White Paper

Rapidly decelerating climate change with atmospheric methane removal

SIXTEEN44

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EXECUTIVE SUMMARY

Methane is a powerful short-lived climate pollutant that is responsible for roughly 30% of current global warming. The atmospheric concentration is rising due to both human emissions (from agriculture, waste, oil & gas) and natural sources (such as wetlands and thawing permafrost). Existing mitigation efforts (cutting emissions) are essential but may not suffice to prevent dangerous warming, particularly if natural feedbacks accelerate. Atmospheric methane removal (AMR) technologies present a promising complementary tool to reduce warming in the near term. This White Paper delves into methane as a potent greenhouse gas, how its atmospheric removal compares to Direct Air Capture (DAC), reviews candidate technologies, and discusses implementation challenges.

TABLE OF CONTENTS

INTRODUCTION

Methane: A Potent Greenhouse Gas

Global average surface temperatures broke all-time records in 2023 at 1.45 ± 0.12 °C above pre-industrial levels.[1] Methane (CH_4) is the second largest driver of recent climate change after carbon dioxide (CO_2). Methane is responsible for around 30% of the rise in global temperatures (~0.5 °C of warming) since the industrial revolution, two-thirds as much warming as CO_2.[2] Although it remains in the atmosphere for a shorter period (~10-12 years),[3] its potency over that time is far greater per molecule than CO_2. Per unit of mass, the instantaneous global warming potential (GWP) of methane is approximately 120 times stronger than CO_2 (**Figure 1**).[4]

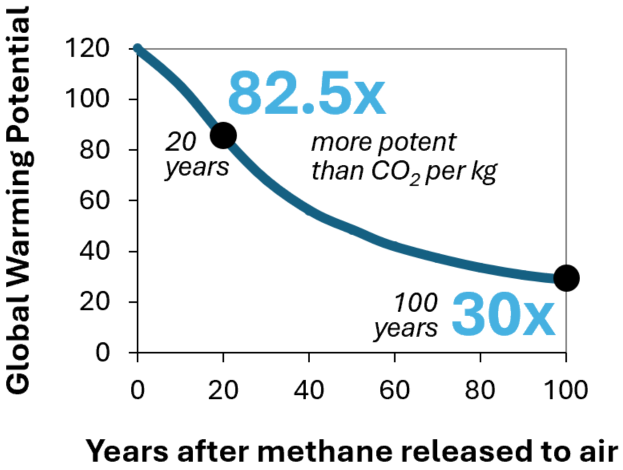

Figure 1. Global warming potentials for methane (kg CO_2 emissions equivalent to a kg of methane emissions), as a function of time used in the GWP calculations. Adapated from [4] with updated estimates from [5].

Over time, methane is converted in the atmosphere to CO_2. For approximately the first decade of a 100-year period, the carbon emitted as methane remains as methane, and as time progresses the methane oxidizes to CO_2, lowering the radiative forcing. Historically, GWPs of methane are referenced over 20 years (82.5 times stronger than CO_2) and over 100 years (30 times stronger) (IPCC AR6).[5] Not only does methane have a warming effect, it also acts as a precursor for the toxic air pollutant ozone. The relatively short atmospheric lifetime of methane, combined with its strong warming potential, means that targeted strategies to reduce emissions can provide climate and health benefits within a few decades.

Methane is rising faster in relative terms than any major greenhouse gas and is now 2.6-fold higher than pre-industrial times.[6] Global average methane concentrations reached 1.934 ppm in May 2025 (an increase from pre-industrial concentrations of ~0.75 ppm). To get on path to holding warming to 1.5 °C, the world must reduce baseline methane emissions by 35-40% in 2030.[7] The most important step in lowering the atmospheric methane concentration is preventing emissions from reaching the atmosphere. Certain emissions avoidance measures are straightforward and pay for themselves, such as stopping natural gas leaks.[8] However, ~40% of anthropogenic emissions (produced from human activities) are estimated to be technologically infeasible to avoid.[9,10] Furthermore, there are few technologies proposed to reduce natural emissions (primarily from wetlands and freshwaters) which are projected to increase as global temperatures rise.[11]

Nevertheless, even aggressive emissions controls may not fully counter the rising rate of warming that arises from existing atmospheric methane and future natural emissions. Thus, removal of methane already in the atmosphere is being explored to fill that gap.[12,13]

Where Does Methane Come From?

Despite estimates of methane emissions being subject to uncertainty, the most recent comprehensive assessment[14] suggests that annual global methane emissions are around 600 million tonnes using a top-down approach (using atmospheric observations and models) and are closer to 685 million tonnes using a bottom-up approach (activity data from a sector with emission factor).[15] Methane emissions come from natural sources (~33-45% of emissions) and anthropogenic sources (~55-66% of emissions) (**Figure 2**).

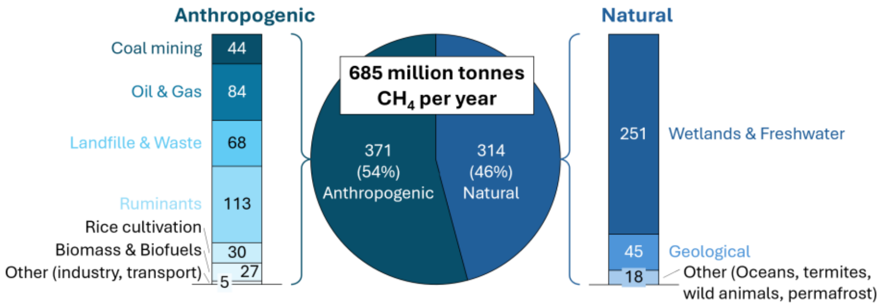

Figure 2. The global methane budget (teragrams (Tg) or million tonnes of methane per year) based on bottom-up methods for anthropogenic sources and natural sources. Data summarized from [14,15].

Anthropogenic methane emissions reached 371 Tg methane per year based on bottom-up estimates (average 2018-2020) and come primarily from three sectors: fossil fuels (coal minging and oil & gas): ~35%; agriculture (ruminants (e.g., cows) and rice cultivation): ~40%; and waste (landfills): ~20%. Emissions from livestock are the largest source of agricultural emissions with enteric fermentation the dominant process and cattle the dominant animal causing the emissions. These emissions are 50-60 Tg methane per year (15-20%) higher than for the period 2000-2002 (two decades earlier).

Natural methane emissions reached 314 Tg methane per year (bottom-up) and are dominated by wetlands and freshwater sources. Changes in emissions from natural sources of methane are likely to create positive feedbacks as emissions increase in a warming climate.

HOW AMR COMPARES TO DAC

Because methane is far more potent than CO_2 as a greenhouse gas, much less needs to be removed to achieve the same climate benefit.[12] Restoring atmospheric methane to preindustrial levels (~0.75 ppm) would require removing about 3.2 of the 5.3 gigatonnes (Gt, equal to a billion tonnes) currently present.[13] Maintaining those levels would then require continuous removal to offset today's anthropogenic emissions of ~0.37 Gt per year, which is far smaller in scale than annual CO_2 emissions, which are roughly 40 Gt.[16] However, atmospheric methane is challenging to remove because it is 200 times less abundant than CO_2 and lacks the chemical properties (such as a quadrupole moment or acidity) that make CO_2 easier to capture.

A recent study estimated the minimum thermodynamic work required to separate methane and CO_2 from the atmosphere.[12] For CO_2 at an average atmospheric concentration of 410 ppm, with 70% capture efficiency and 97% outlet purity, the minimum work is 459 MJ per tonne of CO_2. Under the same capture and purity conditions, methane requires only 24 MJ per tonne CO_2e (using GWP20 = 86) or 62 MJ per tonne CO_2e (using GWP100 = 34). Thus, the theoretical energy cost of methane capture, when compared on a radiative forcing basis, is roughly 19 times lower than that for CO_2 using GWP20, or 7 times lower using GWP100. **Figure 3** illustrates how the minimum work of atmospheric methane capture depends on outlet purity and concentration, assuming a fixed 70% capture fraction.

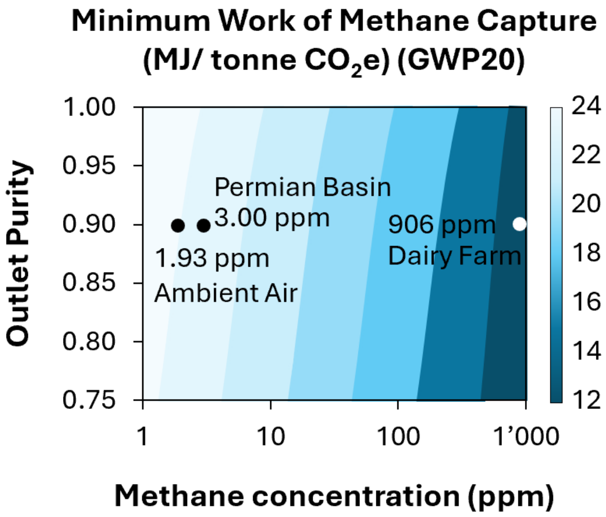

Figure 3. Graph of the minimum work of methane capture (normalized to MJ/tonne CO_2e using GWP20) for varying outlet purities and different concentrations of methane (holding capture fraction constant at 70%). Three different cases are highlighted (ambient air at 1.93 ppm of methane, Permian Basin at 3.00 ppm, and a dairy farm at 906 ppm). Graph adapted from [12].

The higher the methane concentration, the less energy is required for its removal. This makes it strategic to target sources with elevated concentrations, such as oil and gas sites, abandoned coal mines, landfills, and agriculture.[17] For example, methane levels at dairy farms can reach up to 1,000 times the atmospheric average,[18] making them prime candidates for methane oxidation where direct emission reductions are difficult.

METHANE REMOVAL TECHNOLOGIES

Because methane has a much higher global warming potential than CO_2, reducing its climate impact doesn't require capturing the gas (as with CO_2 removal); it only needs to be destroyed through oxidation. In contrast to CO_2, CH_4 can be oxidized catalytically, without the need for capture, in a thermodynamically favourable reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \ (\Delta H_r = -803 \text{ kJ/mol})$$

However, such a reaction is extremely difficult at typical conditions of atmospheric temperature and pressure.[19] Methane destruction by oxidizing it to CO_2 and water reduces its 20-yr warming impact by 99% or its 100-yr warming impact by 97%.[20]

Although atmospheric methane removal is still a recent consideration to fight climate change, several technologies and processes have been proposed, and the state-of-the-art methane oxidation proposals are summarized in **Table 1**. We first consider the energy source to activate methane oxidation and then describe the associated applied technology type: biological energy (such as biofilters and methanotrophic soils), heat (combustion, thermo-catalysis), light (photolysis and photocatalysis), and electric potential (electrocatalysis).

Enhanced microbial oxidation of methane in agricultural and other soils or in biotrickling filters is a microbially based approach for atmospheric removal.[21,22] Microbes provide the second-largest natural sink for atmospheric methane of approximately 40 Tg methane annually.[23] Methanotrophs (bacteria that obtains energy by oxidizing methane), such as methane monooxygenase (MMO), have been applied in biofilters[24] (flow reactors that facilitate bacterial growth) at landfills,[25] wastewater treatment plants (at concentrations as low as 1000 ppm),[26] and coal mines.[27] Modelling suggests that bacterial biofilters could operate down to 500 ppm methane before the concentration is too low for bacteria survival.[28] This is a current significant drawback of methanotrophic biofilters: (atmospheric) methane concentrations (i.e., <500ppm) are too low to enable cell survival. One promising idea is to include fungi in biofilters that create a structural support for methanotrophs, which has been shown to allow for oxidation down to 20 ppm of methane.[29]

Considering heat as an energy source, the simplest approach to oxidize methane is flaring, which requires methane concentrations in air above 44 000 ppm to sustain a flame, so is not generally applicable to atmospheric methane removal. Sub-flarable concentrations as low as 2000 ppm are commercially oxidized with Regenerative Thermal Oxidizers (RTOs), another heat-based technology currently used for coal mine ventilation air, among other applications.[30] However, RTOs require air temperatures of ~1000 °C. RTOs that incorporate noble metal catalysts, known as Regenerative Catalytic Oxidizers (RCOs), operate down to 1000 ppm methane, but still require high temperatures for activation. Other metal catalysts, such as copper (Cu)- and iron (Fe-)zeolites, and porous polymer networks (PPNs), are additional methane-oxidizing catalysts that are of interest.[13] A copper zeolite has been shown to oxidize 2ppm of methane if the air is heated to 330 °C.[31] Methane can also be concentrated from the atmosphere with these porous materials, but its interaction with zeolites is weak (~5 kcal/mol) as it relies only on van der Waals interactions with the oxygen atoms in the walls of the zeolite lattice to trap methane; scientists have screened more than 87 000 zeolite structures as potential methane sorbents.[32] After methane molecules are weakly bound by oxygen groups on the zeolite, Cu, Fe or other metal ions embedded on the lattice can oxidize the sorbed methane (at elevated temperatures) and release it as CO_2 (which can require heat or pressure swings).[12] The energetic constraints from the high temperature activation for thermal catalysis often negates their use for atmospheric methane removal.[8]

Low concentrations of methane have also been oxidized via light-based methods. Researchers have proposed iron-salt aerosols (ISA) with light activation as a methane removal method.[33,34] ISA approaches attempt to convert methane into CO_2 in the lower troposphere by enhancing natural sinks of the hydroxyl radical (responsible for 90% of the natural methane sink) and the chlorine atom (3-4% of the natural methane sink). One study demonstrated oxidation of 2ppm of methane at ambient temperature through photolysis of chlorine gas into chlorine radicals[35] and other studies demonstrated methane oxidation with hydroxyl radicals through ozone photolysis[36–38]. However, the pursuit of atmospheric enhancement with ISA is proceeding cautiously due to the unknown and long-term risks of introducing vast quantities of ISAs into the atmosphere. Photocatalysts, such as titanium dioxide (TiO_2)[39] and silver-decorated zinc oxide (Ag-ZnO),[40] which are often applied as thin films, can oxidize methane and other hydrocarbons through heterogenous catalysis and are active when exposed to ultraviolet (UV) radiation (e.g., 387nm for anatase TiO_2). In general, the reaction products (water and CO_2) of methane oxidation desorb or release after their formation,[41] eliminating the need for concentration and capture. Light-based methods are however limited by low apparent quantum yields of the photocatalysts.[8]

Methane oxidation using electric potential may also be feasible, although current proposals primarily focus on converting high concentration methane streams into value-added end productions.[42]

All these technologies are still in their development infancy, with research being needed on techno-economic analyses, efficiency, scaling, social barriers to deployment, co-benefits, and potential negative side effects.

Table 1. Proposed methane removal technologies (adapted from [8]).

Energy	Technology Type	Materials	Mechanism	Minimum methane concentration (ppm)	Development Stage	Key Technical Challenges
Biological	Biofilters and methanotrophic soils	Methanotrophs (Methane monooxygenase (MMO))[24,25]	Uses methanotrophic bacteria/ archaea (natural or engineered) to oxidise methane, in soils, filters, or bioreactors	1,000 (bacteria) 20 (bacteria + fungi)	Varied TRLs; moderate research; field trials limited; some success in soil and waste	Scaling (land usage), maintaining biological activity under varying conditions (temp, moisture), avoiding unintended emissions (e.g., N_2O), ensuring sufficient methane flux to make system viable
Heat	Combustion		Flaring	44,000	Commercially readily available & widespread adoption in industry	High methane concentration requirement negates application in atmospheric removals
			Regenerative Thermal Oxidizers (RTOs)	2,000		
	Thermocatalysis	Noble metals[43], metal oxides[44], hexa-aluminates[45], and perovskites[46]	Flow reactors and Regenerative Catalytic Oxidizers (RCOs) that maximize material surface area for maximal reaction efficiencies	1,000		High temperature of activation (>300 °C) negates application in atmospheric removals; stability; durability; cost; fouling
		Metal-doped zeolites and porous polymer networks[31,47]		2	Low TRL (lab scale); very few field demonstrations	Low reaction rates at low methane concentrations; catalyst stability; catalyst durability; cost; fouling
Light	Thermo-photocatalysis	Perovskites, semi-conductors, and composites[48]		500		
	Photolysis	Chlorine gas[35]	Enhanced atmospheric oxidation introduces or boosts oxidants to speed its conversion to CO_2 and water; flow reactors	2	Low TRL (lab scale); few field demonstrations	Ensuring selectivity (avoid unwanted byproducts like ozone or harmful halogen chemistry); high uncertainty; potential long-term climate and health risks; low quantum yield
		Ozone gas[38]		Not tested at low concentrations		
	Photocatalysis	Iron Salt Aerosols[49]				
		Semiconductors and noble metals (TiO_2, Ag-ZnO)[40,50,51]	Flow reactors, painting surfaces (passive), aerosols, solar chimneys	100		Scaling (land usage); catalyst fouling
Electric potential	Photo-electrocatalysis	Semiconductors[52]	Electrochemical cells	Not tested at low concentrations	Low TRL (lab scale)	Slow reaction rates due to weak methane adsorption
	Electrocatalysis	Noble metals and various supports[53]				

Due to the unknown risks of using ISAs as an atmospheric methane removal method, and the difficulties in scaling and the longevity of enhanced microbial oxidation of methane, photocatalysts and metal catalysts associated with zeolite and PPNs incorporated into flow reactors are front-running technologies to achieve the difficult task. Both technologies currently rely on (atmospheric) oxygen as the oxidant of methane, which is very limiting in reaction rate and yield. Stronger oxidizing agents are known that can achieve faster reaction rates and achieve higher efficiencies, such as the hydroxyl radical, which provides one of the largest atmospheric sinks for methane. The technology developed at Sixteen44[54] uses a multi-pronged approach to produce *in-situ* reactive oxygen species (ROS) in a flow reactor to oxidize methane in air to CO_2 and water. The production of these ROS relies on an intricate interaction among localized plasma discharges and catalysts, which provides an energy efficient and new treatment method to solve the problem of atmospheric methane removal.

IMPACTS AND CONSIDERATIONS OF ATMOSPHERIC METHANE REMOVAL

Atmospheric methane removal offers two major benefits: it can reduce global temperatures more quickly than CO_2 removal and improve air quality by lowering surface ozone concentrations. Earth system model simulations suggest that a 40% reduction in methane emissions by 2050 would decrease global temperatures by ~0.4 °C.[55] Beyond climate impacts, methane removal reduces ozone levels,[56] which improves air quality and crop yields.[57] Unlike CO_2 removal, methane oxidation does not require capture and storage, thereby avoiding long-term monitoring costs and risks of storage reversal. For example, California requires CO_2 injection sites to be monitored for 100 years to ensure permanence.[58] Verification of methane oxidation should also be relatively straightforward, as it can be quantified from gas flow rates and measured concentration changes of methane and CO_2. Finally, enhanced methane oxidation may achieve costs below $50 per tonne CO_2e, substantially lower than many current carbon dioxide removal methods, creating strong financial incentives to pursue atmospheric methane removal.[59]

Although atmospheric methane removal holds considerable promise, it also presents risks and challenges that require careful management. Some oxidations or radical amplification strategies may generate harmful byproducts (e.g., chlorinated compounds or other reactive species)[60] that could impact air quality, ecosystems, or human health. Because atmospheric methane is highly dilute, removal requires processing large volumes of air, raising concerns about energy demand and its source; reliance on fossil energy could negate net climate benefits.[61] Accurately quantifying methane removal, ensuring additionality, and demonstrating persistence are technically complex and require the development of transparent, peer-reviewed methodologies. Atmospheric methane removal should be viewed as a complement to, not a substitute for, reducing methane and CO_2 emissions, as overreliance risks delaying essential mitigation. Broader social, regulatory, and logistical factors, including land use, infrastructure needs, and long-term uncertainties, may also slow deployment. Early public engagement is critical to avoid ethical pitfalls and strengthen societal alignment.[62] Experience with other climate interventions illustrates this point: limited consultation contributed to public opposition and restrictions on ocean fertilization and geological carbon storage projects, whereas enhanced weathering experiments that incorporated early community dialogue achieved more ethically robust and socially accepted outcomes.[63]

To meaningfully move atmospheric methane removal forward, policymakers should begin incorporating methane removal into climate policy portfolios, including allocating funding for research, setting regulatory pathways for safe pilot projects, and considering methane removal in carbon pricing or credit frameworks. Researchers and innovators should prioritize scaling up lab-benches to field trials, improving MRV methodologies, and advancing understanding of environmental side effects. The public should engage, advocate for strong oversight, and help ensure that atmospheric methane removal does not undermine emission reduction efforts or equity goals.

Atmospheric methane removal remains in the early stages of development, with only few companies, such as Sixteen44, preparing for large-scale deployment. Nevertheless, the urgency of climate change (driven by rising methane concentrations and the risk of natural feedbacks) demands accelerated research, funding, and regulatory preparation. Natural sources such as permafrost thaw and methane hydrate release in Arctic coastal systems could amplify future emissions, meaning that methane removal may be necessary even if anthropogenic emissions are substantially reduced.[12] Despite methane being responsible for roughly one-third of anthropogenic greenhouse gas warming, only ~1% of international climate finance is directed toward methane mitigation and removal.[64] Greater investment is needed across three fronts: (i) rapid implementation of emission-reduction methods, (ii) development of new strategies for diffuse sources, and (iii) research into atmospheric methane removal technologies to clarify risks, costs, and benefits. Enabling progress will require robust R&D and pilot projects, governance frameworks and standards to ensure safety, environmental integrity, and reliable MRV, economic incentives through carbon markets or policy instruments, and active engagement with stakeholders to build trust and ensure equitable deployment. Importantly, atmospheric methane removal should be integrated into broader climate strategies that prioritize rapid emissions reductions, nature-based solutions, and CO_2 removal.

CONCLUSION

Atmospheric methane removal holds significant promise as a high-impact, near-term lever to slow climate warming, particularly in combination with sustained emissions reductions. Though the technologies are nascent and carry risks including environmental side effects, energy costs, verification challenges, and social acceptance, they deserve urgent attention. With coordinated action, investment, strong governance, pilot deployment, and stakeholder engagement, AMR can become a reliable part of the climate response toolbox and help avoid the worst impacts of warming.

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