability of cost-effective abatement options—particularly in oil and gas. The report stresses regulatory and financing gaps, uneven global policies, and emerging business models that can turn methane mitigation into economic value. Rapid methane cuts are positioned as one of the fastest levers to slow warming.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Foreword

For decades we have focused on CO_2 given its long atmospheric lifetime and its role as principal anthropogenic driver of climate change. However, CH_4 has gained prominence given its significant greater contribution to near-term warming. CH_4 is responsible for nearly 25% of global warming since the pre-industrial era despite its relatively shorter atmospheric lifetime of ~12 years.

Unlike CO_2, CH_4 emissions are variable across time and space, arising from both natural and anthropogenic sources. CH_4 emissions have long been difficult to monitor, measure, and estimate accurately, contributing to underestimation of scale and impact. Recent satellite advances reveal that actual emissions are up to ~10x greater than company reported emissions.[1] However, uncertainty in methane emission estimates remains considerable, particularly for natural emissions.

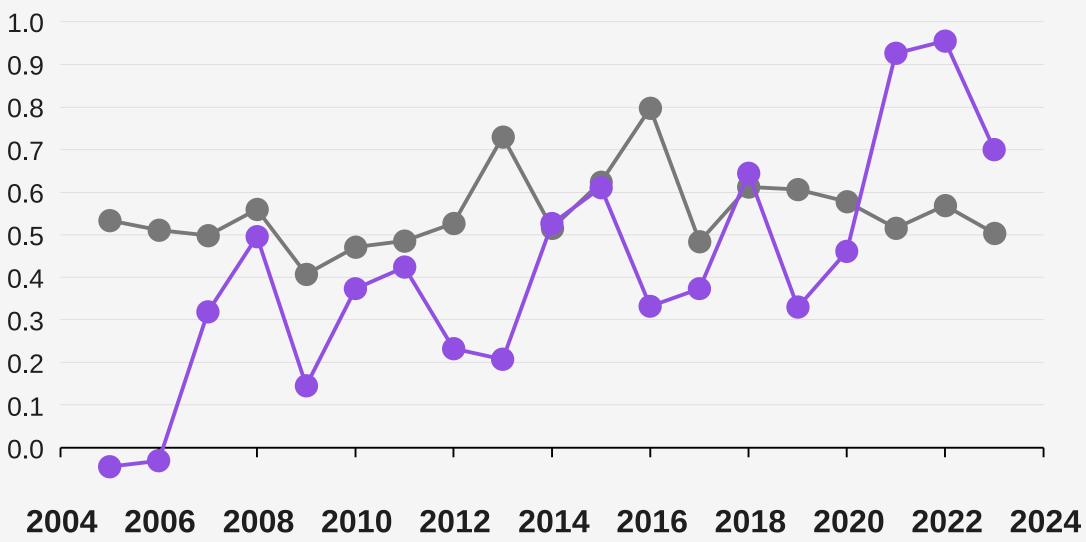
A wide range of technically proven and commercially available solutions exist to mitigate CH_4 emissions, and often at a relatively low cost. For example, in a more consolidated sector, such as oil and gas, >40% of CH_4 emissions could be eliminated at no net cost as the captured gas value offsets implementation expenses. However, the financial case for adoption in more fragmented sectors, such as agriculture, is less clear.

The urgency of CH_4 abatement is increasingly reflected in global regulatory and policy momentum. Governments are going beyond voluntary pledges to binding measures. More than 150 countries have endorsed the Global Methane Pledge, committing to a 30% cut by 2030.

CH_4 abatement is one of the most effective levers for rapid climate mitigation. With a global warming potential ~86x greater than CO_2 over a 20-year period, CH_4 poses a critical short-term climate threat. Reducing human-caused CH_4 emissions by 45% by 2030 could avoid 0.3 °C of global warming by 2045, “buying” time for deeper decarbonization of CO_2-intensive sectors while realizing major health and economic benefits.

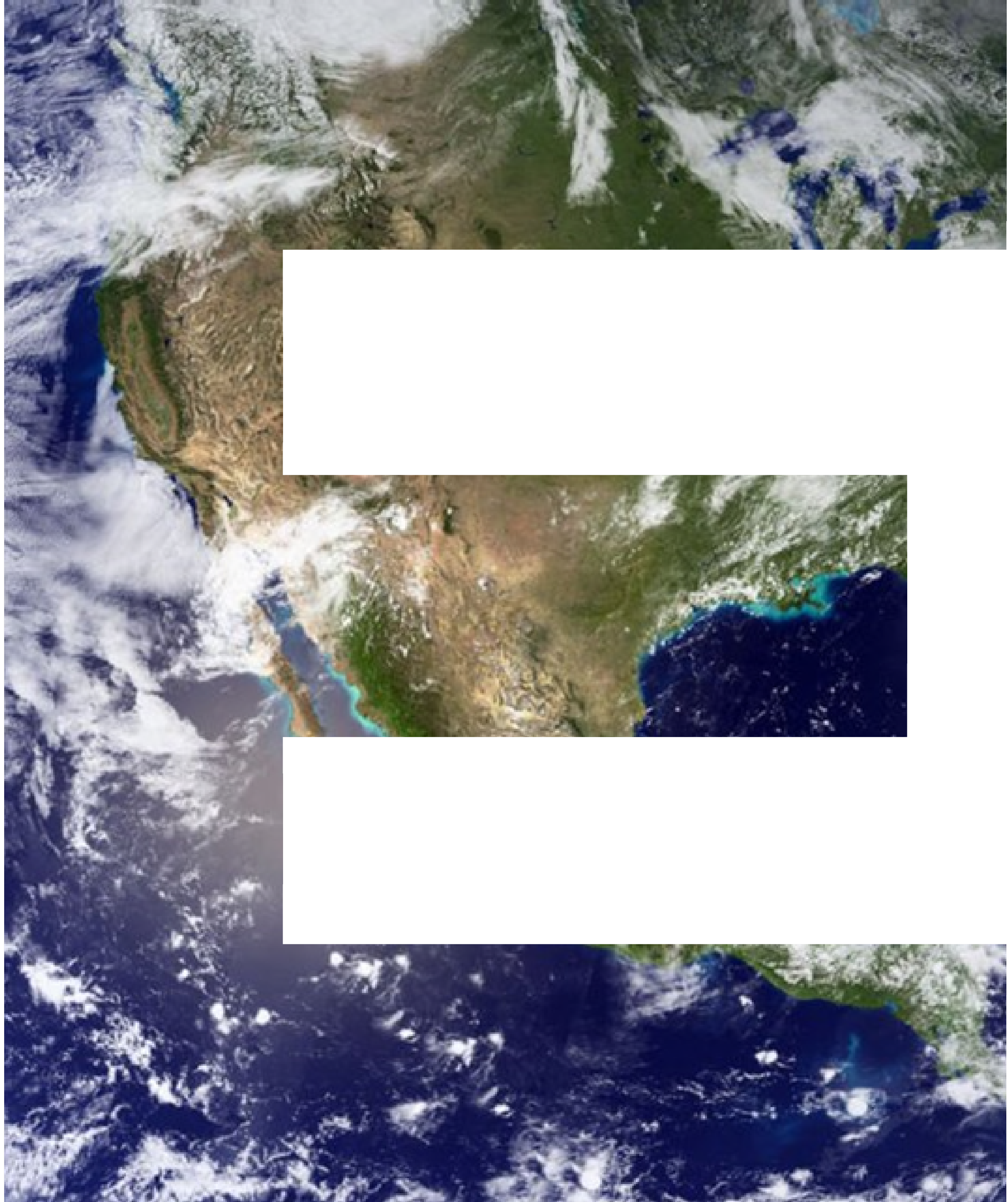
Accelerated growth in atmospheric CH_4 in recent years stresses the urgency for targeted abatement to curb further warming

Annual change in atmospheric CO_2 and CH_4 concentrations, (%, 2005–2023)



[1] As stated by Kayrros, emission factors understate methane emissions by approximately a factor of 10 versus satellite-based observations.
Source: Kearney Energy Transition Institute

1. Impact of methane



Introduction and summary

Methane is a short-lived but highly potent greenhouse gas, **making it central to near-term climate action.**

Methane emissions arise from both natural and anthropogenic sources, moderated by natural sinks, yet **estimates diverge widely between** bottom-up inventories and top-down atmospheric measurements.

Persistent measurement gaps obscure the true scale, while **limited awareness** and **underfunding delay abatement.**

Surging emissions, outsized impact	**Anthropogenic CH_4 emissions** have accelerated sharply, reaching about **9.1 $GtCO_2e$ by 2023**, and now contribute roughly **16% of global greenhouse gas** radiative forcing due to their high near-term potency.
Short-lived high-impact pollutants	Methane is a potent yet short-lived gas. It **persists** in the **atmosphere** for roughly **12 years** but traps approximately **80 times more heat than CO_2** over a 20-year span.
Inventory gaps and uncertainty	**Official methane inventories are highly uncertain**, with bottom-up atmospheric measurements often exceeding top-down estimates by wide- but narrowing – margins.
Underestimation and funding shortfalls	**Methane's risks** remain underestimated by society and policy, with **low public awareness** and **limited financing** deprioritizing methane abatement and delaying mitigation.

Unless explicitly mentioned, the factbook references bottom-up estimates from the latest global methane budget.

Source: Kearney Energy Transition Institute

1.0 Chapter summary

Though emitted in smaller quantities than CO_2, methane's rising emissions are intensifying global warming due to its strong climate impact

Since the Industrial Revolution, methane emissions have surged more sharply than other GHGs, reaching 9.1 of the global 49.0 $GtCO_2e$ in 2023.

X total — **Global emissions** of major anthropogenic GHG

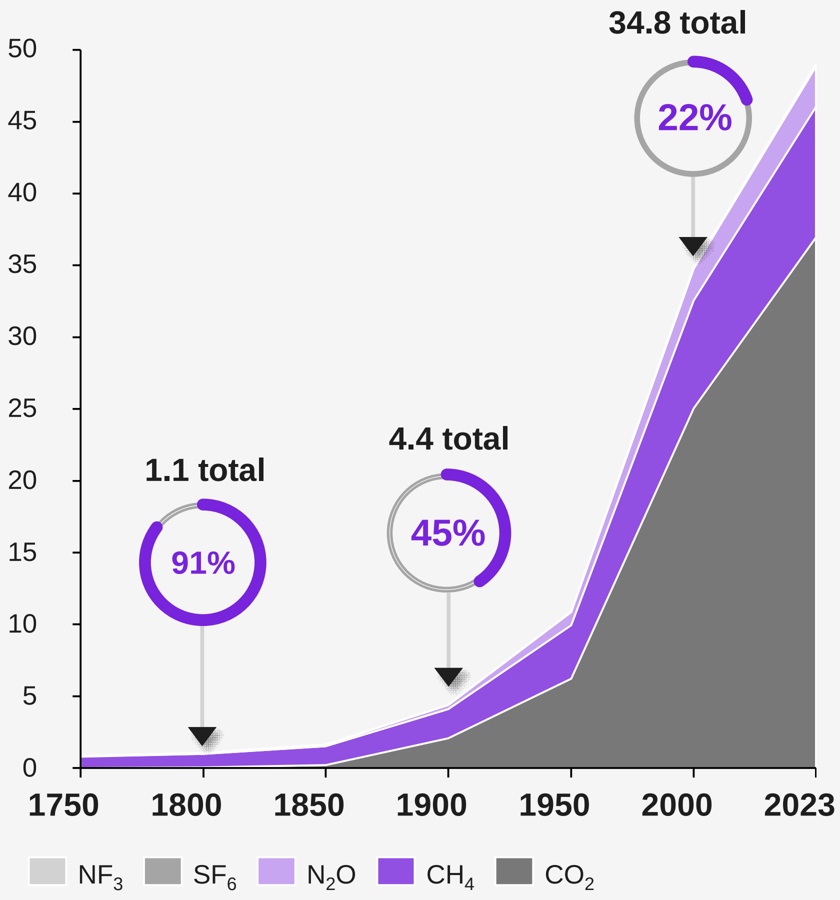
X% — **Methane share** of total global anthropogenic emissions

Timeline points: 1800, 1900, and 2000

1.1 Climate impact

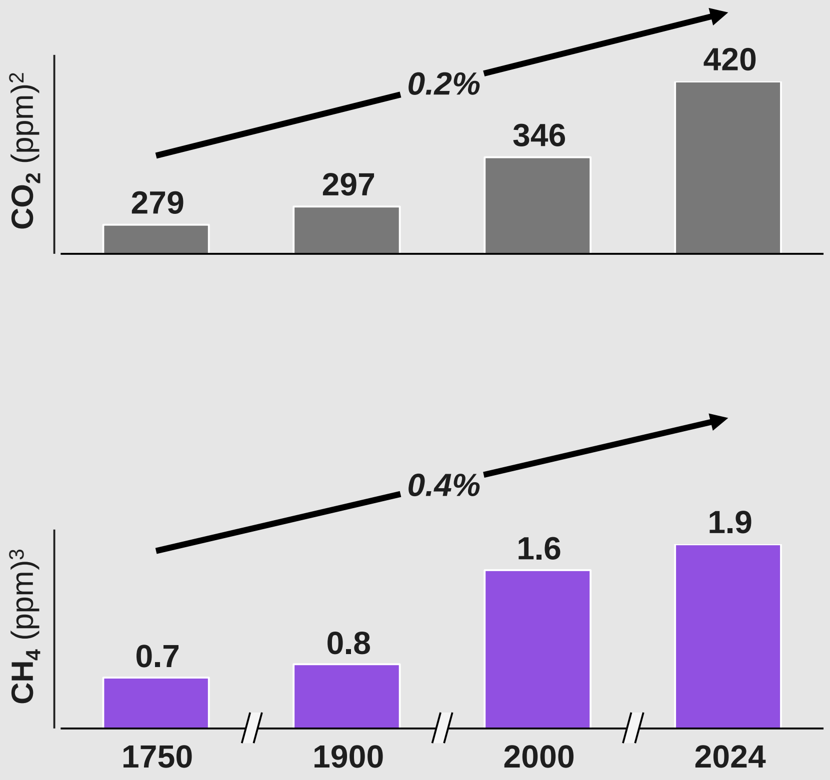
Global emissions of major anthropogenic GHG[1,2]

($GtCO_2e$, 1750–2023)



Global atmospheric concentration of major[1] anthropogenic GHG

(1750–2024)



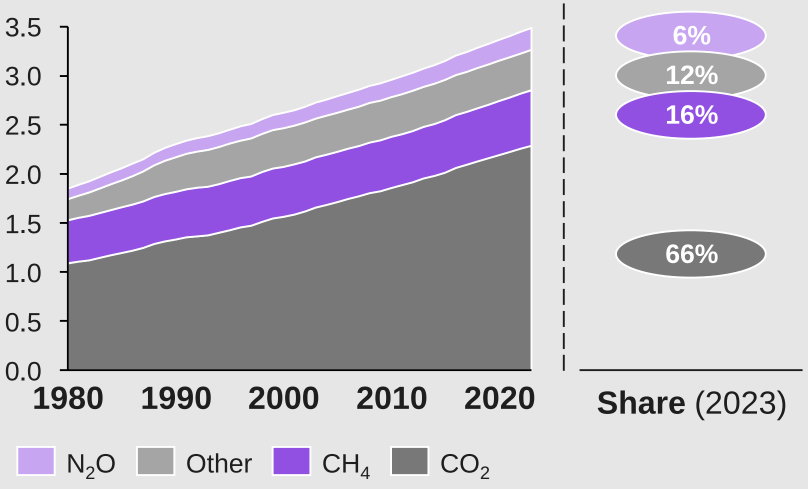
Before 1750, GHG levels grew slowly; industrialization sparked a sharp, exponential surge in CO_2 and CH_4.

[1] Excluding emissions from land use, land-use change, and forestry sector; [2] Converting non-CO_2 gases to CO_2e considering GWP_{100} values defined by IPCC AR6

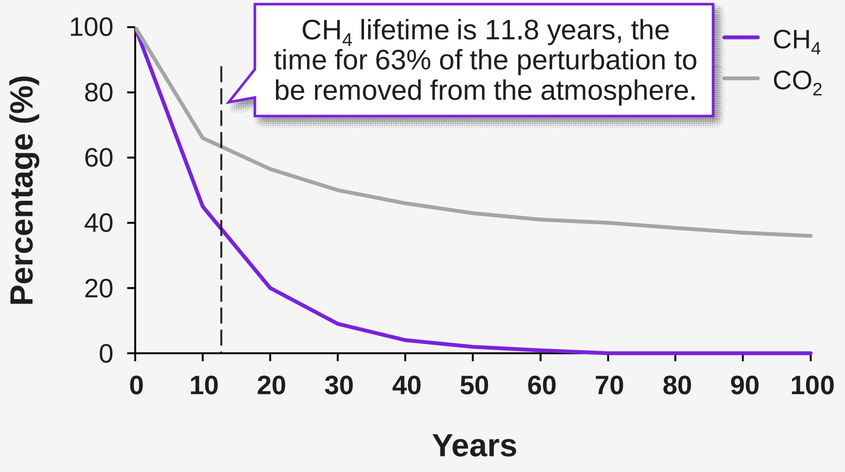
Sources: IPCC, 2024, IPCC Global Warming Potential Values; IPCC, 2005, Special Report on Carbon dioxide Capture and Storage; Lau, B., 2022, What Are the Major Sources of Methane in the Atmosphere?; National Grid, 2024, What is SF6?; PRIMAP, 2025, The PRIMAP-hist national historical emissions time series (1750-2023) v2.6.1; World Resources Institute, 2013, Nitrogen Trifluoride Now Required in GHG Protocol Greenhouse Gas Emissions Inventories; Kearney Energy Transition Institute

Because methane is a short-lived but potent gas, cutting its emissions is key to slowing near-term global warming

1 **ERF[1]:** Quantity of heat trapped by atmospheric GHG (W/m^2)

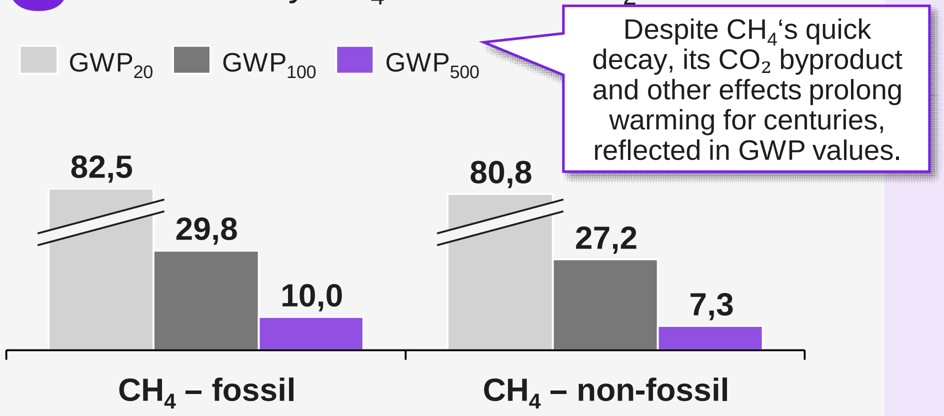


2 **Atmospheric lifetime:** Time scale over which the concentration decays to 37% of its initial value (years)[2]



GWP of CH_4 falls quickly with greater duration from GWP_{20}-GWP_{500}, creating opportunity for **rapid global warming reduction in the next 10–20 years** given an outsized impact near term.

3 **GWP[3]:** Measures the cumulative energy absorbed by CH_4 relative to CO_2



Source-specific methane GWP

For methane (CH_4), a difference is made between fossil and non-fossil:

– CH_4 from fossil accounts for additional CO_2 created by oxidation of CH_4 in the atmosphere.

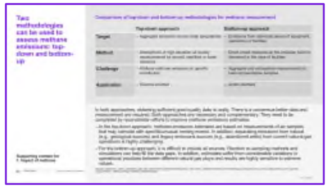
– For non-fossil sources, the emitted CO_2 offsets what was previously absorbed by biological processes. As a result, the global warming potential (GWP) for non-fossil CH_4 is slightly lower than fossil CH_4.

[1] ERF is effective radiative forcing; [2] Decay factor of *e*, corresponds to a constant of ~2.718; [3] GWP is global warming potential, expressed over X years, denoted by GWP_X; even though methane decays quickly, its presence contributes to cumulative warming that lasts centuries (through its CO_2 byproduct, tropospheric ozone, and stratospheric water vapor), and using its long-term GWP captures this tail effect.

Sources: IPCC, 2021, Climate Change 2021: The Physical Science Basis; NOAA, 2024, The NOAA Annual Greenhouse Gas Index; Kearney Energy Transition Institute

Uncertainty arises across the whole methane accounting chain and shows up when comparing sector, country, and method-based estimates

Two methodologies can be used to assess CH_4 emissions: top-down and bottom-up approaches. Refer to the appendix for more information.



Press Ctrl and click the image to navigate to the details in the Appendix.

1.2 Methane uncertainties

Methane uncertainty drivers

- **Measurement limitations** lead to divergent results between bottom-up approaches (inventories based on emission factors and/or measurements combined with modeling) and top-down approaches (atmospheric measurements combined with inverse modeling).
- **Temporal and spatial emissions variability** are episodic (e.g., one-off leaks, venting) as well as continuous (e.g., gas transmission line leak, livestock farming).
- **Model assumptions** induce errors from atmospheric transport models, background concentrations, and boundary conditions
- **Emission factors** used are generic or outdated factors, not site-specific
- **Activity data** are incomplete or inconsistent

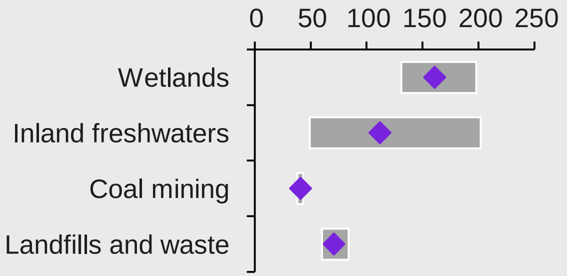
Where uncertainty exists

- **Sectoral inventories:** agriculture, energy, waste, wetlands, or other sources
- **National reporting:** underreported or outdated inventories
- **Company reporting:** reliance on standardized emission factors rather than direct measurements
- **Bottom-up vs. top-down approaches:** systematically different output values because they operate at different spatial and temporal resolutions and do not capture the same emission processes or parameters. Bottom-up may miss sporadic large events, while top-down cannot easily separate spatially overlapping sources.[1,2]
- **Mitigation assessment:** uncertainty in baseline emissions makes it hard to measure abatement impact

Uncertainties are material

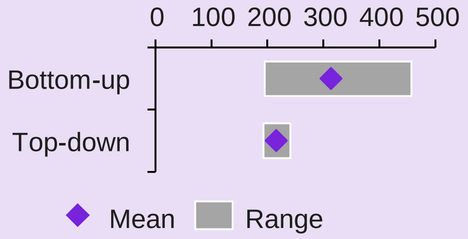
Sectoral inventories estimation ranges exhibit significant variability depending on the sector under consideration

Global methane emissions by source type – bottom-up estimates
($Mt\ CH_4/y$, 2020)



Bottom-up vs. top-down approaches diverge by up to 31% in reported emissions

Global methane emissions for natural and indirect sources
($Mt\ CH_4/y$, 2020)



[1] Bottom-up approaches compile emissions by summing individual sources using emission factors, process models, and inventories.
[2] Top-down approaches infer total emissions from atmospheric concentration measurements using inverse modeling.
Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Measurement gaps underreport the true scale of methane emissions…

Non-exhaustive

Methane emissions estimates from the energy sector are **about 80% higher** than the total reported by national governments

1.3 Why progress has lagged

Limitations of official methane inventories

Inherent uncertainties
Methane emissions are characterized by high variability, making it difficult to accurately quantify them.

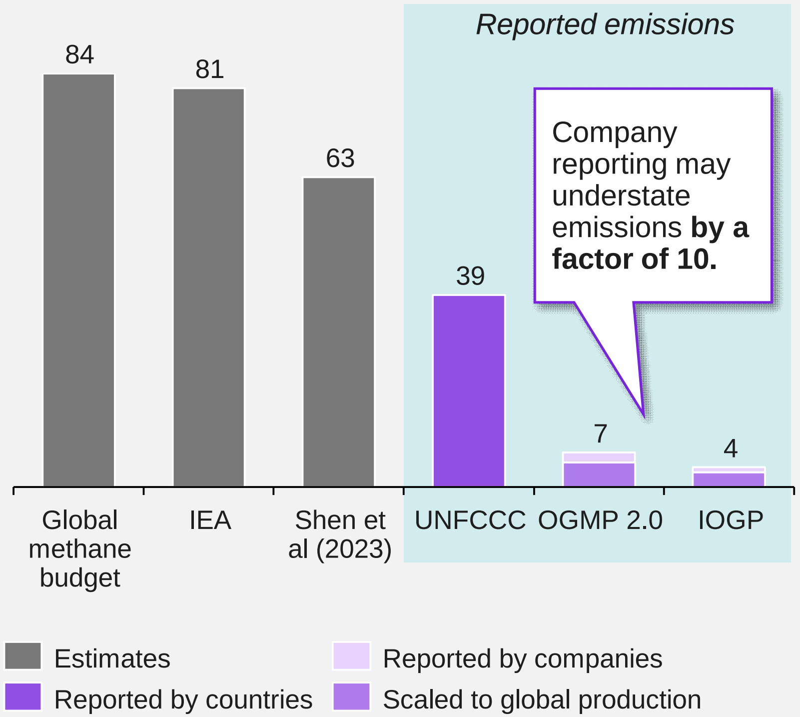
Legacy approach
Most of the current inventories are based on multiplying activity data by standardized emission factors, which do not fully account for methane's impacts.

Lack of revision
Many official greenhouse gas submissions to the UNFCCC have not been updated for years.

[1] UNFCCC is United Nations Framework Convention on Climate Change. OGMP 2.0 is Oil & Gas Methane Partnership 2.0. IOGP is International Association of Oil and Gas Producers. IEA estimates are for 2024, other estimates are for the latest year available. The Global Methane Budget refers to the top-down estimate. Emissions from company reporting are scaled to the global level based on the reporting companies' share of production and assuming non-reporting companies have the same average emissions intensity
Sources: IEA, 2025, Global Methane Tracker; Kearney Energy Transition Institute

Gap in estimated and reported methane emissions[1]

(Global oil and gas company reporting, 2025, $MtCH_4$)



Lack of data transparency and disclosure

– Only select oil and gas companies have committed to detailed emissions reporting for all operated and non-operated assets within a set time frame.
– Often, commercial sensitivities are cited as a reason for not detailing methane emissions.

… while perception and funding gaps deprioritize methane abatement, delaying mitigation

Non-exhaustive

Reducing human-caused CH_4 emissions by 45% by 2030 could avoid 0.3 °C of global warming by 2045, "buying" time for deeper decarbonization of CO_2-intensive sectors while realizing major health and economic benefits.

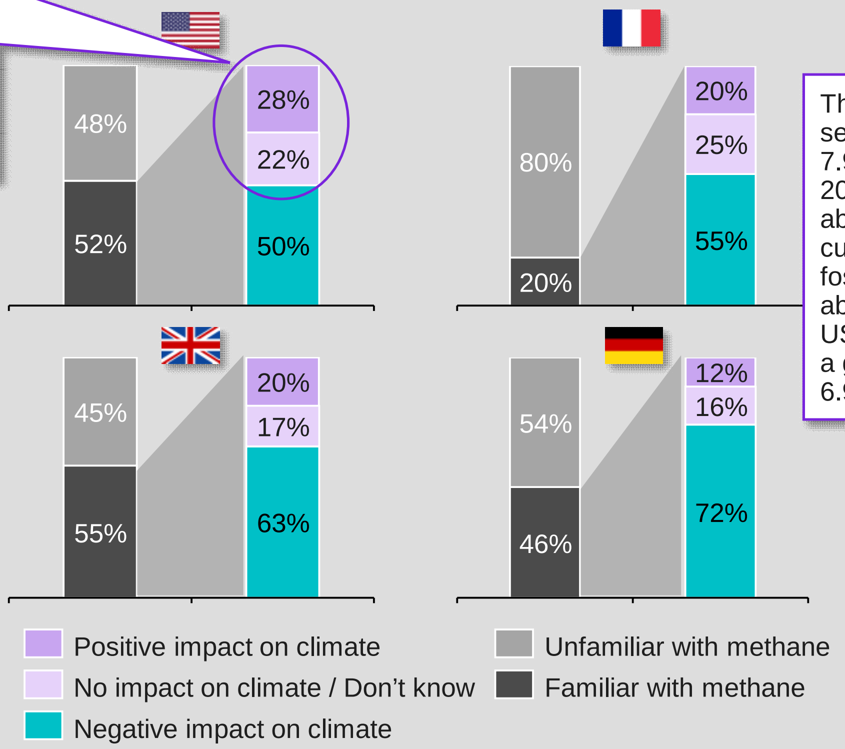
Perception gap

Significant potential exists in increasing public awareness regarding methane's impact.

Average familiarity and understanding of methane impact on the global climate across selected countries
(% of respondents, 2024)

Even among those who think they know methane, understanding is lacking.

In the US, for example, up to 50% of people "familiar" with methane do not realize its impact on the climate.

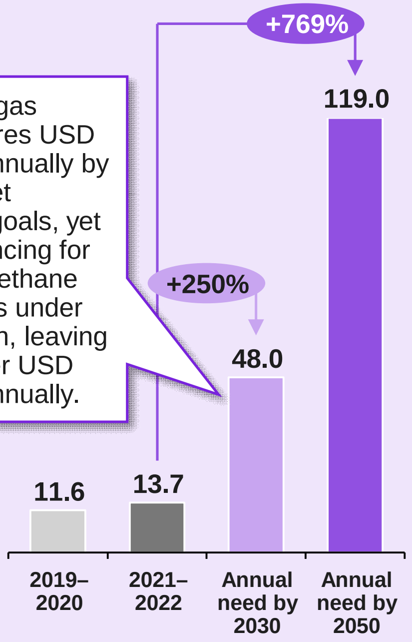


Funding gap

At $13.7 billion, methane abatement finance is at its highest level yet, but annual flows need to be at least 3.5 times larger until 2030.

Global finance to methane abatement vs. annual needs (2030 and 2050)
(USD billion)

The oil and gas sector requires USD 7.9 billion annually by 2030 to meet abatement goals, yet current financing for fossil fuel methane abatement is under USD 1 billion, leaving a gap of over USD 6.9 billion annually.



- **Current finance is far below** the USD 48 billion annual **needed by 2030.**
- **Estimated needs** are set to grow significantly from 2030 to 2050, **demanding faster, scaled-up investment.**
- **Even considering data gaps**, this implies that **current methane emissions reduction measures fall short** of those needed to meet climate goals.

Source: IEA, 2025, Global Methane Tracker; Burson, 2025, Global Methane Poll Wave 2: Total Study Results Overview; Climate policy initiative, 2023, Landscape of Methane Abatement Finance; OECD, 2024, Methane Abatement in Developing Countries: Regulations, Incentives and Finance, OECD Development Policy Tools; Kearney Energy Transition Institute

1.3 Why progress has lagged

In addition to adversely impacting climate, methane also affects human health and safety through multiple interconnected pathways

Human health

Methane contributes to the formation of **ground-level (tropospheric) ozone**, which is a harmful air pollutant:
- Methane-ozone mechanism is attributable to **760 respiratory-related deaths per million metric tons of methane** globally.

Food systems

Methane **reduces crop yields** across major food crops via ground level ozone formation that disrupts photosynthesis:
- Estimated reduction in yields globally: **2.6% for rice, 3.6% for maize, 7.2% for wheat, and 6.7% for soybean**

Human safety

Methane is extremely flammable, presenting **explosion risks** in natural gas, coal mine, manure-related, and waste infrastructure:
- In the US, fossil fuel pipelines have resulted in more than **5,500 accidents, 800 fires, 300 explosions, 600 injuries, and 125 fatalities.**[1]

Environmental and ecosystem degradation

Methane is a key driver of global temperature increases, **contributing to increasingly extreme droughts** in which established ecosystems fail, including human population.
- **~400 million hours of work globally are lost yearly** due to CH_4-driven extreme heat.

[1] From January 2010 to November 2018
Sources: McDuffie et al., 2023, The Social Cost of Ozone-Related Mortality Impacts From Methane Emissions; Montes, C et al., 2021, Approaches to investigate crop responses to ozone pollution: from O3-FACE to satellite-enabled modeling; GCHA, 2023, Mitigating Methane - a Global Health Strategy — Overview; Kearney Energy Transition Institute

2. Origin of methane

Introduction and summary

While human activity accounts for the majority of methane emissions, natural feedback loops and poorly quantified indirect sources also demand closer scrutiny.

Methane accounts for a significant share of anthropogenic greenhouse gas emissions, **second only to carbon dioxide, but differs in potency and lifetime.**

Natural sinks, mainly atmospheric reactions and soil uptake, **are vital but limited, underscoring the need for direct emission cuts.**

Anthropogenic sources outweigh natural and indirect ones

Human-driven sources account for the majority of methane emissions, approximately **55% of the total[1]**, led by agriculture, fossil fuels, and waste.

Regional patterns vary

Asia is the largest emitter overall, at approximately **38% of global emissions**, while natural and indirect sources outweigh anthropogenic ones in South and North America, as well as Australasia.

Methane contributes significantly to global climate

Methane accounted for about 20% of human-caused GHG emissions in 2023, exerting a much stronger warming effect in the short term than CO_2 despite its far lower atmospheric concentration.[2]

Natural sinks present finite capacity

More than 90% of methane removal occurs via chemical reactions with hydroxyl radicals in the lower atmosphere, but their finite capacity cannot offset rising emissions.

[1] Considering bottom-up calculation, rising to 65% if considering top-down calculation; [2] Emissions are expressed in CO_2-equivalent using IPCC AR5 Global Warming Potential values over 100 years (GWP100).
Source: Kearney Energy Transition Institute

Global CH_4 emissions continue to rise, driven by anthropogenic sources

Anthropogenic sources

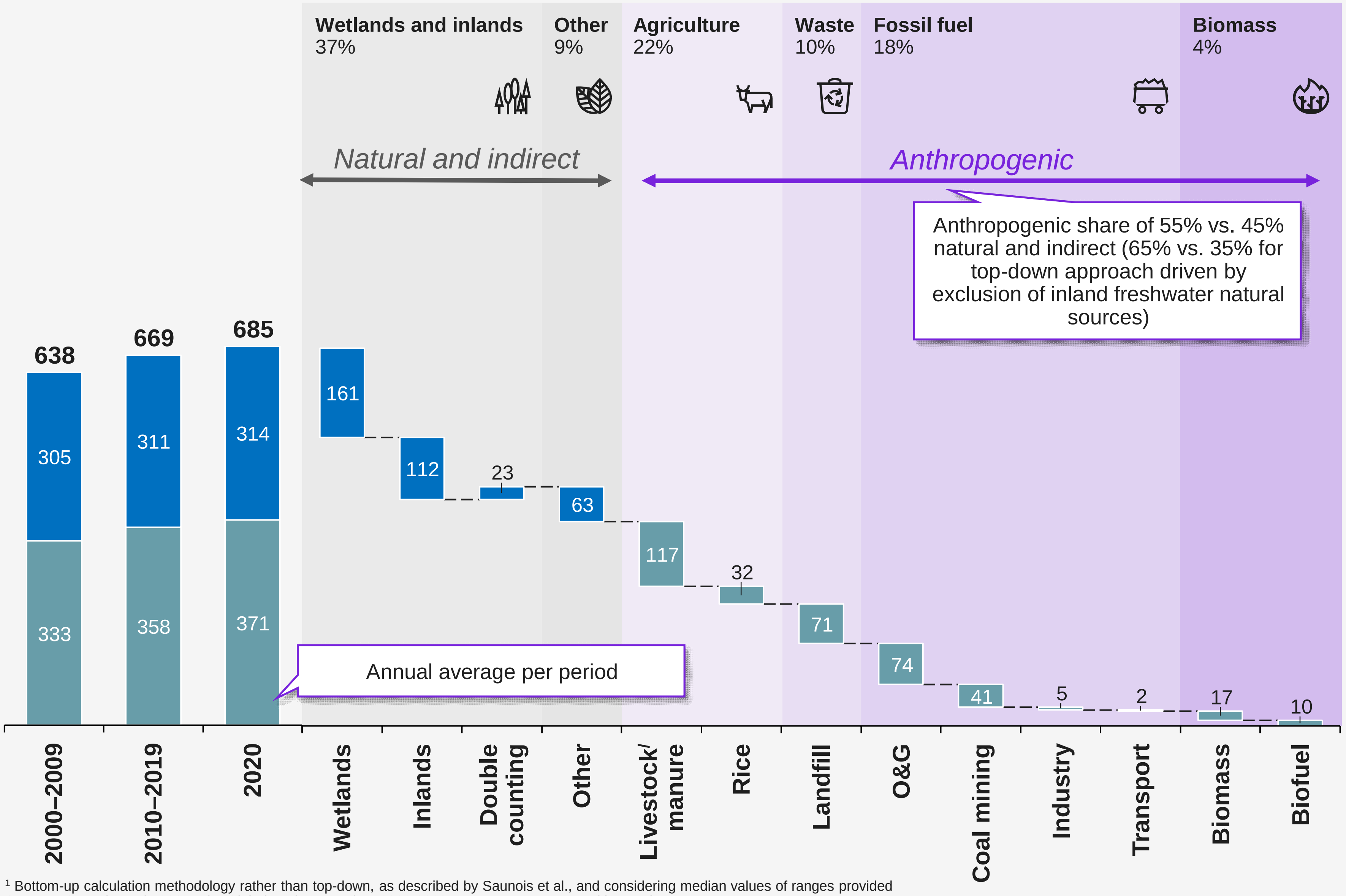
Natural and indirect sources

Non-exhaustive

CH_4 emissions data are often coarse; **detailed and verified breakdowns are available for earlier years,** but recent years (2021 onward) rely on provisional estimates with less sectoral granularity.

2.1 Methane sources and sinks

Global CH_4 emission sources[1]
($MtCH_4$, 2000–2020)



[1] Bottom-up calculation methodology rather than top-down, as described by Saunois et al., and considering median values of ranges provided
Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Agriculture, fossil fuels, waste, and bioenergy are the main sources of anthropogenic methane emissions

Press Ctrl and click the image to navigate to the details in the Appendix.

Livestock and manure management

CH_4 is emitted from ruminant digestion and from anaerobic decomposition of manure in pastures, storage, or soils.

Rice cultivation

Flooded rice paddies emit CH_4 as organic matter decomposes under oxygen-poor conditions.

Oil and gas

CH_4 is emitted from oil and gas operations during the extraction, processing, transportation, and storage stages.

Coal mining

CH_4 is released from coal seams during mining, mainly through ventilation and seepage from extracted coal.

Industry

CH_4 is emitted from industrial processes such as the production of chemicals and metals.

Transport

CH_4 emissions in transport arise from both fuel combustion and fugitive leaks during fuel handling, storage, and transfer.

Landfill

CH_4 is generated by the anaerobic decomposition of organic waste in landfills as the waste breaks down in oxygen-poor conditions.

Wastewater

CH_4 is released as organic material in wastewater decomposes under anaerobic conditions.

Biomass burning

CH_4 is released when biomass burns through incomplete combustion of organic matter.

Biofuel burning

CH_4 is emitted when biofuels are burned as fuel under incomplete combustion.

Sources: Desktop research; Kearney Energy Transition Institute

2.2 Methane sources

Wetlands and inland freshwater are the largest natural methane emission sources

Press Ctrl and click the image to navigate to the details in the Appendix.

Sources: Desktop research; Kearney Energy Transition Institute

Wetlands

Wetlands produce CH_4 through underwater anaerobic decomposition of organic matter such as leaves and stems or soil organic matter.

Inland freshwater

CH_4 production in freshwater environments is produced mainly by acetoclastic and hydrogenotrophic methanogenesis in anaerobic sediments.

Land sources

Land-based methane emissions come from geological sources, from animals such as termites and wild ruminants, and even from soils and vegetation under certain conditions.

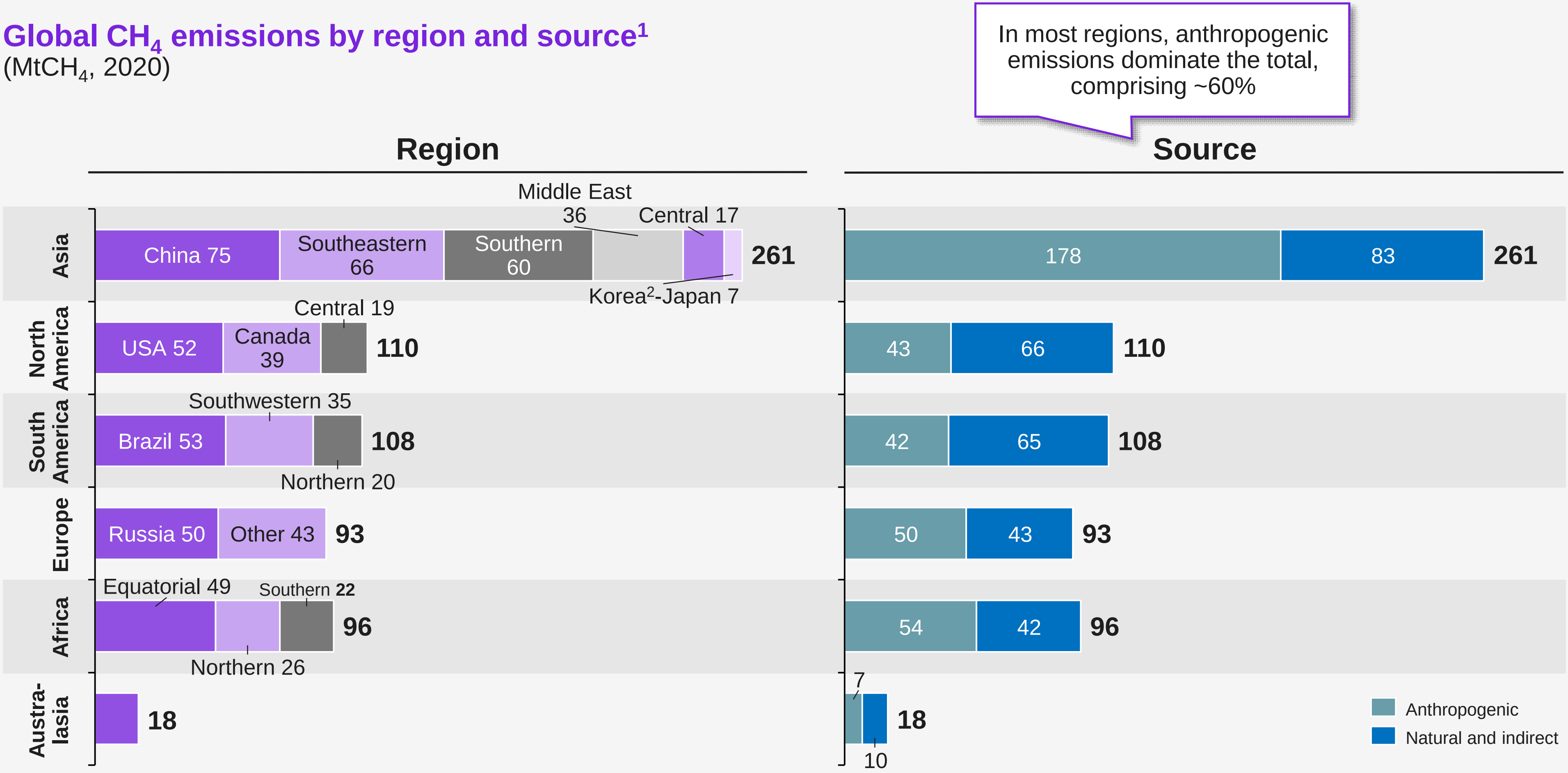
Coastal and oceanic sources

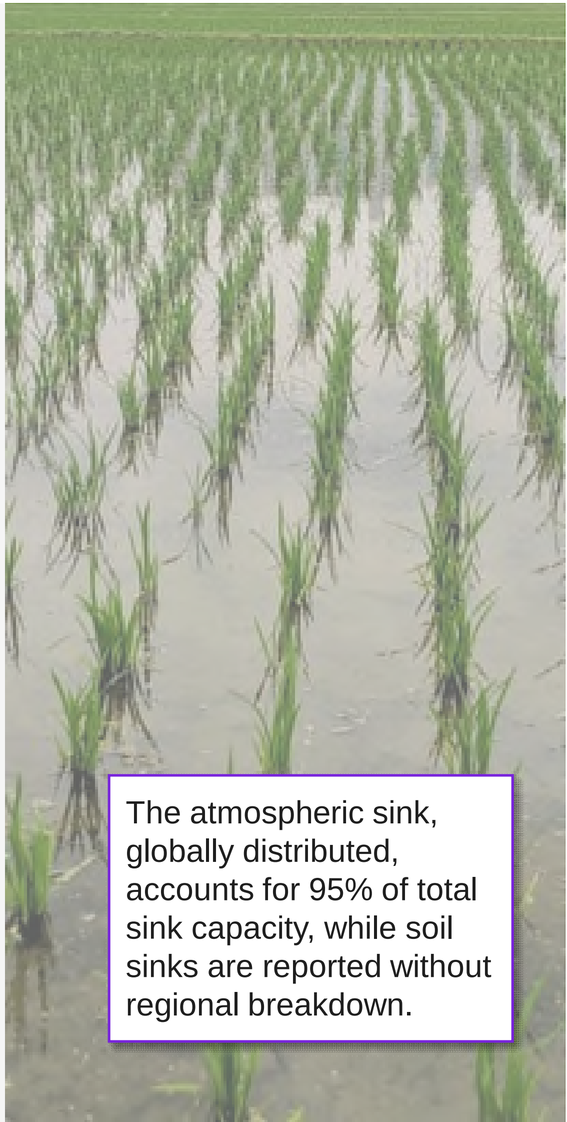
Coastal and oceanic CH_4 comes from undersea geological seeps and vents, microbial activity in sediments, and the breakdown of methane hydrates on the seafloor as oceans warm.

With 38% of global methane emissions, Asia leads due to a mix of natural and human-driven sources

Global CH_4 emissions by region and source[1]

($MtCH_4$, 2020)





The atmospheric sink, globally distributed, accounts for 95% of total sink capacity, while soil sinks are reported without regional breakdown.

[1] Bottom-up calculation methodology rather than top-down, as described by Saunois et al., and considering median values of ranges provided; [2] North and South Korea.
Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

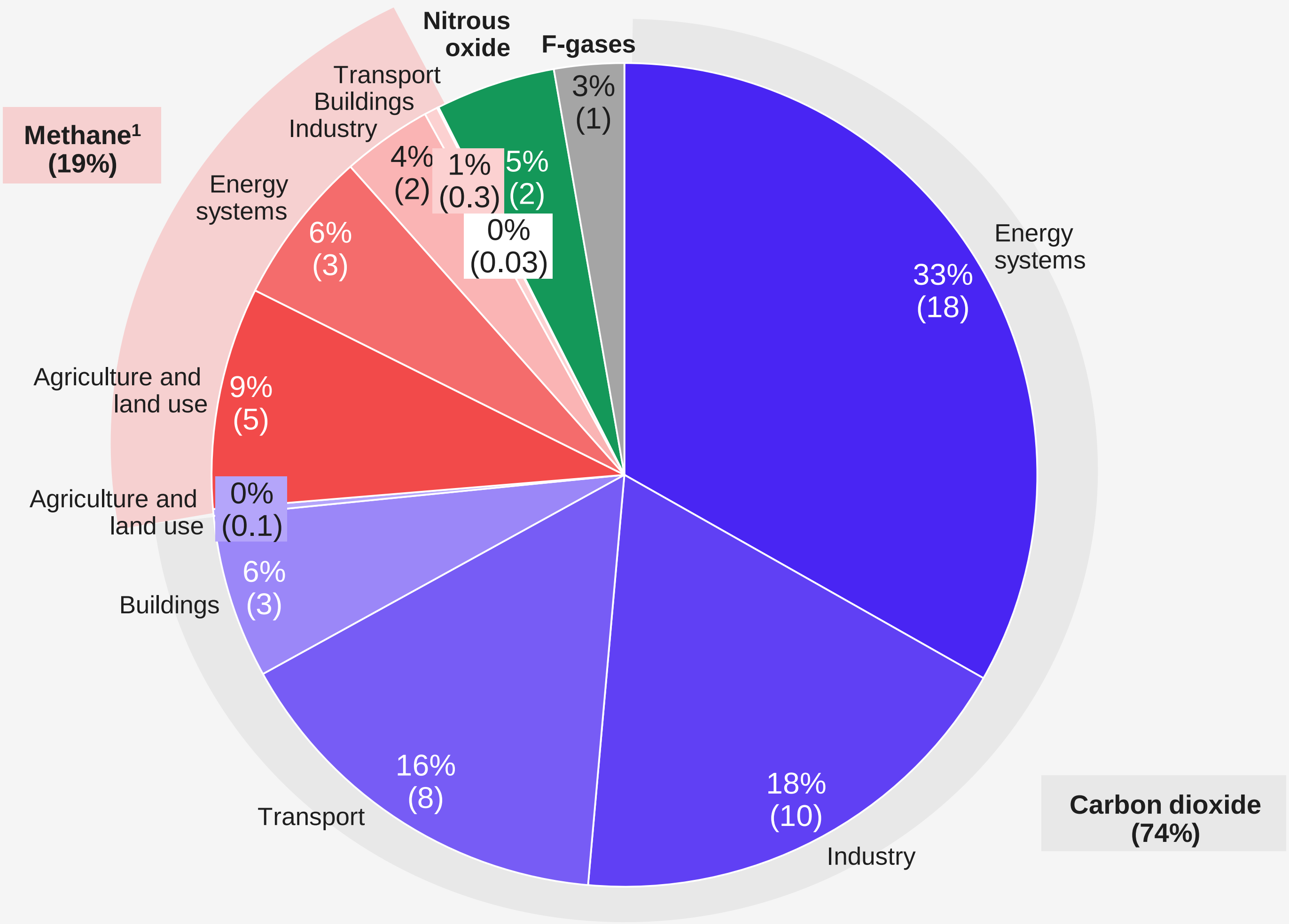
Methane represented 19% of overall anthropogenic global greenhouse gas emissions in 2023

Non-exhaustive

Total GHG emissions represented **52.9 $GtCO_2eq$** in 2023, about **10.0 $GtCO_2eq$** from CH_4 emissions.

2.2 Methane sources

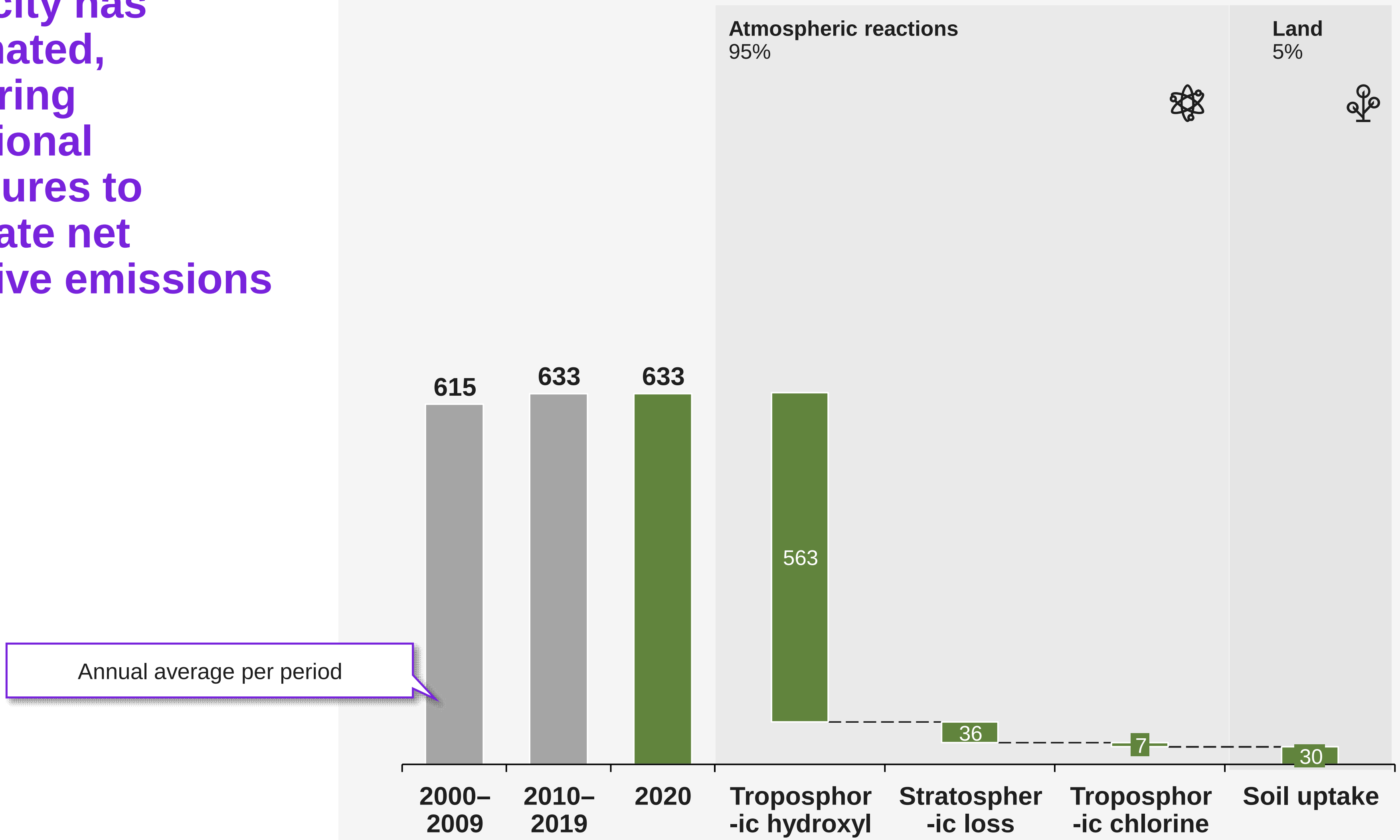
Anthropogenic global greenhouse gas emissions in 2023
(% of total GHG and $GtCO_2e$)



Note: For global CH_4 (GWP-100 (AR6)), N_2O and F-gases emissions.
[1] Methane emissions are converted to CO_2-equivalent (CO_2eq) using Global Warming Potential (GWP) values from IPCC's Fifth Assessment Report. The GWP_{100} metric compares the warming impact of 1 kg of methane to 1 kg of CO_2 over a 100-year time horizon. IPCC AR5 assigns methane a GWP_{100} of 28–30, meaning methane is ~28–30 times more potent than CO_2 over this period.
Sources: European Commission, EDGAR, 2024, GHG emissions of all world countries; Kearney Energy Transition Institute

Methane sinks' capacity has stagnated, requiring additional measures to mitigate net positive emissions

Global CH_4 emission natural sinks[1,2]
($MtCH_4$, 2000–2020)



- **Tropospheric OH:** In the troposphere, most CH_4 reacts with hydroxyl radicals (OH). **This reaction converts CH_4 into water vapor and CO_2**, making it the dominant natural removal pathway.
- **Tropospheric Cl:** In marine boundary layers, **chlorine radicals** (Cl) derived from sea salt aerosols also **react with CH_4, triggering its oxidation.**
- **Stratospheric loss:** A portion of **CH_4** ascends into the stratosphere, where it **undergoes photochemical breakdown. Reactive species** such as excited oxygen atoms and halogen radicals **react with CH_4**, leading to its destruction.
- **Soil uptake:** Well-aerated soils act as a CH_4 sink through the **activity of methanotrophic bacteria**, which oxidize methane as an energy source.

2.3 Methane sinks

[1] Bottom-up calculation methodology rather than top-down, as described by Saunois et al., and considering median values of ranges provided.; [2] The growth in sinks is not statistically significant given model uncertainties. Sinks are dominated by OH oxidation (563±100 Tg CH_4/yr), with uncertainties stemming from OH concentration estimates (±10–20% interannual variability), differences in atmospheric chemistry models, and limited constraints on soil uptake variability.
Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Atmospheric chemical processes in the troposphere and stratosphere are the most effective methane sink; however, they offer finite capacity

Press Ctrl and click the image to navigate to the details in the Appendix.

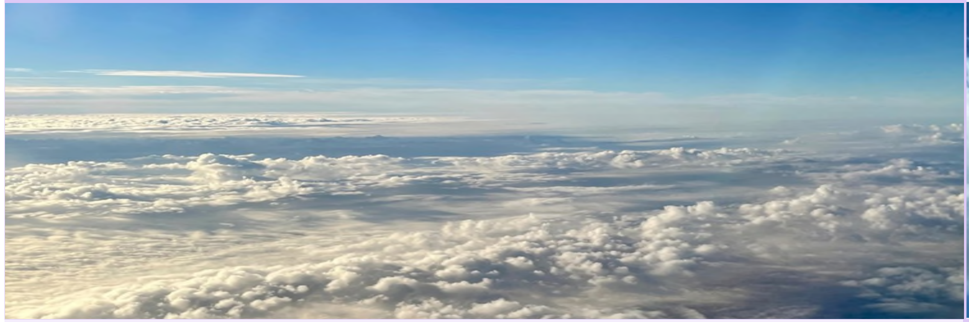
OH radicals remove more than 90% of CH_4 but are scarce and consumed by other pollutants such as CO and nitrogen oxides, limiting the atmosphere's ability to scale CH_4 removal as emissions rise.

Sources: Desktop research; Kearney Energy Transition Institute

2.3 Methane sinks

Tropospheric OH

Emitted CH_4 reaches the troposphere, where it is broken through tropospheric OH reaction, forming H_2O and CO_2.



Tropospheric Cl

Emitted CH_4 reaches the troposphere, where it is broken down by Cl radicals from sources such as sea salt.

Stratospheric loss

Emitted CH_4 reaches the stratosphere, where it is broken down through stratospheric loss driven by reactive radicals, especially halogens and excited oxygen.

Soil uptake

Unsaturated oxic soils are sinks of atmospheric CH_4 due to the presence of methanotrophic bacteria, which consume CH_4 as a source of energy.

3. Monitoring approaches and advancements

Introduction and summary

Multiple approaches exist to monitor methane emissions, each with its pros and cons. No single platform is enough—snapshots alone miss intermittency; continuous systems alone miss scale. Satellites are essential for spatial coverage but can underperform proximal systems in certain situations.

Integrated systems solve for blind spots and technology advancements enable robust and real-time monitoring. Progress in data interoperability and global monitoring standards is crucial.

Different approaches to monitoring emissions	Monitoring systems differ in their spatial coverage, temporal flexibility, and resolution.
Managing trade-offs	Required coverage–sensitivity–cost mix decides the choice of monitoring platform to be deployed.
Satellite revolution	Satellites, as a breakthrough solution, can help identify large-scale emissions and super-emitter events previously undercounted.
Toward integration and innovation	Integrated systems, leveraging fast-maturing technology stack and AI/cloud capabilities, can break the barriers in methane monitoring.

Source: Kearney Energy Transition Institute

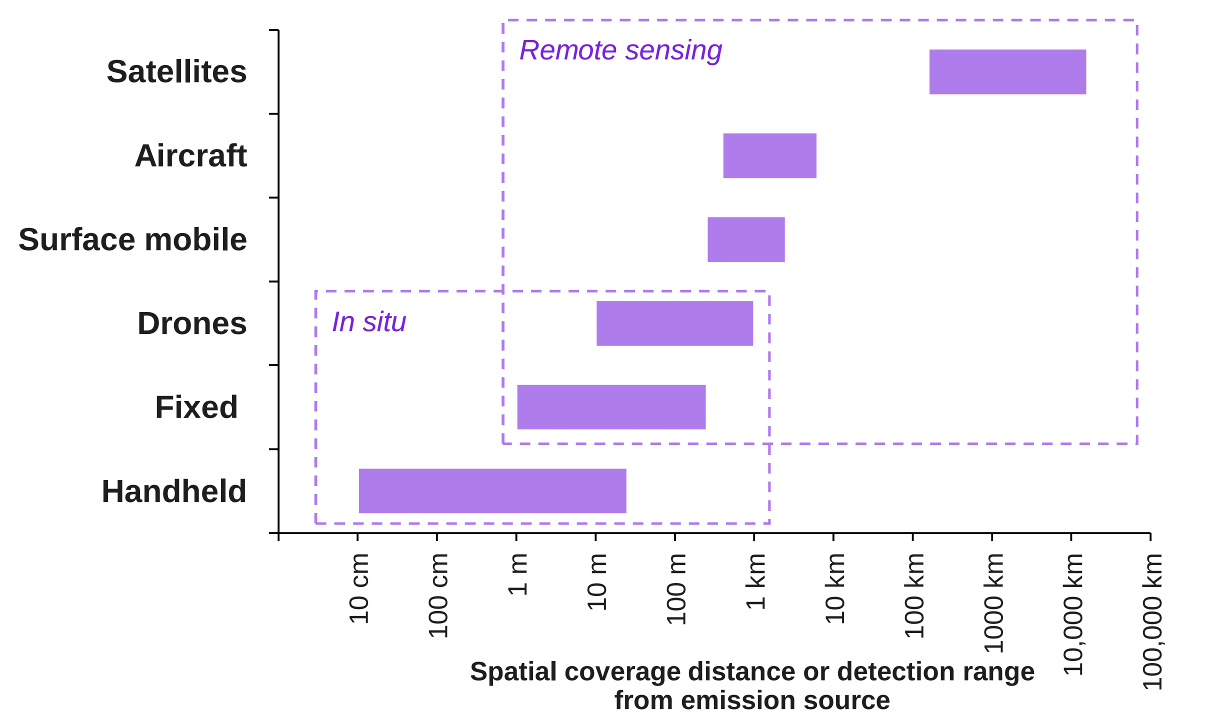
Based on sensor placement, monitoring approaches are classified as in-situ or remote sensing

Illustrative, non-exhaustive

Monitoring solutions also **vary in timescales** as some capture a single “snapshot” of methane emissions, while others are based on recurring or continuous measurements.

Sources: Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Kearney Energy Transition Institute

Key monitoring approaches



No single detection method is enough:

- Snapshot systems are affordable and scalable, yet they miss intermittent leaks.
- Continuous monitoring ensures compliance, though it comes at a higher cost.

Only an integrated approach delivers both coverage and reliability.

In-situ	Remote sensing
Measures methane directly at the point of release or within the air sample	Detects methane concentrations indirectly, usually by measuring how methane absorbs or scatters electromagnetic radiation
Localized, point-based; requires many units for wide coverage	Wide area to global coverage, as it can map plumes to different scales (i.e., facility to region)
Fails to capture unexpected, unintended, or uncharacterized emissions sources	Limited precision and sensitivity; results are highly dependent on atmospheric models and source attribution

No single platform is sufficient as sensor placement defines coverage, accuracy, and use case

Non-exhaustive

Submarine methane leaks often dissolve in seawater, which prevents identification from satellites. Identification of emissions in offshore environments is also challenged by the water reflectivity that hampers satellite detection.

Handheld sensors	Fixed sensors	Drones	Surface mobile	Aircraft	Satellites
					
– Mainly used to identify methane emissions from individual components and sources at facilities – However, it requires close access to all components and is time consuming – Multiple measurements may be required to achieve higher certainty	– Continuous monitoring solutions are sensors placed downwind of operations to detect emissions – Useful for continuous monitoring in hard-to-reach or confined areas	– Drones allow for atmospheric measurements in three dimensions and these measurements can observe the concentrations in the vertical column – Can be used to calculate wind speed and direction in the different layers of the atmosphere	– Vehicles detect methane concentrations along survey routes using open-path systems – Real-time emission maps of surveyed areas can be created by integrating GPS and meteorological conditions	– Can carry multiple high-precision sensors for methane and other gases – Their major advantage is that they can fly at all altitudes and have a long range	– Satellites identify methane's unique spectral fingerprint by analyzing radiations that are reflected to it – These radiations could be solar radiation (backscattered by the Earth and its atmosphere) or satellite's own backscattered laser signal
Examples					
– GFM 2.0 (AddGlobe) – Ultra M (Distran) – EyeCGas 2.0 (Opgal), etc.	– Mileva 33F (Sensia) – GF77a and G300a (Teledyne FLIR) – Soofie (Scientific Aviation)	– Lumen Sky (Baker Hughes) – Ventus OGI (Sierra Olympic) – DJI Matrice (ChampionX)	– Advanced Mobile Leak Detection with ALD 4.0 (Picarro) – SENSIT® VMD (Vehicle Methane Detector)	– AVIRIS-NG (NASA JPL) – ChampionX – LeakSurveyor (Kairos Aerospace)	– Sentinel-2 – PRISMA – MethaneSAT – TROPOMI

Sources: Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Kearney Energy Transition Institute analysis

Monitoring platform choice depends on trade-offs between coverage, sensitivity, and cost

Indicative

	Handheld sensors	Continuous fixed monitoring solutions	Drones	Surface mobile	Aircraft	Satellites
Distance	10 cm – 30 m	1 – 500 m	10 m – 1 km	500 m – 2 km	500 m – 2 km	500 km – 2,000 km[2]
Lower detection threshold	~1 ppm	<0.1 – 3.5 kg/h	<1 kg/h	5 kg/h	10 kg/h	160 – 950 kg/h
Costs	~$230 – $620	Capex: $75k – $100k per system Opex: ~$3k/year per well	~$3k – $20k+	~$10k – $100k per van	$5k – $50k+ per campaign	$10 million+ to launch and operate
TRL[1]	8–9	7–9	6–8	7–8	7–8	6–8
Advantages	– Portable and low cost – High accuracy – Easy to use	– Real-time, continuous data – High sensitivity – Pinpoints leaks precisely	– Access to remote sites – Flexible surveys – Cost-effective for targeted monitoring	– Suitable for medium/larger sites – Real-time mapped results	– Large regional coverage – Rapid surveys – Detects large leaks	– Global/wide-area coverage – Repeatable monitoring – Supports policy and compliance
Limitations	– Labor-intensive – Limited coverage – Discontinuous (snapshot only)	– Fixed location (no mobility) – Installation and calibration costs – Limited scalability	– Limited range/ flight time – Snapshot, not continuous data – Requires trained operator	– Terrain restrictions – Requires on-site personnel – Data quality depends on driving route	– High operating costs – Limited spatial detail – Airspace/flight restrictions	– Low spatial resolution – Limited temporal resolution (not real time) – Very costly

[1] Technology readiness level
[2] For near orbit satellites. For geostationary satellites, the distance is 35,786 km directly above the equator.
Sources: Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Kearney Energy Transition Institute

Satellites have unique capabilities but also blind spots where other methods are necessary

Where satellites are essential

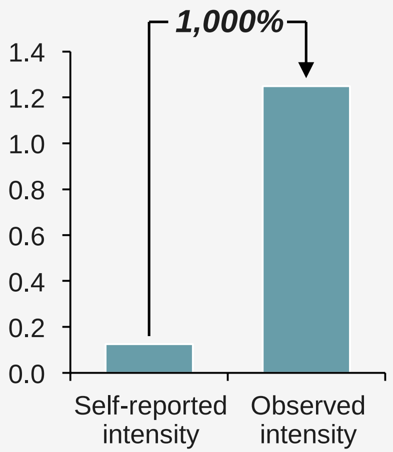
Detecting large-scale emissions and super-emitter events, especially over vast and remote regions

In the oil and gas sector, company-reported emissions can be understated by a **factor of 10**, as operators rely on legacy methodologies based on emission factors.

– Self-reported intensity figures are weighted averages from company disclosures (November 2020) covering producers responsible for ~27% of global hydrocarbon output.

– In contrast, observed intensity is derived from inversion models developed by Kayrros, using a weighted average of seven oil and gas basins across four countries.

Methane intensity of oil and gas production
(kg CH_4 per BOE)



Where satellites can fall short

Detecting small, dispersed emissions and accurately quantifying them under complex atmospheric conditions

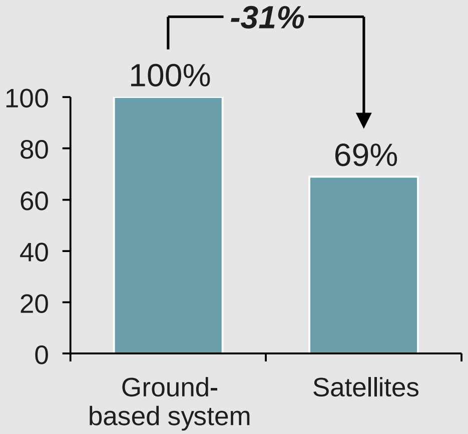
Satellites often **underperform ground-based and proximal monitoring systems** due to lower sensor sensitivity and higher vulnerability to atmospheric and surface variability.

– In 2022, a controlled trial tested nine satellite systems from three continents during 82 controlled methane releases.

– Each release was precisely metered with high-accuracy Coriolis meters at rates from 0.03 to 1.6 tons per hour.

– Ground-based systems delivered immediate results, while satellite data required days to weeks for analysis.

Emission events correctly identified
(%)



Sources: Kayrros; Sherwin et. al., 2024, Single-blind test of nine methane-sensing satellite systems from three continents; Kearney Energy Transition Institute

3.4 Monitoring differences

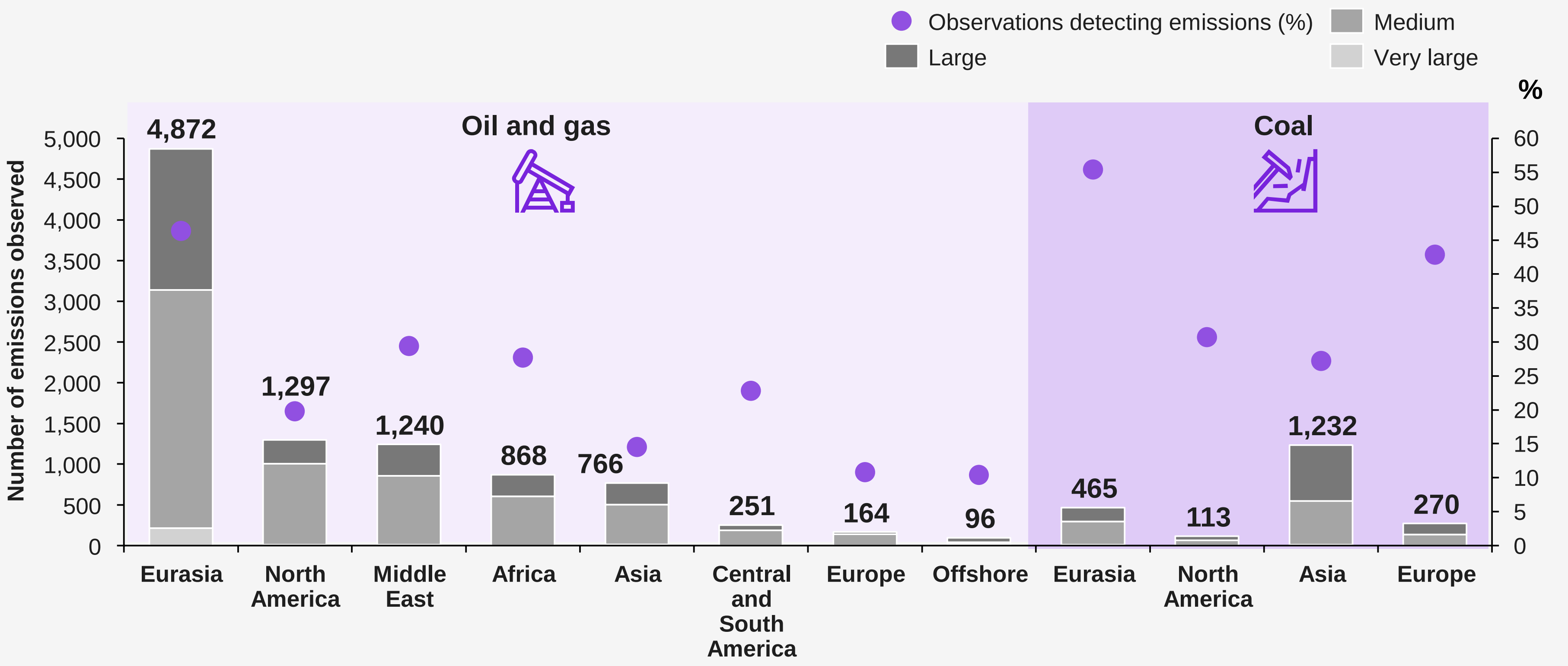
Unlike satellites with large detection areas for spotting emissions, certain satellites have a much finer resolution and can target specific locations

Most comprehensive measurement campaigns and targeted satellite-based activities have to date focused on **the United States and Canada.**

3.5 Satellites impact

Methane leaks at fossil fuel sites detected

(by GHGSat satellites, 2024)

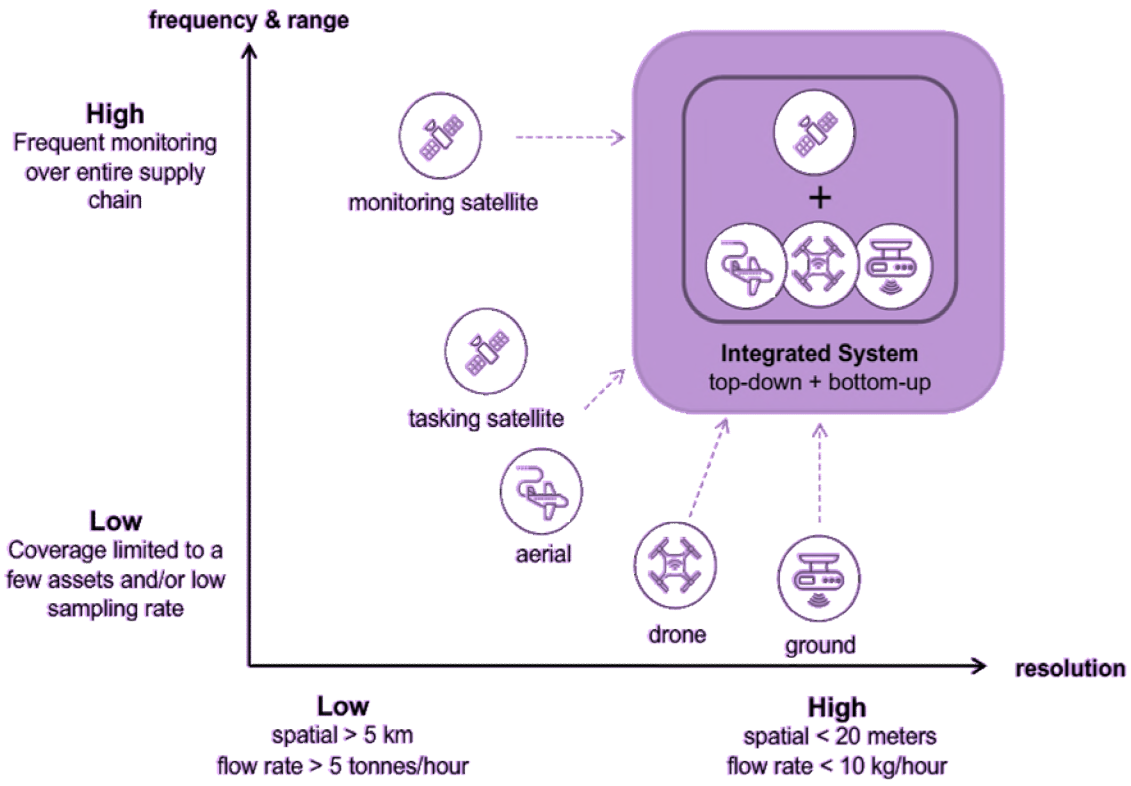


Key insights

- In 2024, **GHGSat's satellites** conducted **16,400 observations** at global oil, gas, and coal facilities.
- Industry pattern: **11,700** leaks were identified (multiple leaks were often seen during a single observation). Oil and gas operations accounted for **82%** of these leaks, while coal operations were responsible for remaining **18%**.
- Regional pattern: Only **~11%** of observations conducted at oil and gas facilities in Europe saw any emissions, compared to Eurasia, where **almost 50%** of the observations conducted detected at least one methane leak
- Fewer measurement data collected and reported for a number of major emitters—including **Russia, Venezuela, India, China, Brazil, and Nigeria**—and uncertainty over emissions levels in these countries is significantly higher.

Sources: IEA, 2025, Global methane tracker; Kearney Energy Transition Institute analysis

Integrated systems accelerate detection and alert time, enabling faster response



3.6 Monitoring integration

[1] Wind speed and direction, atmospheric interference, temperature, surface albedo, etc.
Sources: Kayrros; IEA, 2025, Global methane tracker; Kearney Energy Transition Institute

Non-exhaustive

Hybrid systems reduce blind spots

Trade-offs in sensor placement	Ground-based systems offer temporal advantage but lack spatial coverage (missing super-emitter events) and even though satellites provide better spatial capabilities, they miss lower thresholds leaks.
Impact of weather conditions	Environmental conditions significantly affect the accuracy, sensitivity, and reliability of measurements, especially those based on the remote sensing platforms.[1]

Hybrid systems ensure better ***breadth*** (no missed emissions across assets) and ***depth*** (detailed attribution where needed) by resolving for the above constraints more effectively than isolated systems.

Data interoperability and credible verification remain bottlenecks

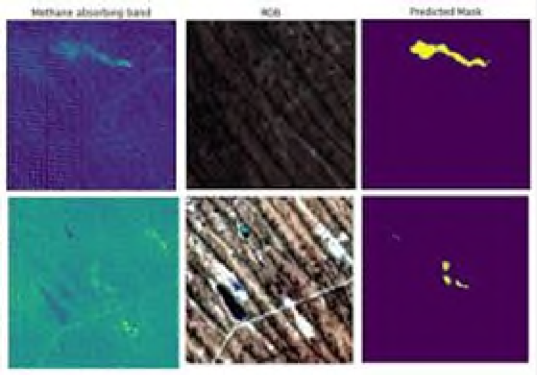
Diverse hardware and data formats hinder **comparability and aggregation**	**Lack of standard protocols** to reconcile anomalies emanating from in-situ and remote sensing observations	Verification frameworks (independent, regulator- or market-accepted) **lag behind** technological advances

Without trusted verification standards, monitoring data has limited policy or market value. Hence, integration is as much about ***governance*** as about technology.

Data fusion, AI, and alert systems are changing the landscape from passive monitoring to real-time accountability

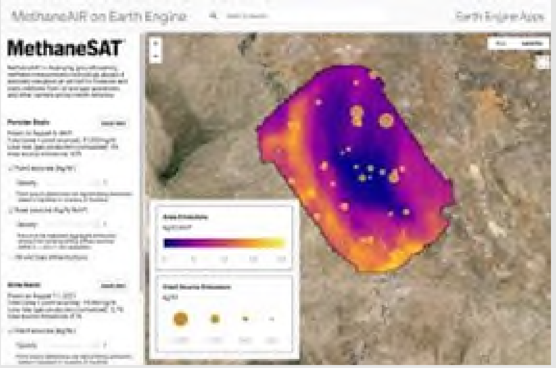
Neural networks

Deep learning models have been trained on multispectral and hyperspectral satellite imagery (e.g., Sentinel-2, PRISMA) to automatically locate and quantify methane emissions down to plume sizes of **0.01 km²** corresponding to **200-300 kg CH_4 per hour sources.**



Cloud computing platforms

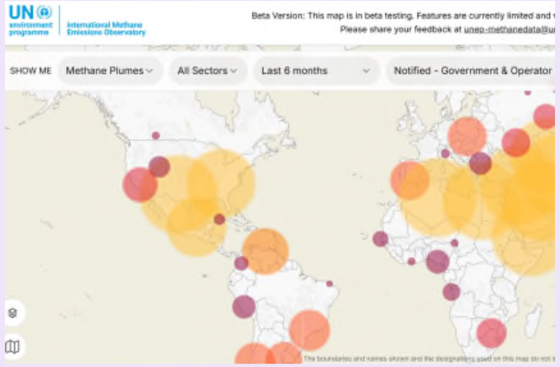
Cloud-based platforms like **Google Earth Engine and IMI Cloud** offer scalable infrastructure for processing vast volumes of data from satellites (such as TROPOMI and MethaneSAT), running AI-powered detection algorithms, and inferring methane emissions at city, regional, and facility levels.



Enhancing real-time alerts

AI satellite alerts

UNEP's International Methane Emissions Observatory (IMEO) launched MARS in 2022, an **AI-driven satellite detection and notification system**, enabling **near-real-time detection and response** through mass dataset compilation and advanced machine learning models.

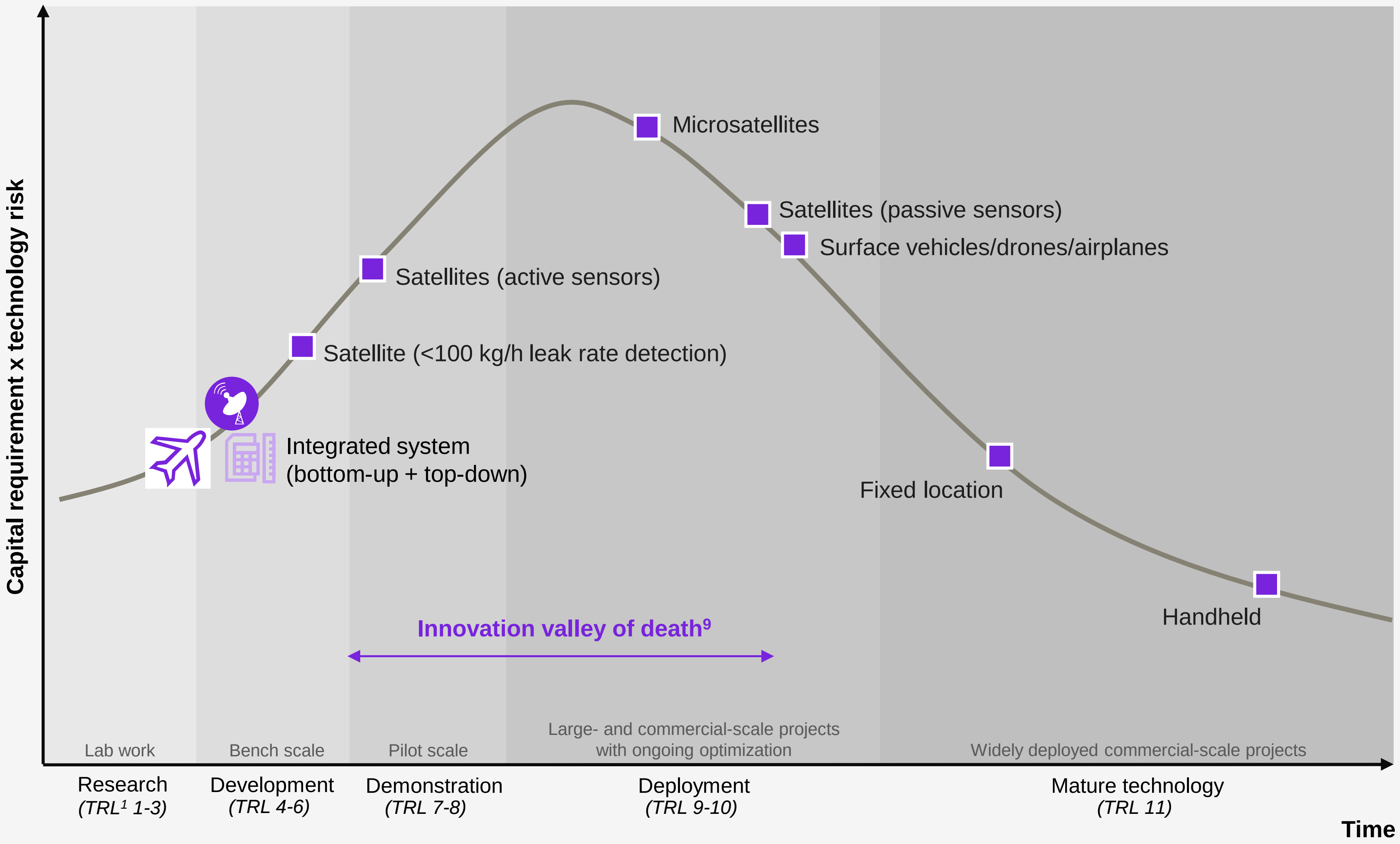


Sources: Rouet-Leduc, B. and Hulbert, C., 2024, Automatic detection of methane emissions in multispectral satellite imagery using a vision transformer; Marjani, M. et al., 2024, PRISMethaNet: A novel deep learning model for landfill methane detection using PRISMA satellite data; IEA, 2025, Global Methane Tracker; MethaneSAT; Kearney Energy Transition Institute

Many new technologies are being developed and deployed to solve for increased coverage resolution, accuracy, and frequency

Non-exhaustive

Maturity curve of methane monitoring technologies



Sensor deployment options

[1] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide.
Sources: Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Methane Guiding Principles partnership, 2024, Best Practice Guide: Identification, Detection, Measurement and Quantification; Kearney Energy Transition Institute

3.8 Maturity curve

4. Mitigation technology solutions

Introduction and summary

Mitigation options vary widely in maturity, scalability, and cost, but many are commercially available and economically viable today.

The oil and gas sector stands out for its high abatement potential at low cost, while agriculture and biomass offer emerging innovations with longer-term promise.

Systemic barriers, such as financing gaps, weak data, and policy misalignment, constrain deployment despite technical feasibility.

Large low-cost mitigation potential	Proven, low-cost solutions in oil and gas can deliver immediate, high-impact methane reductions.
Scaling challenge	Cost-effective mitigation options are also available in coal, waste, and agriculture, but scaling requires targeted investment and policy support.
High potential, low maturity	Emerging technologies in agriculture and biomass show high potential but remain pre-commercial.
Deployment gap	Most barriers to methane mitigation are non-technical: addressing finance, policy, data challenges, and social barriers is critical to accelerate deployment.

Source: Kearney Energy Transition Institute

Mitigation measures for anthropogenic emissions span all stages of maturity, with fossil fuels and waste leading in mature solutions

4.1 Classification of key mitigation solutions

Non-exhaustive

- Research
- Development
- Demonstration
- Mature technology
- Deployment

of methane emissions

Anthropogenic emissions

	Fossil fuels (18%)		Waste (10%)		Agriculture (22%)		Biomass (4%)
Avoid[1]	Pre-mine methane drainage		In-vessel aerobic composting	Organic waste reduction at source	Novel plant-based meat and dairy alternatives	Plant-based diet adoption	No-burn residue management
	Zero-bleed pneumatic devices		Source separation and diversion to composting		Conversion to wetlands, salt marshes, and tidal forests		
	Enhanced horizontal directional drilling for gas drainage		High-rate aerobic mechanical–biological treatment		Aerobic rice cultivation		Biomass pyrolysis for biochar
	Modular gas processing and capture systems		Advanced aerobic bio-drying systems		Low-methane rice varieties	Cultivated (cell-based) meat	
Reduce[2]	Leak detection and repair		Aerobic-finishing after dry anaerobic pretreatment		Controlled-release fertilizers	Manure storage covers	Improved biomass cookstoves
	Improved flaring systems				Biochar soil amendment	Methane-inhibiting feed additives	
	Real-time continuous monitoring networks		Engineered landfill bio-cover and biofilter systems		Alternate wetting and drying	Slurry acidification	
	Smart pneumatic controllers with integrated sensors				AI-driven feed optimization	Cable bacteria bioaugmentation	
					Anti-methanogen vaccine	Microbiome-targeted breeding	
Remove[3]	Vapor recovery units	Catalytic and regenerative thermal oxidation for VAM	Landfill gas collection and upgrading system		Anaerobic digestion of manure		Methane oxidation catalysts
	VAM thermal oxidation systems[4]	Gas-to-liquid conversion systems	Anaerobic digestion with biogas capture		Mobile methane collection systems		
	Abandoned mine gas recovery	Bio-electrochemical VAM treatment systems	Wastewater biogas recovery systems		Livestock methane capture wearables		Electrochemical methane converters
	Membrane-based methane separation technologies	Recovery and monitoring of abandoned wells	Membrane-based methane capture technologies				

[1] Avoid refers to preventing methane from ever entering the atmosphere by eliminating the activities or processes that generate it.; [2] Reduce refers to minimizing releases from existing sources through technological upgrades and operational improvements.; [3] Remove refers to capturing or converting residual atmospheric methane that persists after avoidance and reduction.; [4] VAM is ventilation air methane.
Sources: Desktop research; Kearney Energy Transition Institute

Emerging mitigation solutions target methane from natural and indirect sources and enhancing natural sinks capacity

4.1 Classification of key mitigation solutions

Non-exhaustive

- Research
- Development
- Demonstration
- Mature technology
- Deployment

of methane emissions

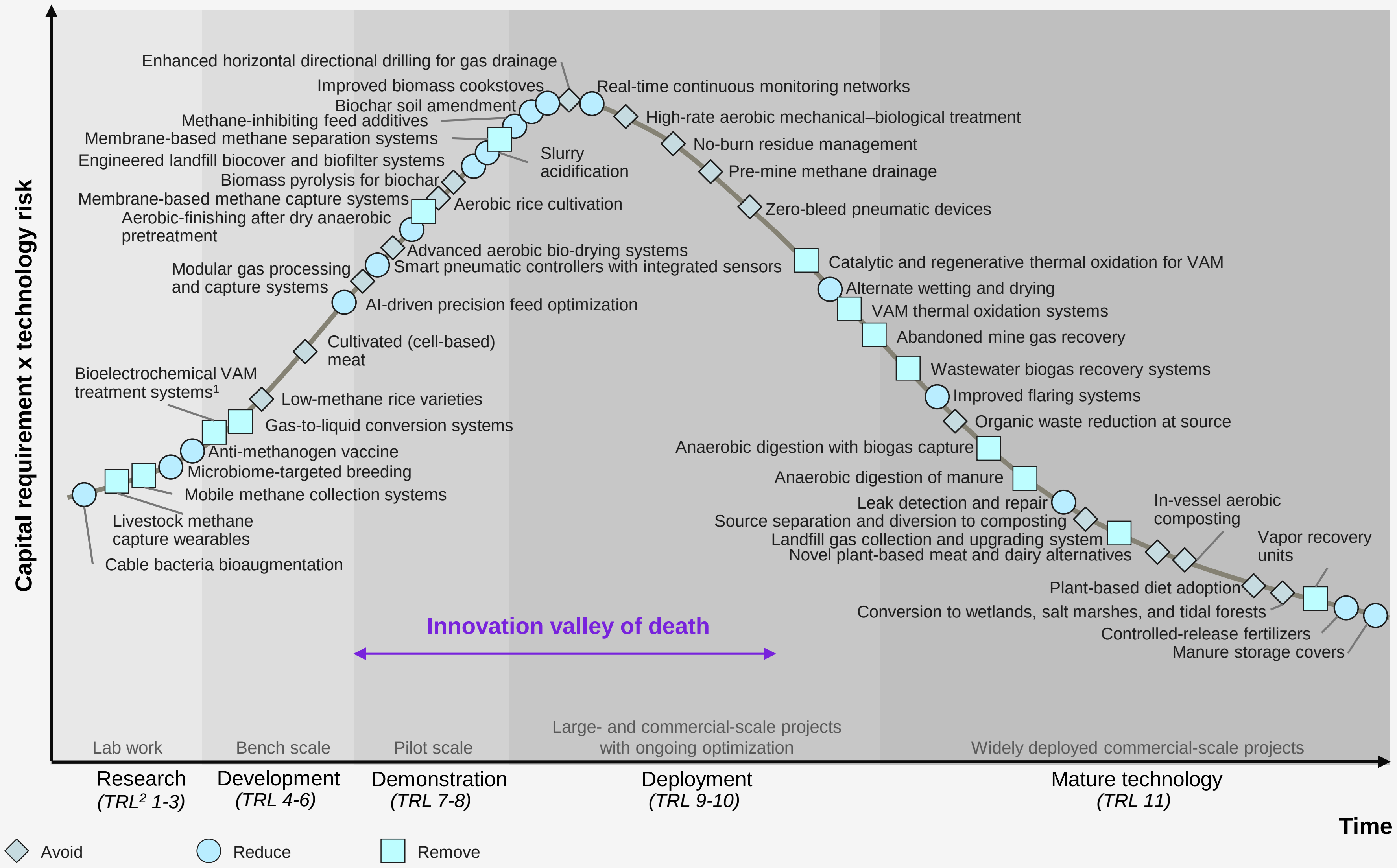
	Natural and indirect sources		Natural sinks	
	Wetlands and inlands (37%)	**Other natural sources (9%)**	**Atmospheric reactions**	**Land**
Avoid	Water-level control in wetlands	Tidal marsh restoration	*No technology available*	Optimized nitrogen management
	Optimized constructed-wetland design	Arctic grazing management		
	Redox-manipulation via electron-acceptor amendments	Permafrost thermal stabilization		
Reduce	Biochar soil amendment	*No technology available*		
	Hypolimnetic aeration in inland waters			
	Metal-oxide amendment in wetlands			
	Microbial fuel-cell deployment			
Remove	Membrane-based methane capture	Subsurface methane biofiltration	Plasma-photocatalytic hybrid reactor	Biochar soil amendment
		Gas hydrate extraction and utilization	Tropospheric hydroxyl radical boost	
		Seep gas capture and combustion systems	Tropospheric chlorine radical boost	
			Photocatalytic solar chimney reactor	
	Enhanced degassing and treatment systems	Marine methanotrophic reactors	Photocatalytic surface treatment	Methanotrophic bioaugmentation
			Photocatalytic ozonation reactor	
		Seafloor methane capture domes	Stratospheric hydroxyl radical boost	
			Electrochemical methane processor	

Sources: Desktop research; Kearney Energy Transition Institute

Mitigation technology solutions for anthropogenic methane emissions are spread across the maturity curve

Non-exhaustive

Maturity curve for mitigation measures for anthropogenic methane emissions



[1] VAM is ventilation air methane. [2] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide
Sources: Desktop research; Kearney Energy Transition Institute

4.2 Technology maturity curve

Advanced, mature, and cost-effective methane mitigation solutions in oil and gas can drive rapid emissions reductions at scale

	Leak detection and repair *(oil and gas)*	Vapor recovery units *(oil)*	Smart pneumatic controllers *(oil and gas)*
Oil and gas sector			
Working principle	– Periodic inspections to detect unintentional **methane leaks from equipment components** like valves, flanges, and connectors – Uses optical gas imaging cameras or handheld instruments	– **Mechanical units** that capture methane that would otherwise be **vented during storage, loading, or processing** – **The recovered gas** is compressed and reused or sold instead of being released	– **Advanced pneumatic devices** using electric solenoid valves instead of continuous gas bleeding to prevent **venting** losses – **Achieve zero natural gas consumption** during steady-state operation, while traditional controls vent gas continuously
Basic parameters	– Infrared spectral detection – Detection threshold variability – Survey frequency optimization	– Compression-based recovery – Three-stage process – Control automation	– Solenoid valve operation – Smart digital integration – Power supply requirements
Cost	○	○	◑
TRL[1]	11 (Mature)	11 (Mature)	7-8 (Demonstration)
Methane mitigation potential	◕	◕[2]	◑

Low ○ - *High* ● cost / methane mitigation potential

[1] TRL is technology readiness level.; [2] Technologies that also present CO_2 capture capabilities.
Sources: Desktop research; Kearney Energy Transition Institute

Deployment-ready coal sector technologies offer immediate, high-impact opportunities for methane mitigation and mine safety

Coal sector	Pre-mine gas drainage	Ventilation air methane thermal oxidation	Abandoned mine gas recovery
			
Working principle	– **Extracts methane from coal seams before mining** via directional drilling – Enhances mine safety by **reducing in-mine methane concentrations** and converts gas to power or pipeline feed	– **Treats low-concentration ventilation air** (0.2–1.0% CH_4) by auto-thermal oxidation in a regenerative thermal reactor – **Generates heat recovery up to 95%** for electricity generation or mine heating	– **Extracts methane from sealed or flooded abandoned coal mines** via boreholes or galleries – **Prevents long-term uncontrolled emissions** while providing renewable energy
Basic parameters	– Drilling pattern and sealing – Pressure drawdown – Surface gas collection	– Heat exchange media – Flow reversal cycle – Emission destruction efficiency	– Sealing and pressure control – Wellfield design – Gas conditioning and use
Cost	◔	◔	◔
TRL[1]	9-10 (Deployment)	9-10 (Deployment)	9-10 (Deployment)
Methane mitigation potential	◔[2]	◑	◔[2]

Low ○ - *High* ● cost / methane mitigation potential

[1] TRL is technology readiness level.; [2] Technologies that also present CO_2 capture capabilities.
Sources: Desktop research; Kearney Energy Transition Institute

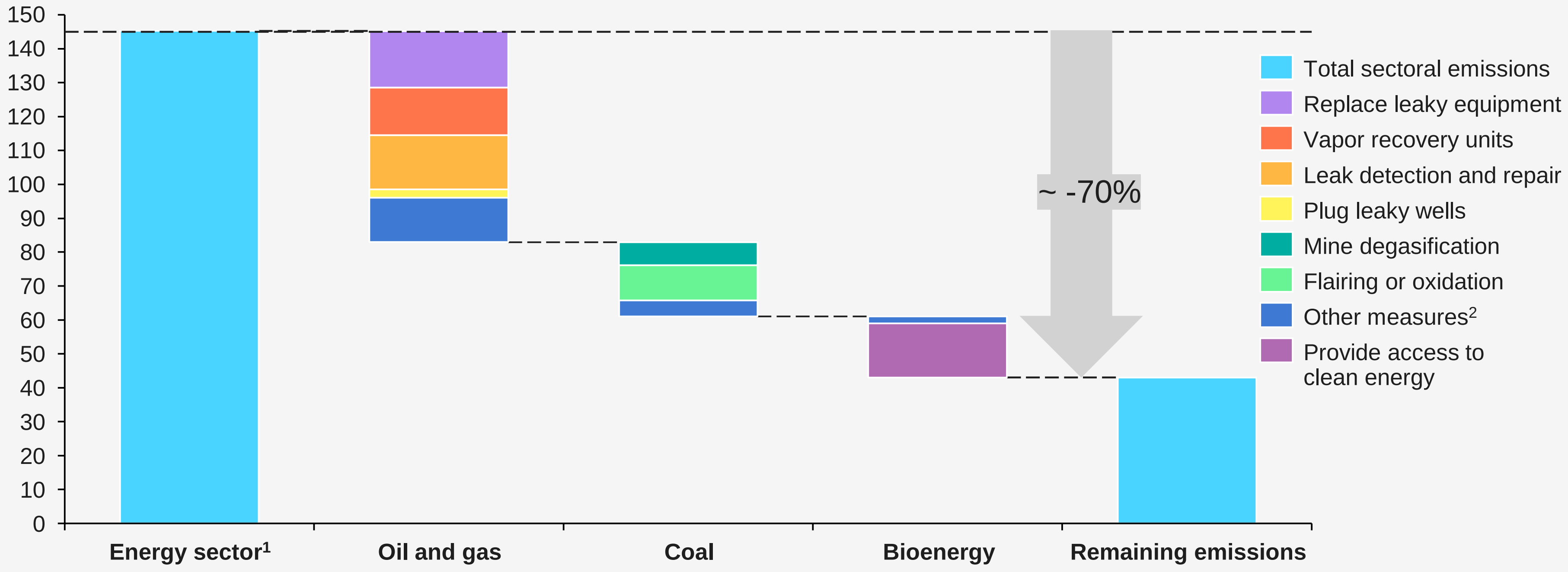
Around 70% of methane emissions from the energy sector could be reduced with existing solutions

Up to 35 Mt of methane emissions across oil, gas, and coal could be eliminated at **zero net cost**, given 2024 average energy price.

4.3 Overview of select mitigation solutions

Opportunities to reduce methane emissions in the energy sector

($MtCH_4$, 2024)



Key insights

- **Oil and gas operations** account for the largest share of methane reduction potential, mainly through leak detection and repair, replacing leaky equipment, and vapor recovery. These are among the most cost-effective interventions, offering significant near-term gains.
- **Coal-related emissions** can be mitigated through methane capture and utilization, as well as flaring or oxidation technologies.
- Reducing **residual emissions** will require sustained innovation and stronger policy measures.

[1] Includes oil and gas, coal, and bioenergy.; [2] Includes efficiency improvements, installing plungers, blowdown capture, installing methane-reducing catalysts, reduced-emission completions and capturing methane emissions from waste streams.
Sources: IEA, 2025, Global methane tracker 2025 (Link); Kearney Energy Transition Institute

Transformative agricultural innovations can significantly reduce livestock and rice methane emissions, but need investment to scale

Agriculture sector	Alternate wetting and drying	Methane-inhibiting feed additives	Anti-methanogen vaccine
			
Working principle	– **Intermittent flooding practice** in rice paddies, alternating between flooded and drained soil conditions – **Disrupts anaerobic conditions** to inhibit methane-producing microbes	– **Rumen-targeted compounds** that block methanogenesis enzymes – **Delivered** via premixed feed or bolus for **continuous ruminal exposure**	– **Vaccination strategy to elicit host antibodies** against rumen methanogenic archaea – Designed for administration via **standard livestock vaccine delivery**
Basic parameters	– Water table management – Drainage interval typically every 5-10 days, depending on soil and climate – Requires simple field-level monitoring	– Inhibits methyl-coenzyme M reductase – Effective dose range – Formulated for minimal degradation before reaching the rumen	– Antigen design – Immunization schedule – Delivery platform
Cost	◔	◕	◕
TRL[1]	9-10 (Deployment)	9-10 (Deployment)	1-3 (Research)
Methane mitigation potential	◔	◑	◔

Low ○ - *High* ● cost / methane mitigation potential

[1] TRL is technology readiness level.
Sources: Desktop research; Kearney Energy Transition Institute

Ready-to-implement waste management technologies unlock scalable methane capture with strong climate benefits and energy recovery potential

Waste sector	Landfill gas collection and upgrading systems	Anaerobic digestion with biogas capture	Membrane-based methane capture technologies
			
Working principle	– **Captures CH_4-rich landfill gas from decomposing organic waste** using vertical wells and/or horizontal trenches – **Energy recovery system** that converts **captured landfill gas into electricity, heat, or upgraded biomethane**	– **Organic matter is decomposed by microorganisms** in O_2-free environments, producing biogas and digestate fertilizer – **Four-stage biochemical process**: hydrolysis, acidogenesis, acetogenesis, and methanogenesis	– **Selective separation technology** with differential permeability that allows CO_2 to pass through while retaining methane – **Multi-stage purification process** involving pre-treatment, compression, and membrane separation stages **to upgrade raw biogas**
Basic parameters	– Extraction mechanism – Collection efficiency – Gas composition management	– Temperature control – pH and biochemical balance – Hydraulic retention time and loading	– Membrane selectivity and permeability – Operating pressure and stage configuration – Operating temperatures
Cost	◔	◕	◑
TRL[1]	11 (Mature)	11 (Mature)	7-8 (Demonstration)
Methane mitigation potential	◑[2]	◔[2]	◔[2]

Low ○ - *High* ● cost / methane mitigation potential

[1] TRL is technology readiness level.; [2] Technologies that also present CO_2 capture capabilities.
Sources: Desktop research; Kearney Energy Transition Institute

Scaling up proven methane technologies is feasible today, while high-potential but immature technologies risk stalling without policy and finance support

	Barriers to adoption of methane mitigation technologies	Technological maturity	Infrastructure needs	Operational complexity	Cost	Regulation / policy	Social acceptance	Adoption rate	Adoption growth potential
Oil and gas	Leak detection and repair	Low	Low to medium	Medium	Low	High	Low	◕	▲
Oil and gas	Vapor recovery units	Low	Medium to high	Medium	Low	High	Low	◕	▲
Oil and gas	Smart pneumatic controllers	Low	High	Medium	Medium to high	High	Low	◑	▶
Coal	Pre-mine gas drainage	Low	Medium	Medium	Low	High	Low	◕	▲
Coal	Ventilation air methane thermal oxidation	Medium	High	High	Medium	High	Low	◔	▼
Coal	Abandoned mine gas recovery	Medium	Medium	Medium	Medium	High	Low to medium	◔	▼
Agriculture	Alternate wetting and drying	Low	High	Medium	Low	Medium	Medium	◑	▶
Agriculture	Methane-inhibiting feed additives	Medium	High	Medium	High	Medium	Medium	◔	▼
Agriculture	Anti-methanogen vaccine	High	Medium	Medium	Medium	Medium	Medium	◔	▼
Waste	Landfill gas collection and upgrading systems	Low	Medium	Medium	Medium to high	High	Low to medium	◑	▶
Waste	Anaerobic digestion with biogas capture	Low	High	Medium	High	Medium	Medium	◑	▶
Waste	Membrane-based methane capture technologies	High	High	High	High	Medium	Low	◔	▼

Adoption rate
● High ○ Low

Adoption growth momentum
▲ High ▶ Medium ▼ Low

Barrier impact magnitude
Low | Low to medium | Medium | Medium to high | High

Sources: Desktop research; Kearney Energy Transition Institute

5. Policy and regulation

Introduction and summary

Global methane emissions from fossil fuels showed a 2% decrease since 2019, which lies within measurement uncertainties and represents no evident significant progress. This near-stagnation falls far short of the rapid reduction required to align with the **IEA's Net Zero pathway.**

While international pledges have raised political visibility**, only half of targeted cuts are backed by enforceable policies. Regulatory coverage** remains **fragmented and major emitters are absent.**

Proven interventions—flaring bans, performance standards, methane pricing—**demonstrate large and low-cost abatement potential.**

Current policies fall short

In the past 5 years, methane emissions from fossil fuels have only dropped 2%. To stay on track, they must fall by 68% in the next 5 years and by 80% within 10 years.

Global pledges lack enforcement

Only 18% of targeted cuts from the Global Methane Pledge are backed by binding policies.

Fragmented policy leadership

A handful of frontrunners (EU, Canada, China, Brazil, Kazakhstan) are introducing methane-specific regulations, but most major emitters remain uncovered.

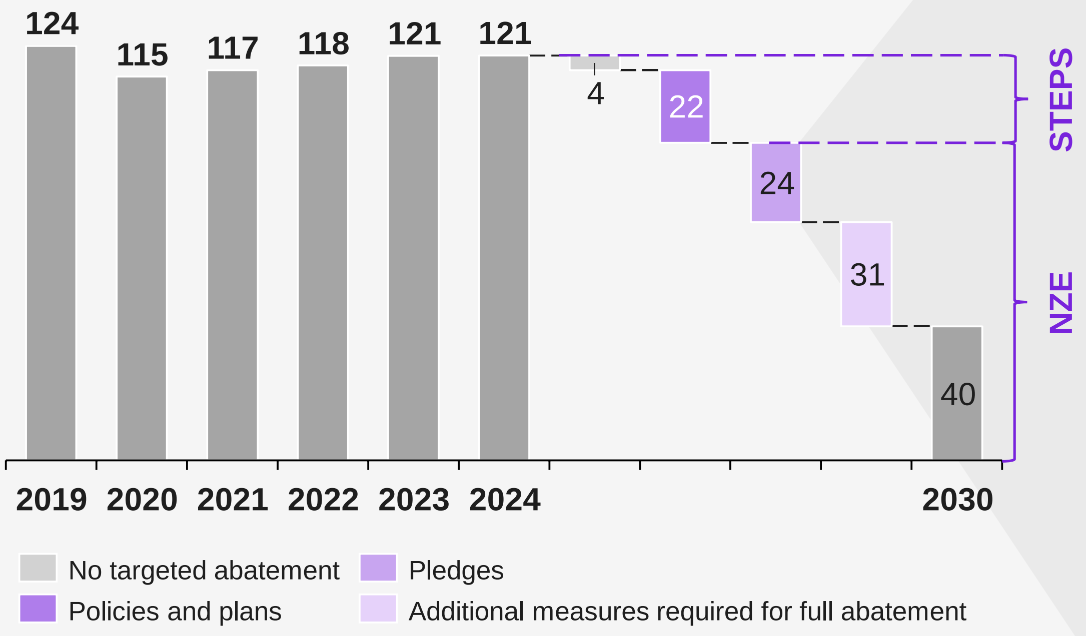
Proven solutions exist

Simple policy levers could cut oil and gas methane emissions by up to 75% by 2030, with additional pressure from importers reshaping global trade standards.

Source: Kearney Energy Transition Institute

Global pledges remain weak, with only half of targeted methane cuts backed by enforceable policies or regulatory measures

Global methane emissions reductions in fossil fuel industry by current policy, plans, and pledges
(Mt, 2019–2030)



Global Methane Pledge

Major international climate initiative launched at COP26, 2021, led by US and EU, representing 80% of 24 Mt reduction by 2030.[1]

Goal

Reduce global methane emissions by at least 30% by 2030 relative to 2030 levels

Participation

As of 2024, >150 countries representing globally >50% emissions and 70% GDP

Status of implementation

- 38% reduction by 2030 possible if all pledges are fully implemented
- 18% backed by legislated policies and official targets
- 20% based on aspirational pledges not yet included in policy frameworks

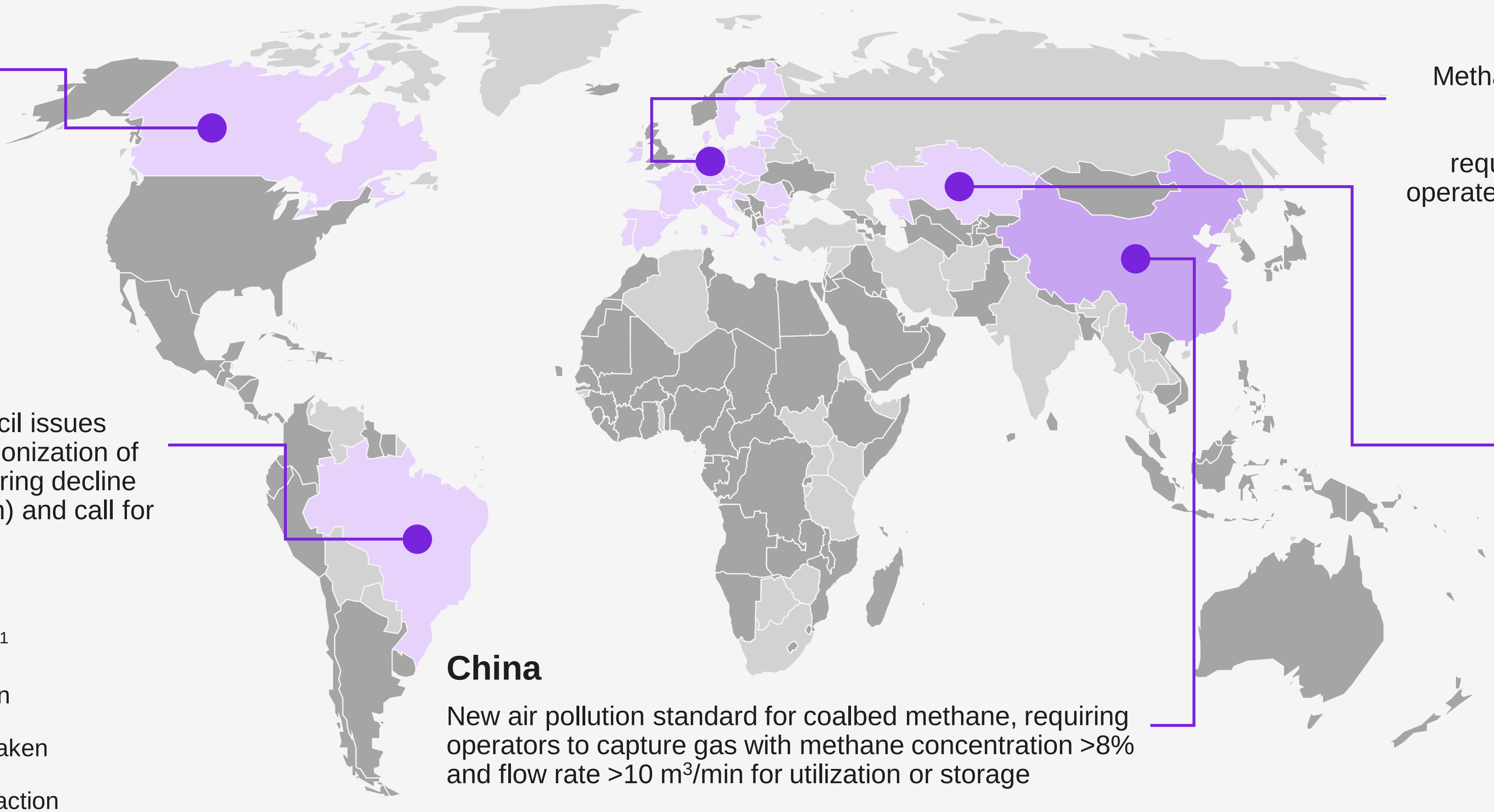
Gaps and challenges

- Major emitters outside the pledge: China, India, Russia (together >35% of global methane)
- Enforcement gap: even among signatories, rules and penalties are inconsistent.
- Monitoring challenge: lack of standardized MRV (measurement, reporting, verification) frameworks slows progress.
- Risk: without policies, pledges risk being “voluntary only,” undermining credibility. The United States remains part of the Global Methane Pledge (GMP) in 2025, but domestic policy uncertainty could affect the strength and credibility of its commitment.

[1] COP26 is Conference of the Parties, 26th meeting.
Sources: Global Methane Pledge, 2025, About the Global Methane Pledge; Global Methane Pledge. 2024, Factsheet: 2024 Global Methane Pledge Ministerial; IEA, 2025, Global Methane Tracker 2025; IEA, 2025, Stated Policies Scenario (STEPS); Kearney Energy Transition Institute

A handful of frontrunners set the pace on methane regulation, but global coverage remains uneven

Non-exhaustive



Canada

Draft regulation for national cap-and-trade system for GHG emissions from oil and gas

EU

Methane regulation on emissions reduction in energy sector, including mandatory MMRV requirements at source level for operated and non-operated assets[2]

Brazil

National Energy Policy Council issues guidelines to promote decarbonization of oil and gas activities (e.g., flaring decline and routine flaring elimination) and call for methane leakage reduction

Kazakhstan

Regulation under development to reduce methane emissions from fossil fuel sector, including non-emergency methane venting, LDAR requirements, and MMRV framework[3]

China

New air pollution standard for coalbed methane, requiring operators to capture gas with methane concentration >8% and flow rate >10 m^3/min for utilization or storage

- GMP member; action taken[1]
- GMP member; limited action
- GMP non-member; action taken
- GMP non-member; limited action

[1] GMP is Global Methane Pledge.; [2] MMRV is measurement, monitoring, reporting, and verification.; [3] LDAR is leak detection and repair.
Sources: Global Methane Pledge, 2025, About the Global Methane Pledge; Government of Canada, 2024, Oil and Gas Sector Greenhouse Gas Emissions Cap Regulations; IEA, 2024, Coalbed Methane (Coal Mine Gas) Emission Standard (China); IEA, 2025, EU regulation on the reduction of methane emissions in the energy sector; IEA, 2025, Global Methane Tracker 2025; Official website of the President of the Republic of Kazakhstan, 2024, U.S.-Kazakhstan Joint Statement on Accelerating Methane Mitigation to Achieve the Global Methane Pledge; Kearney Energy Transition Institute

Methane is largely missing from NDCs, with only 15% of global emissions covered by methane-specific targets

Nationally Determined Contributions (NDCs) are legally recognized climate plans under the Paris Agreement. They are the **main enforcement mechanism** countries use to report progress on GHG mitigation.[1]

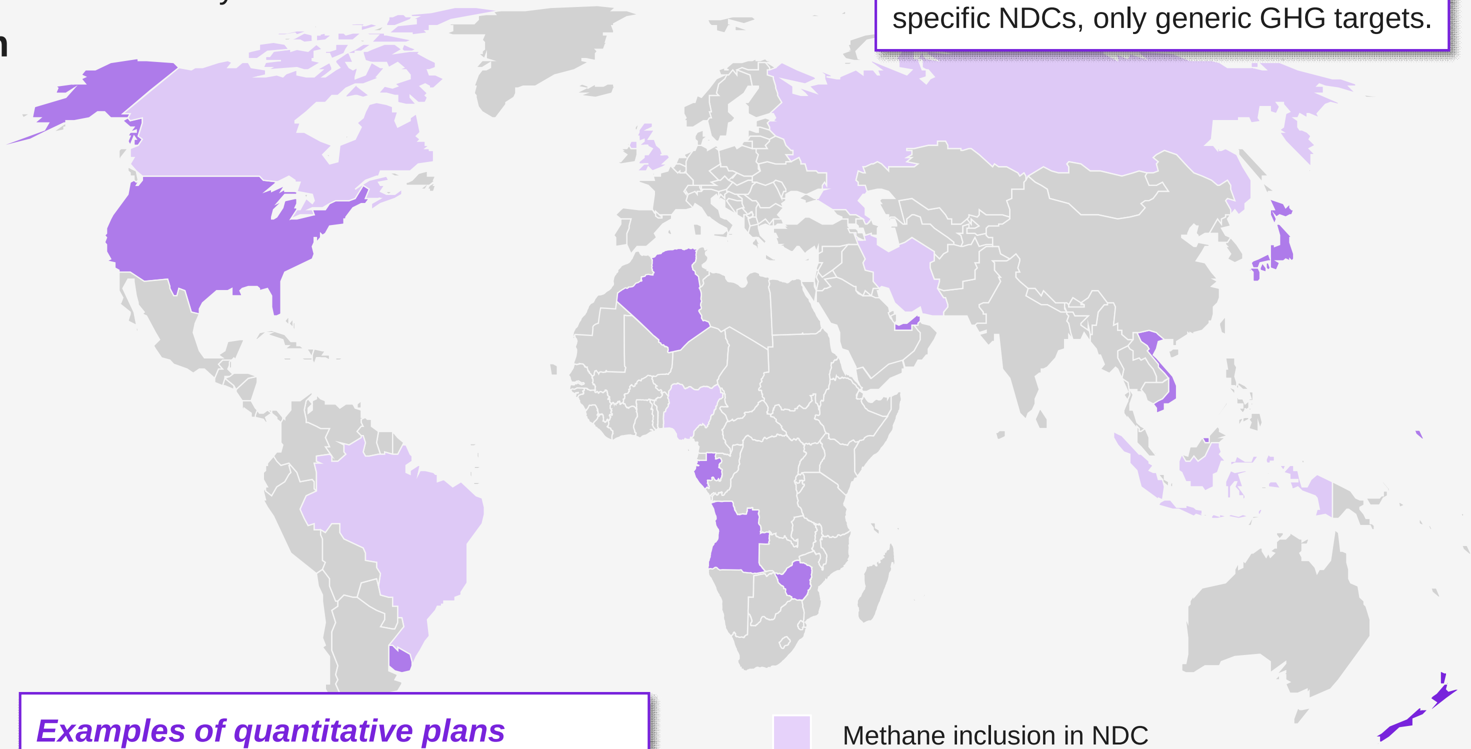
- As of 2025, more than 160 countries have joined the Global Methane Pledge, with methane increasingly mentioned in NDCs, though quantified targets with reduction commitments remain limited.
- Current methane commitments in NDCs cover only around 15% of global methane emissions.

Challenges and risks

- Most NDCs reference methane only implicitly under "GHG reductions," thus no measurable targets.
- Agricultural waste (40% of emissions) is rarely addressed.
- Without binding methane targets, progress is hard to track and finance.
- The Trump administration's withdrawal from the Paris Agreement will take effect in January 2026, rendering the US NDC void.

Selected countries with methane in NDC

As of July 2025



Coverage gap
Many major emitters (China, Russia, India, Brazil) do not have methane-specific NDCs, only generic GHG targets.

Examples of quantitative plans
- **Vietnam:** 30% reduction by 2030 vs. 2020
- **Japan:** 11% reduction by 2030 vs. 2013

[1] GHG is greenhouse gas.
Sources: GMP, 2025, Pledges; IEA, 2025, Global Methane Tracker; UNFCC NDC reports; US Congress, Methane Emissions: US and International Mitigation Efforts, 2025; Kearney Energy Transition Institute

Proven methane policies can cut oil and gas emissions by up to 75% by 2030 with no new technology required

Policies worldwide show methane cuts are possible without major monitoring systems, offering first steps to mitigation.

Key policy levers

Many low-cost, proven interventions exist and have already delivered major reductions in some jurisdictions.

- **Flaring and venting bans:** prohibiting routine burning of methane, forcing capture or alternative use
- **Methane taxes/pricing:** created an incentive for companies to deploy abatement quickly
- **Performance standards:** leak detection and repair (LDAR) mandates; limits on venting; efficiency standards for compressors and pneumatic devices
- **Financing incentives:** subsidies or low-interest loans for capture and utilization infrastructure; crediting methane reductions in carbon markets

Quantified potential

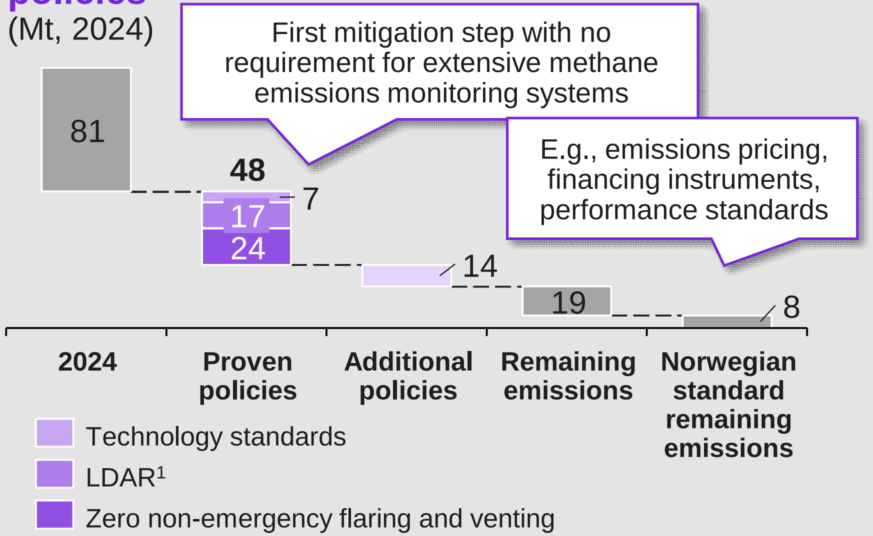
- **Simpler proven policy interventions for methane emissions mitigation have been implemented successfully globally** without complex monitoring systems with potential to realize a 59% (48 Mt) reduction in oil and gas emissions as of 2024 if adopted by countries globally.
- **Mass adoption of additional policies** would realize a further 14 Mt reduction to mitigate 2024 oil and gas emissions by 75%.

Country spotlight

- **Norway banned non-emergency flaring in 1971 and imposed a tax on CH_4 flaring and venting in 2015,** providing policy models for other countries to adopt.
- **Implemented measures have driven methane emissions reductions** and realized the lowest intensity of any country worldwide.
- **If all countries globally followed Norway's example** and achieved the same methane emissions intensity in the O&G sector, 2024 emissions levels would fall by 90% to 8.1 Mt.

CH_4 reduction potential of proven oil and gas policies

(Mt, 2024)



[1] LDAR is leak detection and repair.
Sources: IEA, 2025, Global Methane Tracker 2025; Kearney Energy Transition Institute

5.4 Policy levers

Fossil fuel importers can drive methane cuts abroad by making low-methane supply chains a trade standard

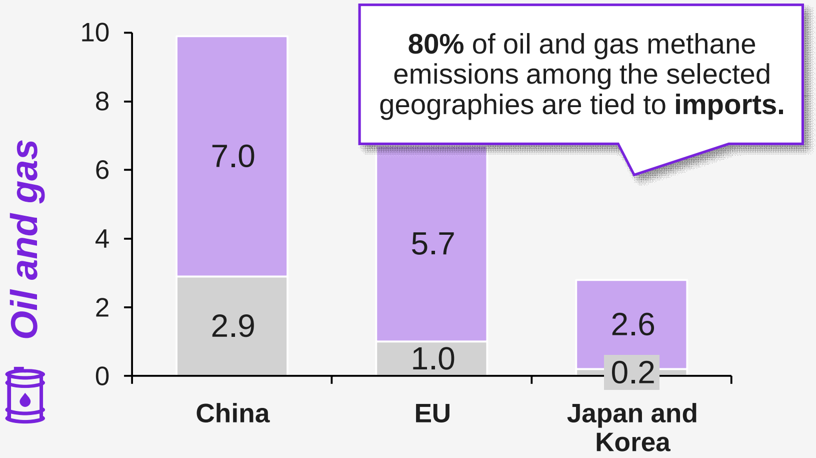
Major fossil fuel exporters such as China, Russia, India, and Iran account for **~30% of global methane emissions** but remain outside the Global Methane Pledge and lack CH_4-specific NDC targets.

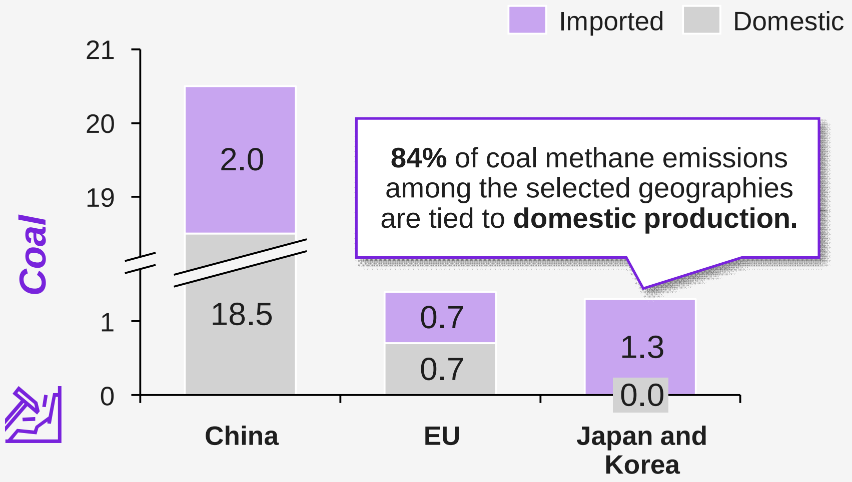
The $750 billion US-Europe LNG deal (2025–2028) highlights trade-offs: US LNG has 2–3% methane leakage compared to less than 1% for Norway or Qatar, conflicting with EU methane rules. Higher imports risk raising Europe's indirect emissions.

5.5 Methane import dynamics

CH_4 emissions due to fossil fuel consumption for selected countries and regions

(Mt, 2024)





Importing countries participating in the Global Methane Pledge (EU, Japan, Korea) have significant leverage to cut methane in oil and gas supply chains.

Methane from coal remains tied to domestic production, requiring stronger domestic regulation in major emitters (e.g., China).

Opportunities for importers of fossil fuels

Trade measures

- Set CH_4 intensity performance standards for imported products.
- E.g., EU Methane Regulation in force from 2030

Economic incentives

- Purchase CH_4 otherwise vented or flared and create preferential marketplaces.
- Price premiums for lower CH_4 emission fossil fuels

Technical and institutional support

- Drive implementation of CH_4 policy, regulation, and technologies in exporting countries.
- E.g., JOGMEC signed agreements with Malaysian and Indonesian national oil companies to advance collaboration on CH_4 emissions measurement and reduction.[1]

[1] JOGMEC is Japan Organization for Metals and Energy Security.

Sources: GMP, 2025, Pledges; JOGMEC, 2023, Indonesia's PERTAMINA and Japan's JOGMEC Joint Effort on Methane Emission Measurement and Quantification to Accelerate the Energy Transition; IEA,2025, Global Methane Tracker; PETRONAS, 2023, Integrated Report; UNFCC NDC reports; U.S. Department of Energy, 2023, Greenhouse Gas Supply Chain Emissions Measurement, Monitoring, Reporting, Verification Framework; Kearney Energy Transition Institute

Regulation creates enforceable methane business cases; compliance costs are often lower than penalties or lost licenses

Regulations-driven abatement measures can increase business resilience and flip risks to rewards.

[1] Canada's carbon penalty is calculated based on market price of compliance units (currently ~C$30/t$CO_2$e) and capped at fixed excess-emissions charge of C$95/t$CO_2$e under federal OBPS.
Sources: Belfer Center for Science and International Affairs, 2025, Methane Abatement Costs in the Oil and Gas Industry: Survey and Synthesis; Desktop research; Kearney Energy Transition Institute

5.6 Regulation shapes business opportunities

Enforceable methane abatement

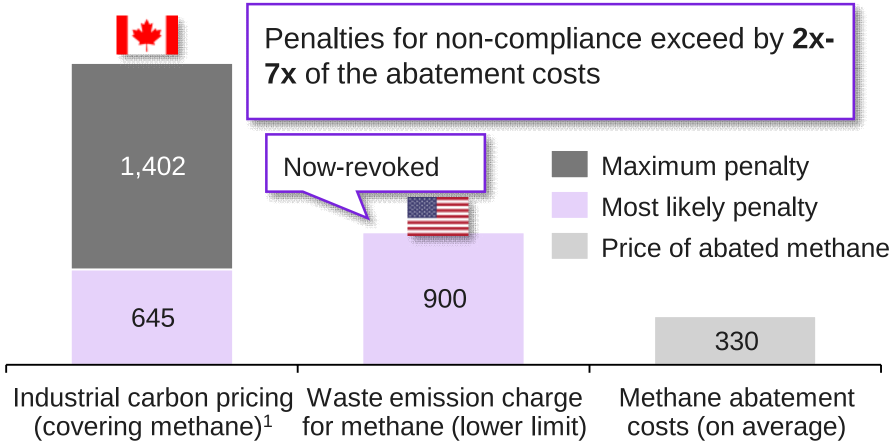
Regulators are deploying fines; bans; mandatory monitoring, verification, and reporting (MRV); and targeted incentives to curb methane emissions.

Lack of compliance can create material operational risk beyond financial fines.

- **Market access:** Future market access for gas may depend on compliance with emerging methane import standards, including MRV systems and performance thresholds.
- **Contractual impacts:** Buyers add methane-related KPIs, step-downs, and termination clauses. Failing KPIs can lead to forfeit of premiums or volumes.

Penalties under an 80% methane reduction assumption in the oil and gas sector

($USD/t\ CH_4$)



Recovered gas/credits generation revenue streams can further improve economics for abatement measures.

Severity of regulation policies on selected sectors

Sectors	Severity of regulatory penalties
	
	
	
	

- **Fossil fuels:** Dedicated and specific methane rules with higher fines (such as turnover-linked penalties in EU), revocation of permits/licenses, market access risk due to import restrictions
- **Waste:** Strict mandates on capture/flare, permits tied to destruction efficiency
- **Agriculture and biomass burning:** Few binding rules which are not strictly enforced, MRV difficult for distributed, small farms/assets

High Low

6. Business models of methane abatement

Introduction and summary

Methane mitigation technologies offer some of the most **cost-effective and high-impact opportunities** for climate action.

Unlocking this potential requires not only technology deployment but the scaling of **viable business models.**

Capturing methane as a revenue-generating resource, generating carbon credits, and monetizing monitoring and data shift methane from liability to value creation.

Massive abatement, minimal cost	Cost-effective methane mitigation technologies exist today and offer outsized climate returns per dollar invested.
Turning emissions into value	Where infrastructure and market access exist, capturing methane converts a climate liability into economic value, making methane abatement financially viable without requiring new capital burden on operators.
Carbon credits and premium markets	Carbon credits offer a revenue path for methane abatement but depend on robust monitoring and credibility.
Data-driven monetization	Monitoring-as-a-service and methane data platforms are creating new value chains by turning transparency into a market differentiator.

Source: Kearney Energy Transition Institute

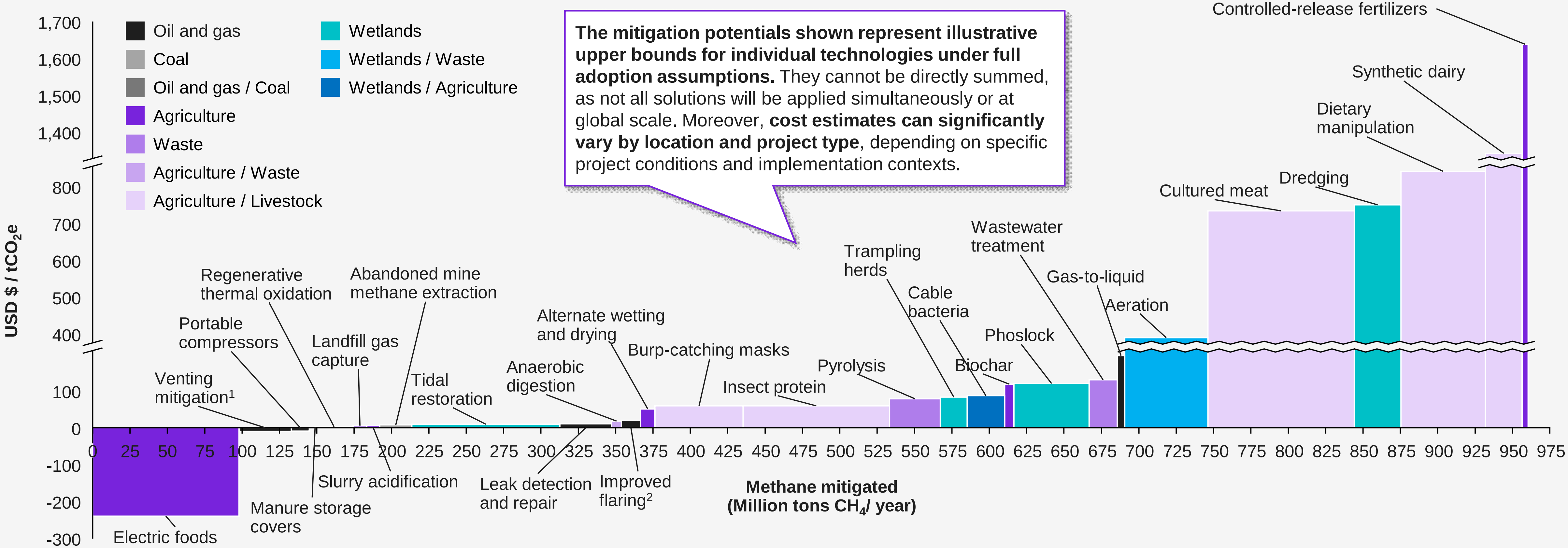
Methane abatement has one of the lowest marginal costs across greenhouse gases, with around half of methane emissions potentially abatable below USD 60/tCO_2e

6.1 Marginal abatement cost of methane mitigation

Example; non-exhaustive

Cost of selected methane mitigation technology solutions

(USD \$/tCO_2e, 2024)



[1] Under the venting mitigation category, the following technologies are included: vapor recovery units, gas capture and reinjection, and improved controls.; [2] Under the improved flaring category, the following technologies are included: flaring efficiency and flaring with heat recovery.

Sources: IEA, 2025, Global methane tracker; Mundra, I., et Lockley, A., 2024, Emergent methane mitigation and removal approaches: A review; Desktop research; Kearney Energy Transition Institute

Valuation of wasted methane

Opportunity overview

Methane emissions from flu gas (leaks, venting, waste, etc.) can be **captured, processed, and commercialized** in various forms (natural gas, LNG).

This is especially effective for **oil and gas sector,** where **40%** of methane emissions can be abated at negative cost.

Sector relevance

Fossil fuels | Waste | Agriculture | Biomass

PROs

- **Additional revenues** in the range of **\$120–\$200/t CH_4** at \$3–4/MMBtu
- **Market demand** for natural gas, utility purchase agreements, etc.
- **Premium pricing** for RNG and RSG (responsibly sourced gas)
- **Proximity to pipelines**, compression facilities, or LNG infrastructure

CONs

- **High upfront capex** (capture technology, pipeline, treatment, digesters, storage tanks, etc.) while **opex** needs are moderate
- Low collection efficiencies for some applications
- More suitable for **large-scale, centralized facilities (**economies of scale)

Example; non-exhaustive

- Low/no relevance
- Low-medium relevance
- Medium relevance
- Medium-high relevance
- High relevance

Project examples

Oil and gas

- **Southwestern Energy** sold certified low-methane natural gas to New Jersey Natural Gas. The gas deal was priced at a **premium to local Appalachian index prices.**

Waste

- **The Hamm Sanitary Landfill project** increased methane capture by **32%** and generated an estimated **\$3.8 million** in annual revenue from renewable natural gas sales.

Agriculture

- **Project 3229:** Dairy/pig farms installed biogas systems that capture methane from manure, converting it into renewable electricity for the national grid, as well as nutrient-rich fertilizer.

Sources: IEA, 2025, Global methane tracker; Biomass magazine, 2024, LoCI Controls increases methane capture at Landfill Group project by 32%; Kearney Energy Transition Institute

Monetizing carbon credits

Opportunity overview

Methane abatement projects can generate **carbon offsets, credits, or certificates**, enabling direct revenue generation and attracting investments.

Reductions are quantified and verified by third-party parties according to industry standards and sold on **carbon markets or through offtake agreements.**

PROs

- Methane capture credits range in price from **\$5-\$20/t CO_2e** but newer vintage projects with higher standards, additional environmental and social co-benefits can fetch higher prices
- **Strong demand** from corporates and governments to meet net-zero targets and ESG mandate
- **Access** to green finance

CONs

- **Lack of harmonization** in MRV standards[1]
- Complex, rigorous **verification requirements** for high-quality credits
- Volatility and credibility issues in **voluntary carbon markets**

Sector relevance

Fossil fuels	Waste	Agriculture	Biomass
High relevance	Low-medium relevance	Medium relevance	Medium relevance

Example; non-exhaustive

- Low/no relevance
- Low-medium relevance
- Medium relevance
- Medium-high relevance
- High relevance

Project examples

Coal

- **Coal mine methane (CMM) capture** projects are a major source of carbon offset globally. As of June 2020, CMM projects under California's compliance offset program have issued credits for **7.24 million metric tons** of CO_2e reductions.

Waste

- Early methane capture enhancement **at Loess Hills Regional Sanitary Landfill** in Iowa (US) captured approximately 229,000 metric tons CO_2-e of methane between 2021 and 2023, generating **228572 offset credits.**

Agriculture

- **Ar-Joy Farm** in Cochranville (US) utilizes methane digester on a dairy farm, turning waste into electricity. Digester provides more than **2,100 metric tons CO_2-e credits and renewable energy credits** annually to sell.

[1] MRV is measurement, reporting, verification.
Sources: Carbon.Credit, 2024, How Are Different Carbon Credits Valued?; Berkeley Carbon Trading Project accessed September 2025; Kearney Energy Transition Institute

Monitoring-as-a-service

Opportunity overview

Third-party providers deploy methane detection sensors and deliver leak detection data, emissions reports, and alerts **as a service rather than selling equipment.**

Enables companies to **demonstrate compliance**, secure investor confidence, and **differentiate** with credible low-methane credentials.

Sector relevance

Fossil fuels | Waste | Agriculture | Biomass

PROs

- **Flexible** subscription model (for continuous monitoring) or service contracts (for periodic surveys) **reducing cost pressure on clients**
- **Aids i**n meeting stricter MRV requirements and ESG mandates[1]
- Cost of monitoring is often **lower** than the value of gas lost
- **Credible** transparency

CONs

- **Inconsistent** regulatory mandates
- **Cost disadvantage and insufficient scale** for smaller operators
- **Lack of harmonization** in verification standards
- **Low interoperability** of monitoring data

Example; non-exhaustive

- Low/no relevance
- Low-medium relevance
- Medium relevance
- Medium-high relevance
- High relevance

Project examples

GHGSat

- **Operates a private satellite constellation** to spot methane leaks globally.
- Offers clients periodic site emissions reports or live monitoring solutions.

Kairos Aerospace

- **Uses sensor-equipped aircraft** to survey oil and gas fields for leaks.
- Provides leak detection campaigns on a contract basis, charging per site or region surveyed.

Project Canary

- **Deploys continuous methane monitors on well pads (and facilities)** and provides a real-time analytics dashboard.
- Offers a subscription for 24/7 on-site monitoring.

[1] MRV is measurement, reporting, verification.
Sources: SLB, 2023, Continuous methane monitoring: The fastest tech rollout in energy?; Project Canary, 2023, The Financial Benefits of Continuous Methane Monitoring for Small and Medium-Sized Oil & Gas Operators; Cenci, S., et Biffis, E., 2025, Lack of harmonisation of greenhouse gases reporting standards and the methane emissions gap; Desktop research; Kearney Energy Transition Institute

Data-as-a-service

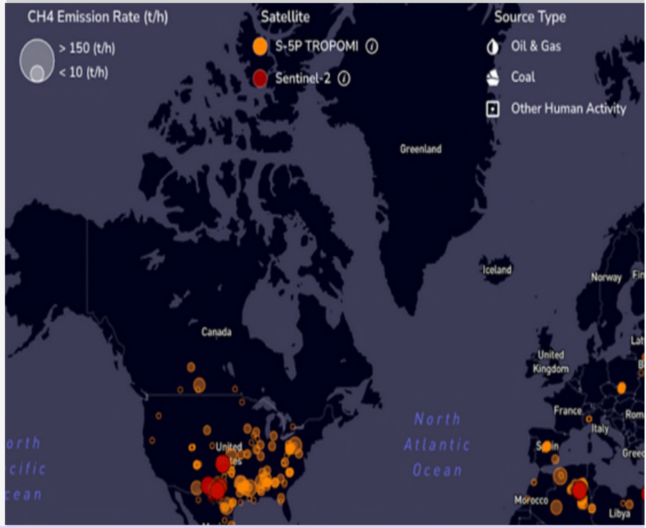
Opportunity overview

Companies **aggregate methane emissions data**, often from multiple monitoring platforms, operators, and regions, into digital platforms or datasets.

Raw satellite, sensor, and field data is transformed into **actionable intelligence**, and monetized as subscriptions, APIs, and benchmarking tools.

Sector relevance

Fossil fuels | Waste | Agriculture | Biomass



PROs

- **Aids regulators, investors, and operators** to track compliance, manage climate risks, and monetize low-emissions performance
- **Unlocks** gaps and **enables** benchmarking and risk management across assets and regions

CONs

- **Inconsistent** data quality leading to low trust
- Corporate secrecy
- **High** market competition and free alternatives
- **Lack** of data interoperability

Example; non-exhaustive

- Low/no relevance
- Low-medium relevance
- Medium relevance
- Medium-high relevance
- High relevance

Project examples

Kayrros

- Kayrros sells access to dashboards and APIs, **based on satellite monitoring**, showing emissions by region/operator.
- Used by regulators like IMEO and the US government for methane oversight.

Bluefield Technologies

- **Processes satellite sensor data** to quantify methane leaks worldwide.
- Revenue comes from providing detailed emissions datasets to oil and gas companies and even government programs.

Geofinancial Analytics

- **Provides weekly satellite scans** of oil and gas facilities on a subscription basis.
- Clients subscribe at a low monthly fee per site for continuous monitoring data.

Sources: SLB, 2025, How the EPA's methane rules are pushing for transparency and accountability in 2025 and beyond; BNP Paribas, 2024, Kayrros and BNP Paribas join hands to accelerate methane abatement; Desktop research; Kearney Energy Transition Institute

Acronyms, bibliography, and photo credits

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Acronyms (1/2)

BOE	Barrel of oil equivalent
Capex	Capital expenditure
CH_4	Methane
Cl	Chlorine
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Conference of parties
COP	California's compliance offset program
ERF	Effective radiative forcing
GHG	Greenhouse gases
GMP	Global Methane Pledge
Gt	Gigatonnes
GWP	Global warming potential
IEA	International Energy Agency
IMEO	International Methane Emissions Observatory
IOGP	International Association of Oil & Gas Producers
JOGMEC	Japan Organization for Metals and Energy Security
Kg	Kilograms
Kg/h	Kilograms per hour
Km	Kilometers
LDAR	Leak detection and repair
LNG	Liquefied natural gas
MARS	Methane Alert and Response System
MMBtu	Metric Million British Thermal Unit
MMRV	Measurement, monitoring, reporting, and verification
MRV	Measurement, reporting, verification
Mt	Megatonnes
N_2O	Nitrous oxide
NDCs	Nationally Determined Contributions
NF_3	Nitrogen trifluoride
NO_x	Nitrogen oxide
O_2	Oxygen
OGMP 2.0	Oil & Gas Methane Partnership 2.0
OH	Hydroxyl
Opex	Operational expenditure
ppb	Parts per billion
ppm	Parts per million
RSG	Responsibly sourced gas
SF_6	Sulphur hexafluoride
tCO_2e	Tonnes of CO_2 equivalent
TRL	Technology readiness level

7.1 Acronyms

Acronyms (2/2)

UNEP	UN Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollars
VAM	Ventilation air methane
VOC	Volatile organic compounds

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Slide 79	Methane emissions from termites	Link
Slide 84	Detection and measurement of methane emissions	Link

Appendix

Supporting content for 1. Impact of methane

Two methodologies can be used to assess methane emissions: top-down and bottom-up

Return to main-deck slide

Return to the slide of the main deck by pressing Ctrl and clicking on the box above.

Supporting content for 1. Impact of methane

Comparison of top-down and bottom-up methodologies for methane measurement

	Top-down approach	Bottom-up approach
Target	– Aggregate emissions across large geographies	– Emissions from individual pieces of equipment, operations, or facilities
Method	– Atmospheric or high-elevation air-quality measurements by aircraft, satellites, or tower networks	– Direct onsite measures at the emission point or downwind in the case of facilities
Challenge	– Attribute methane emissions to specific contributors	– Aggregate and extrapolate measurements to build representative samples

In both approaches, obtaining sufficient good-quality data is costly. There is a consensus better data and measurement are required. Both approaches are necessary and complementary. They need to be completed by reconciliation efforts to improve methane emissions estimates.

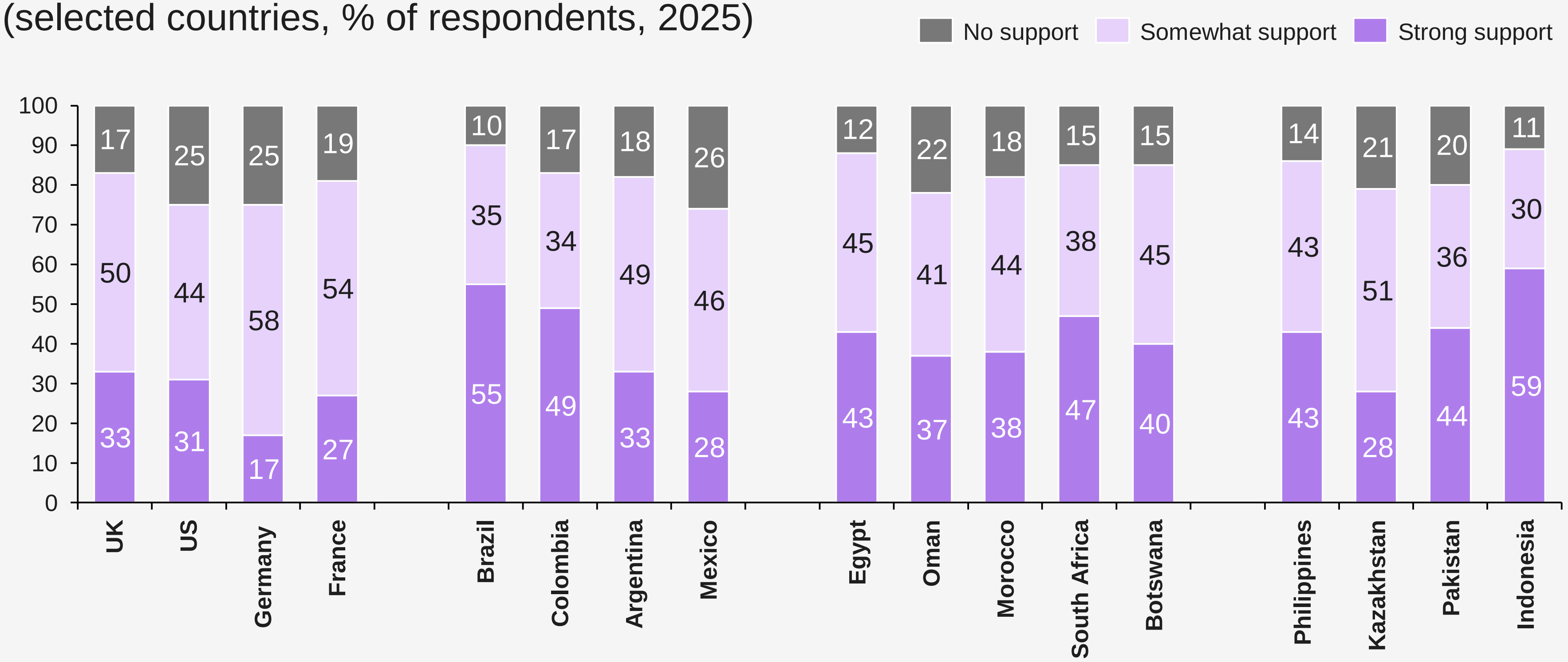
– In the top-down approach, methane emissions estimates are based on measurements of air samples that may coincide with specific/unusual venting events. In addition, separating emissions from natural (e.g., geological sources) and legacy emissions sources (e.g., abandoned wells) from current natural gas operations is highly challenging.

– For the bottom-up approach, it is difficult to include all sources. Random re-sampling methods and simulations can help fill the data gaps. In addition, estimates suffer from considerable variations in operational practices between different natural gas plays and results are highly sensitive to extreme values.

Sources: Brandt et al. (2014), “Methane Leaks from North American Natural Gas Systems“; Allen (2014), “Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements”; Kearney Energy Transition Institute

High overall support for reducing methane emissions is exhibited across regions

Support for action to minimize methane emissions
(selected countries, % of respondents, 2025)



Key insights

– **Nearly 3 in 4 (74%) respondents** in all countries surveyed support actions taken to minimize methane emissions.

– Total support is high overall but majority (50% and more) backing strong support is reported **only in Indonesia and Brazil.**

– **Mexico** registered the highest opposition to the support measures followed by **the US and Germany.**

Source: Burson, 2025, Global Methane Poll Wave 2: Total Study Results Overview; Kearney Energy Transition Institute

Supporting content for 1. Impact of methane

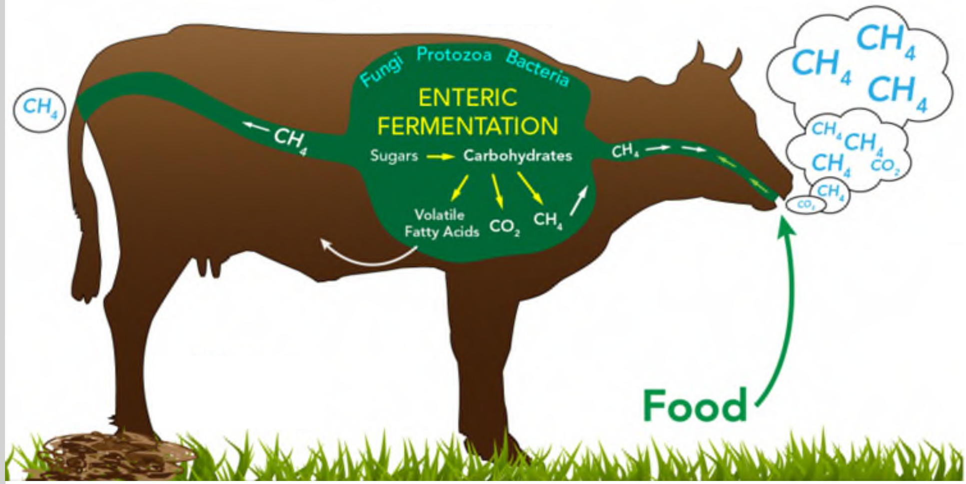
Supporting content for 2. Origin of methane

Due to the large population, cattle are the main source of emissions associated with enteric fermentation

Methane emissions from enteric fermentation

- Enteric fermentation is a natural part of the **digestive process** in ruminant livestock.
  - Fungi, protozoa, and bacteria break down carbohydrates and **CH_4 is produced as a by-product.**
    - CH_4 production (methanogenesis) is a mechanism in ruminants to **dispose of H_2,** which may inhibit carbohydrate fermentation and fiber degradation.
  - CO_2 is produced as well, but its emission is **assumed to be zero in inventories** since it re-enters in the carbon cycle of regrowing vegetation.
- Gaseous waste products (CH_4 and CO_2) are mainly **removed by eructation.**

Methane from methanogenesis



Methanogenesis: $CO_2 + 4H_2 \xrightarrow{\text{Archaea methanogens}} CH_4 + 2H_2O$

Main drivers of CH_4 emission are feed quality and quantity, animal age and size, and ambient temperature.

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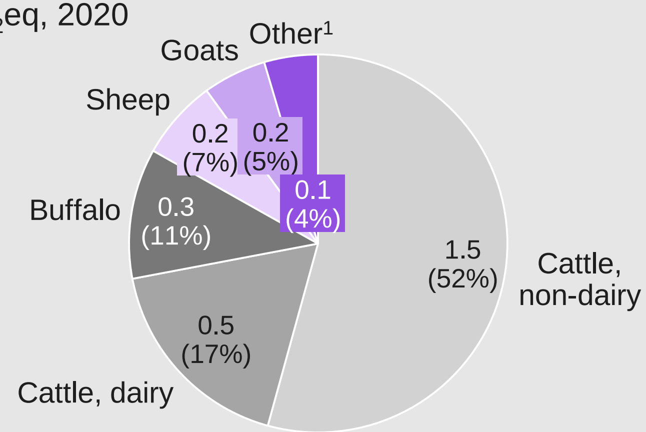
Supporting content for
2. Origin of methane

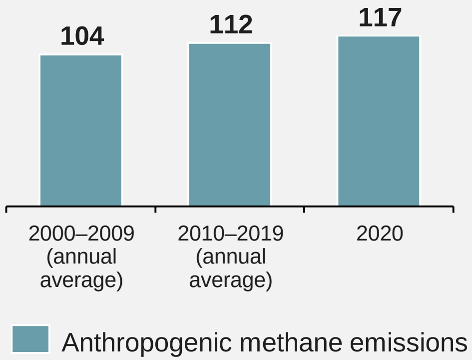
Global GHG emissions per key livestock type

$GtCO_2eq$, 2020



Growth trend and key emitting regions

Mt CH_4, % of global CH_4 emissions from enteric farming and manure management



South Asia (18%)

Africa (15%)

Brazil (11%)

[1] Other: camels, horses, swine, asses, llamas, mules, and hinnies
Sources: FAO; IPCC; Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

In rice cultivation, methane emissions are produced from anaerobic decomposition of organic matter in flooded paddy fields

Rice cultivation is the second biggest source of methane in agriculture GHG emissions.

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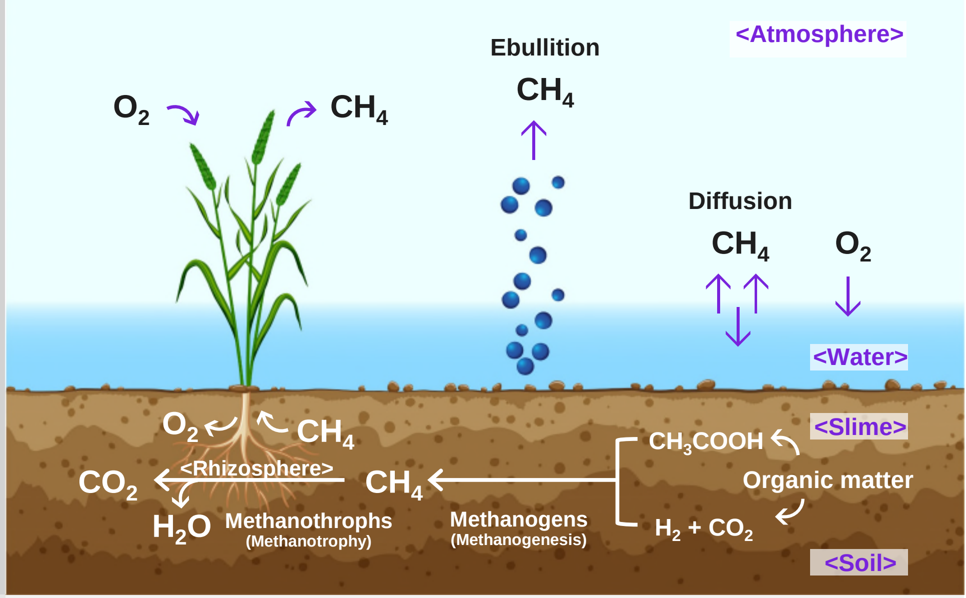
Supporting content for
2. Origin of methane

Methane emissions from rice cultivation

- **Methane emissions (CH_4) come from organic matter decomposition** (mainly rice straw residue) under anaerobic conditions in flooded paddy rice.
- Methane is emitted through three main processes:
  - Diffusion across the water interface
  - Ebullition
  - Emissions through rice stems and leaves serving as conduits for methane contained in the ground

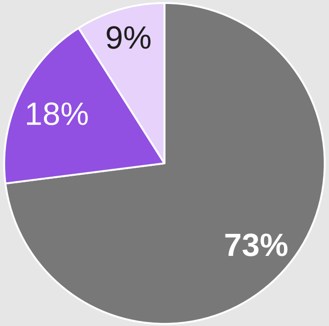
Methane from rice aerenchyma



Main emissions drivers

Emissions are mostly dependent on agricultural practices but also on water management practices, rice variety, harvest number and duration, or soil quality, type, and temperature.

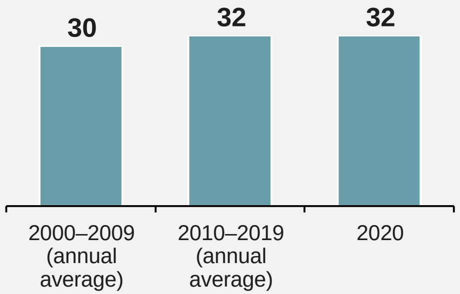
Typical GHG emissions from rice cultivation[1]



- Flooded rice
- Fertilizer use
- Other (residue burning, energy use, other)

Growth trend and key emitting regions

Mt CH_4, % of global CH_4 emissions from rice



Anthropogenic methane emissions

Southeast Asia (29%)

China (28%)

South Asia (25%)

[1] Rice GHG emissions other than methane may be covered in inventories under other categories such as synthetic fertilizers, crop residues (burning and left on fields), in farm energy.
Sources: Hyo Suk et al., Research Revie of Methane Emissions from Korean Rice Paddies, 2022; Rahman M., Yamamoto A., Methane Cycling in Paddy Field: A Global Warming Issue, 2020; FAO, Rice Landscapes and Climate Change, 2018; Carlson et al., Greenhouse gas emissions intensity of global croplands, 2016; World Bank, Greening the rice we eat, 2022; Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Upstream oil and gas operations account for the majority of methane emissions

Most of the methane from oil and gas infrastructure is either vented (67%) or escapes (19%) to the atmosphere, while the remaining is flared (14%).

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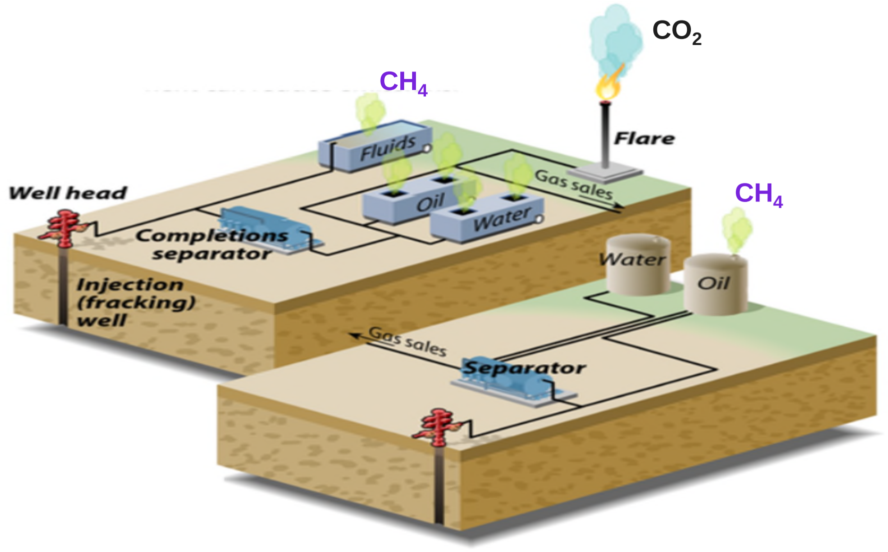
Supporting content for
2. Origin of methane

Methane emissions from oil and gas

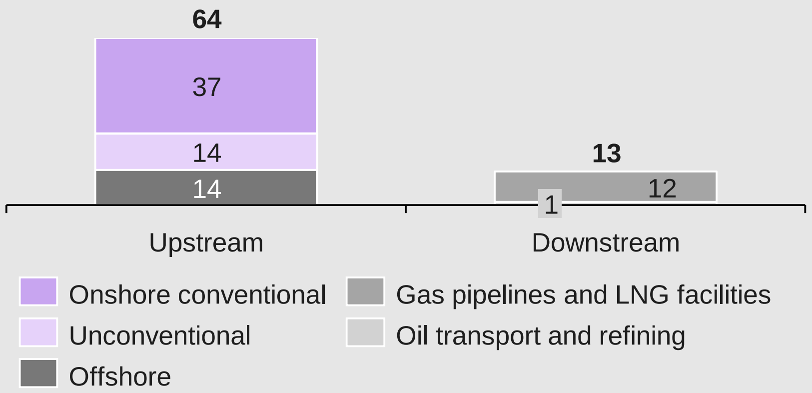
- CH_4 emissions in the oil and gas sector occur through several mechanisms during the extraction, processing, transportation, and storage stages.
  - Venting, i.e., intentional release during maintenance, pressure control, or equipment blowdowns
  - Flaring (incomplete combustion) to CO_2
  - Fugitive emissions, i.e., unintentional leaks from equipment due to aging infrastructure, poor maintenance, or faulty seal
  - During the operation of pneumatic devices powered by pressurized natural gas
  - Release during the completion of new wells or maintenance of existing ones
- Old wells that are improperly sealed can leak methane for decades.

Methane flaring from oil and gas



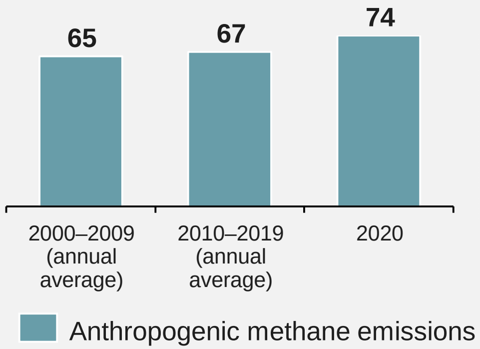
Emissions per asset type

2024, Mt CH_4



Growth trend and key emitting regions[1]

Mt CH_4, % of global CH_4 emissions from oil and gas



Middle East (24%)

Russia (18%)

Africa (16%)

[1] 8 Mt CH_4 should be added on top of this estimate to acknowledge the ultra-emitters contribution.
Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; IEA, 2025, Global Methane Tracker; Kearney Energy Transition Institute

Steam coal (used for power generation) mining accounts for most of the emissions followed by coking coal (used for industry use)

Depth of the coal seam, coal type and rank, geological structure, and mining method are the key factors influencing methane emissions from coal mines.

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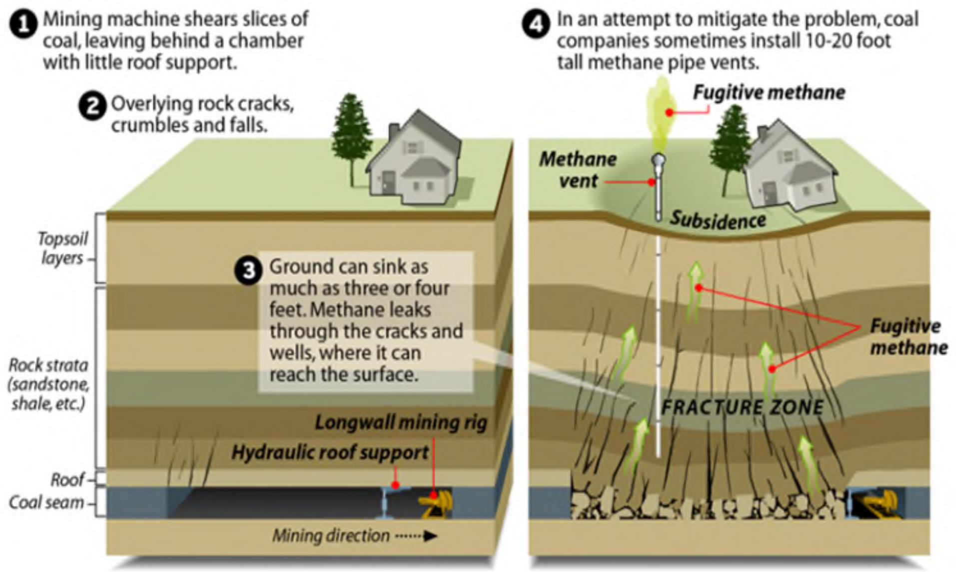
Supporting content for 2. Origin of methane

Methane emissions from coal mining

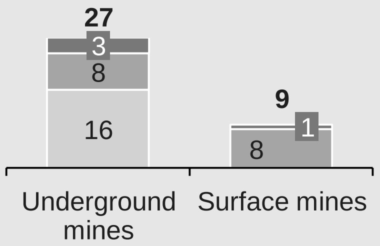
- CH_4 is formed during the coalification process and is stored in coal seams in two main forms: **adsorbed methane** (bound to the surface of coal particles) and **free methane** (trapped in pores/fractures/cavities).
- Methane release mechanisms:
  - Desorption, i.e., when coal is mined, the pressure drops, causing methane to desorb from the coal surface.
  - Fracturing and permeability induced migration toward mine openings
  - Ventilation systems
  - Degasification systems
- Even after closure, abandoned mines can emit methane. However, properly flooded mines generally emit negligible amounts of methane.

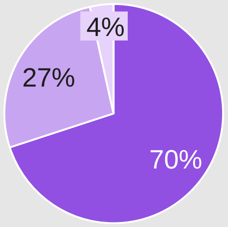
Fugitive methane from coal mines



Emissions per type of mine and end use

2024, Mt CH_4, % of total

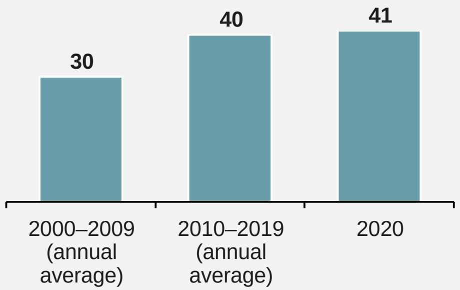




- Other
- Drainage systems, outcrops and workings
- Ventilation systems
- Steam coal
- Coking coal
- Other coal uses

Growth trend and key emitting regions

Mt CH_4, % of global CH_4 emissions from coal mining



Anthropogenic methane emissions

China (54%)

Southeast Asia (10%)

Russia (7%)

Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; IEA, 2025, Global Methane Tracker; Kearney Energy Transition Institute

Methane is emitted by both road and non-road transport modes but is generally minor compared to CO_2

Current active LNG-fueled vessels now account for more than 2% of the global shipping fleet (2024 end).

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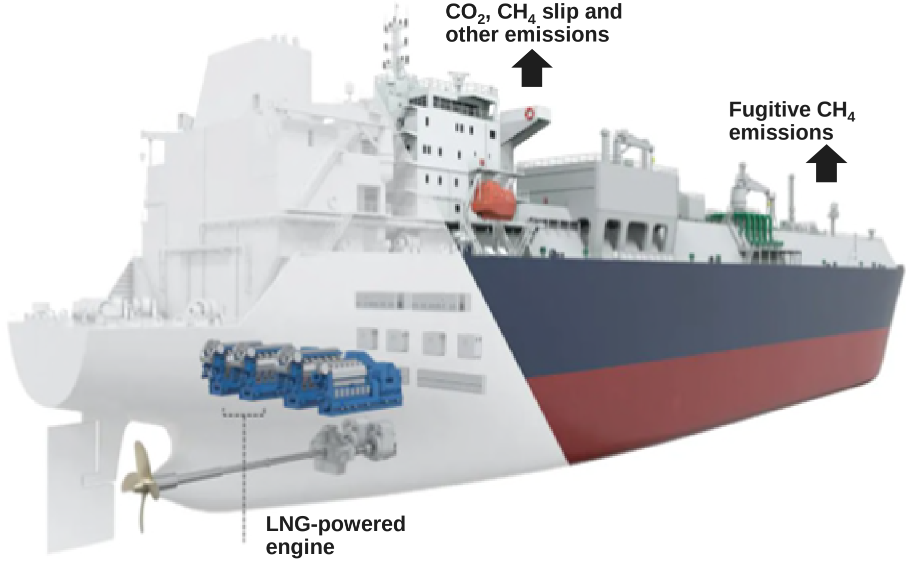
Supporting content for 2. Origin of methane

Methane emissions from industry and transport

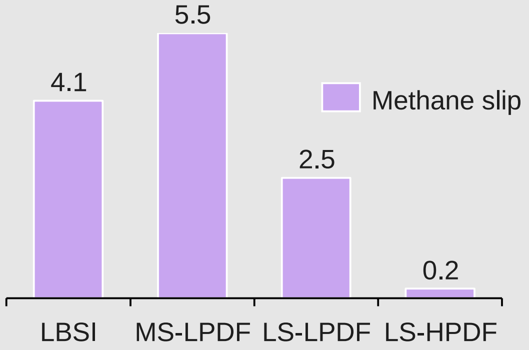
- Emissions in this category include small industrial contributions such as the production of chemicals and metals, and transport (road and non-road).
- Methane emissions in transport arise from both **fuel combustion and fugitive leaks** during fuel handling, storage, and transfer.
  - **Methane slip:** unburned methane escapes through the exhaust due to incomplete combustion in the engine.
  - **CNG/LNG powered transport modes** are the primary contributors due to higher methane slip rates (vs. gasoline/diesel powered modes).
- Recent research indicates that **ship movement in shallow, organic-rich waters** can trigger methane release from sediments.

Methane emissions from marine LNG engines



Marine LNG engine type and methane slip

gCH_4/kWh

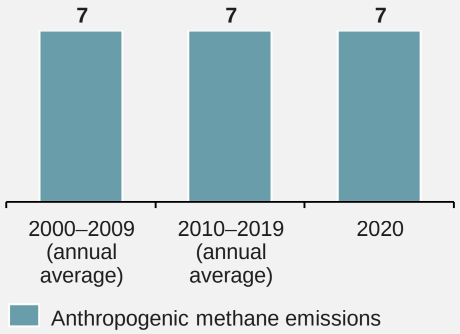


Methane slip can account for up to **24%** of GHG emissions from an LNG-fueled vessel.

It is influenced by **engine type, age, and after-treatment systems.**

Growth trend and key emitting regions

Mt CH_4, % of global CH_4 emissions from industry and transport



Russia (17%)

Equatorial Africa (16%)

China (13%)

Sources: DNV, 2025, Methane slip measurements to reduce reported GHG emissions; Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Organic matter in the waste is converted to methane through anaerobic digestion

Methane emissions from waste and landfills

– Bacteria decompose landfill waste in four phases and composition of gases changes in each phase. The optimum pH for CH_4 emission is between 6.8 and 7.4.

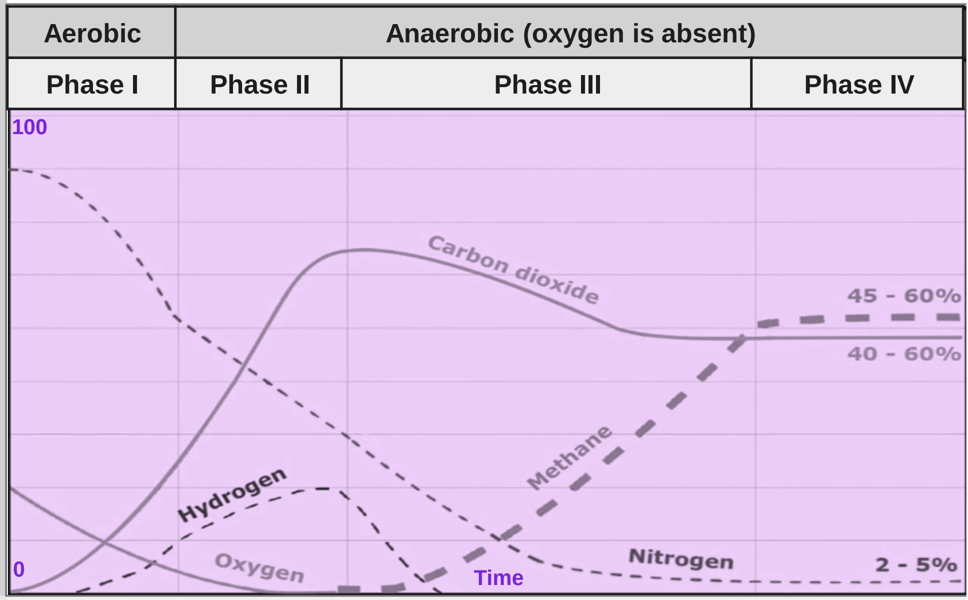
Hydrolysis (phase I)
Aerobic bacteria breaks down complex organic substrates.

Acidogenesis (phase II)
Compounds are converted to acids and alcohols raising the pH.

Acetogenesis (phase III)
Organic acids are consumed by bacteria to form acetate.

Methanogenesis (phase IV)
Methane composition and production rates stabilizes.

Methane from landfills



CH_4 production from waste depends on the pH, moisture, and temperature of the material.

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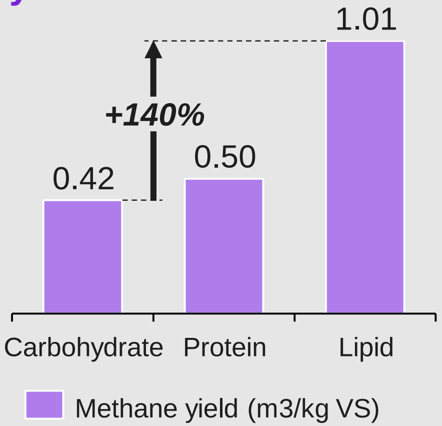
Supporting content for 2. Origin of methane

Theoretical methane yield

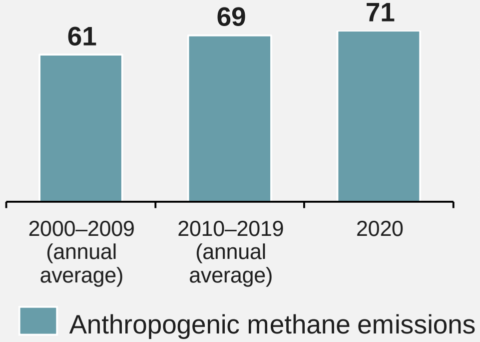
Substrates rich in lipids such as fats hold a greater potential for methane yield.

However, its degradation also releases long-chain fatty acids that could be toxic to the microbial community and causes a drop in pH.



Growth trend and key emitting regions

Mt CH_4, % of global CH_4 emissions from waste and landfills



China (16%)

South Asia (13%)

Europe (12%)

Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Burning biomass emits several types of GHG, including methane

Incomplete combustion of organic matter is the main reason for the large quantities of non-CO_2 GHG produced in fires.

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Supporting content for 2. Origin of methane

Methane emissions from burning biomass and biofuels combustion

- Combustion of organic matter releases CO_2, CH_4, and N_2O and affects both above-ground and below-ground carbon pools.
  - Incomplete combustion from biomass, due to the lack of oxygen, leads to non-CO_2 GHG gases production (direct and indirect emissions).

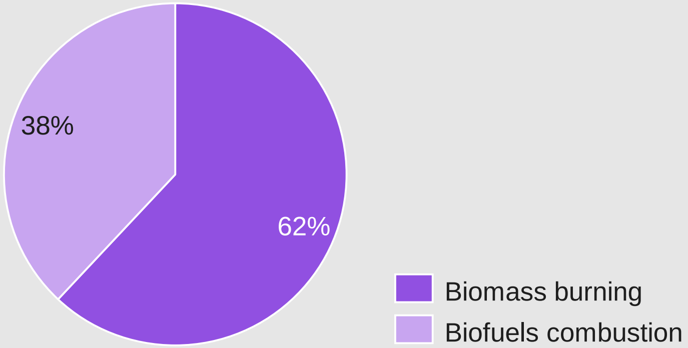
GHG inventories considerations

	Organic soils fires	Above-ground vegetation
Inventories estimation	Include both CO_2 and non-CO_2 gases (CH_4 and N_2O).	Include just non-CO_2 gases. CO_2 from forest fires are excluded since they are covered in the carbon stock changes calculations in forest sources (Forestland (L1) and Net forest conversion (L2)).

Biomass burning

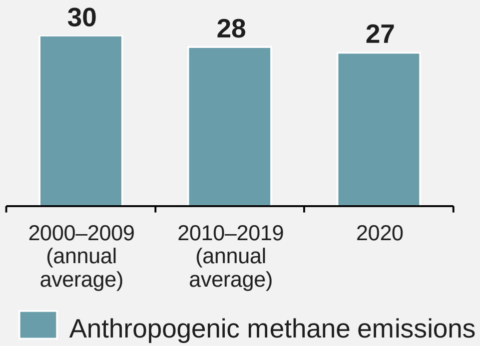
Split of methane emissions

2020, in %



Growth trend and key emitting regions

Mt CH_4, % of global CH_4 emissions from biomass burning and biofuels combustion



Equatorial Africa (18%)

South East Asia (16%)

Southern Africa (10%)

[1] Indirect emissions: formation of GHG from precursor gases such as NH_4+ and NO_3- from combustion gases deposition of biomass burning.
Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Wetlands are the largest source of natural methane emissions

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Greenhouse effect of the emitted CH_4 can be mitigated by the **removal of atmospheric CO_2 and storage into peat.** However, wetlands are fragile ecosystems, and anthropogenic or climate disturbance of soil or hydrology disturb their carbon sink effect.

Supporting content for 2. Origin of methane

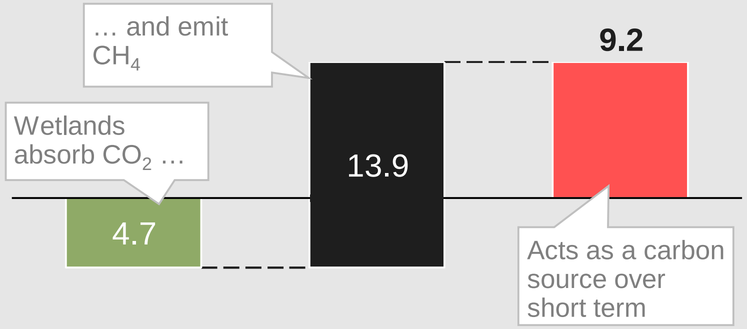
Methane emissions from wetlands

- Wetlands ecosystems include **marshes, swamps, and peatlands**
  - Wetlands cover **~5%** of the world's total land surface.
  - Forested wetlands are **~60%** of total global wetland areas.
- Wetlands produce methane through **underwater anaerobic decomposition of organic matter such as leaves and stems or soil organic matter.**
- Methane is released to the atmosphere through various pathways such as **diffusion**, **plant-mediated transport** (some wetlands plants have specialized tissues that allow to methane transport), and **bubbling** from soil.

Wetlands

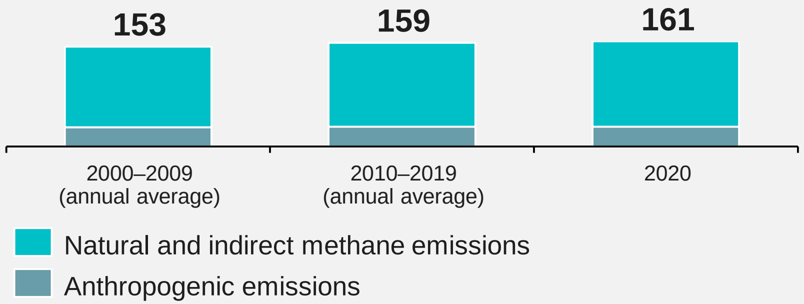
GHG balance on a 20-year time horizon

$GtCO_2eq$/year, global, 2020



Growth trend and distribution of emissions

Mt CH_4,% of global CH_4 emissions from wetlands



Anthropogenic flux (19%)

Natural flux (81%)

Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Inland freshwater methane emissions are a result of diverse processes involving both archaea and bacteria

A significant part (~50%) of CH_4 emissions from inland freshwater emissions are attributed to anthropogenic activities.

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Supporting content for 2. Origin of methane

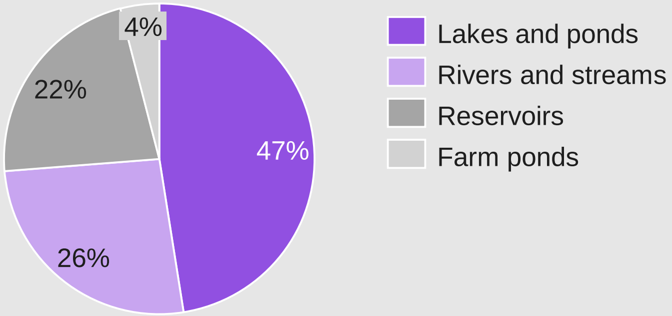
Methane emissions from freshwater sources

- This category includes CH_4 emissions from freshwater systems such as streams and rivers, lakes and ponds, and man-made reservoirs.
- CH_4 production in freshwater environments can be contributed to multiple mechanisms based on microbial processes:
  - **Acetoclastic** (splitting of acetate into CH_4 and CO_2) and **hydrogenotrophic** (reduction of CO_2 using H_2) methanogenesis which mainly occur in anaerobic (anoxic) sediments
  - Recent research shows that CH_4 can also be produced in oxic surface waters and columns through **demethylation of phosphonates** and **chlorophyll photometabolism**

Inland freshwater sources

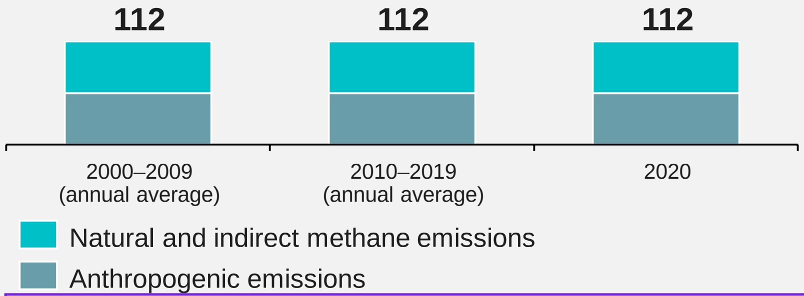
Share of emissions

% of global CH_4 emissions from freshwater sources, 2020



Growth trend and distribution of emissions

Mt CH_4,% of global CH_4 emissions from freshwater sources



Anthropogenic flux (50%)

Natural flux (50%)

Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Various other natural sources and mechanisms contribute to methane emissions

37.2% of methane fluxes due to termites were attributed to South America, followed by 31.5% to Africa and 18.1% to Asia.

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Supporting content for 2. Origin of methane

Methane emissions from other natural sources

– Significant amounts of CH_4, produced within the **Earth's crust**, naturally migrate to the atmosphere through tectonic faults and fractured rocks.

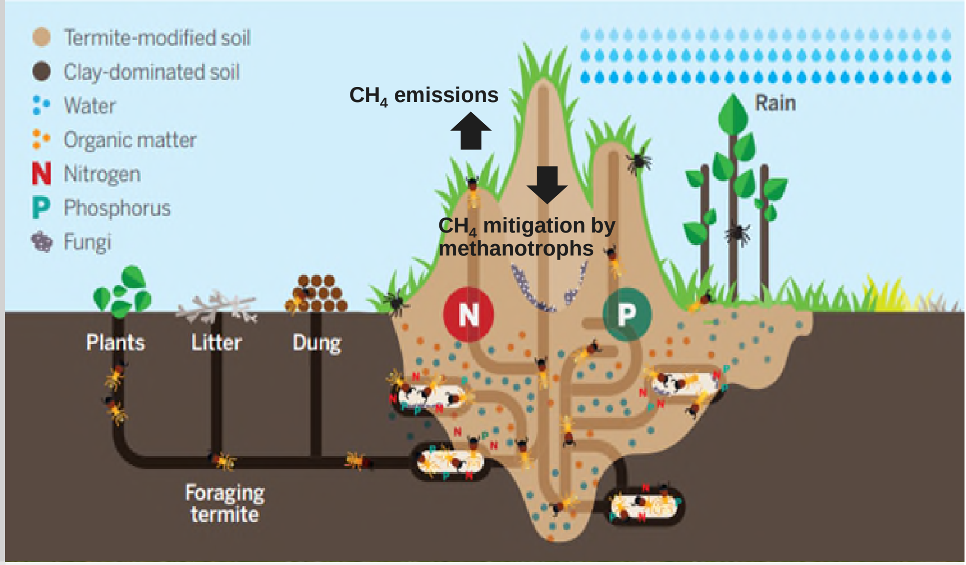
– Methanogenic microorganisms that live in the gut of **termites** break down the cellulose entering the body and release methane.

– **In-situ biogenic production** through various pathways in oxygenated sea-surface waters is a key coastal and ocean source of methane.

– **Wild ruminants** emit CH_4 through microbial fermentation that occurs in their rumen.

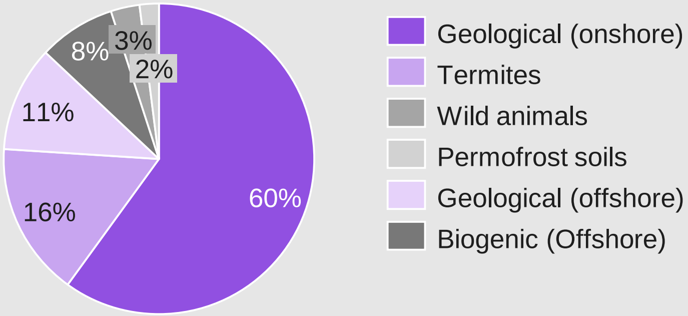
– The thawing **permafrost** can generate direct and indirect CH_4 emissions.

Methane emissions from termites



Key sources of emissions

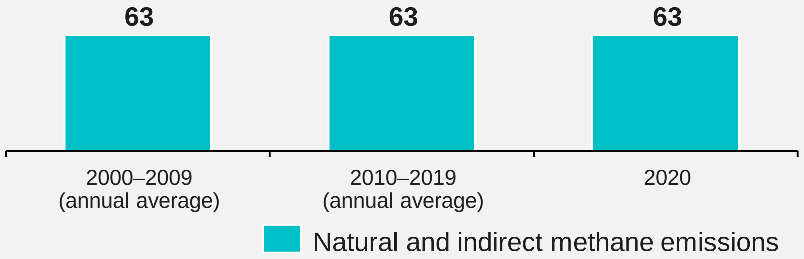
% of global CH_4 emissions from other natural sources, 2020



Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Growth trend and distribution of emissions

Mt CH_4,% of global CH_4 emissions from other natural sources



Land sources (81%)

Coastal and oceanic sources (19%)

Atmospheric chemical processes in the troposphere and stratosphere are the most effective methane sink

CH_4 is the most abundant reactive trace gas in the troposphere and its reactivity is important to both tropospheric and stratospheric chemistry.

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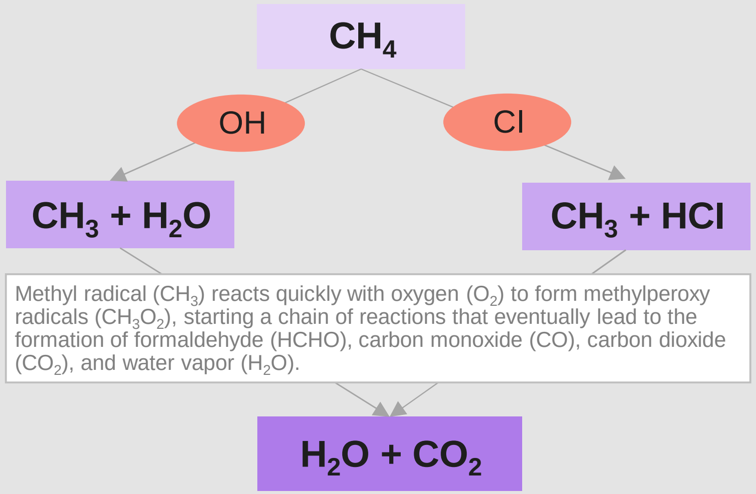
Supporting content for 2. Origin of methane

Atmospheric methane sink

- Emitted CH_4 reaches troposphere and stratosphere where it is broken down through natural processes:
  - **Tropospheric hydroxyl radicals (OH) reaction:** CH_4 reacts with OH forming H_2O and CO_2
  - **Tropospheric chlorine (Cl) reaction:** Cl radicals, mainly from sources such as sea salt emissions, react with CH_4. This effect is particularly notable in marine boundary layers.
  - **Stratospheric loss:** Chemical breakdown process driven by reactive radicals, particularly involving halogens and excited oxygen
- Tropospheric loss can be quantified with relatively good accuracy based on the mean global OH concentration whereas large uncertainties exist in the stratospheric chemical loss.

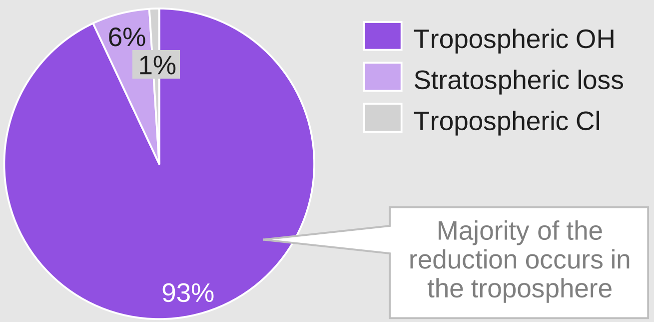
Tropospheric methane oxidation pathways

Indicative



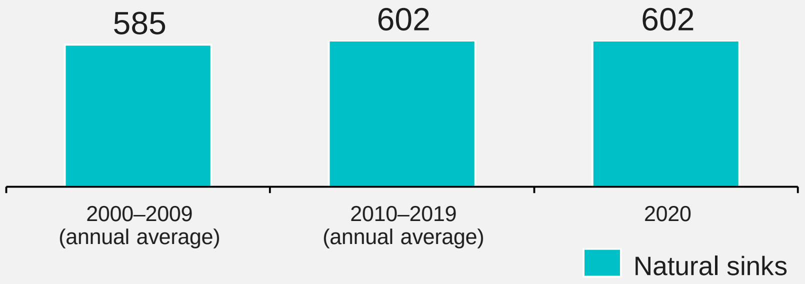
Distribution of atmospheric chemical loss

% of global CH_4 chemical loss, 2020



Growth trend and % of global sink capacity

Mt CH_4,% of global CH_4 sink capacity 2020



Atmospheric sink constitutes ~95% of the global methane sink capacity

Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Methanotrophs in soil oxidize methane through a series of enzymatic reactions

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Water content of the soil, soil temperature and the concentration of nutrients (especially nitrogen) are crucial factors in determining whether a particular soil will act as a methane sink or source.

Supporting content for 2. Origin of methane

Soil as a methane sink

- Unsaturated oxic soils are sinks of atmospheric CH_4 due to the presence of methanotrophic bacteria, which consume CH_4 as a source of energy.
- This process typically occurs in the oxygen-rich upper layers of soil. Two main types of methanotrophs exist:
  - **High capacity - low affinity methanotrophs** that thrive at high methane concentrations (e.g., waterlogged soils with high methane flux)
  - **Low capacity - high affinity methanotrophs** capable of consuming trace atmospheric methane (~1.8 ppm) in well-drained soils
- However, as the soil water content increases enough to inhibit the diffusion of oxygen, the soil becomes a methane source (for example, seasonal wetlands).

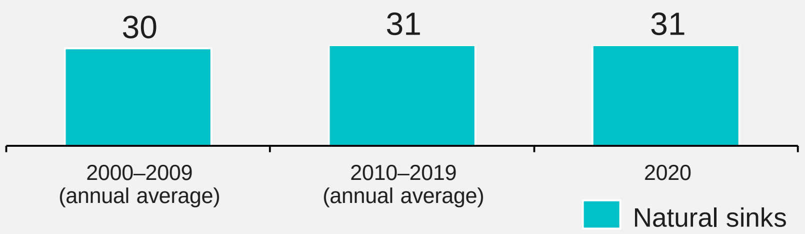
Forest soil traps methane

Effect of land use change

Land use change	Effect on methane oxidation	Mechanisms
Forest to pasture	↓	Shift to methanogens dominance, altered soil conditions
Natural grassland to agriculture	↓	Soil disturbance, changes in moisture and nutrients
Grassland to afforestation	↑	Improved soil and microbial conditions

Growth trend and % of global sink capacity

Mt CH_4,% of global CH_4 sink capacity 2020



Soil uptake constitutes ~5% of the global methane sink capacity

Sources: Saunois et al., 2025, The Global Methane Budget 2000-2020; Kearney Energy Transition Institute

Increased microbial emissions are the primary driver of recent increases in atmospheric methane

Models are sensitive to assumptions about sink processes and uncertainty, in time and space, in the isotopic signatures of different source categories.

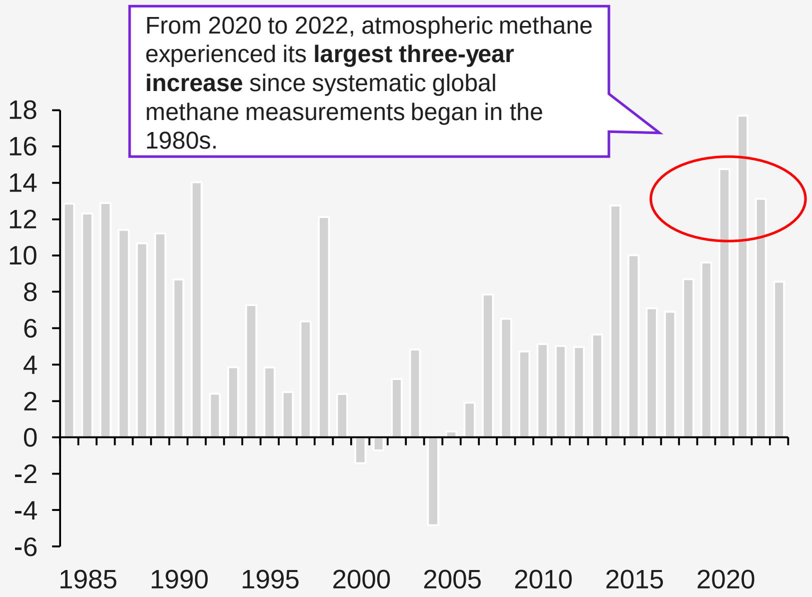
This can lead to wide variations in the results.

[1] ‰ corresponds to parts "per mil" (parts per thousand). Hence, 62‰ = 62 parts per thousand lighter in carbon-13 compared to the reference standard
Sources: NOAA, Global Monitoring Laboratory, Trends in Atmospheric Methane; Michel et al., 2024, Rapid shift in methane carbon isotopes suggests microbial emissions drove record high atmospheric methane growth in 2020–2022; Kearney Energy Transition Institute

Supporting content for 2. Origin of methane

Growth in atmospheric methane abundance

Annual increase in ppb, 1984–2023



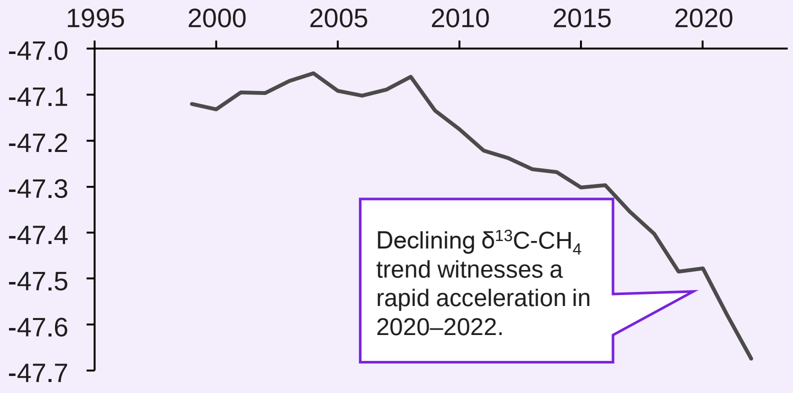
Estimating methane sources' fingerprints

- CH_4 is mostly carbon-12 (^{12}C), but a small fraction is the heavier isotope carbon-13 (^{13}C).
- Ratio of ^{13}C to ^{12}C is **$\delta^{13}C–CH_4$** which informs whether CH_4 is "heavier" (more ^{13}C) or "lighter" (more ^{12}C).
- **Microbial** CH_4 (from wetlands, agriculture, waste, etc.) is "very light" and has global mean of **–62‰ .**[1]
- **Fossil fuel** CH_4 (from oil and gas, coal, etc.) is moderately "light" with global mean of **–45‰.**
- **Pyrogenic** CH_4 (from burning biomass or biofuels) is relatively "heavier" with a global mean of **–24‰.**

By measuring $\delta^{13}C–CH_4$ in the atmosphere, it can be estimated which mix of sources is adding methane.

Globally averaged $\delta^{13}C$-CH_4

Annual mean values in ‰, 1999–2022



- **Lowest** global average $\delta^{13}C$-CH_4 value was observed 2022.
- The global $\delta^{13}C$-CH_4 growth rate from 2020–2022 was –0.09 ± 0.01‰ yr−1, **a much faster decrease** than –0.04 ± 0.02‰ yr−1 in 2014–2020 and –0.03 ± 0.02‰ yr−1 in 2008–2014.
- Based on observed $\delta^{13}C$-CH_4 decline, it can be concluded that **microbial emissions have dominated the increase in atmospheric CH_4 since ~2007.**

Observations and model simulations attribute increase in 2020–22 to emissions from **natural wetlands** in response to warmer temperatures and particularly wetter land conditions during the 2020–2022 La Niña. As the global climate transitioned to an El Niño phase, a slowdown was observed in 2023.

Supporting content for 3. Monitoring approaches and advancements

Sensor types, sensor placement, and calculation technique are the key factors influencing detection and measurement of emissions

Supporting content for
3. Monitoring approaches and advancements

1 Sensor types

The sensor type and design determines what can be measured and under which conditions:

- **In-situ:** some types of in-situ sensor-based solutions can only be used in a plume as gas molecules must be in contact with the sensor for chemical or physical interactions.
- **Remote sensing:** other sensor technologies are based on detection of an electromagnetic signal, typically infrared light from the sun or a dedicated laser; it can be ground based or spaceborne.

2 Sensor placement

The placement determines **where in or around the plume** measurements take place (which may vary over time and space) and how many data points are captured, in addition to capture of relevant meteorological data:

- The distance determines the **spatial and temporal resolution** of what the sensor is able to detect (e.g., a small leak from a pipeline close to the sensor).
- The situation is different for a **geostationary satellite** (more than 35,000 km away from the source) that takes images at high temporal resolution independent of its distance to a source but will only see a huge leak.

3 Calculation method

The calculation technique determines the **emission flow rate and the uncertainty** based on different types of models (atmospheric inversion models).

- However, the estimation methods can only give estimates, and multiple factors can contribute to uncertainty.
- Uncertainties in the calculations can arise from multiple factors, including sensor precision, the quantity and spatial extent of measurement data, simulation of atmospheric transport, and a priori information and other settings of atmospheric inversion models.

Please refer to Kearney Energy Transition Institute's **Carbon Emissions Assessment FactBook** for more details

Sources:; Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Kearney Energy Transition Institute

Underreporting of leaks is common during gas production, leading to much lower reported emissions

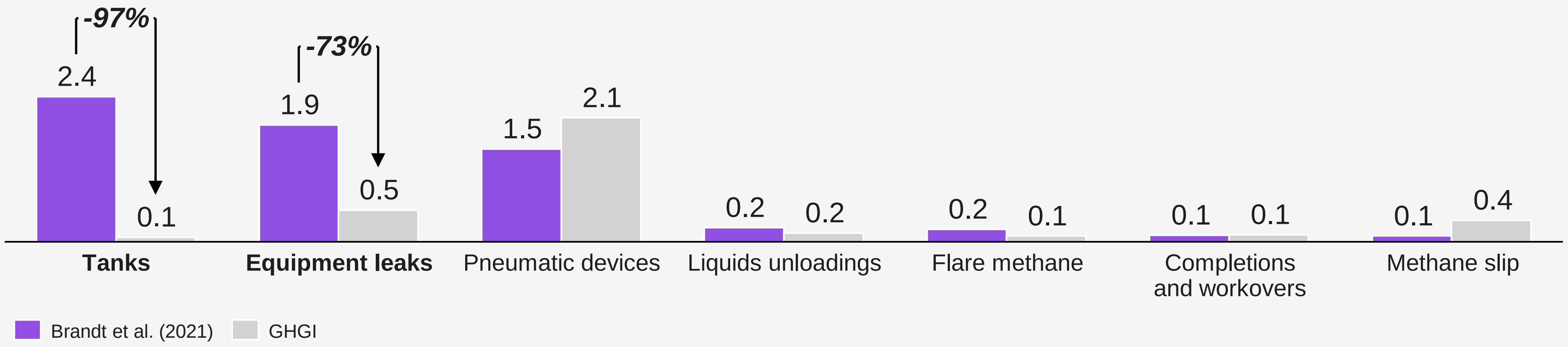
A recent study identified the two main sources of underestimation of methane leaks by US GHGI.

Another recent study presented a method for improving GHGI by applying a resampling statistical analysis within a component-level bottom-up approach. Their total estimate is ~1.8 times that of the GHGI. Super-emitters are better assessed.

Supporting content for 3. Monitoring approaches and advancements

Source-specific emissions comparison between the recent study and the US GHGI

$TgCH_4$.yr-1, 2015



Differences in emissions from storage tanks are decomposed into two factors.

High-emissions events are frequently observed at storage tanks, and the frequency of unintentional emissions events is much higher than the rate suggested by the EPA (2%).

Emissions from tanks = **unintentional** + intentional

unintentional = Emissions per event × frequency of events per tank

Emissions per event: 1 order of magnitude higher than GHGI

Frequency of events per tank: 1 order of magnitude higher than GHGI

GHGI underestimates unintentional equipment-level emissions from tanks by two orders of magnitude.[1]

Differences in equipment leaks are decomposed into three factors.

GHGI underlying equipment measurements lack accuracy, regarding the fraction of leaking equipment, their emissions per unit time, and the equipment count per site.

Equipment leakages = fraction of leaking eq. × eq. count × emission factors[2]

- fraction of leaking eq.: ×1 to ×0.06 compared to GHGI
- eq. count: ×0.05 to ×20 compared to GHGI
- emission factors: ×5 to ×46 compared to GHGI

At the equipment level, equipment leaks are underestimated by a factor of five to seven.[1]

[1] Equipment-level emissions are then multiplied by activity factors and extrapolated to the national level, which explains that the differences on the graph above are not equal to those described here; [2] The term "emission factor" refers to the emissions per component or equipment per unit of time.

Sources: J.S. Rutherford, E.D. Sherwin, A.P. Ravikumar, G.A. Heath, J. Englander, D. Cooley, D. Lyon, M. Omara, Q. Langfitt, A.R. Brandt, "Closing the methane gap in US oil and natural gas production emissions inventories," Nature Communications (2021); Kearney Energy Transition Institute

There are a variety of sensors to detect a concentration of GHG, each with its own application

Not exhaustive

Within indirect measurements, **passive sensors** measure changes in background energy, such as reflected sunlight caused by the presence of GHG in contrast to **active sensors**, which transmit bursts of energy in the direction of interest, e.g., a laser beam, and record the origin and strength of the backscatter (LIDAR: Light Detection and Ranging).

Supporting content for 3. Monitoring approaches and advancements

Different types of sensors

Type	Technique	Deployment
Metal-oxide semiconductors	Electric circuits are doped with oxide materials to react with the target gas, where tin dioxide used for methane and VOC detection. Gas particles react with the oxide material and result in change in measured electrical resistance.	Handheld, fixed
Printed nanotube sensors	The gas molecules change the electrical response of the carbon nanotube sensors, which can be detected and converted to a methane concentration.	Handheld, fixed
Gas chromatography	A gas passes through a separator column, and the molecular weight of the gases determines the time it takes to pass. The timing and magnitude of the peaks indicates the type of gas, and gas sensors in combination with the technique can therefore determine their presence.	Can be used in laboratory on samples from mobile units
Mass spectrometry	Mass spectrometers are used to identify molecules by ionization of the sample and measuring the mass to charge ratios. Mass spectrometer systems may be used to distinguish between thermogenic and biogenic methane.	Can be used in laboratory on samples from mobile units
Absorption spectroscopy	It utilizes the wavelength-dependent absorption of light/laser to quantify the concentration of any gas in a mixture. Furthermore, the amount of light depends on the specific gas, gas concentration, wavelength, and total path length over which this light goes through air.	Vehicle mounted and fixed
Optical gas imaging	Optical gas imagers (OGI) are specialized infrared cameras that use a narrow range of the infrared spectrum, which GHG absorb. The cameras are not able to distinguish between specific gases (depending on their spectral resolution and domain).	Vehicle mounted, handheld, and fixed
Multispectral and hyperspectral imaging	Spectral imaging sensors consists of many different techniques to image multiple bands across the electromagnetic spectrum that go beyond the RGB bands of visible light. Spectral imaging sensors may have the capability to distinguish between gases based on their specific wavelength absorption properties.	Vehicle mounted and fixed
Dual frequency comb spectroscopy	A spectroscopic tool that exploits the frequency resolution, frequency accuracy, broad bandwidth, and brightness of frequency combs for ultrahigh-resolution, high-sensitivity broadband spectroscopy. By using two coherent frequency combs, dual-comb spectroscopy allows a sample's spectral response to be measured on a comb tooth-by-tooth basis rapidly and without the size constraints or instrument response limitations of conventional spectrometers.	Vehicle mounted and fixed

In-situ air samples
Remote sensing

Sources: Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Kearney Energy Transition Institute

The key aim of a calculation technique is to determine the flow rate

Not exhaustive

Even with well-designed measurement campaigns using precise instruments under ideal conditions, there is an **uncertainty range in the quantification estimates**.

Supporting content for 3. Monitoring approaches and advancements

Different calculation methods

Type	Description
Mass balance	– This approach is based on the law of conservation, and by accounting for GHG entering and leaving a system, emission flows from the system can be measured. By measuring the concentration and wind speed and direction at many altitudes and positions around an emission source, a mass balance can account for net GHG emitted by a source.
Inverse dispersion modeling	– Inverse dispersion modeling is based on upwind and downwind GHG concentration measurements using an array of sensors. By using meteorological fields and models to calculate how a plume would disperse downwind to result in a concentration as measured, the emission rate is estimated. – The meteorological parameters are either based on measured or modeled wind fluxes in the different layers of atmosphere and turbulence/stability.
Downwind tracer flux	– Tracer measurements involve access to a site for controlled releases of known amounts of tracer gases, near emission sources, and measurements downwind to measure the enhancements and ratios of tracer gas to GHG. Since the emission rate of the tracer is known, GHG (especially methane) emissions are calculated by multiplying the integrated methane concentration enhancement by the tracer ratio. – The tracer flux correlation approach is a highly accurate method for quantifying site emissions and has been used to assess other methodologies; unlike dispersion methods, tracer flux methods do not require knowledge of micrometeorological conditions such as turbulence and exact wind conditions. – However, the requirement for onsite tracer release is a disadvantage.
Quantitative imaging	– For technologies using hyper-, multispectral, or optical gas imaging, quantification can be done by using the image data and to derive a leak rate from the images by using a method to measure and control all the variables and derive quantitative results. – Background concentration, temperature of gas and background, wind speed, and measuring distance are important variables. The camera signal is then correlated to an empirically derived calibration curve to determine a release rate.

Sources: Carbon Limits, 2024, Overview of methane detection and quantification technologies for offshore applications; Kearney Energy Transition Institute

Advances in satellite technology is enabling access to more reliable methane emissions data

Non-exhaustive

Supporting content for
3. Monitoring approaches and advancements

List of prominent satellites with methane detection capabilities

As of 2024

Name	Start year	Revisit time (days)	Data collection method[1]	Spatial resolution (pixel size)	Detection limit (kg/h)	Retrieval swath size (km)[2]
GOSAT	2009	3	Continuous	10 x 10 km	7,000	790
Landsat 8	2013	16	Continuous	30 x 30 m	900	185
World – View 3	2014	1	Tasked	3.7 x 3.7 m	TBD	13.1
Sentinel-2A	2015	5	Continuous	20 x 20 m	900	290
GHGSat	2016	14	Tasked	25 x 25 m	100	12
TROPOMI - Sentinel 5P	2017	16	Continuous	7 x 5.5 km	4,000	2,600
Sentinel-2B	2017	5	Continuous	20 x 20 m	900	290
GOSAT 2	2018	3	Continuous	10 x 10 km	4,000	790
PRISMA	2019	7	Tasked	30 x 30 m	500	30
Landsat 9	2021	16	Continuous	30 x 30 m	900	185
EnMap	2022	4	Tasked	30 x 30 m	500	30
EMIT	2022	ISS dependent	Tasked	60 x 60 m	500	75
MethaneSAT[3]	2024	7–14	Continuous	0.1 x 0.4 km	500	200
Tanager	2024	1–7	Tasked	30 x 30 m	100	18

[1] Monitoring satellites scan the entire atmosphere and generate large volumes of data, which in the case of public satellites (such as Sentinel-5P) is freely available in raw, unprocessed form. Tasking satellites only scan specifically requested areas, and in the case of commercial satellites, the data is provided only to clients.
[2] Horizontal distance a satellite covers along its orbit as it retrieves readings
[3] Mission operations lost contact with the satellite on 20 June 2025.
Sources: IEA, 2025, Global methane tracker; Sherwin et. al., 2024, Single-blind test of nine methane-sensing satellite systems from three continents; Kearney Energy Transition Institute

Satellite technology limitations include temporal issues, attribution of emissions events, and geographic constraints

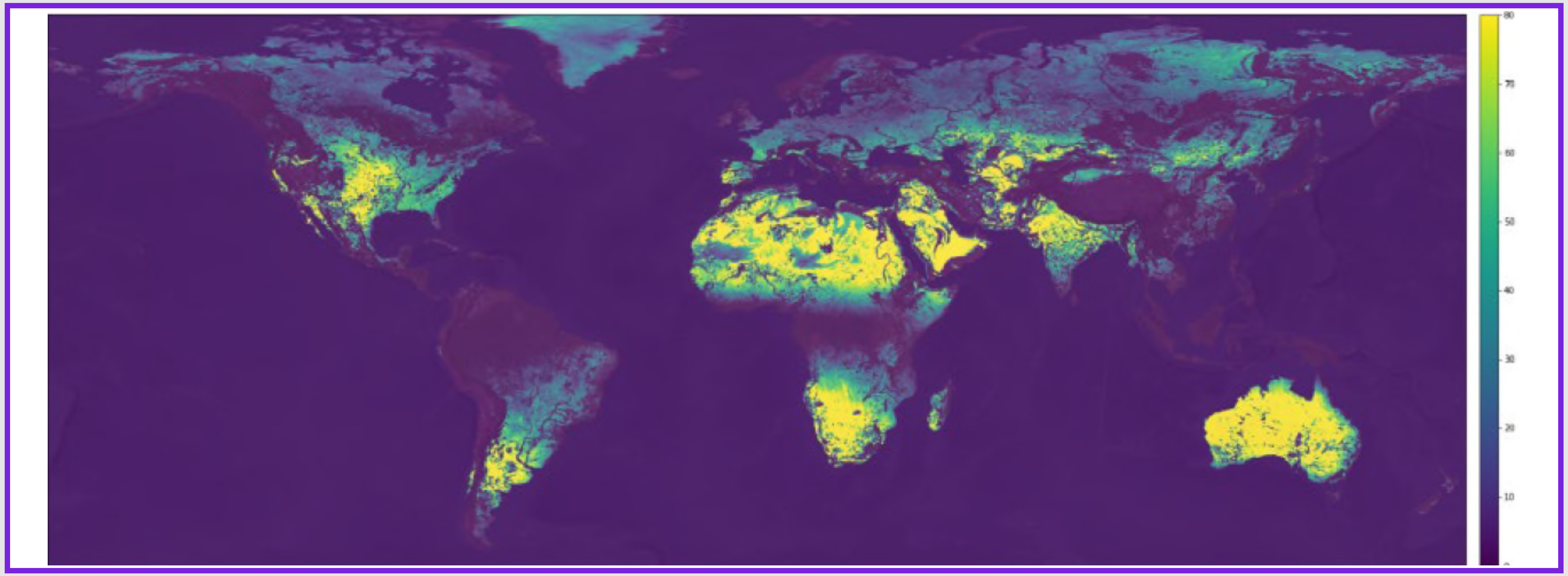
Significant oil and gas assets are out of scope, i.e., southern Mexico (offshore production and high humidity) and Nigeria (proximity to equator).

Data quality issues prevent data to be used in global inversions for methane budget so far.

Supporting content for 3. Monitoring approaches and advancements

Sentinel-5P TROPOMI coverage: usable pixels in a year (2020–2021)

Yellow indicates the highest number of pixels, and dark purple indicates no available data.



Temporal issues

Most satellites have 2- to 5-day revisit times and can miss transient sources of emissions vs. persistent sources.

Attributional issues

Inability to discern the exact source of a given event when there may be overlap of multiple potential sources, e.g., agriculture and energy infrastructure

Geographic constraints

Inability to accurately measure over wetlands, snow, and offshore installations, high latitudes or along the equator

However, several planned satellites will use sun-glint technology to provide some measurements over water.

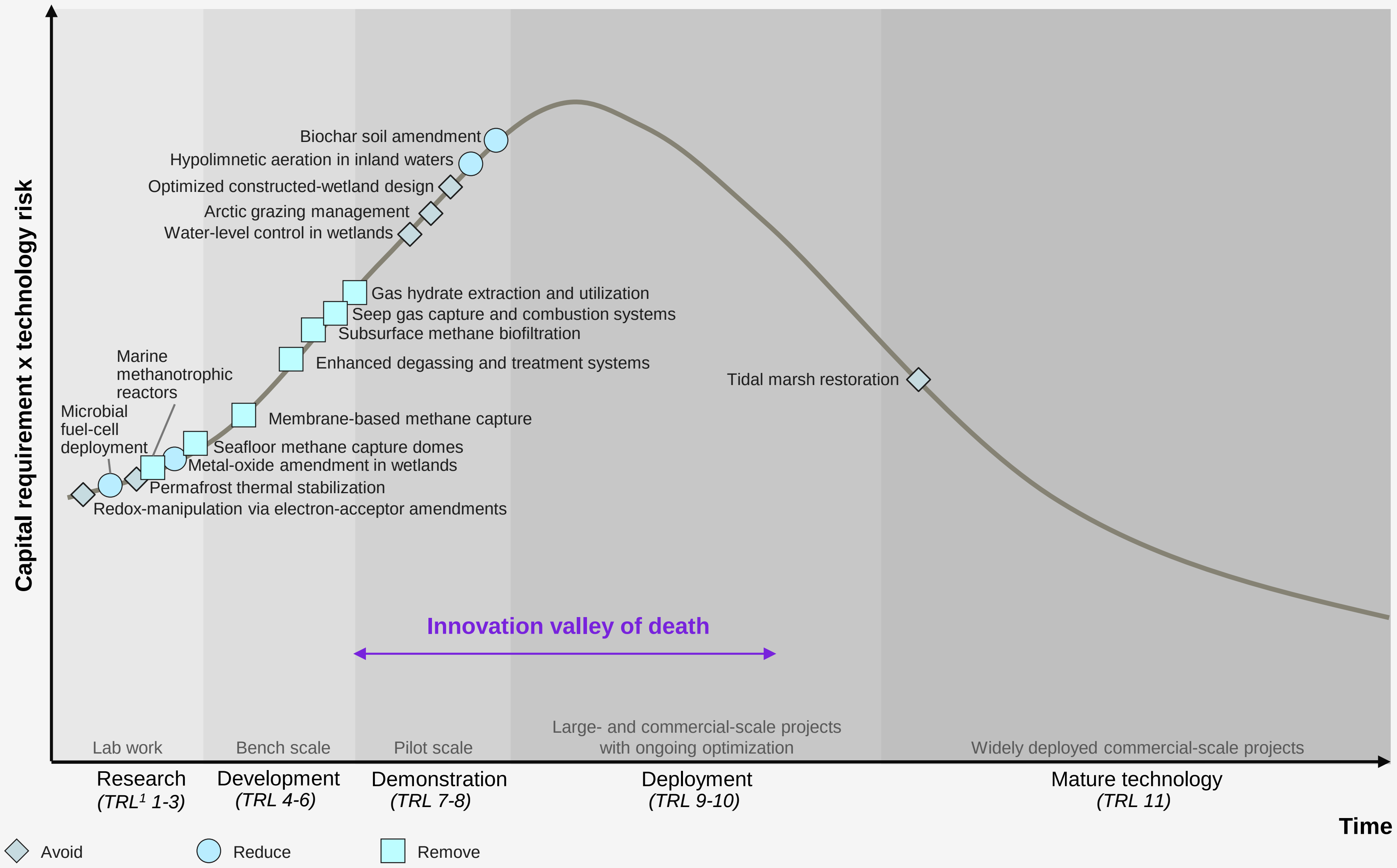
Sources: Kayrros; Kearney Energy Transition Institute

Supporting content for 4. Mitigation technology solutions

Mitigation technology solutions for natural and indirect methane emissions remain mostly at research and development stage

Non-exhaustive

Maturity curve for mitigation measures for natural and indirect methane emissions



Supporting content for 4. Mitigation technology solutions

[1] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide
Sources: Desktop research; Kearney Energy Transition Institute

Mitigation measures for natural sinks emissions

Supporting content for
4. Mitigation technology solutions

Non-exhaustive

1 Atmospheric reactions

Remove
Stratospheric hydroxyl radical boost
Tropospheric hydroxyl radical boost
Tropospheric chlorine radical boost
Photocatalytic solar chimney reactor
Photocatalytic surface treatment
Photocatalytic ozonation reactor
Plasma-photocatalytic hybrid reactor
Electrochemical methane processor

2 Land

Avoid
Optimized nitrogen management

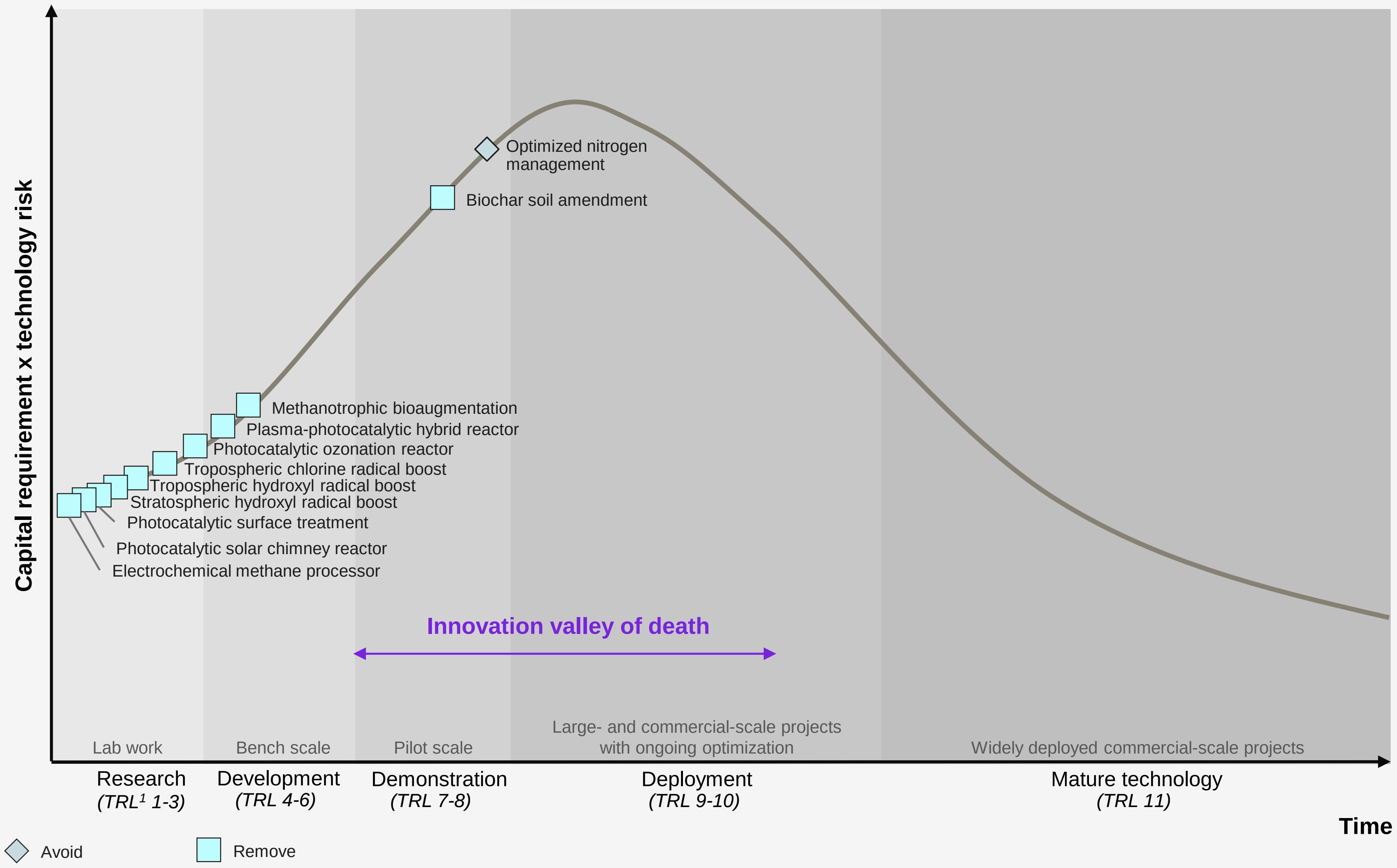
Remove
Methanotrophic bioaugmentation
Biochar soil amendment

Sources: Desktop research; Kearney Energy Transition Institute

Mitigation technology solutions for natural sinks methane emissions are largely in the research and development stage

Non-exhaustive

Maturity curve for mitigation measures for natural sinks methane emissions



[1] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide
Sources: Desktop research; Kearney Energy Transition Institute

Supporting content for 4. Mitigation technology solutions

Supporting content for 5. Policy and regulation

CH_4 is rising in visibility but few Nationally Determined Contributions fully reflect GMP ambition with quantitative aims for emissions reduction

Non-exhaustive

A total of ~11 countries include CH_4-specific aims, **constituting ~15% global emissions;** with COP30 on the horizon, **2025 is critical to elevate CH_4 action** by pivoting from GMP pledges to NDC action.[1]

[1] Nationally Determined Contribution, legally-recognized plans to reduce GHG emissions under Paris Agreement; [2] GHG is greenhouse gas; Source: GMP, 2025, Pledges; IEA,2025, Global Methane Tracker; UNFCC NDC reports; Kearney Energy Transition Institute

Supporting content for 5. Policy and regulation

Country	CH_4 emissions (Mt, 2024)	GMP signatory	CH_4 inclusion in NDC	CH_4 quantitative NDC plans	Commentary
China	56.6	✗	✗	✗	No CH_4-specific plan; implicit in overall GHG ambition[2]
Russia	20.2	✗	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
USA	35.3	✓	✓	✓	35% CH_4 reduction by 2035 relative to 2005
India	31.6	✗	✗	✗	No CH_4-specific plan; implicit in overall GHG ambition
EU	26.6	✓	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
Brazil	19.3	✓	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
Zimbabwe	12.4	✗	✓	✓	Collect 42% CH_4 emissions from waste for energy by 2030
Indonesia	11.4	✓	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
Iran	7.90	✗	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
Nigeria	5.88	✓	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
Canada	4.69	✓	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
Vietnam	3.68	✓	✓	✓	30% CH_4 reduction by 2030 relative to 2020 with sector limits
Algeria	3.31	✗	✓	✓	Reduce gas flaring to 1% of O&G production by 2030
UK	2.5	✓	✓	✗	No CH_4-specific plan; implicit in overall GHG ambition
UAE	2.07	✓	✓	✓	30% CH_4 reduction by 2030 relative to 2020 with sector limits
Japan	1.42	✓	✓	✓	11% CH_4 reduction by 2030 relative to 2013
Angola	1.59	✓	✓	✓	Flaring reduction of 490 MMSCF/day by 2030
Uruguay	0.09	✓	✓	✓	Unconditionally commits to not exceed 818 Mt CH_4 by 2030
Brunei	0.06	✗	✓	✓	Unconditionally pledges zero routine flaring by 2030
Gabon	0.05	✓	✓	✓	63% flaring-related CH_4 reduction by 2025 relative to 2000
Micronesia	0.05	✓	✓	✓	65% CH_4 reduction from diesel power by 2030 relative to 2000

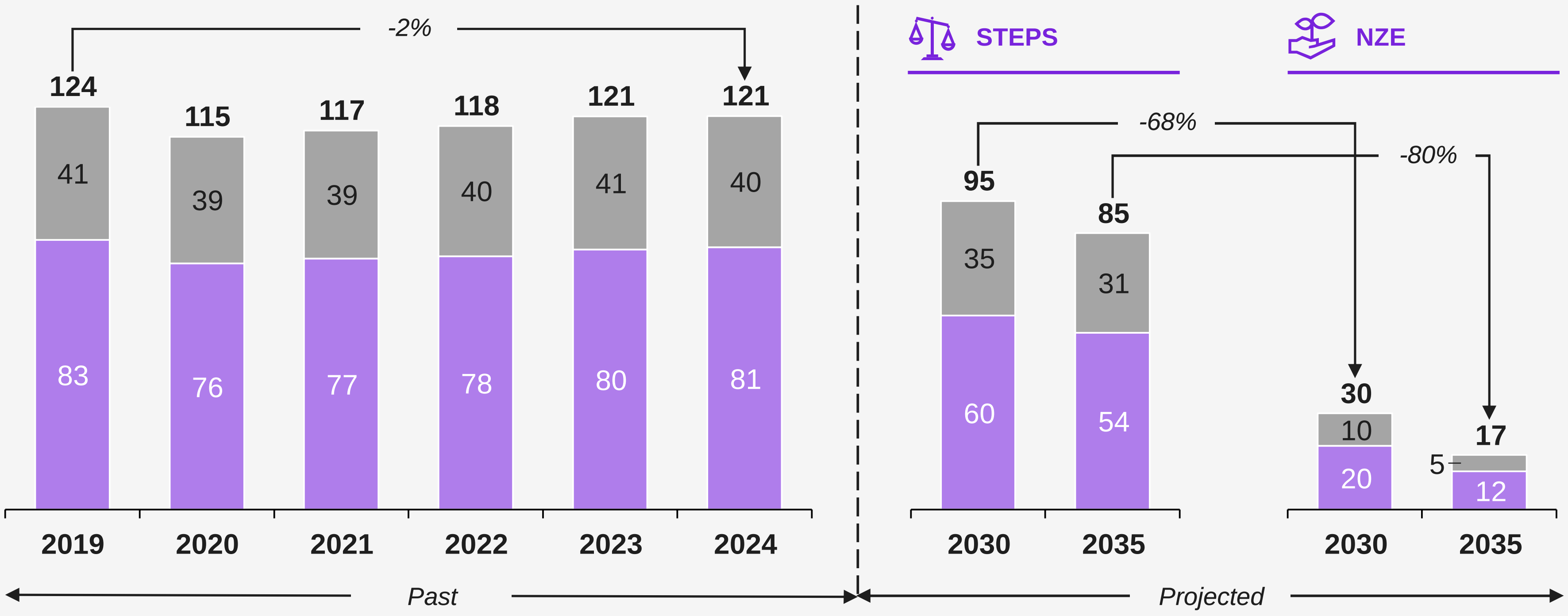
Effective reduction of methane emissions is dependent on targeted action at a national, regional, and global level

The IEA's STEPS describes the **methane emissions trajectory for current policy landscape, which falls short of reductions required** by 2030 and 2035 to limit global temperature rise to 1.5°C per NZE.[1,2]

Supporting content for
5. Policy and regulation

Global CH_4 emissions and intensity by energy source and scenario

Mt, 2019–2035



Key insights

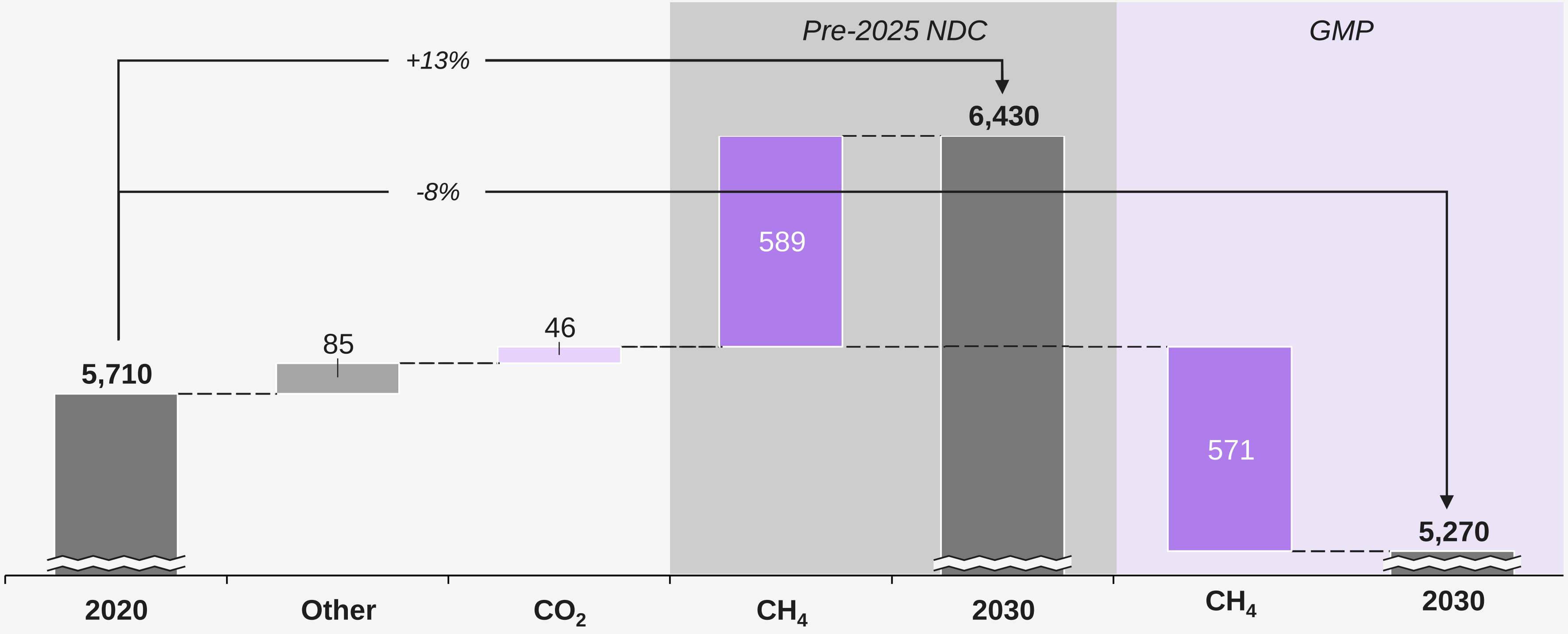
- Global methane emissions from fossil fuels **fell by only 2% to 121 Mt during 2019–2024; further decrease of 68% to 30 Mt by 2030 and 80% to 17 Mt by 2035** are required to align with the IEA's NZE, driven by explicit deployment of methane abatement technology.
- **Under current policy and regulation described by STEPS, global emissions reductions are not on track to meet NZE,** falling short of 2030 and 2035 targets by 68% and 80%, respectively.

[1] STEPS is Stated Policies Scenario.; [2] NZE is Net Zero Emissions by 2050 Scenario.; [3] O&G is oil and gas.
Source: IEA, 2025, Global Methane Tracker 2025; IEA, 2025, Stated Policies Scenario (STEPS); Kearney Energy Transition Institute

The IEA identified 65 GMP signatories for whom cutting domestic CH_4 emissions by 30% would represent a greater reduction in GHG emissions than what is included in pre-2025 NDCs

Change in GHG emissions for selected countries pre-2025 NDC vs. domestic GMP implementation

$MtCO_2e$, 2020–2030



Key insights

- **Many NDCs fail to detail emissions reduction targets specific to CH_4,** defaulting to a "business-as-usual" scenario.
- **If all 65 signatories considered followed a business-as-usual scenario for all GHG, total emissions would rise by 13%;** however, if the countries implemented domestic policies for a 30% reduction in CH_4 emissions alone in line with the GMP, overall GHG emissions would decline by 8%.
- **The result would be a 1.2 $GtCO_2e$ decrease from 2020–2030** (difference between 6,430 $MtCO_2e$ and 5,270 $MtCO_2e$ under NDC and GMP, respectively, in 2030), equivalent to eliminating all emissions from international aviation and shipping.

Source: IEA, 2025, Global Methane Tracker 2025; Kearney Energy Transition Institute

Supporting content for
5. Policy and regulation