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Review

A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness

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SUMMARY

Achieving the Paris Agreement 1.5°C target requires a reversal of the growing atmospheric concentrations of methane, which is about 80 times more potent than CO_2 on a 20-year timescale. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report stated that methane is underregulated, but little is known about the effectiveness of existing methane policies. In this review, we systematically examine existing methane policies across the energy, waste, and agriculture sectors. We find that currently only about 13% of methane emissions are covered by methane mitigation policies. Moreover, the effectiveness of these policies is far from clear, mainly because methane emissions are largely calculated using potentially unrepresentative estimates instead of direct measurements. Coverage and stringency are two major blind spots in global methane policies. These findings suggest that significant and underexplored mitigation opportunities exist, but unlocking them requires policymakers to identify a consistent approach for accurate quantification of methane emission sources alongside greater policy stringency.

INTRODUCTION

The Paris Agreement 1.5°C objective cannot be met without reducing man-made methane emissions by at least 40%–45% by 2030 compared with the 2020 levels according to the Global Methane Assessment.[1] The Assessment shows that mitigation of man-made methane emissions is one of the most cost-effective strategies to reduce the rate of warming, while also having a positive impact on air quality. The need for comprehensive CO_2 and targeted non-CO_2 mitigation strategies (e.g., addressing methane emissions) is highlighted by a growing body of literature because combating climate change necessitates tackling short-term (<2050) and long-term (>2050) warming.[2] But instead, methane emissions are increasing faster than at any time since the 1980s[3,4] While our understanding of the reasons behind this increase and the global methane budget[5] is improving, significant uncertainties exist; e.g., regarding the contribution of processes such as wetlands and sinks[6] and fossil methane[7–9] sources.

Man-made methane emissions originate from three sectors: agriculture (enteric fermentation, manure management, rice cultivation, and crop waste burning), fossil fuels (extraction, transport, and use), and waste (solid and liquid), with substantial regional variations. There are significant differences in mitigation potential across the sectors and regions, but full deployment of available mitigation measures would decrease projected 2030 methane emissions by half, with a quarter of cumulative emissions reduction at no net cost.[10] This change would prevent about 0.25°C of additional global-mean warming in 2050 and 0.5°C in 2100. It would require elimination of some sources and minimization of others; e.g., ending fossil fuel emissions, reducing biomass burning, improving landfills, and alternating cattle farming practice.[11]

Methane mitigation has moved from the shadow into the spotlight in 2021 because of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) and the launch of the Global Methane Pledge (GMP) at the UN Climate Change Conference in Glasgow (COP26).[12,13] Although there is a strong case for methane mitigation, accurate emission identification, attribution, measurement and verification is challenging. Global, sectoral, and regional emission estimates remain uncertain, with substantial differences between ambient methane concentration measurements (top-down methods) and emission estimates from individual sources widely used in national greenhouse gas (GHG) inventories (bottom-up) and between independent top-down inventories; e.g., inverse fluxes derived from different satellite observations.[14–16]

While tackling methane emissions is critical to reduce the rate of global warming, surprisingly little is known about methane policies and their effectiveness. Until now, there has been no comprehensive review of global methane policies. In particular, the impact of methane policies ex post, instances of policies used in developing nations, and the interaction between (formal and informal) institutions and policies are topics that have

Table 1. Classification of methane policy instruments

Instrument	Agriculture	Waste	Energy
Regulatory	animal waste utilization, inducing new technologies and change in farming practices (e.g., to minimize agricultural residue burning), target setting	solid waste management regulations, landfill gas management, liquid waste management, target setting	flaring and venting regulations, leak detection and repair (LDAR) regulations, coalbed methane (CBM) ownership and utilization, coal mine methane (CMM) capture, recovery, and utilization, ventilation air methane (VAM) regulations, facility abandonment
Economic	Emissions Trading System (ETS), offset credits, taxes and charges, fiscal and financial incentives, incentives for price-regulated entities		
Information	measurement, reporting, and verification (MRV), technical guidance, certification system, awareness-raising measures		
Complementary	voluntary programs, research and development (R&D) subsidies, green public procurement		

not yet undergone a thorough assessment.[17] Because of the underreporting in official GHG inventories and the lack of publicly available and robust data, studies assessing policy impact are limited and, at times, offer diverging conclusions; e.g., whether the policies lead to a decline in methane emissions. The lack of robust methane data limits better design and evaluation of methane policies.

In this review, we therefore explore the state of the art of methane policies to target the blind spots in our understanding and lay the foundation toward developing effective methane policies. By systematically examining existing methane policies and carrying out a further investigation on existing literature that has explored the effectiveness of methane polices, we found that, despite political declarations (e.g., nationally determined contributions [NDCs]), methane emission reduction remains a largely underexplored opportunity. Only ∼13% (minimum [min.] 10%, maximum [max.] 17%) of global methane emissions are covered by direct methane mitigation policies, while limited policy stringency and reliance on inaccurate emission estimates remain barriers to effective policy. These findings suggest that a consistent approach for accurate identification, quantification, and verification of methane emission sources alongside greater policy coverage and stringency (e.g. measurable objectives and enforcement) must be put into place to realize significant methane emission reduction opportunities.

IDENTIFYING GLOBAL METHANE POLICIES

Introducing methane policy instruments

The starting point of our analysis was identification of relevant policy instruments and creation of the global methane policy database comprising 666 policies. After the initial screening, the number of policies was reduced to 281. Then, the content of policy instruments currently in force (n = 255) was examined to provide further details: (1) the policy aim (emission monitoring or mitigation), (2) policy instrument type and subtype, (3) scope of policies (type of emissions, facility, and part of the supply chain covered), and (4) comparison of policy coverage with methane emissions by region and by country (supplemental information, points 1 and 2).

We define methane policies as actions by governments explicitly aiming to monitor, prevent, or reduce methane emissions from man-made sources. Policies that do not explicitly regulate methane emissions but have material impact on methane emission reduction (e.g., landfill regulations) are also included. On the contrary, policies whose impact on methane emissions is not immediate and material (e.g., land use change) are out of the scope of this analysis. Moreover, the GMP was not included because of its collective nature. Governments use various tools (policy instruments) to purse their policies. However, because the difference between “policy” and “policy instrument” is subtle, those terms will be used interchangeably. While different taxonomies of methane policy instruments exist,[18,19] this study classifies methane policy instruments into four categories: regulatory, economic, information, and complementary (Table 1).

Through regulatory instruments, a policymaker mandates adoption of technologies and operational processes (prescriptive or command-and-control regulation) or specifies the outcomes (e.g., source-level or facility-level emission standards), leaving the choice of the compliance method to the operator (performance based or outcomes based).[18] In the case of performance-based regulations, the level of flexibility depends on whether it introduces an emission level or an emission rate obligation; e.g., emissions per unit of output or input.[20] A standard specifying an emission level is usually more flexible because it can be met by a change in input mix or reducing the output. A clear distinction is not always possible because methane policies usually combine prescriptive and performance-based standards, imposing obligations at a component, facility, operator, or industry level. Hence, in this study, regulations are further categorized based on the type of emissions or behavioral change they are targeting.

Methane regulations are common in the energy sector, especially with regard to flaring and venting, but significant differences in the regulatory approaches exist. While some jurisdictions concentrate on restricting the volume and situations when flaring and venting is allowed by introducing flaring and venting permits (e.g., Texas and Utah) or imposing restrictions/bans on routine flaring and venting (e.g., Colorado and New Mexico), others promote use of the associated gas; e.g., by setting associated gas use targets (e.g., Russia). More recently, jurisdictions have started to combine flaring and venting regulations with provisions mandating the operators to find and fix methane leaks through regular leak detection and repair programs (e.g., US, Canada, and Mexico). Some jurisdictions have introduced regulations specifying the operators’ obligations in relation to facility abandonment (e.g., Argentina and Alberta) and others on creating comprehensive remediation programs (e.g., Colorado's Orphaned Well Program funded by oil and gas operators). The regulations adopted in China to reduce emissions in the coal sector mandate higher coal mine methane (CMM)/coalbed methane (CBM) capture, recovery, and use; e.g., through installation of CMM drainage systems and preferential treatment of CMM power generation projects.

In the waste sector, the regulations focus primarily on landfills and landfill gas management (e.g., European Union [EU], Washington, British Columbia), introducing new monitoring and mitigation requirements for active and closed landfills (e.g., Oregon). There is a growing number of food waste regulations affecting methane emissions, especially in Europe (e.g., France and Italy) and parts of Asia-Pacific; e.g., South Korea introduced a ban on direct landfilling of food waste. In the agricultural sector, the regulations mandate better management and higher rates of animal waste (manure) utilization (South Korea and China) or incentivize biogas/biomethane production (e.g., Denmark, Germany, France, Italy, and China). Regulations can also play a role in inducing new technologies and changing farming practices (e.g., by endorsing the system of rice intensification in Vietnam), while the Indian government introduced a series of regulations to minimize agricultural residue burning.

Economic instruments—emission trading systems (ETS), offset credits, taxes and charges, fiscal and financial incentives, and incentives for price-regulated entities—incentivize the private sector to include pollution abatement into their investment decisions.[20] An ETS limits an aggregate emission level, allowing polluters facing higher abatement costs to purchase allowances from those with lower marginal abatement costs.[20] Methane emissions are covered under seven domestic ETSs: four operating at subnational level (California [US], Chongqing province [China], Quebec [Canada], and Nova Scotia [Canada]) and three at the national level (New Zealand, South Korea, and Switzerland). Most systems include methane from energy and industrial processes, while South Korea and New Zealand also include emissions from the waste sector. Some ETSs include offset schemes allowing generation of transferrable instruments (credits) representing a reduction of emissions by given quantity (e.g., 1 metric ton) and are certified by a government or an independent certification body (e.g., in California's and Quebec's cap-and-trade system). An offset scheme can constitute a separate system (e.g., the Emissions Reduction Fund in Australia).

Taxes and charges are specific payments for every unit of GHG, or methane specifically, released into the atmosphere. When a tax is established, the polluter weighs the cost of reducing emissions against the cost of emitting and paying the tax; as a result, the polluter is likely to implement only abatement measures that are cheaper than paying the tax. Hence, in contrast to ETSs, taxes specify the effective price of polluting but do not ensure a particular level of emissions.[21] Taxes are widely used in the waste sector; e.g., 23 of 27 EU member states introduced a landfill tax with a tax rate ranging from 5–100 €/ton.[22] In late 2022, the government of New Zealand proposed a tax on livestock emissions of methane and nitrous oxide.[23]

Governments also encourage emission reduction through fiscal and financial incentives, such as environmental subsidies, grants and loans, and fiscal incentives (royalty waivers and tax deductions). For instance, government-backed loans and more broadly improved access to credit and financing are key incentives the Brazilian Low-Carbon Agriculture Plan ABC Plan (2010–2020) and Plan for Adaptation and Low CarbonEmission in Agriculture (ABC+) Plan (2020–2030), promoting sustainable agriculture through, e.g., improved manure management.[24] The last subcategory of economic instruments consists of incentives for price-regulated entities designed for specific groups of network operators that are active in the transmission and distribution parts of the gas supply chain, where revenue is subject to the national regulators' decision. Examples of these instruments include the shrinkage incentive (with premiums for exceeding targets for reduction of gas lost in the gas network because of leakage, own use of gas, and theft of gas) and the Environmental Emissions Incentive (EEI) with additional payments for reducing methane emissions below their leakage targets, adopted in the UK.[25]

Information instruments improve awareness of emission and mitigation options among different stakeholders, including companies, consumers, and the general public. Examples of information instruments include measurement, reporting, and verification (MRV), technical guidance, public certification systems, and awareness-raising measures. An MRV system introduces transparent and consistent rules for monitoring, reporting, and verification of emissions. It potentially results in a greater understanding of emission sources and trends, allows tracking progress on emissions mitigation, and ensures greater credibility of regulatory and economic policy instruments. Dissemination of technical information through guidance documents is an example of information instruments aimed at setting standards and reducing the asymmetry of awareness among polluting companies. Technical guidance documents provide information on key emission sources, available emission quantification methodologies, and mitigation practices; e.g., the best available technologies for reducing emissions. Certification systems provide additional information concerning the emission footprint of a given product, which is independently verified, allowing consumers to make informed decisions. While there has been a substantial increase in private certification systems, there are also examples of schemes supported or developed in cooperation with public institutions; e.g., the Carbon-Neutral Brazilian Beef certification launched by the Brazilian Agricultural Research Corporation (Embrapa) and Marfrig to differentiate Brazilian meat in domestic and export markets.[26] Moreover, awareness-raising measures are used to support regulations in the waste sector; e.g., solid waste management rules in India.

Regulatory, economic, and information instruments can be complemented by voluntary programs, research and development (R&D) subsidies, and public procurement. Voluntary programs usually take the form of voluntary agreements or private-public programs. The former is a result of negotiations between governments and industrial sectors that commit to achievement of specific goals. For instance, Dutch offshore oil and gas producers pledged to halve methane emissions in the period of 2019–2020 (reductions from 8,562 tons of methane per year in 2017 to 4,281 tons of methane by the end of 2020) based on a covenant signed by the Minister of Economic Affairs and Climate Policy.[27] Another example is a letter of intent signed by the Norwegian government with agricultural organizations to reduce emissions and increase carbon uptake by a total of 5 million tonnes of carbon dioxide equivalent (Mt CO_2eq) between

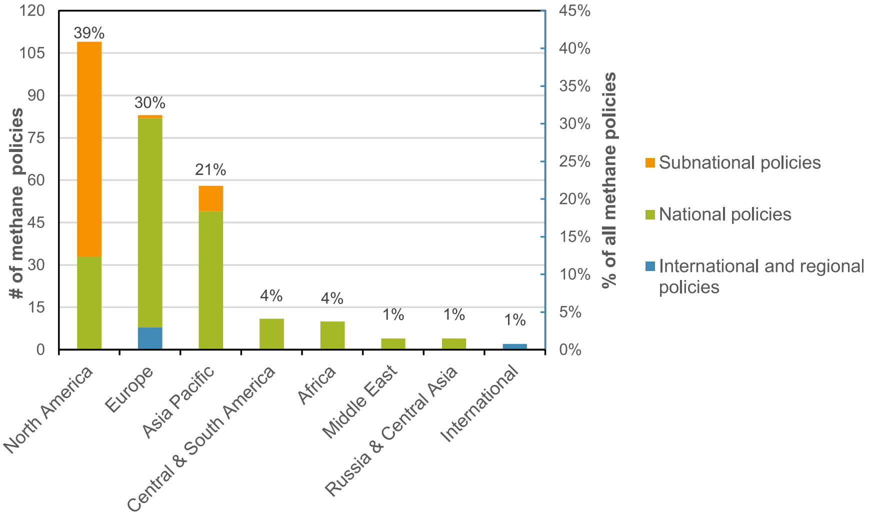


Figure 1. Methane policies by region adopted at the subnational, national, and international/regional level

The number of policies presented in the figure is 281, and the majority of them (90%) have been adopted in three regions: North America, Europe, and Asia-Pacific. The left axis shows the numbers of methane policies, and the right axis shows the percentages.

2021 and 2030.[28] Public voluntary programs involve a government regulator developing programs in which industry and firms may choose to participate on a voluntary basis. In some cases, voluntary programs help regulators gain insights ahead of implementation of regulatory standards; e.g., the proposed EU methane regulation builds on the voluntary Oil & Gas Methane Partnership 2.0 (OGMP2.0) reporting standard. Another complementary instrument is R&D subsidies, targeted funding for development of detection, quantification, and mitigation technologies, stimulating technology innovation and creation of markets for new technologies. In some cases, dedicated institutions are set up to administer such programs; e.g. the Brazilian Agricultural Research Corporation (Embrapa).

Although the choice of a specific policy instrument is an important decision in policymaking, a distinction should be made between effective policy formation and how effectively policies are implemented (putting new rules into practice) and enforced (ensuring that policy violators are brought back into compliance via supportive or punishing actions).[29] Implementation and enforcement of a well-designed regulation require broad and constant political commitment, an institutional capacity, independent verification, and the commitment of regulated entities to follow the rules, which may be hampered by a number of factors, including corruption. Hence, the effectiveness of the same policy instrument may be different depending on its design and stringency but also whether and how it is implemented and enforced and whether it leads to any unintended policy consequences. Before discussing these issues, the next section presents the major advancements in methane policies.

Three regions drive major policy developments

281 policies directly aimed at reducing methane adopted or expected to be adopted between 1974 and 2024 were included in the database (supplemental information). The database comprises policies adopted at international, regional (EU), national, and subnational levels. Almost half of them (n = 138 or 49%) target methane emissions arising from fossil fuels (coal, oil, and gas), where 42% (n = 117) of policies target biogenic methane originating from the agriculture and waste sectors. The remaining 9% (n = 26) cover fossil and biogenic methane emissions. 255 are currently in force; the remaining 26 policies include terminated policies (10), revoked policies (10), and six policies that have been proposed but are not yet finalized; e.g., the proposed EU methane regulation. 70% of revoked policies targeted emissions in the oil and gas sector, while economic instruments were the most frequently revoked, accounting for half of all repealed policies.

Ninety percent of identified national policies have been adopted in three regions: North America (39%), Europe (30%), and Asia-Pacific (21%) (Figure 1). This contrasts with limited policy developments in Central and South America, Africa, the Middle East, Russia, and Central Asia accounting for the remaining 10%. In some regions (e.g., North America), policy adoption is driven by developments at the subnational level (US states and Canadian provinces), in contrast to other regions, where national and regional (EU) policies prevail. The Global Methane Initiative and the Kyoto Protocol's market-based instruments Clean Development Mechanism and Joint Implementation have been identified as the only policy instruments adopted at the international level, but the role of the Clean Development Mechanism (CDM) role has diminished since 2011.[30]

These findings suggest that new regional and national policies are necessary to unlock methane mitigation opportunities in Russia and Central Asia, the Middle East, Africa, Central and South America, and parts of Asia-Pacific. This is important because of the contribution of those regions to methane emissions globally (~80% vs. 20% share of North America and Europe),[31] their dominance in global fossil fuel production (North America and Europe account for the remaining ~30% of global oil and gas production and ~13% of coal production),[32] and faster economic growth projections in emerging economies located in those regions than in advanced economies (3.7% vs. 1.1% in 2023), likely to drive higher consumption.[33]

Breakdown of policies by year of adoption shows a gradual increase in methane policies since 1974 with a peak in 2018 (Figure 2). The observed increase coincides with the 2016 North America Leaders' Summit, during which Canada, Mexico, and the US pledged to reduce methane emissions from their oil and gas sectors by 40%–45% by 2025 (compared with 2012 levels) by adopting respective methane regulations, urging other Group of 20 (G20) members to make similar commitments.[34] Moreover, the increase in the number of adopted methane policies after 2000 is accompanied by more frequent termination of policies, which may suggest a lack of political consensus

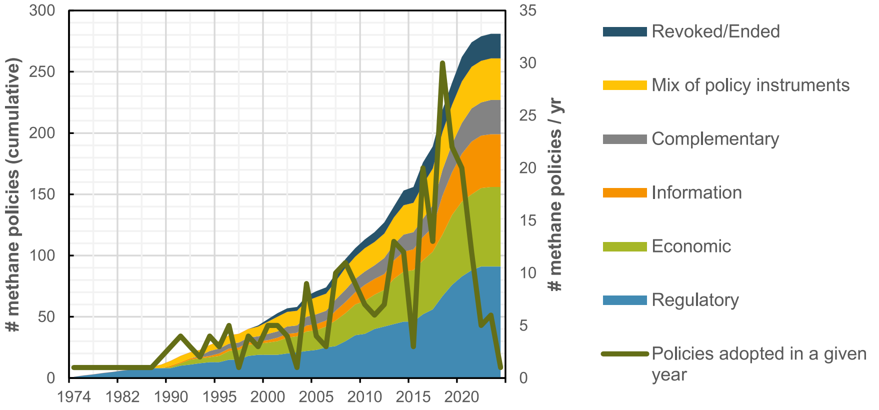


Figure 2. Methane policies adopted/expected to be adopted between 1974 and 2024

The number of policies presented in the figure is 281. The number of policies has been increasing since the 1970s, with a peak in 2018, when 23 policies were adopted. The primary axis shows the number of policies (cumulative), and the secondary axis (dark green line) shows the number of policies adopted in a specific year.

over the necessity to reduce methane emissions. Hence, in case of a conflict, other policy objectives (e.g., economic development) prevail.

To better characterize methane policies, we divided the policies based on their aim (emissions monitoring, reduction, or both) and type of policy instrument (regulatory, economic, information, and complementary) and 25 subtypes (Table 1). The majority of identified policies focus on emission prevention and reduction, with only 1 in 5 adopted with the explicit objective to improve emission monitoring. This is important because, in some sectors (e.g., oil and gas), the remaining portion of the reduction potential likely could not be realized without improved emission monitoring. Despite recent studies showing consistently that reporting of methane emissions (e.g., in bottom-up inventories) is inaccurate and underestimated,[35–37] little has been done to improve it. The continued reliance on inaccurate emission estimates constitutes a barrier to effective policy.

Policymakers designing methane policies more often choose regulatory (35%) and economic (25%) instruments than other types of policy tools: information (17%) and complementary (9%) or mixes of policy tools (14%). This trend is consistent with a shift in climate policies toward regulatory and carbon pricing instruments at the expense of information policies and voluntary efforts.[38–40] However, significant differences between policies targeting fossil and biogenic methane exist (Figures 3, S1, and S2). Regulations are more frequently used to address fossil than biogenic methane because they account for 41% of all policies targeting fossil methane but only 25% in the case of biogenic methane. With economic instruments, taxes and charges are more common for biogenic than fossil methane (11% vs. 3%), where fiscal and financial incentives are more common (12%). Mixes combining different policy instruments (e.g., landfill requirements and landfill tax or a combination of a regulation, financial incentives, and awareness-raising campaigns to address crop waste burning) are more commonly used in addressing biogenic emissions.

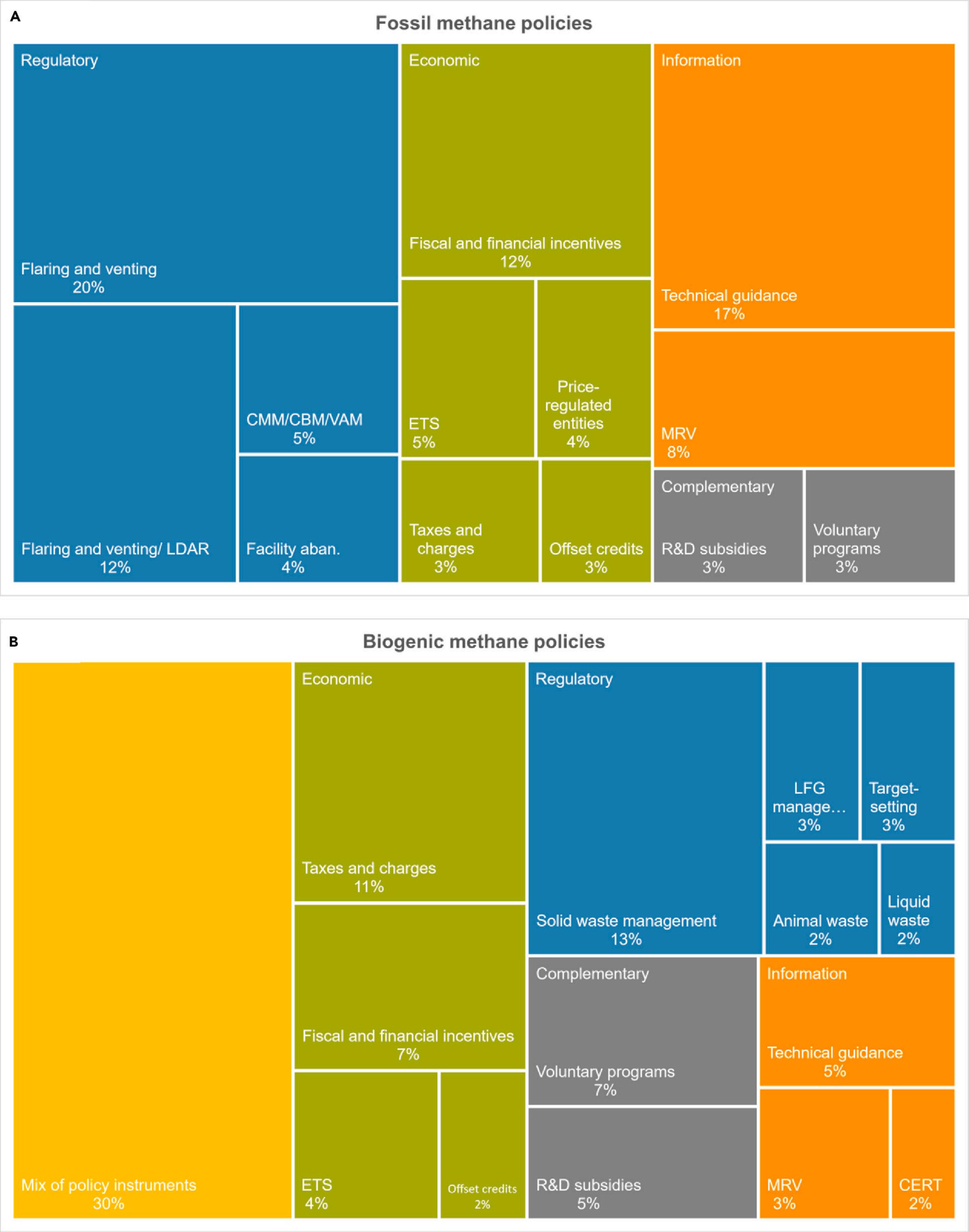
IDENTIFYING THE BLIND SPOTS IN GLOBAL METHANE POLICIES

To identify gaps in existing methane policies, we analyzed their scope in terms of type of emissions, facilities, and part of the supply chain covered under those policies and compared them with regional emission estimates (Figure 4). While the number of policies has increased over the last years, we calculated that only ∼13% (min. 10%, max. 17%) of global methane emissions are currently covered by direct methane mitigation policies (emissions covered under regulatory and economic policy instruments aimed at reduction of methane emissions), with significant differences across regions and sectors (Figures S3 and S4). The focus on regulatory and economic policy instruments (to ensure higher accuracy of our estimate) together with language barriers may explain the low share of policies adopted in some regions; e.g., the Middle East. Moreover, some countries located in this region (e.g., Kuwait, Saudi Arabia, and Qatar) have relatively low emissions from the oil and gas industry, which contrasts with methane-intense oil and gas production in countries such as Iran, Turkmenistan, and Oman.[41,42]

The policies in the energy sector concentrate on reduction of emissions from the largest sources. In the case of the oil and gas sector, emissions from burning of methane (flaring) followed by intentional release of methane (venting) are the major and most frequently regulated types of emissions. One example is resolution 806/2020, establishing procedures for control and reduction of flaring and waste of natural gas and oil during exploration and production, issued by the Brazilian National Agency of Petroleum, Natural Gas, and Biofuels (ANP), which superseded regulations adopted in 2000.[43] An increase in leak detection and repair (LDAR) regulations targeting fugitive emissions coincides with the improvements in methane detection and quantification technologies over the last decade.

Moreover, the majority of identified policies (n = 110) focus on upstream emissions (production, gathering, and processing) and decrease along the supply chain, with only 6 identified policies targeting end-use emissions. Further, only few policies (n = 3) aiming at methane emission reduction upon facility abandonment (e.g., through identification and repair of leaking plugs) have been identified in the oil and gas and coal sector. Emissions from underground coal mines are targeted by policies almost three times more frequently than surface mines. This may be due to several factors. Emissions from surface mines are diffused over a wide area, constituting an area source; as a result, those emissions are usually assumed to be lower than emissions from underground mines (point sources) and, hence, are rarely measured directly. Moreover, while surface-mine methane can be mitigated (pre-mine drainage), this method is considered infeasible in many jurisdictions.[44]

The lower number of identified policies in the coal sector could be partly explained by the fact that coal production, trade, and



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the resulting emissions are more concentrated than with oil and gas, with only a few major coal producers and consumers. Hence, there are fewer jurisdictions and regulators concerned with this issue. Moreover, it could be due to the perception that closure of coal mines minimizes or even eliminates all emissions. Hence, in countries with coal phase-out policies, introducing additional obligations with regard to methane emission control may be considered an undue burden on coal mine operators, potentially forcing some of them to terminate their operations before the agreed phase-out date. Finally, methane emissions arising from the oil and gas supply chains are heterogeneous and dispersed across the supply chain operated by different types of companies, including price-regulated companies. As a result, different types of policies and regulations may be needed to adjust to the specificity of each segment, whereas coal mine emissions arise from a limited number of point sources, which are geographically much more concentrated.

In agriculture, the policies target mostly emissions from animal waste (manure), which, globally, is a smaller source of methane emissions than enteric fermentation. This may be explained by the fact that technologies utilizing manure for energy production (e.g., anaerobic digestion) are widely available partly because of policy support for this renewable energy source; e.g., feed-in tariffs for biogas production. Strategies to mitigate emissions from enteric fermentation (animal and feed management, diet formulation, and rumen manipulation) are not yet widely used, and the barriers to their wide-scale adoption are not well understood.[45] As a result, emissions from enteric fermentation are rarely targeted by any policies despite constituting the major source of methane emissions in agriculture.

The policies in the waste sector target mostly solid waste, especially landfills, but there is a growing number of policies focusing on biowaste prevention, collection, and management; e.g., food waste regulations. The management of liquid waste is also frequently overlooked. In most subsectors, only a few countries had methane policies in place 20 years ago. While the situation has improved over the last decade, it is insufficient even to ensure a country coverage consistent with GMP membership, which now has 150 signatory countries (Figure 5).[46]

This suggests that, in jurisdictions with fossil methane policies in place, further mitigation opportunities include emissions farther along the supply chain (e.g., emissions from liquefied natural gas [LNG] carrier ships[47] and emissions from transmission, distribution and end use); emissions from coal mine ventilation shafts, the major source of emissions from the coal sector; and finally emissions from surface coal mines, because recent measurements suggest that they may be a significant source of emissions.[48] Further emission reductions could be achieved by regulating methane emissions at each stage of project life, including requirements for new facilities as well as abandoned and inactive facilities. In the case of biogenic methane policies, additional mitigation opportunities include emissions that are up the supply chain (e.g., biowaste prevention), from biogas/biomethane plants and supply chain segments,[49,50] and waste water treatment facilities.

Moreover, effective policies targeting rice cultivation and biomass burning (burning of crop waste residues such as rice paddy straw) are missing in selected regions; e.g., China, South Asia (especially India) and South East Asia, Korea, and Japan account for 87% of emissions from rice cultivation.[14] But crop waste burning remains a concern in other regions.[51] While open crop field burning has declined globally, it is on the rise in densely populated agricultural areas in China and India.[52] Biomass burning leads to climate change and emissions of short-lived climate pollutants, but it also contributes to poor air quality and imposes a significant health burden.[53] It has been one of the major public concerns in some regions (e.g., in northwestern India [Punjab, Haryana, and Uttar Pradesh]) that are largely based on a rice-wheat cropping system. While Indian federal and state rules (e.g., advisories, bans, and incentive systems) have been adopted since 2014, they have been only partially enforced.[54] In particular, a better understanding of the reasons behind low effectiveness of the policy interventions in India would be instrumental to other jurisdictions.

While options to reduce emissions from enteric fermentation exist, they are not widely adopted. Countries with significant livestock production (e.g., Australia, Brazil, Canada, Ireland, the Netherlands, New Zealand, and the US) continue to focus on providing R&D funding and supporting international research initiatives; e.g. the Global Research Alliance on Agricultural GHGs.[55] Another challenge, shown by Arndt et al.,[45] is that full adoption of the most effective mitigation strategies will not be sufficient to meet 2050 climate targets because CH_4 mitigation effects are offset by projected increases in methane emissions as a result of higher milk and meat demand in low- and middle-income countries. Leahy et al.[56] suggest that this challenge can be addressed through adoption of demand-side policies complementing efforts to reduce emission intensity of agricultural production, highlighting another blind spot in government approaches to methane emission mitigation.

Fossil methane policies are less stringent than biogenic methane policies

While the previous section outlined the number of policies, the following assesses the strength, or stringency, of the policies currently in force. To do so, we analyzed the content of policies in terms of six criteria:[57] policy objectives, scope, integration with other policy instruments, costs, implementation, and monitoring (SI: Table S2). While the effectiveness of policies can be assessed in different ways, the selected approach has been designed specifically to assess climate policies and denotes equal attention to policy design (objectives, scope, and integration with other instruments) and policy implementation (costs,

Figure 3. Fossil and biogenic methane policies currently in force by type of policy instrument

(A and B) The total number of policies is higher than 255 (Introducing methane policy instruments) because some policy instruments cover more than one emission source (percent of total; A, n = 146; B, n = 121). CBM, coalbed methane; CMM, coal mine methane; VAM, ventilation air methane; Facility aban., facility abandonment; ETS, emission trading system; LDAR, leak detection and repair; MRV, measurement, reporting, and verification; R&D, research and development; LFG, landfill gas; INT, inducing new technologies; CERT, certification. Regulatory and information instruments are more frequently used to address fossil methane emissions than biogenic methane, where a mix of policy instruments (e.g., regulatory and economic) is more prevalent.

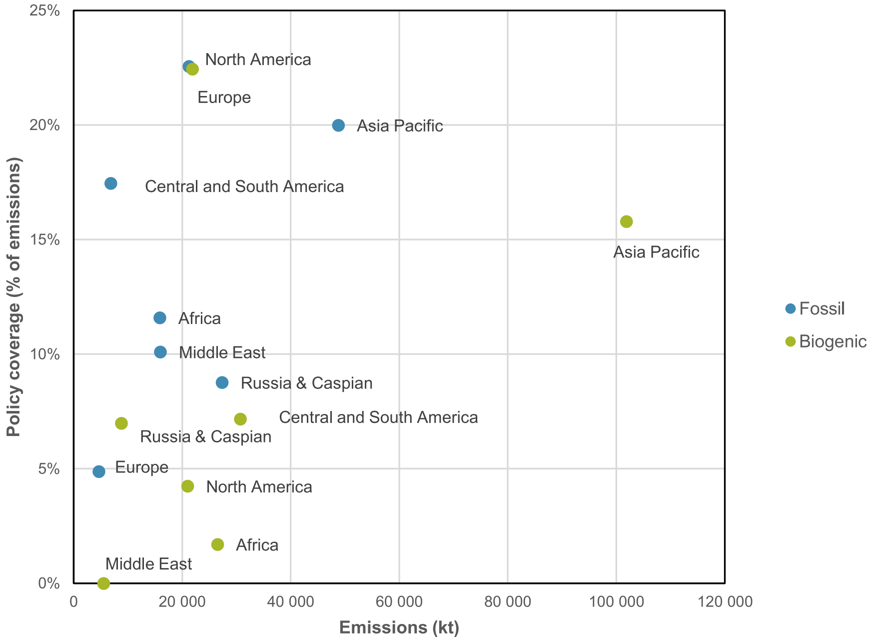

Figure 4. Methane policy coverage: Percentage of emissions covered by direct methane mitigation policies

Only ~13% of global methane emissions are currently covered by direct methane mitigation policies, with significant differences across regions and across biogenic and fossil sources of emissions. Data source: International Energy Agency (IEA).[43]

implementation, and monitoring). Each policy is assigned a specific score, which allows us to rank them and compare the scores of different policies within each sector and region (Figure 6; Table S3).

Analysis at the sectoral level shows that the stringency of policies targeting fossil methane (mean [M] = 0.32, SD = 0.13) is lower than that targeting biogenic methane (M = 0.38, SD = 0.13). However, the stringency of biogenic methane policies is mostly driven by policies targeting animal and solid waste (M = 0.37, SD = 0.11), which contrasts with other agricultural policies; e.g., targeting enteric fermentation (M = 0.29, SD = 0.12). Hence, the sub-sectoral analysis provides a more nuanced picture, with waste policies being the most stringent (M = 0.37), followed by oil and gas policies (M = 0.33, SD = 0.13), agricultural policies (M = 0.29), and coal policies (M = 0.25, SD = 0.10).

There may be several reasons for the difference in stringency between biogenic and fossil methane policies, relating to the opposition of the fossil fuel and agricultural industry to new policies that raise the cost of production for industries facing international competition,[58,59] the relative importance of those industries to national and subnational economies,[60] and energy and food security/rural poverty considerations.[56,61] But it may also be a result of a one-sided focus on marginal abatement cost (MAC) curve projections, leading some policymakers to direct insufficient attention to, e.g., barriers to policy implementation. While the MAC curve is a useful tool for policymaking, policymakers should be mindful of its assumptions and limitations to reach a balanced decision.[62] MAC curve-based projections help to identify and rank the financial cost and abatement benefit of individual mitigation actions, showing which options have a low or negative cost and which have the largest mitigation potential given a set of assumptions regarding time horizon, geographic focus, energy prices, baseline emissions, new technology learning rates, and discount rates.[63] But the regulated entities may not always be able to take all cost-effective measures as some technologies may not be widely applied because they are associated with a high risk of failure, or due to information barriers (e.g., principal/agent problem or split incentives).[64] Hence, the reduction of fossil methane requires more stringent regulatory and economic instruments addressing major barriers to policy implementation.

LIMITED EVIDENCE OF THE EFFECTIVENESS OF POLICIES

Here we investigate the effectiveness of implemented policies in terms of methane emission reduction and the cost of their implementation. A systematic review of academic and gray literature was conducted (supplemental information), but because of limited evidence pf the impact of policies on methane emissions in agriculture and waste, we are only able to focus on fossil methane policies. Seventeen studies were assessed, which concentrated on five groups of policies: flaring regulations, LDAR programs, comprehensive methane regulations combining flaring/venting and LDAR, and coal mine methane regulations (Table 2). However, this literature review could be limited because we mostly relied on information freely available in English; hence, the study may not fully capture policy developments in developing economies because of language barriers (supplemental information).

Studies analyzing the effectiveness of methane policies offer a limited evidence base for policymaking because their conclusions appear to differ depending on the data used for analysis. In two cases, analysis based on use of bottom-up data and operators' self-reporting led to different conclusions than analysis based on satellite observations. Lade and Rudik[83] found that the flaring regulations adopted by the North Dakota Industrial Commission (Order 24,665) were effective in reducing flaring, although similar mitigation results could be achieved at a lower cost if taxes were applied. This study, using well-level data on oil firm operations, concluded that the well operators reduced flaring rates by 14%–20% percentage points, in line with the targets set in the regulations. But a later study by Lee[78] using satellite imagery data concluded that the reduction in flaring was overstated by 5.6% (1/3 of the achieved reduction of 16.8%) because the regulated entities were purposefully misreporting their emissions.

Similarly, Gao et al.[65] used bottom-up inventory data to find that China's regulations have curbed the growing CMM emissions, leading to a 37% decrease (2010–2019) with a peak in 2012. Conversely, Miller et al.[69] used the data from the

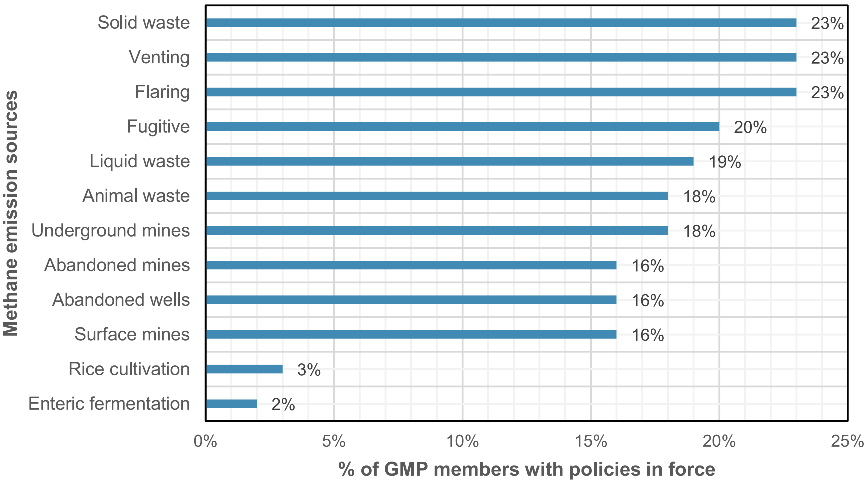

Figure 5. Country coverage: Percentage of Global Methane Pledge (GMP) countries with direct methane mitigation policies in force/proposed by specific emission sources

Emissions associated with venting, flaring and solid waste are the most frequently targeted by policies, in contrast to emissions associated with rice cultivation and enteric fermentation.

Greenhouse gases Observing SATellite (GOSAT) satellite to suggest that China's CMM regulations had no significant impact; methane emissions from coal mining continued to increase by 1.1 ± 0.4 teragrams (Tg) CH_4/year $^{-1}$ between 2010 and 2015. This also suggests that publicly available data from satellites have begun to unveil information on emissions that were previously opaque. Other studies using top-down and bottom-up methods report an increase in methane emissions from China with hotspots over coal-mining regions (e.g., Shanxi, Hebei, and Heilongjiang)[84] and a significant contribution of these emissions to the overall uncertainty of regional methane budget estimates[85] in the early 2000s.

However, there is more alignment between studies looking at the effectiveness of flaring regulations in Russia adopted in 2009 through Decree 7, requiring 95% of associated petroleum gas (APG) to be utilized.[61] Analyses using bottom-up and top-down data observed that, despite the decrease in associated gas flaring in the first years after the regulation was adopted, the 95% utilization target was unlikely to be met/has not been met.[71–75] In 2012, Decree 7 was replaced by Government Decree 1148, introducing higher fines for exceeding the limit but also significant exemptions to the 2009 rules; e.g., for new oil fields. Unclear metering practices undermined by a lack of obligation to install flow meters was one of the reasons explaining why the flaring limits were ineffective.[71–75] Although the costs of installing flaring meters are considered to be low, some companies continued to use calculation methods, which allow approximation and may not account for higher flaring events, such as emergency flaring.[72] Moreover, inconsistent enforcement undermined by a lack of political consensus has further compromised the implementation of flaring regulations in Russia and Nigeria.[50,51]

Two studies have examined the effectiveness of LDAR regulations: quarterly LDAR inspections with US Environmental Protection Agency (EPA) Method 21 under California state-wide regulations targeting oil and gas upstream and natural gas midstream emissions (storage and transmission) and optical gas imaging-based LDAR surveys at 36 upstream facilities in Alberta, Canada.[79,80] Despite significant differences in policy design and the resulting limitations, both papers call for frequent, comprehensive, low-cost, and rapid LDAR programs. This is because of two factors: the high frequency of new leaks and a highly skewed leak-size distribution with a dominance of tank-related emissions. As a result, LDAR regulations could be designed in a way that ensures broad coverage of emissions across facilities and component types, with higher frequencies of monitoring for components/regions/times with higher emission risks.[79]

Despite the increasing importance of accurate quantification of methane emissions articulated in the academic literature, monitoring obligations involving emission measurement are rare, undermining a gap in the current regulatory practice. Only a few countries, except for Nigeria and countries in North America and Europe, have adopted provisions requiring operators to measure or estimate all flaring and venting volumes and submit the information to the regulator on a regular basis.[86] Moreover, recommendations to improve the coverage and robustness of reported data feature frequently in the literature on waste and agriculture.[87–89]

The results of this review suggest a need for expanded investigation of the effectiveness of different types of policies in reducing methane emissions. Currently available studies are limited and focus only on the energy sector in a few regions (North America, Russia, and China). Because of the existing discrepancies between the bottom-up and top-down inventories, further studies investigating the effectiveness of methane policies should combine both approaches to better understand the reasons behind discrepancies.

Designing and assessing policies despite uncertainties

Design and assessment of the effectiveness of methane management strategies and policies are clearly hindered by challenges related to measurement and verification of methane emissions; e.g., the lack of a credible baseline. Significant underreporting of methane emissions in some sectors (e.g., energy sector emissions are 70% higher than the official government reporting according to the IEA estimates[90]) may give the false impression that the problem is not serious enough to attract the policymakers' attention and to justify policy intervention. Moreover, the government and businesses may be encouraged to provide higher estimated baseline emissions to emphasize the effectiveness of a measure or a policy. Without a comparison of scenarios "with" and "without implemented measures/policies," assessing policy effectiveness is challenging.

The measurement challenge hinders the ability to verify emissions reported under existing policies and regulations. On the

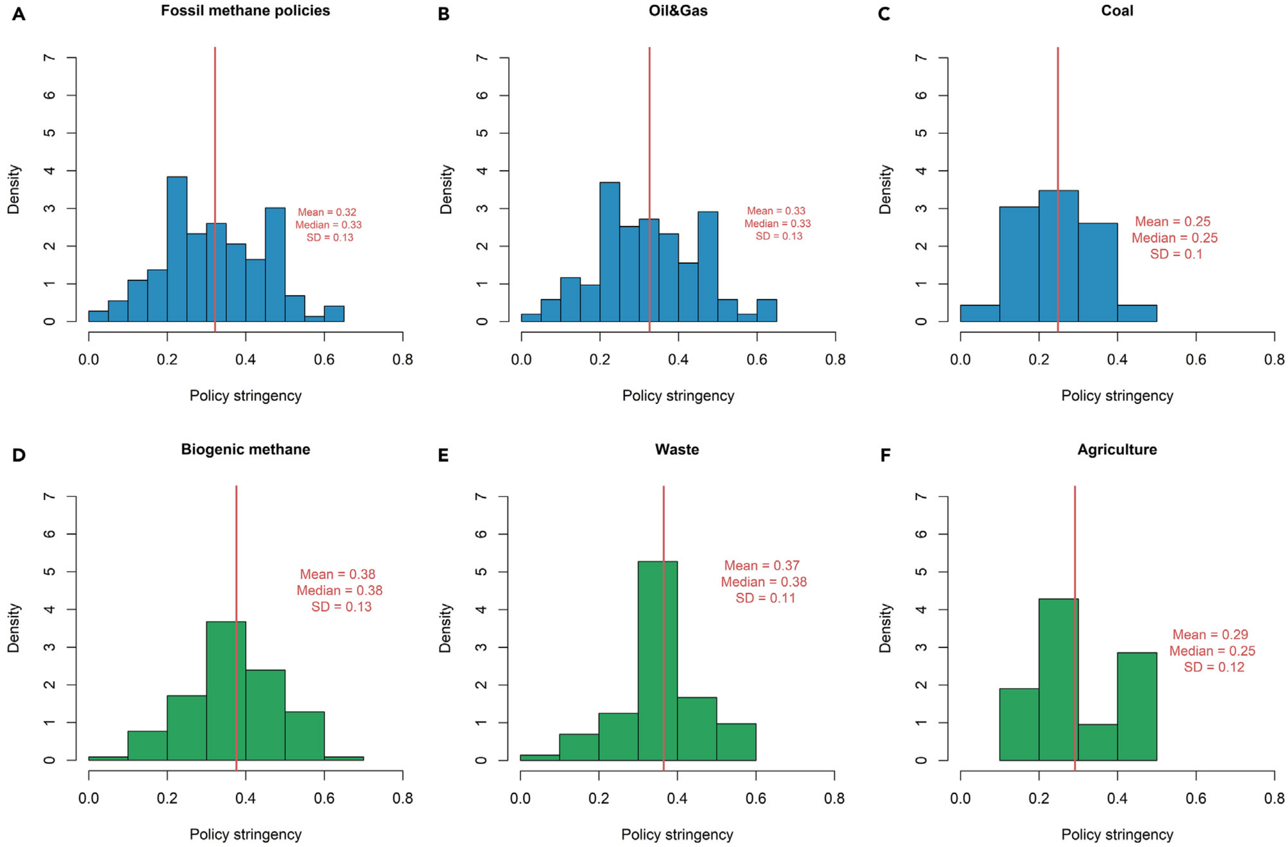

Figure 6. The stringency of methane policies (regulatory, economic, monitoring, and complementary) across different sectors
Shown are the mean (M), median, and standard deviation (SD).
(A and D) Fossil methane policies (A) tend to be less stringent than biogenic methane policies (D).
(B and C) Among fossil methane policies, policies adopted in the oil and gas sector (B) are more stringent than policies adopted in the coal sector (C).
(E and F) Among biogenic methane policies, policies adopted in the waste sector (E) are more stringent than policies adopted in agriculture (F).

contrary, independent verification may be a significant driver of compliance and credible proof that the adopted policy is effective. But there are diverging perspectives on what verification should and should not entail because no methane-specific verification standard exists, and the capacity of third-party verifiers is limited, especially outside of North America and Europe.[91] The recent developments in methane measurement technologies contribute to tackling this challenge, enabling wider use of top-down methods involving measurement of atmospheric methane concentration over a specific region using a wide range of tools (fixed ground monitors, mobile ground monitors, unmanned aerial vehicles [UAVs], aircraft, and satellite monitoring) in combination with atmospheric transport models to estimate an emission rate and attribute it to a specific source. Apart from the technology, there are other design features supporting effective monitoring and verification: robust and frequent monitoring/verification ensuring that the data collected are accurate and reflective of the compliance status of the facilities; clear boundaries and defined measurement/verification protocols; requiring responsible corporate officials and third-party verifiers to certify the accuracy of the monitoring, reporting, and verification; and penalties for misrepresentation or fraud.[92] Together, robust monitoring, reporting, and verification are essential in driving compliance, making methane policies more effective.

The literature offers suggestions how to design effective methane policies despite the difficulties with accurate emissions quantification. They can be grouped into three categories: (1) using a mix of policy instruments involving GHG pricing, (2) changing the regulatory approach (performance-based instead of prescriptive regulations), and (c) focusing on super-emitters. The existing policies could be improved by designing a mix of policy instruments introducing GHG pricing (e.g., regulatory and economic)[87,93,94] or linking a few instruments within the same category (e.g., tax and cap-and-trade system).[95,96] Additionally, taxes could be more effective by changing the object of taxation; e.g., output taxes (or input taxes) levied on agricultural products may be more cost-effective than “taxes on emissions as such,” alleviating the challenges related to emission monitoring and limited emission intensity mitigation options in agriculture.[97] Despite a substantial body of academic literature supporting the economic effectiveness of GHG pricing, taxes are often politically infeasible to implement; e.g., because of problems to gain and maintain political support.[98] This is confirmed by this analysis showing that GHG pricing instruments, especially cap-and-trade systems, are the most frequently repealed policy types.

One of the recommendations suggested in the literature focusing on the oil and gas sector is use of performance-based instead of prescriptive regulations.[81,99] By setting

Table 2. Literature review results summary

Policy	Entry into force	Jurisdiction	Policy instrument	Effective	Ineffective/partly effective
CBM/CMM drainage and utilization	2010	China	Regulatory/ economic	Gao et al.[65]	Yang[66] IEA[67] Tao et al.[68] Miller et al.[69]*[a] Cheng et al.[70]
95% associated petroleum gas (APG) utilization target (Decree 7, Decree 1148)	2012	Russia	regulatory		Loe and Ladehaug[71] Korppoo[72] Zhizhin et al.[73]* Ialongo et al.[74]* Crowley-Vigneau et al.[75]
Associated Gas Reinjection (Continued Flaring of Gas 1984) regulation The Nigeria Gas Flare Commercialization Program 2017	1985 2017	Nigeria	regulatory/ economic		Olujobi et al.[76]
Flaring regulations (Order 24,665)	2014	North Dakota (US)	regulatory	Lade and Rudik[77]	Lee[78]*
Leak detection and repair (LDAR)	2018	California (US)	regulatory	Cheadle et al.[79]	
LDAR	2020	Alberta (Canada)	regulatory	Ravikumar et al.[80]	
2012 and 2016 New Source Performance Standards	revoked	US	regulatory		Ravikumar and Brandt[81] Kleinberg[81]
Regulations Respecting Reduction in the Release of Methane and Certain VOCs (SOR/2018-66) and Directive 60	2020/2023	Canada	regulatory	Johnson and Tyner[82] (SOR/2018-66)	Johnson and Tyner[82] (Directive 60)

[a] Papers using remote sensing data are marked with an asterisk.

performance-based leakage targets (e.g., mass-based [absolute emissions cap] or rate-based [based on system throughput]) combined with an appropriate incentive structure, the operators are expected to reduce methane emissions faster. Outcome-oriented regulations may be more cost effective because they are technology agnostic and so can support technology innovation. However, performance-based regulations rely on accurate emission monitoring (characterization of baseline emissions, accurate quantification of emissions, and third-party verification of compliance), which may limit their wide application.

Another strand in the literature suggests focusing on super-emitters; that is, the highest-emitting facilities.[100] Methane emissions are highly variable, and the majority of emissions occur from a small number of large sources (highly skewed leak-size distribution). These large emitters may be continuous or intermittent and may change over time but are not always accounted for in the GHG inventories. Policies focusing on fewer but larger sources could be more cost effective than the same rules applied uniformly across all the emitting sources.[101] This observation is backed up by Johnson and Tyner,[82] who concluded that the 2018 federal regulations in Canada are expected to result in ∼26% more methane mitigation at full implementation than provincial regulations in Alberta (Directive 60). The federal regulations impact fewer sites but achieve higher total methane reductions because of use of a “potential to emit” threshold exempting small sites handling limited gas volumes. It has significant implications for how methane policies should be designed and for compliance monitoring.[102]

However, super-emitter policies remain rare. This may be because such policies are difficult to implement: how are super-emitters classified, and how are they detected?[100] Moreover, detection across all facilities is necessary regardless of the policy option, and there are also benefits from abatement of relatively low-emitting sources. It is likely that super-emitter policies will become more common with the launch of a methane emitters global monitoring tool[103] under the proposed EU methane regulation and the Super Emitter Response Program[104] under the US EPA’s Supplemental Proposal to Reduce Pollution from the Oil and Natural Gas Industry. Both programs focus on early detection of super-emitters and ensuring prompt response by the operators to eliminate the detected super-emitter emissions events. Although the presence of super-emitters has been demonstrated across all methane-emitting sectors (agriculture,[105,106] waste,[36,107] and energy[108–112]), no papers discussing the design of super-emitter policies in agriculture and waste have been found. This is likely due to the focus on reducing energy-related emissions and lower numbers of super-emitters in those sectors than in the energy sector.

Avoiding unintended policy consequences

Apart from recommendations on how to design better methane policies, the literature offers examples of policy interventions that led to unintended or undesirable consequences. A common problem relates to policies with a narrow focus, which may lead to higher emissions from unregulated sources. One example are policies aiming to limit associated gas flaring (gas that is co-produced from an oil well). Calel and Mahdavi[113] show that policies focusing only on limiting flaring can result in shifting to more harmful (but difficult to detect) venting. Such a change in the behavior of operators has been observed in Turkmenistan and coincides with the introduction of a ban on continuous flaring.[113,114] Three large methane plumes detected by satellites over the Korpezhe oil and gas field released 142 kilotons of methane between February 2018 and January 2019, a volume comparable with the 4-month release from the Aliso Canyon blowout.[110] There are also cases when financial incentives introduced to reduce methane emissions act as subsidies incentivizing higher production and, hence, methane emissions. For instance, construction of the Balhaf LNG terminal (Yemen) in 2009 did not help to reduce flaring but incentivized higher gas production, eventually leading to higher downstream emissions.[113]

Another example is the California offset program, which allows GHG emitters to comply via credits generated by reducing methane in sectors not covered by the ETS (e.g., reduction of methane emissions from coal mining and rice cultivation). Haya et al.[115] found that the program is likely to lead to a number of unintended consequences: (1) increasing the profits of high-emitting activities (e.g., coal mines, leading to higher emissions from mines that produce longer than they otherwise would have, or switching from corn to more GHG-intense rice production), (2) weakening or delaying the adoption of legally binding regulations targeting CMM in California, and (3) inducing business-as-usual mitigation projects to shift their activities to earn offset credits (e.g., incentivize flaring of captured methane to earn offset credits instead of using it for power or heat generation).

Similarly, agricultural policies providing subsidies to producers (e.g., the EU Common Agricultural Policy), low-interest loans to farmers (e.g., Brazil's low-carbon agriculture [ABC] plan) or offset programs (e.g., Australia's Emissions Reduction Fund) are likely to be less efficient at reducing emissions than those based on the polluter-pays principle if they incentivize higher production or fail to assist a shift to production of less-GHG-intense commodities.[88,97,116–119] Conversely, GHG taxes levied on food production are likely to raise food prices[120] and are regressive[121–124] because they impose a higher burden (relative to resources) on lower-income households than higher-income households in the absence of compensatory mechanisms. Methane reduction policies in agriculture (e.g., targeting animal manure and rice cultivation) may lead to an increase in the flow of other GHGs ("emission exchange"), such as nitrous oxide (N_2O); hence, a careful assessment of the impact of methane policies on other GHGs is necessary.[125,126] Finally, policies aiming to reduce organic waste (e.g., manure and food waste) via anaerobic digestion may unintentionally lead to higher GHG emissions if methane is leaked at various points across biomethane and biogas supply chains.[49,50,127–131]

The unintended policy consequences may extend beyond environmental and economic impacts posing safety risks. One example is the CBM/CMM regulations adopted in 2008/2010 in China, mandating coal mine drainage systems with a methane concentration of 30% or greater to use or flare gas but allowing release of methane when the concentration is less than 30%. This policy created an incentive to dilute CMM to avoid the flaring/use requirement, posing a greater risk of explosion from lower-concentration CMM streams.[67] This implies that methane policies may pose risks to safety in the absence of effective safety regimens.[132]

This risk of methane policies creating unintended consequences could be alleviated by designing more holistic policies targeting various emission sources to avoid the increase of emissions from unregulated sources. Moreover, Calel and Mahdavi[113] suggest adopting new production taxes as the primary way of financing the additional infrastructure projects to offset emissions associated with higher natural gas consumption because of new infrastructure. Short-term investment in methane mitigation projects should be aligned with long-term mitigation goals, with a combination of both decreasing emission intensity and production. This could be achieved by introducing higher emission standards for new facilities and predictable phase-out policies, prioritizing avoiding emissions and effective use of captured methane. Flaring of methane should be used as a last resort.

Conclusions

By exploring the state of the art of methane policies via a synthesis of their scope, stringency, and effectiveness, in this review, we uncover that, despite the growing scientific evidence, methane emission reduction remains underexplored, with only ~13% (min. 10%, max. 17%) of global methane emissions covered by direct methane mitigation policies. Methane policy development is recent (last one or two decades) and concentrated in three regions (North America, Europe, and parts of Asia-Pacific). Unlocking underexplored mitigation opportunities will require policymakers to target the blind spots: coverage of policies (e.g., underregulated sources across the supply chain and facility/project lifetime) and their stringency (e.g., measurable reduction objectives, proper monitoring, and verification and enforcement).

Moreover, it is important to understand methane reduction within the broader context of clean energy and just transition. Effective methane mitigation across a diverse set of fossil and biogenic sources requires stronger social support and political consensus. Yet, methane reduction is still perceived as a choice rather than a necessity complementing the ongoing decarbonization efforts focused largely on CO_2. Here, we highlight the value of setting policies that are predictable and clear for the industry, which can help to make effective investment decisions aligned with the long-term climate mitigation scenarios. This implies a combination of a decrease in emission intensity and in production across developed and developing economies. This interdependence also suggests that greater attention is needed to emissions from non-operated joint ventures (usually owned by international companies but operated by local partners) and supply chain emissions, especially in the case of internationally traded commodities such as LNG and metallurgical coal.

Further reductions rest on continued development of methane detection and quantification technologies, with satellites holding the biggest promise for policymaking: early detection of super-emitters, emission verification, and compliance monitoring. It also requires scaling up mitigation solutions for major sources where mitigation options are less developed; e.g., coal mine ventilation shafts and livestock emissions. Providing additional financial flow for R&D and mitigation efforts while the world transitions away from fossil fuels will be a significant challenge.

Hence, government priorities and policies based on a social mandate will have a substantial role in driving timely mitigation outcomes realized by private and public companies.

More research on methane policies is needed to explore the effectiveness of various types of policies; e.g., the performance of economic instruments in reducing methane emissions across all sectors. Studies that can strengthen policy options building on remote sensing to improve methane monitoring and detection of super-emitters are necessary. Barriers to widespread adoption of measures limiting livestock emissions deserve further in-depth investigation, and it is important to carry out more inter/transdisciplinary research to help key stakeholders better understand the impact of and barriers to demand-side and consumption-oriented policies.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Maria Olczak (m.olczak@qmul.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

All original datasets used in this work were made available as part of the publications referenced and described in the text. The methane policy database, the literature review, and the R code used to create histograms have been deposited at Zenodo Data: https://doi.org/10.5281/zenodo.7883701.

Methane policy database

To explore the blind spots in global methane policies, we first identified relevant methane policies and created a methane policy database (MS Excel file deposited at Zenodo Data: https://doi.org/10.5281/zenodo.7814090). Methane policies are defined as actions by governments aiming to address (monitor, prevent, or reduce) methane emissions from man-made sources or with material impact on methane emissions; e.g., landfill regulations and food waste policies. Policies that do not have immediate or material impact on methane emissions (e.g., land use change) are out of the scope of this analysis. Governments use various tools to advance their policies to address public concerns or accomplish a pre-determined set of goals, known as policy instruments. To support our analysis, we created a separate list of political declarations, framework policies, and strategies, but they are out of the scope of core analysis (Tables S1–S3).

During data collection, we used the following sources: (1) policy databases and analyses developed by international organizations and initiatives (the International Energy Agency (IEA)'s Methane Policy and Regulation Database; the Climate and Clean Air Coalition (CCAC)'s Policies, Plans, and Regulations database; ECOLEX; the Climate Policy Database by the NewClimate Institute; Food and Agriculture Organization (FAO), International Bank for Reconstruction and Development (IBRD)/World Bank (WB), Organisation for Economic Co-operation and Development (OECD), United Nations Economic Commission for Europe (UNECE), United Nations Environment Programme (UNEP)); (2) academic literature found via Scopus, ScienceDirect, PubMed, and Google Scholar; (3) gray literature, including studies conducted by consulting companies (e.g., consortium Wood, Netherlands Organisation for Applied Scientific Research (TNO), Carbon Limits, The Sniffers, and Environmental Resources Management (ERM)); and reports conducted by different stakeholders and research institutions (e.g., Gas Infrastructure Europe [GIE]/Marcogaz, Oxford Institute for Energy Studies [OIES], Environmental Defense Fund [EDF], Pembina Institute, and World Resources Institute [WRI]). Initially, 656 policies were identified.

In the second step and after the initial screening, the number of policies were reduced to 271. 10 additional policies were added based on reviewers' suggestions (n = 281). The inventory includes 138 policies targeting man-made fossil methane (coal, oil, and gas sectors), 117 targeting biogenic methane (agriculture and waste), and 26 policies targeting biogenic and fossil methane (e.g., the Quebec cap-and-trade system). In the case of emissions from waste and agriculture, the inventory includes policies that are have direct impact on methane emissions even without specifying methane reduction as one of the policy objectives; e.g., biogas/biomethane support schemes.

The policy database (n = 281) is cross country and cross sectoral. It includes policy instruments adopted/to be adopted at any time between 1974 and 2024 ("in force," n = 255), planned/announced ("in development," n = 6), revoked (n = 10), and terminated ("ended," n = 10). The database includes policies adopted at subnational, national, regional (e.g., EU), and international levels, except for policies adopted at local and municipal levels. It includes policy documents in English, French, Spanish, Portuguese, Italian, Arabic, and Russian. For EU member states, laws transposing EU Directives are typically not included in the database, except when national legislation introduces additional requirements compared with the EU legislation. Policies adopted by companies, including state owned, are excluded. The database was regularly updated throughout this research to account for the updates and new policies adopted. We consulted with four other scholars focusing their research on waste and agriculture to ensure that all relevant policies were included.

In the last step, the content of policy instruments currently in force (n = 255) was analyzed to provide further details: (1) whether they aim mostly to monitor emissions or to reduce them, (2) policy instrument type and subtype, (3) scope of policies (type of emissions, facility, and part of the supply chain covered), and (4) comparison of the policy coverage with methane emissions by region and by country.

Assessment of the stringency of methane policies

To identify the stringency of methane policies, we assessed the content of policies in terms of six criteria suggested by Schaffrin et al.:[57] policy objectives, scope, integration with other policy instruments, costs, implementation, and monitoring. While the effectiveness of policies can be assessed in different ways, the approach suggested by Schaffrin et al.[57] has been designed specifically to assess climate policies and pays equal attention to policy design (objectives, scope, and integration with other instruments) and policy implementation (costs, implementation, and monitoring). Some of the questions originate from the framework suggested by Schaffrin et al.,[57] and other have been modified to account for the specificity of methane mitigation or analyzed sectors.

Systematic review of academic and gray literature

We conducted a systematic review of peer-reviewed and gray literature to identify the direct impact of adopted policies on methane emissions. The review was compiled by searching the databases and webpages (below) with Boolean combinations of pre-determined search terms: "methane" AND "policy" AND "impact"; "methane" AND "policy" AND "effectiveness"; "methane" AND "policy" AND "systematic review". It yielded evidence from 213 publications (MS Excel file deposited at Zenodo Data: https://doi.org/10.5281/zenodo.7814090).

Subsequently, we screened the titles and abstracts of publications and reduced the number of studies to 101. We included for further analysis papers (1) assessing direct impact of selected policy/policies on methane emissions; (2) including suggestions regarding improvement of existing policies or proposing new policies; (3) including ex ante and ex post analyses; (4) papers comparing the impact of different policy instruments or policies adopted by different jurisdictions; (5) focusing on policies adopted at the international, national, or subnational level, except for policies adopted at the local or municipality level; and (6) looking at policies adopted across the world at any time. We excluded (1) reviews of methane mitigation options and/or their cost effectiveness, (2) papers looking at the broader impact (e.g., social, economic, and environmental, including air quality) of policies, (3) papers analyzing regulatory developments in specific countries or over time but without any conclusion regarding the impact of analyzed policies on methane emissions, and (4) focusing on whether and how to promote specific mitigation strategies leading to methane emission reduction (e.g., promotion of biomethane in heating and cooling).

Based on the analysis of the study objectives, we divided them into three categories: (1) policy options (papers proposing specific policy measures that could be applied by the policymakers), (2) policy insights (papers providing broader context for the study of policy impact), and (3) policy impact (papers estimating the impact of proposed/adopted policies in terms of methane emission reduction). The last group of papers (n = 19) was the subject of the core analysis, as reported under "Limited evidence of the effectiveness of methane policies." The insights from other papers informed "Designing and assessing policies despite uncertainties" and "Avoiding unintended policy consequences."

The following resources were used:

- Peer-reviewed academic journals
  - Scopus
  - ScienceDirect
  - PubMed
- Web search engines

  - ○ Google Scholar
- ● Websites of relevant organizations, including but not limited to
  - ○ Climate and Clean Air Coalition (CCAC)
  - ○ Environmental Defense Fund (EDF)
  - ○ Food and Agriculture Organization (FAO)
  - ○ International Bank for Reconstruction and Development (IBRD)/World Bank (WB)
  - ○ International Energy Agency (IEA)
  - ○ Organisation for Economic Co-operation and Development (OECD)
  - ○ Pembina Institute
  - ○ United Nations Economic Commission for Europe (UNECE)
  - ○ United Nations Environment Programme (UNEP)
  - ○ World Resources Institute (WRI)

Additional information regarding national GHG reporting

The current understanding of individual methane emission sources and their magnitude is based on the country GHG estimates—national inventory reports (NIRs)—applying mostly bottom-up methods in line with the IPCC guidelines. These rules do not apply equally to all countries that are party to the United Nations Framework Convention on Climate Change (UNFCCC). While Annex I countries report their emissions annually, the so-called Non-Annex I countries, the group of developing economies including China, report their GHG inventory emissions less frequently and with less detail. For example, China's latest biennial update report (BUR2) available on the UNFCCC webpage was submitted on June 25, 2019 and presents the 2014 national GHG inventory. GHG reporting is likely to become more coherent under the Paris Agreement Article 13 Enhanced Transparency Framework.

Even among Annex I countries, the quality of national GHG inventories varies. The countries can report their emissions by applying one of three methods or tiers. Tier 1 (T1) and T2 build on bottom-up estimates with multiplying activity data (usually coal production or number of mines) and emission factors (standard emission factors [EFs] in the case of T1 and country or basin-specific EFs in the case of T2). The T3 method requires facility-specific measurements (e.g., from ventilation and degasification systems in the case of underground mines) to develop national estimates. T1 estimates are characterized by the highest level of uncertainty (the actual emissions could be greater or smaller by a factor of 2 or 3 in the case of emissions from coal mining), while T3 estimates, when properly applied, are the least uncertain (e.g., uncertainty varies ± 2%–5% in the case of drainage gas and ± 5%–30% in the case of methane from ventilation shafts).

Study limitations

Despite efforts to capture the variety of methane policies, this study has several limitations. First, there is bias toward developed economies where information is more widespread because it is frequently the focus of the media and research community attention. Second, there is a Western focus because of the language limitations and use of automated translation software to understand the content of identified policies. Third, there is bias toward the national policies; the study may not fully capture policies adopted at the subnational, local, and municipal level. Fourth, the study does not capture policies with indirect impact on methane emissions. Finally, because the recent policy developments are concentrated in the energy sector, the study has a strong energy focus, which we tried to mitigate through consultations with scholars focusing their research on agriculture and waste. Hence, this study also recognizes that the causes of the emissions across different sectors are really different, and so one solution for one sector may be unlikely to be suitable for another.

The study of methane policies and policy tools poses several challenges. First, we mostly relied on information freely available in English; hence, the study may not fully capture the policy developments in developing economies. This is because of limited media and research community attention as well as language limitations (the Western focus). Third, we tried to be as inclusive as possible, but the database may not fully capture policies adopted at the subnational, local, and municipal level, which may have a significant impact on waste-related emissions.

Fourth, methane is a potent GHG but also an air pollutant, safety hazard, and energy resource as the major component of natural gas and biomethane. As a result, policies impacting methane emissions have been driven by various motivations: efficient use of energy resources (e.g., reducing gas leaks/vents), enhancing safety (e.g., reducing the potential for explosive atmospheres), increasing the supply of cleaner and domestically produced energy (e.g., CBM), and, more recently, air quality concerns and climate change mitigation. In effect, an array of policies impacts methane emissions either directly (e.g., explicitly targeting methane reductions) or indirectly (e.g., land use change policies). Hence, the study does not capture policies with indirect impact on methane emissions.

Finally, because methane emissions arise from diverse and diffuse sets of sources, so far, methane policies tend to be sector specific with limited policy learning and cross-sector comparisons. A distinction can be made between biogenic methane (methane produced and released from plants and animals) and fossil methane (released during extraction, transport, and use of fossil fuels—coal, oil, and gas). Given that methane from biogenic and fossil sources impacts the climate in a slightly different way, the AR6 suggests updated global warming potential (GWP) values: 82.5 (GWP20) and 29.8 (GWP100) for fossil methane and 80.8 (GWP20) and 27.2 (GWP100) for biogenic methane.[133] While there have been significant policy developments in some areas, especially regarding oil and gas, development has been more limited in sectors with limited or more costly mitigation potential, such as agriculture. Hence, this review is "biased" toward policies targeting energy-related emissions.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.04.009.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.O. and P.B.; methodology, M.O. and P.B.; data visualization, P.B. and M.O.; writing—original draft, M.O.; writing—review and editing, P.B. and A.P.; supervision, P.B and A.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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