Methane emissions and global warming: Mitigation technologies, policy ambitions, and global efforts

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HIGHLIGHTS

- Limiting methane emissions is necessary for both achieving long-term climate goals and mitigating impacts in the next 20 years.
- Monitoring most methane emission sources is difficult because they are intermittent, diffuse, and at low concentration. Tools with higher resolution in space and time, along with new detection strategies, are needed.
- A significant portion of emissions from the oil and gas sector could be prevented by widespread use of proven revenue-neutral technology and policies.
- A fraction of emissions from agriculture and waste can be cost-effectively mitigated, while most are not manageable with existing methods.
- Collaboration between private and public sectors would promote mutually beneficial policies and technologies to effectively reduce global methane emissions.

Methane emissions are the second highest contributor to climate change. Despite having a much lower atmospheric concentration than carbon dioxide, anthropogenic methane emissions account for almost one-third of anthropogenic warming since the pre-industrial period. Recently, the reduction of methane emissions has been recognized as an effective lever for reducing the impact of climate change in the next decade with less drastic economic and industrial costs than equivalent carbon dioxide mitigation. However, the wide range of methane emission sources, many of which are intermittent and at low concentration, poses a challenge for current detection and mitigation tools. Promising technical progress has been made on both fronts over the past decade, especially within the oil and gas sector, yet widespread implementation of mitigation policies and technologies lags considerably. The 2021 Global Methane Pledge for a 30% reduction in emissions by 2030 signals an increase in political will and can be achieved with these existing tools. It is estimated that the majority of these reductions can be accomplished through revenue-neutral or positive actions. Yet, a faster rate of reductions and sustained reductions beyond what is already available will be needed to maintain a 1.5°C pathway. In the long term, more comprehensive policies, coupled with significant innovations in methane emission monitoring and mitigation, could enable an effective climate change mitigation strategy.

The past decade has been the hottest in recorded history, with an average global temperature more than 1°C (1.8°F) above pre-industrial [1], and warming more than 2°C (3.6°F) for some regions [2]. This warming trend is expected to continue and has already driven significant changes in the Earth’s climate and weather patterns: The frequency and severity of extreme droughts, flooding, and hurricanes has increased, with drastic and potentially irreversible impacts to people and the natural world [3]. Sea level rise due to polar ice cap melting poses immediate danger to coastal communities, while marine ecosystems and fisheries face increasing disruption from acidification and changes in ocean currents. Collectively, these extreme events and local disruptions will exacerbate the long term impacts of climate change on vulnerable ecosystems and communities [4, 5].

While it is unequivocal that human activity is the main driver of climate change [6], progress to address this crisis has been slow and uncertain. International efforts to understand and address climate change center around the Intergovernmental Panel on Climate Change (IPCC), which serves as a bridge between the scientific community and governments and policymakers. The IPCC issues regular reports on scientific consensus, implications, and potential adaptation and mitigation options. These reports are intended to be objective; yet their scope, content, and language implicitly inform policymakers’ understanding of the issues and solution space. While these reports have included information about many greenhouse gases, their impact has been to focus the attention of the public and policymakers on carbon dioxide emissions, the primary anthropogenic driver of global warming. It is only recently that this focus is expanding, driven by the dual realization that the mitigation of other greenhouse

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Methane emissions are the second highest contributor to warming after those of carbon dioxide, with historical emissions accounting for almost one-third of anthropogenic warming since the pre-industrial period [8]. This warming is due to a 150% increase in the concentration of atmospheric methane as a result of human activity. Unlike anthropogenic carbon dioxide, which is dominantly released from the burning of fossil fuels, methane originates from a range of sources, presenting new challenges for mitigation. About 60% of emissions are anthropogenic, while 40% come from natural sources such as decomposing organic material in wetlands. Many natural sources are predicted to increase in a positive feedback cycle with climate change, yet addressing this increase raises complex questions about whether, and to what extent, intentional intervention in natural systems is prudent [9]. Once in the atmosphere, methane is a potent greenhouse gas, trapping 120 times as much heat as an equivalent mass of carbon dioxide [10]. The majority of methane in the atmosphere is oxidized into carbon dioxide and water vapor, resulting in an atmospheric half life of only 12 years, much shorter than that of carbon dioxide [11]. Due to this short-term potency, current methane emissions significantly influence the climate we will experience over the next decades. Thus, rapid reductions are a powerful lever for immediately slowing the rate of global warming and mitigating the impacts of climate change in the coming decades [12].

To promote the important role of action on methane for climate change mitigation, the next sections detail the global methane cycle and the mechanisms by which this cycle interacts with the climate. Subsequently, technologies for detecting and quantifying methane emissions are introduced as critical enablers for understanding the magnitude of the problem as well as the efficacy of reduction policies and actions. The potential for existing technology and policy to yield meaningful progress in the current decade is highlighted, showing that methane emissions can be reduced with less drastic economic impact and industrial changes than equivalent reductions of carbon dioxide emissions. Finally, an overview of the entire mitigation space is used to understand the potential for deep reductions in the long term.

**Global methane cycle**

The atmospheric concentration of methane and its subsequent effect on the climate is controlled by the balance of sources and sinks between the atmosphere, ocean, and land. By understanding the relevant processes involved, policymakers can make informed decisions on which areas to address for maximum effectiveness at reducing the impact of methane on climate change. Figure 1 presents a breakdown of the estimated sources and sinks for atmospheric methane.

![Figure 1: Average annual global methane emission sources and sinks (Million metric tons (MT) CH\textsubscript{4} per year) for the period of 2008 to 2017 by Saunois et al. [13] using a top-down estimation. "Atmospheric chemical reactions" refers to conversion of methane to other chemicals, primarily water vapor and carbon dioxide.](https://doi.org/10.38105/spr.8u4spqvc0e)
coal and is inadvertently released during drilling and mining operations. Methane can also be released from natural gas reservoirs during drilling, or leak from natural gas pipelines and processing facilities. Furthermore, incomplete combustion or conversion of natural gas in end uses may also result in methane release to the atmosphere. Finally, incomplete combustion of other fossil fuels and biomass can generate methane, which is released in combustion exhaust.

In contrast to the numerous pathways that generate methane, there are only two main pathways for its removal from the atmosphere [18]. About 95% of methane removal is due to chemical reactions in the atmosphere, producing carbon dioxide, ozone, and water vapor [19]. The remainder is primarily attributed to uptake by methanotrophic soil bacteria that utilize methane as an energy source. At present, there are no significant anthropogenic methane sinks. Estimates for these sinks are also included in Figure 1. Based on these fluxes, the current atmospheric lifetime of methane is approximately 12 years [10].

Methane and climate change

The Earth’s average temperature is determined by a balance of energy flowing into and out of the planet. The energy input primarily comes from the Sun’s light in visible wavelengths, while the energy out is in the form of thermal infrared radiation from the Earth’s surface and atmosphere. Greenhouse gases like methane and carbon dioxide are transparent to incoming visible light, allowing this energy to reach the earth’s surface, yet absorb outgoing infrared radiation, preventing energy from leaving. This process, referred to as the greenhouse effect, causes an increase in the temperature of the earth’s surface and atmosphere [20]. In combination with this direct warming effect, methane emissions also indirectly contribute to warming, as methane decomposes and reacts with other chemicals in the atmosphere to produce ozone, carbon dioxide, and stratospheric water vapor, which are also greenhouse gases [8].

Although the connection between greenhouse gases in general and observed global warming is relatively straightforward [21], it is difficult to directly compare the effect of different greenhouse gases due to their different physical properties and lifecycles. A common metric to normalize and compare the impact of different greenhouse gases is the Global Warming Potential (GWP). GWP measures how much energy a greenhouse gas will absorb over a specified time horizon relative to the same mass of carbon dioxide [22]. The time horizon in years is indicated as a subscript, as in GWP$_{100}$. Table I gives the GWP values for several greenhouse gases as calculated and used by the IPCC in the Sixth Assessment Report [10]. Like any metric used to simplify a complex system, the use of GWP has limitations and may be misleading in certain applications. For example, the GWP value for methane varies by nearly a factor of ten between the 20-year and 500-year time horizons, due to its short atmospheric lifetime relative to that of carbon dioxide. While GWP$_{100}$ has been the de facto standard due to its primacy in official usage, the choice of a relevant time horizon is a policy question that may be contested, and some advocate for increased emphasis on GWP$_{20}$ or reporting of multiple values [23]. This is especially salient for decisions that balance trade-offs between emissions of greenhouse gases with different lifetimes, as GWP$_{20}$ and GWP$_{100}$ may provide seemingly contradictory support for different options.

The use of GWP to translate the effect of methane into that of an equivalent amount of carbon dioxide obscures key differences between their lifecycles that inform the role of methane mitigation in an overall climate strategy. Human activity does not directly influence the atmospheric concentration of methane or carbon dioxide, which is what controls their respective impacts on the climate, but rather indirectly influences this through changing rates of emissions. Carbon dioxide’s long lifetime [17] means that the atmospheric concentration in the coming decades is essentially determined by the accumulation of all emissions, so reducing emissions to zero will merely lock in a higher concentration. In contrast, the shorter lifetime of methane means that atmospheric concentration is controlled by the balance of emissions and sinks in the present. Thus, reducing methane emissions can lead to a reduction in atmospheric concentration and associated warming on a decadal timescale [8].

Methane emissions are also less directly coupled to industrial activity than carbon dioxide emissions, presenting a parallel path to work around the economic trade-offs and political interests that have stymied carbon dioxide reductions. The current global economy is supported by a small number of critical industrial processes (e.g. fossil fuel burning, metal ore reduction, and cement production) based on chemical reactions that inherently produce carbon dioxide in defined ratios, resulting in a strong correlation between emissions and economic activity [24]. In contrast, methane emissions are

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lifetime (yr)</th>
<th>GWP time horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO$_2$)</td>
<td>multiple*</td>
<td>1 1 1</td>
</tr>
<tr>
<td>Methane (CH$_4$)</td>
<td>11.8</td>
<td>82.5 29.8 10</td>
</tr>
<tr>
<td>Nitrous Oxide (N$_2$O)</td>
<td>109</td>
<td>273 273 130</td>
</tr>
<tr>
<td>CFC-11 (CCl$_3$F)</td>
<td>52</td>
<td>8,320 6,230 2,090</td>
</tr>
</tbody>
</table>

Table I: Global warming potential (GWP) values used in the IPCC Sixth Assessment Report, summarized from table 7.15 therein [10]. *For carbon dioxide, no single lifetime has been defined as there are multiple removal processes with rates ranging from decades to centuries. About half of carbon dioxide emitted today will be gone in a century, but a portion will persist for millennia [17].
Detecting methane emissions

Detecting and quantifying specific methane sources provides critical information for reducing emissions. Emission sources can be characterized by their spatial extent, the concentration of methane that is released, and the variability of methane flux over time. For example, a leak in a natural gas pipeline is a point source with high concentration, while a wetland or thawing permafrost can be considered a diffuse source with large area. In some cases, this characterization depends on the resolution of measurement and the intended application of the information. Low resolution measurement of a cattle farm may show diffuse low concentration emissions similar to a wetlands, while a high resolution survey would indicate that each animal is actually a small point source. While lower resolution measurements are adequate for accounting, higher resolution measurements are essential for discerning the precise emission source and informing potential mitigation strategies.

![Graph showing growth of GDP, carbon dioxide emissions, and methane emissions relative to 1990 levels for China, Vietnam, Argentina, and India. Data obtained from the World Bank Group.](https://doi.org/10.38105/spr.8u4spqvc0e)

Figure 2: Growth of GDP, carbon dioxide emissions, and methane emissions relative to 1990 levels for China, Vietnam, Argentina, and India. Data obtained from the World Bank Group [25]–[27].

The oil and gas industry’s concern with methane emissions predates the present focus on climate change and has been motivated by revenue loss and safety issues associated with high concentration leaks of natural gas. The immediate pragmatic nature of these efforts created a focus on the identification of point sources, which must be found to be fixed, rather than on quantifying total emissions. This is primarily accomplished through periodic on-site inspection of facilities using portable sensors such as infrared cameras, optical spectrometers, and bubble test kits [28]. This work is time-consuming, and much of the natural gas production and distribution infrastructure is in remote or hard-to-access locations. Thus, only a portion of this infrastructure is actually inspected, it is rarely revisited, and only a fraction of methane leaks are identified [29].

These on-the-ground efforts can be complemented by satellite-based remote sensing techniques (e.g. TROPOMI, GHGSat, MethaneSAT) as well as aircraft or drone measurements, which scan a large geographical region with sensitivity to detect small changes from the background methane concentration. For example, the TROPOMI instrument carried by the European Space Agency’s Sentinel-5P satellite scans a 2600 km wide swath of the surface — twice the length of California — with a resolution of 7 km [30,31]. TROPOMI data is publicly available and has been used for regional emission rate estimation by governments and the atmospheric research community. It is especially well-suited for evaluating large-area diffuse sources due to its high sensitivity and large coverage area. Yet, the 7 km resolution limits this approach to indicating the presence, but not precise location, of most point sources. At the opposite end of the resolution-coverage spectrum, the commercially operated GHGSat satellite has an instrument with 30 m resolution but does not cover as wide an area (and the data is not publicly available) [31]. The Environmental Defense Fund is planning to launch a 140 m resolution instrument onboard their MethaneSAT satellite in October 2022 [32] to complement the capabilities of TROPOMI and GHGSat. In addition, a partnership led by the non-profit Carbon Mapper plans to deploy a constellation of satellites with performance similar to GHGSat by 2025 [33].

If a combination of remote sensing and on-the-ground inspection can provide the resolution needed to pinpoint emissions, the intermittency of emission sources and measurement frequency become the limiting factors for detection fidelity. For example, a study in California using aircraft-based remote sensing to identify and repeatedly survey more than 250,000 methane sources found that emissions from a given source were only observed in one out of every five surveys of the site, on average [34]. Increasing the frequency of surveys via aircraft or on-the-ground inspection can be cost prohibitive, while the return frequency of a satellite is fixed by its orbital path. Alternatively, continuous monitoring using an installed network of sensors can be used to address source intermittency and quickly identify emissions in certain high value settings. Scientific Aviation has developed and commercialized the SOOFIE system for well pad monitoring, and continuing innovations to drive down the cost and power consumption of methane sensors [35] may enable widespread distributed sensor systems in the future.

Improving the spatial resolution and frequency of measurements will also reduce uncertainty in estimates of
emission rates. Academic and industrial studies use either a bottom-up or top-down approach for estimating the methane emission rate from a certain area. A bottom-up approach entails compiling all emission sources in the area and applying an empirical emission factor for each type of source. Bottom-up approaches typically underestimate true emissions, indicating the existence of unaccounted sources and the difficulty of compiling a representative sample of very diverse methane sources [36]. Continuous sampling of typical emissions sources will improve the accuracy of emission factors, and the reduced cost of sensors will allow for a larger and more representative data set to be collected. In contrast, a top-down approach involves measuring small changes in the ambient methane concentration and using inverse modeling to infer the rate and location of methane emissions that would result in this ambient concentration [37]. This modeling approach can either over- or under-estimate emissions, as the accuracy is determined by the accuracy and extent of ambient methane measurements, which are typically remote sensing data. A dispersed network of on-the-ground sensors could provide a sparse but continuous signal to verify and complement the periodic nature of satellite measurements.

Methane mitigation approaches

The ultimate goal of detecting methane emissions is to minimize them. This can be done by limiting the production of methane where it is an unnecessary byproduct, preventing environmental release where this is not possible, and finally by capturing or converting methane after it is released. In general, interventions early in this causal chain are currently the most effective and have greater leverage, while nascent conversion technologies have limited applicability and high cost.

Limiting unintended production: Methane is an unwanted byproduct in the agriculture and waste sectors, and process changes can be used to limit its production [13]. For example, the methane generated by ruminants is influenced by their diet, which can be optimized to minimize methane production while maintaining animal health and productivity [38]. For animals in concentrated feeding operations where diet is strictly controlled, this may be simply substituting corn in place of grass, while for grazing animals, broader land management changes can be used to introduce new grass and shrub species to the area [38,39]. In both cases, this style of feed substitution has the potential to reduce up to 40% of ruminant methane emissions [40]. The addition of supplements to a ruminant’s diet, including various algae species and the recently commercialized products Bovaer and FutureFeed, can be used to alter the microbiome of their digestive system to inhibit methane production, with greater than 90% reductions in some cases [41]. Similarly, new rice cultivation practices are being developed that limit paddy flooding and the subsequent anaerobic soil conditions that result in methane production. Adoption of these techniques can reduce rice paddy emissions by 25 - 30% [42]. Finally, up to 40% of total agriculture and waste emissions could be avoided by reducing the demand for emission-intensive foods (through nutritionally-equivalent replacement of rice, ruminant meat, and dairy) and reducing food waste [42]. Despite being technically and economically feasible, such behavioral changes would still require broad public adoption to achieve this impact.

Preventing release: Interventions to reduce unintended production are specific to the system and process being considered, and there may not be a feasible or practical intervention in every situation. The production of methane from the decomposition of organic matter already in municipal waste landfills is one such system. Sorting and diverting organic waste to composting or anaerobic digestion facilities can prevent the production of methane, but requires costly changes throughout the waste stream — from consumer sorting habits to the construction of new facilities [43]. In many settings, it is more cost-effective to integrate a system into the landfill that captures the methane that is produced and uses it to generate electricity and industrial heat [44,45]. The management of manure and other agricultural waste presents similar challenges and can also be addressed through the use of enclosed manure collection or anaerobic digestion to produce and capture methane [46].

Release prevention is also the most prevalent approach in the oil and gas industry, where methane is often the product in the form of natural gas and where release to the atmosphere is unintentional and a loss of revenue. Repairing leaks or replacing equipment is technically straightforward, yet it may be logistically or practically difficult due to an inability to temporarily shut down critical infrastructure that typically lacks bypasses or redundant systems. For example, 44% of methane emissions at 36 gas facilities in Canada were reduced by a leak detection (based on infrared camera and thermography) and repair survey [47]. Leak detection and repair can even be profitable in some cases, as the value of the gas that is prevented from leaking may more than offset the cost of abatement [48]. The average natural gas price in the period 2017-2021 means that abatement would have been profitable for 45% of emissions [28], while high prices in 2021 meant that almost all options were profitable [49].

Conversion: In cases where these upstream interventions are not possible due to physical limitations, the only remaining approach is to directly capture ambient methane or convert it into carbon dioxide via oxidation. Flaring, the burning of natural gas that leaks out of oil wells, is the most widespread example of methane oxidation. Many oil wells use this approach because it is not technically possible to prevent the production of natural gas during well operation, and it is not economically feasible to build out pipelines to capture it. Leaked natural gas can be nearly 100% methane (or other flammable gases), yet the vast majority of other methane sources have concentrations well below the 4% flammability limit of methane and thus cannot be flared, as the mixture will not burn on its own. Within the oil and gas sector, 28% of emissions are from sources that do not have upstream solutions and that are too dilute for flaring [28]. This challenge is especially relevant for...
natural methane sources where upstream interventions would require disturbing natural environmental systems and where the methane concentration may be orders of magnitude below the flammability limit (10 – 100 ppm). Commercialized catalyst-based technologies have extended the concentration range for conversion down to 0.3–1.0% with a primary focus on coal mine ventilation [50]. Below this, emerging catalyst materials have demonstrated conversion down to 2 ppm (0.0002%) in a controlled environment and could potentially be used to convert methane from these sources without disturbing them [51].

Current strategies for global emissions reductions

In 2018, the IPCC issued a special report assessing the different pathways to achieving the Paris Agreement’s 1.5°C target [52]. Within the set of assessed pathways that stay below 1.5°C, global methane emissions are reduced by a median value of 34% by 2030 relative to the 2020 levels [53]. While the extent of methane emission reductions to achieve any temperature target depends on the assumed reductions of other greenhouse gas emissions, this value may be interpreted as a general benchmark for methane reductions to achieve the Paris Agreement’s 1.5°C target.

Current global climate commitments and policy ambitions are not consistent with the Paris target, especially with respect to this methane emissions benchmark. Yet, an increasing sense of urgency is bringing methane emissions into the international agenda. Increased scientific understanding of the connection between methane emissions, climate change, and public health may also be a contributing factor, as the value of co-benefits can be quantified in cost-benefit analyses. A recent report by the UN Environment Programme predicts that every MT of emissions mitigation will annually avoid 1,400 premature deaths due to ground-level air quality and 400 million lost working hours due to extreme heat [42]. A growing body of work on potential mitigation opportunities has also made this challenge less daunting, at least in the near-term, by showing the extent of mitigation opportunities that are available at present without technical or economic barriers. For example, a recent review by Ocko et al. estimated that 17% of total anthropogenic methane emissions can be mitigated at no net cost, or up to 24% if already-made commitments by oil and gas companies are included [12].

In 2021, the US and EU launched the voluntary Global Methane Pledge (GMP), which has been joined by more than 100 countries representing nearly 50% of global anthropogenic methane emissions [54]. Signatories pledge to reduce global anthropogenic methane emissions by 30% by 2030 as compared to 2020 levels. If the pledge is successful, this 30% reduction in global emissions would aver over 0.2°C warming by 2050 [55]. India, China, and Russia have not committed to the pledge despite jointly accounting for one-third of total emissions [56]. However, China has committed “to develop a comprehensive and ambitious National Action Plan on methane, to achieve a significant effect on methane emissions control and reductions in the 2020s” [57]. Depending on the actions of these countries, a global reduction of 30% may thus require significantly steeper reductions by the participating countries.

While some prominent members of the Global Methane Pledge, including the US and EU, have begun to propose and enact specific policies towards achieving the pledged reductions, most countries lack a concrete policy plan. The following discussion provides a brief overview of three key dimensions of national-scale methane emissions policy — high level regulatory approaches, the utility of monitoring and mitigation technology, and the existing policy landscape — in order to inform efforts to create new and effective policies.

Policy approaches for mitigation

Without voluntary action by stakeholders in methane-emitting sectors, methane mitigation policies may be needed to drive down methane emissions from anthropogenic sources. Broadly, these policies can follow either a market-based approach that creates economic incentives for action, or a regulatory approach that specifies and requires actions.

Market-based policies work by creating economic incentives like royalties, taxes, or cap and trade systems such that the true cost of emissions is internalized. Market-based policies are also promoted as incentivizing innovation by creating a market for new technologies [58]. The most notable example of a market approach in the US, and the first national cap and trade program, is the Acid Rain Program of the 1990 Clean Air Act Amendments. This program not only effectively reduced sulfur dioxide emissions from coal-burning power plants but encouraged the development of breakthrough technologies that reduced the actual national cost of compliance by 30% to 78% from initial estimates [59]. Globally, national market-based policies for methane emissions have yet to be widely implemented, in part because governments do not have the tools to cost-effectively and accurately measure facility-level inventories of methane emissions [60]. Without this information, it is not possible to formulate appropriate tax rates and cap levels nor to monitor compliance.

Instead, current policies tend to follow one of two regulatory approaches: process-based, where the actual equipment, processes, or protocols that should be used are specified; and performance-based, where overall limits are set for facilities. Table II summarizes these two regulatory approaches with examples for the oil and gas sector. Performance-based regulations are similar to market approaches in that they allow individual actors the freedom to decide how to reach their target. Ideally, individuals can take into account their specific situation to find the most cost-effective solution. Yet it also requires accurate measurements for each site, typically by a third party, to inform implementation and verify effectiveness. In contrast, process-based regulations force the adoption of specific solutions that have been previously tested. This reduces the cost associated with measurement, as compliance is typically easier to verify than impact yet requires high confidence in the applicability of prior studies to be effective.
Sawyer et al. shifted to a performance-based approach [64]. As technologies are developed over time, the policy is effectively technology if the performance can be verified. As additional strategies, and it is politically difficult to implement regulations for Hazardous Air Pollutants (2016) (1) as well as the EU (4, 5), increasingly incorporate performance- and market-based elements. The downside to this requirement is that governments, especially of less-developed countries, do not yet possess comprehensive inventories of facility-level methane emissions. In the United States, methane abatement policies enacted prior to 2020 are predominantly process-based with little focus on emissions detection as technologies for detecting and quantifying methane emissions were still nascent. Yet, studies have shown that these regulations have not been effective in curbing methane emissions [61]. Recent advances in aircraft- and satellite-based technologies (among others) now allow for cost-effective emissions detection and quantification at the facility level, laying the groundwork for performance-based regulations to be implemented [64]. Reflecting this, new and upcoming regulations set forth by the Biden-Harris administration [65] (3) as well as the EU (4, 5), increasingly incorporate performance- and market-based elements. Many categories of emissions still lack feasible mitigation strategies, and it is politically difficult to implement regulations that do not have a viable path to compliance. Yet, without the assurance of demand that comes with regulation, there is little incentive for the development and commercialization of new mitigation technologies. To overcome this conundrum, policies have been suggested that do not initially require advanced emissions measurement and mitigation technologies but instead provide incentives for development through adaptable metrics [66]. This could take the form of a process-based policy relying on known (but potentially sub-optimal) solutions that includes a provision to replace or supplant them with new technology if the performance can be verified. As additional technologies are developed over time, the policy is effectively shifted to a performance-based approach [64].

### TABLE II: Characteristics of process-based and performance-based regulatory approaches for methane emissions abatement in the oil and gas sector [61].

<table>
<thead>
<tr>
<th>Process-based approach:</th>
<th>Performance-based approach:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command-and-control mindset</td>
<td>Incentive based on performance or outcomes</td>
</tr>
<tr>
<td>Focus on single components (pump, pipe, tank)</td>
<td>Focus on facilities or companies</td>
</tr>
<tr>
<td>Separate rules for leaks, vents, and flares</td>
<td>Unified target for all emissions</td>
</tr>
<tr>
<td>Regulators write rules</td>
<td>Facility engineers decide how to hit targets</td>
</tr>
<tr>
<td>Measurements not required</td>
<td>Accurate measurements essential</td>
</tr>
<tr>
<td>Compliance, not efficacy, verified</td>
<td>Efficacy verified by a third-party system</td>
</tr>
<tr>
<td>Binary pass or fail</td>
<td>Owners and operators rated quantitatively</td>
</tr>
<tr>
<td><strong>Example:</strong> (USA) Oil and Natural gas; New Source Performance Standards and New Emissions Standards for Hazardous Air Pollutants (2016) (1)</td>
<td><strong>Example:</strong> (Massachusetts, USA) 310 CMR 7.73 Reducing Methane Emissions from Natural Gas Distribution Mains and Services (2021) (2)</td>
</tr>
</tbody>
</table>

### Policy implications of technology availability:
Performance- and market-based policies typically require an accurate third-party system for measuring emissions and verifying compliance [62]. To this end, the UN Environment Programme has launched The International Methane Emissions Observatory to integrate emissions measurements into a single coherent collection [63]. The downside to this requirement is that governments, especially of less-developed countries, do not yet possess comprehensive inventories of facility-level methane emissions. In the United States, methane abatement policies enacted prior to 2020 are predominantly process-based with little focus on emissions detection as technologies for detecting and quantifying methane emissions were still nascent. Yet, studies have shown that these regulations have not been effective in curbing methane emissions [61]. Recent advances in aircraft- and satellite-based technologies (among others) now allow for cost-effective emissions detection and quantification at the facility level, laying the groundwork for performance-based regulations to be implemented [64]. Reflecting this, new and upcoming regulations set forth by the Biden-Harris administration [65] (3) as well as the EU (4, 5), increasingly incorporate performance- and market-based elements. Many categories of emissions still lack feasible mitigation strategies, and it is politically difficult to implement regulations that do not have a viable path to compliance. Yet, without the assurance of demand that comes with regulation, there is little incentive for the development and commercialization of new mitigation technologies. To overcome this conundrum, policies have been suggested that do not initially require advanced emissions measurement and mitigation technologies but instead provide incentives for development through adaptable metrics [66]. This could take the form of a process-based policy relying on known (but potentially sub-optimal) solutions that includes a provision to replace or supplant them with new technology if the performance can be verified. As additional technologies are developed over time, the policy is effectively shifted to a performance-based approach [64].

### Planned policies and actions to meet the GMP goals:
In the US, the Biden administration has introduced the interagency Methane Emissions Reduction Action Plan (MERAP) led by the Environmental Protection Agency (EPA) [65]. Currently, this action plan aims to reduce annual methane emissions by 41 MT from 2023 to 2035 (3). Although the abatement of 41 MT of methane emissions is not enough to meet the GMP goals, the EPA is working on a supplementary proposal with additional measures [67]. This action plan not only has ramifications for methane emissions from the energy, waste, agricultural, and industrial sectors but also encourages the development and implementation of new methane mitigation technologies through performance-based policies. For example, oil and gas operators will be responsible for detecting and fixing methane leaks as well as preventing methane from venting into the atmosphere. Failure to comply will result in charges equaling up to $1,500 per ton of methane emitted, providing a strong incentive for research and development of next-generation technologies to detect and reduce methane emissions. By 2035, this policy alone is expected to reduce methane emissions from the oil and gas sector by about 75% from 2020 levels [65].

The EU is moving forward with a similar legislative agenda as part of the EU Green Deal. In the energy sector, the new EU methane strategy mandates the measurement, reporting, and verification of all methane emissions. It also requires the implementation of leak detection and repair programs as well as the elimination of venting and flaring (4) (defective or improperly used flares may release a large fraction of methane unconverted, making an upstream solution preferable [68]). Within the agriculture and waste sectors, both the EU Green Deal and US MERAP focus on developing markets and applications for captured methane emissions. Increasing the value of biogas will allow economical capture of methane from existing landfills. It will also promote the formation of new waste management systems specific to municipal and agricultural organic waste to produce methane for this market (5) [65]. In areas where the solutions are less clear, both plans seek to promote innovation and the deployment of new mitigation technologies through improved emissions monitoring, educational programs, and incentives (5) [65].
Long-term innovations for deep reductions

Ultimately, halting or reversing climate change would require the global methane cycle to have net-zero or negative emissions to reduce the atmospheric concentration of methane. Because of methane’s short atmospheric lifetime, this would not necessarily require that anthropogenic emissions are net-zero or negative, although a precise determination of a target is difficult due to uncertainty in the trends of natural sources and sinks. The present policy framework of reducing anthropogenic emissions in key industries is aligned with this goal, yet artificially limits the potential solution space under consideration. Additionally, while the policies and technologies discussed in previous sections are a feasible and cost-effective path for the next decade, their total potential is limited because they only target a subset of source types and sectors.

If the intent of policy in the coming decades is to reduce the atmospheric concentration of methane, this focus may need to be expanded to consider all avenues for reducing atmospheric concentration — reducing anthropogenic emissions, creating artificial sinks, and intervening in natural systems — in order to identify those worth pursuing. To complement the previous attention to reducing emissions at the source-level, the discussion here focuses on the modification of natural systems to enhance natural sinks and the creation of artificial sinks.

Enhancement of natural sinks: The largest natural methane sink is oxidation by hydroxyl radicals in the troposphere, the rate of which is governed by the production rate of hydroxyl radicals, which is essentially fixed based on a photochemical process in the atmosphere. It may be possible to increase the concentration of radicals, and therefore the rate of methane removal, through large-scale atmospheric interventions. One such proposal is to disperse iron salt aerosol particles in the troposphere to increase chloride radical concentrations [69]. Interventions of this scale, even if proven effective, present enormous potential for unintended environmental consequences, ethical and moral disputes, and governance challenges. Understanding these risks and consequences is critical for assessing the potential role of these technologies and guiding technical and policy development. A potential case study for developing a research program in this area is the field of solar geoengineering, where a more established, though still nascent, community studies a similar set of benefits, risks, and consequences [70, 71].

The other principal sink of atmospheric methane, microbial oxidation in anaerobic soil environments, accounts for less than 5% of total methane sinks (Figure 1). Given this small size, drastic and lasting changes to a large portion of land area would be needed to have a similar total effect as a small change to the natural atmospheric oxidation rate. At this scale, attempting to influence microbial processes incurs the same potential unintended consequences and ethical uncertainties associated with atmospheric geoengineering.

Artificial sinks: The remainder of deep reduction processes can be described as artificial sinks, whether directly operating on atmospheric methane or applied to reducing specific anthropogenic or natural emissions by co-locating near a source. While these use cases appear similar to carbon dioxide capture and storage, the challenges and technologies are unique. Carbon dioxide capture technologies operate either on high (3 – 20% in the case of flue gas [72]) or low (400 ppm or 0.04% for ambient air) concentration sources and must also sequester or utilize the carbon dioxide. In contrast, the diversity of methane sources calls for a range of technologies that operate along a spectrum of methane concentrations from the 4% flammability limit down to the 2 ppm (0.0002%) atmospheric concentration [73].

The extremely low concentration of many of these sources makes methane exceptionally difficult to capture compared to carbon dioxide, as the energy required and cost of material separation typically scale with the inverse of initial concentration [74]. Yet, methane can be oxidized and released back into the atmosphere, which also avoids the need for permanent storage. Some form of catalysis is required to facilitate the oxidation reaction at these concentrations. It is still likely that the cost of conversion will scale inversely with concentration when considering the total volume of air that must be processed for a given amount of methane.

Within this space, the most advanced technology, including several commercialized systems, focuses on coal mine ventilation air [50]. Underground coal mines are ventilated to prevent the buildup of methane and other hazardous gases that naturally seep from the ground. The exiting ventilation air is typically 0.1 – 1.5% methane, which relaxes the requirements on the catalyst and reduces the size and cost of the reactor [75, 76]. Additionally, the ability to exploit existing air handling infrastructure and operate continuously likely reduces the system cost. Some concentrated animal feeding operations may present similar source characteristics, but most methane sources have a concentration below the limit of these commercial catalysts and present a greater challenge due to intermittency and lack of existing air handling.

At the far end of this spectrum is the direct conversion of atmospheric methane, which, at 2 ppm, would require 20,000 times the air flow to convert the same amount of methane as a source at 4%. A range of catalyst technologies, including photocatalysts and transition metal zeolites, are being developed that can operate over various ranges within this window [77]–[79]. Conversion as low as 2 ppm has been demonstrated under controlled atmospheric pressure and composition with a copper zeolite catalyst [51]. Additionally, synthetic enzymes and bioreactors that mimic methanotrophic organisms show potential for conversion in aqueous environments [80]. None of these approaches have proven on an industrially relevant scale, nor are there policy or financial incentives in place to create viable business models. Real-world testing is critical to understanding the eventual utility and value proposition of these conversion technologies relative to more traditional mitigation tools.
Conclusion
Cumulative methane emissions from human activity account for almost one-third of total global warming, and reducing future emissions is critical for achieving long-term climate goals. More recently, methane has been identified as a key lever for rapidly reducing the impacts of climate change in the short term (20 years). This is due to both the high near-term warming effect of methane, and the ability to mitigate many sources of methane emissions with lower cost and less drastic industrial changes than equivalent carbon dioxide emissions. About 30% of methane emissions, mostly from the oil and gas sector, are straightforward to find and prevent. Within this, a significant portion of emissions from the oil and gas sector could be prevented at no net cost, although implementation of policies and technologies lags considerably. The remaining 70% of emissions are difficult to identify and monitor due to the intermittency, low concentration, and large spatial extent of many sources. Improved methane detection methods with higher spatial resolution and more frequent or continuous measurement are needed to advance from quantifying these emissions to mitigating them. New technology that can capture or convert methane at low concentration is needed in order to mitigate most emissions from agriculture and waste and could be used to offset natural sources. Overall, a wide range of policies centering on emission monitoring and mitigation tools show promise for reducing methane emissions.

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Legislation Cited

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