Institute for Governance & Sustainable Development

Metrics and Measurement of Methane Emissions

Dr. Gabrielle Dreyfus and Richard "Tad" Ferris[1]

As commissioned by the China Council for International Cooperation on Environment and Development, and published in:

Innovative Technologies for Greenhouse Gas Emissions and Carbon Sequestration Monitoring

CCICED Scoping Study Report

Table of Contents

Background 22

Executive Summary 23

1. Introduction 25

2. Measuring Oil And Gas Sector Methane Emissions 28

2.1 Opportunities and Challenges of Measuring and Monitoring Emissions From the O&G Sector 28

2.2 Measurement Techniques 28

2.3 Gaps and Challenges in Current Approaches 32

3. Why Accurately Measuring Methane Emissions From The O&G Sector Is Important 33

3.1 Examples of Regulatory Approaches 33

4. Current And Emerging Methane Emissions Monitoring System Best Practices For Accuracy And Timeliness 35

4.1 Work Practice Standards Are in Place, Documented, and There Is Evidence of Enforcement 35

4.2 Measurement, Reporting, and Verification (MRV) Standards for Quantification and Coverage 36

4.3 Pairing Voluntary Standards Certification Schemes With Regulation Captures All Players in the Market 37

4.4 Transparency and Timeliness 37

5. Conclusion 38

Background

This section on Metrics and Measurement of Methane Emissions focuses on oil and gas methane emissions and will help answer the following questions:

- Why is it important to accurately measure methane emissions?
- What are the main sources of methane gas emissions, and do these sources pose particular measurement challenges?
- Are there known gaps in current methane measurement approaches?
- Are there current or emerging methane monitoring systems that can improve the accuracy and timeliness of emissions data?

Executive Summary

Key messages:

- Fast action to mitigate non-CO_2 climate pollutants, such as methane, including through implementing methane intensity requirements (such as via procurement specifications) for domestic and imported oil and gas, can have a significant role in reducing the likelihood of triggering catastrophic climate impacts as countries pursue carbon-neutrality goals.
- Without robust monitoring, reporting, and verification (MRV) of methane emissions, we will not be able to know the efficacy of methane mitigation policies and programs or whether we are meeting methane mitigation targets.
- Acting quickly to ensure that new investments in oil and gas infrastructure are built with enhanced MRV systems and methane intensity requirements in mind is essential to limiting risks of stranded assets and aligning with carbon-neutrality goals.

Natural gas is not inherently a low-emission fuel. Over the past decade, many studies have documented significant intended ("vented") and unintended ("fugitive") emissions across the oil and gas sector, from production to transport and distribution. The assertion that a transition from coal to gas will reduce emissions of climate-warming gases depends on the magnitude and extent of these intended and unintended emissions.

Methane (CH_4) is the primary constituent of natural gas and is over 80 times more potent than carbon dioxide (CO_2) at warming the planet over a 20-year period.[2] Conventional wisdom has held that gas is "cleaner" than coal because generating electricity from gas produces about half the CO_2 for a given electricity output than coal.[3] However, this comparison ignores the methane emissions associated with producing natural gas and coal. Many studies have analyzed the cross-over point at which venting and fugitive emissions from gas outweigh the climate benefits of a transition from coal to gas, generally finding that leakage rates above 2.4%–3.4% eliminate the climate benefit.[4] and as low as 0.2% when masking from sulfate co-emission for coal is included.[5]

Reducing intended and unintended emissions to achieve lower-emission goals with a transition to gas, and as we work toward a transition away from gas, requires measurement and MRV along the full well-to-gate scope (producers, processors, and transporters of gas) both for domestic producers and for importers seeking to impose methane emission intensity requirements. Such quantification-based intensity requirements complement established approaches for controlling methane leaks through prescriptive regulations. Measuring methane accurately is key to enabling these types of policies. Further, successful quantification-based emissions policy, such as limits to methane intensity or certification, requires accurate measurement technologies and robust MRV systems coupled with sufficient compliance and enforcement. New investments in the oil and gas sector should build in enhanced MRV systems and methane intensity requirements to limit risks of stranded assets and align with carbon-neutrality goals.

Collaborative efforts such as the International Methane Emissions Observatory (IMEO), which builds on the reporting framework established by the Oil and Gas Methane Partnership 2.0 (OGMP 2.0), offer an opportunity to improve understanding and enable action by governments, industry, and civil society to reduce methane emissions.

1.0 Introduction

Methane, the primary constituent of natural gas, is a short-lived but potent greenhouse gas (GHG). Methane has an atmospheric lifetime of about 10 years and is around 80 times more powerful than CO_2 at warming the climate over a 20-year time frame.[6] As a result, methane mitigation can have a fast impact and "is very likely the strategy with the greatest potential to decrease warming over the next 20 years."[7]The primary sources of anthropogenic methane emissions are energy production (~35%), agriculture (~40%), and waste (~20%), with biomass burning and biofuels as minor sources.[8]

Without the fast, near-term action to slow warming that cutting methane emissions can provide, the Earth's average temperature could exceed the Paris Agreement's 1.5 °C temperature limit (at least temporarily) by the end of this decade.[9] Impacts from warming above 1.5 °C include increasing the risk that self-amplifying climate feedbacks will further accelerate rising temperatures and trigger a cascade of irreversible tipping points in the climate system.[10]

Bilateral, multilateral, and plurilateral actions are essential to raising awareness of the opportunity to slow warming by cutting methane in the sectors involved and the level of ambition necessary. This action includes commitments in the methane emissions reduction outcomes from the 2023 Major Economies Forum on Energy and Climate, the Joint Glasgow Declaration on Enhancing Climate Action in the 2020s between China and the U.S., the Global Methane Pledge, the Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels, and this effort to understand methane metrics and measurement under the auspices of the China Council for International Cooperation on Environment and Development (CCICED).

The oil and gas (O&G) sector presents a unique opportunity to pursue fast action on cutting methane, as 75% of methane reductions from this sector could be achieved at low or no cost.[11] The 2021 Global Methane Assessment estimates this O&G sector potential mitigation at 29–57 million metric tons of methane per year ($MtCH_4/yr$). This potential can be largely realized through capturing fugitive emissions, with most solutions involving mature existing technologies and implementing prescriptive regulations on producers, processors, and transporters of gas together with methane intensity requirements (such as through procurement specifications) for domestic and imported oil and gas.[12] The International Energy Agency (IEA) reported in its 2022 Global Methane Tracker report that there is a wide range of methane emissions intensities from O&G operations in the best-performing countries and companies. Of these best performers, IEA noted in the same report that Norway and the Netherlands have the lowest emissions intensities. Significantly, IEA observed that if all producing countries were to match Norway's methane emissions intensity, O&G sector emissions would fall by 90%.

While different oil and gas resources have different characteristics that contribute to their emissions profiles, production and transportation infrastructure and operation and maintenance practices can significantly affect actual emissions. As discussed in Section 2, bottom-up inventory-based assessments tend to underestimate actual emissions by about 60%–70%[13] and highlight challenges with accounting for the intermittency of emissions.[14]

Box 1. Methane intensity and key considerations

"Methane intensity" is an increasingly important method of communicating O&G industry methane emissions data and performance. There is not yet a universally adopted methane intensity standard, protocol, or guideline. Thus, it is important to consider differences in methane intensity standards or other calculation methodologies. (See "Key Considerations," below.) As an example, the Oil and Gas Climate Initiative (OGCI), a voluntary CEO-led organization including 12 of the largest O&G companies, defines methane intensity as follows:

"[The] total volume of methane emissions divided by total volume of marketed gas. The metric is already used by companies that account for 30% of global production and could be adopted as an industry standard. Note that some companies report an alternative metric of methane emissions normalized to total energy content of their oil and gas production. This metric can be converted to the equivalent OGCI percent emission rate by adjusting the relative fraction of energy production from oil versus natural gas."[15]

Key Considerations in assessing a particular methane intensity calculation methodology include **scope of emission sources** considered and **source characteristics**. Some intensity calculations limit scope to upstream emissions from the well-head facilities, while more comprehensive "well-to-city gate" include upstream and pipeline-gas extraction, processing, and transmission emissions, as well as liquid natural gas liquefaction, shipping, storage, and regasification emissions. **Source-characteristics analysis** accounts for variations between gas extracted from different sources, which can differ based on geological conditions, gas extraction techniques, and characteristics of the gas from production wells.[16]

The increasing importance of understanding O&G sector methane emissions characteristics and intensity has given rise to a surge in performance-rating (or certification) programs for "differentiated gas," including "low-emission" and "responsibly sourced" gas. See Box 2. This is a key factor in why it is so important to go beyond the certification conclusions to determine if there is sufficient information warranting confidence in the performance ratings. For instance, in assessing the credibility of a differentiated gas certification program, it is necessary to obtain clear information on the type of standards used in the methane emissions measurement, the scope of facility certification (e.g., does the certification cover all facilities, or particular facilities, and if particular, are these only the best-performing facilities?), whether conformity with the methane intensity target will result in emissions reductions (i.e., does the standard require reductions over time, what is the starting point?), and whether the certification involves verification from a credible and independent third party. Examples of differentiated gas certification programs include MiQ, grading natural gas volumes produced and gas producer performance, Project Canary's "Trustwell" program, and Xpansiv's Digital Natural Gas and Methane Performance certifications. (See also Highwood Emissions Management (2022) *Voluntary Emissions Reduction Initiatives for the Oil and Gas Industry*.)

For a more detailed discussion of key criteria for differentiated gas certifications, see Grossman and Lackner (19 May 2022) Differentiated gas: Nothing but hot air without these five criteria, Environmental Defense Fund).

Box 2. Definition of "differentiated gas" or "responsibly sourced gas"

"Differentiated gas" or fossil gas that is differentiated as to whether it is "low-emission" or "responsibly sourced gas" refers to "gas that is purported to have been extracted via methods that meet certain environmental, social and methane emission best practices."[17]

2. Measuring Oil And Gas Sector Methane Emissions

2.1 Opportunities and Challenges of Measuring and Monitoring Emissions From the O&G Sector

The two primary purposes for measuring methane are to understand emissions and to mitigate emissions. Figure 1 illustrates how different methane measurement technologies operate at different spatial and temporal scales and can be used to understand and/or mitigate emissions.

Bottom-up inventories are a primary tool for understanding emissions. At their most basic level (IPCC Tier 1) (see Box 4), they multiply industry average emission factors by equipment or activity counts (e.g., number of pneumatic valves) to estimate emissions at one or more facilities up to the national scale. Several tools, such as the Country Methane Abatement Tool (CoMAT) developed by the Clean Air Task Force, allow governments to build an inventory and estimate methane emissions based on parameters including the number of wells, compressor stations, miles of pipeline, and other infrastructure and operations information.[18] Bottom-up inventories provide essential information on potential sources of emissions and are critical for planning mitigation approaches. However, a major challenge is the dependence of this bottom-up approach on emission factors that are developed for equipment and components at normal operation. When compared with atmospheric measurements, these inventory-based approaches are found to systematically underestimate emissions.

Atmospheric measurement-based studies over North America have consistently shown that these bottom-up inventories underestimate site-level emissions.[19] These studies show that methane emissions are highly skewed to a small number of "super-emitter" events that are not generally represented in emission factors.[20] A forthcoming study finds that natural gas emissions in some areas were as much as nine times higher than U.S. government estimates and that fewer than 2% of the aerially measured well sites contribute over half of the total emissions.[21] A small number of ultra-emitters have also been observed globally to contribute a disproportionate 8 to 12% of global oil and gas methane production emissions.[22] This highly skewed profile of emissions from a small number of facilities occurring intermittently presents a challenge both for detecting leaks and quantifying inventories.

Screening technologies (see the M4 green dots in Figure 1) are rapidly improving to enable better detection (and, in some cases, quantification) of fugitive emissions. Diluted and diffuse emissions, such as from small leaks and agricultural sources, continue to be a measurement and monitoring challenge. However, most O&G sources are concentrated and can be prevented or controlled by being contained and captured (as opposed to agricultural and waste sources).

2.2 Measurement Techniques

Techniques for measuring methane operate across a range of scales in space and time (Figure 1). The smallest-scale measurements use in-situ methods from the ground (e.g., handheld or mounted devices) or aerial sensors (e.g., on drones). These close-range methods are essential for source identification, but they can be labour-intensive and miss infrequent emission events.

Leak detection and repair (LDAR) is an essential component of monitoring and reducing methane emissions. Comprehensive monitoring programs (CMP) pair screening technologies that can identify anomalous emissions with close-range detection methods such as optical-gas imaging cameras that can distinguish and detect emitting sources. For additional information, see Fox T.A., Barchyn T.E., Risk D., Ravikumar A.P. and Hugenholtz C.H. (2019) *A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas*, Environ. Res. Lett.: 14 053002.[23]

Atmospheric monitoring approaches combine measurements of atmospheric concentrations (CH_4 mole fraction in the atmosphere) with transport and dispersion models that use meteorological inputs to convert detected concentrations to emissions. These models rely on initial input assumptions about sources (priors) and provide the most accurate results when detailed facility and activity data are available.

Dedicated testing facilities like the Methane Emissions Technology Evaluation Center (METEC) and TotalEnergies Anomaly Detection Initiatives (TADI) are enabling the development of international standards for leak detection and quantification of methane emissions.[24] These are important resources for testing and verification of measurement technologies and approaches. See Figure 1.

Figure 1. Methane detection technologies provide information at a range of spatial and temporal scales

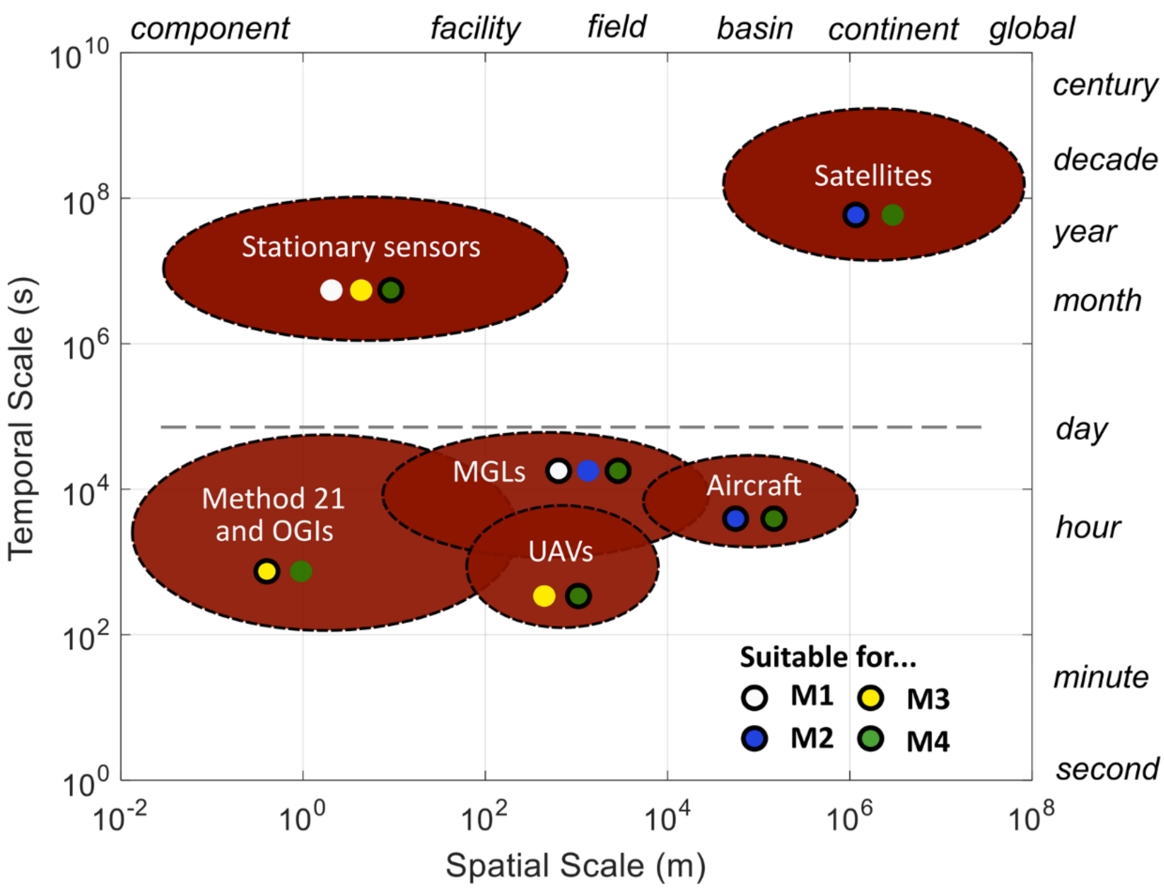

Figure 1. Methane detection technologies provide information at a range of spatial and temporal scales. The coloured dots represent different measurement motivations: M1 = develop and refine emissions factors to improve inventories; M2 = Estimate emissions from a region with multiple sources; M3 = Close-range leak detection; M4 = Rapid screening for anomalous emissions. Dots without black borders either show promise or may be useful in a limited capacity. Method 21 is a U.S. EPA regulatory framework for conducting LDAR; OGIs = optical-gas imaging cameras; MGLs = mobile ground laboratory; UAVs = uncrewed aerial vehicles. The dotted line separates semi-automated (above) and labour-based systems (below), based on current technologies. Reproduced from Fox T. A., Barchyn T. E., Risk D., Ravikumar A. P., & Hugenholtz C. H. (2019) A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas, ENVIRON. RES. LETT. 14(5): 053002.

Box 3. Satellites and the International Methane Emissions Observatory

High-precision spectral imaging instruments mounted on aircraft and satellites have revolutionized methane monitoring and emissions quantification with their potential to cover large spatial scales with almost continuous daily mapping (Figure 2). The International Methane Emissions Observatory (IMEO) at the United Nations Environment Programme (UNEP) was launched in 2021 to collect, reconcile, and integrate methane emissions data from industry reporting through OGMP 2.0, national inventories, scientific studies, and satellite observations through the Methane Alert and Response System (MARS). By providing open, reliable, and actionable data IMEO empowers governments, companies, investors, researchers, civil society, and others to reduce methane emissions.[25]

Figure 2. Classification of satellite instruments

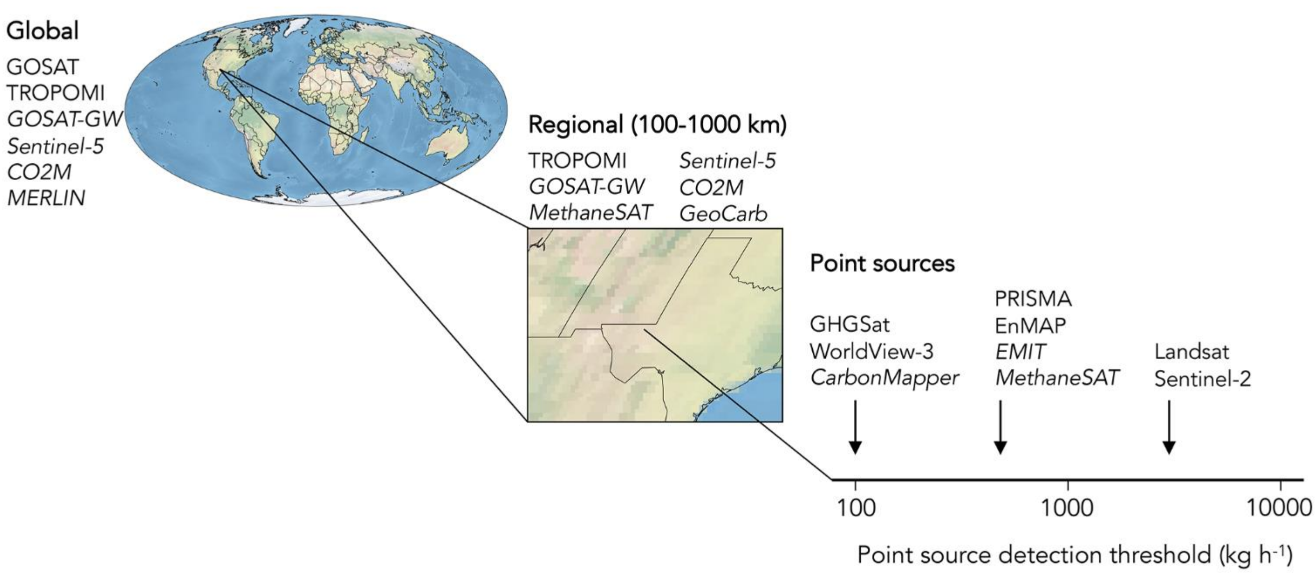

Figure 2. Classification of satellite instruments (italics denotes not launched as of July 2022) based on their capability to observe methane on global, regional scales with high resolution, and for point sources, with detection thresholds given as order of magnitude in kilogram per hour. Reproduced from Jacob D. J., et al. (2022) Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane, ATMOS. CHEM. PHYS. 22(14): 9617–46.

Box 4. Inventory approaches (e.g., IPCC tiers)

The *2006 IPCC Guidelines* developed a tiered approach for estimating GHG emissions:

Tier 1 relies on multiplying activity data by default emissions factors representing emissions per unit of activity.

Tier 2 approaches generally apply country-specific emissions factors to national or regional activity data.

Tier 3 approaches involve additional detail on the activity data (e.g., facility level) and direct measurement or equivalent country-specific approaches.

The *2006 IPCC Guidelines* and *2019 Refinement* provide default emissions factors and additional methodological guidance.

2.3 Gaps and Challenges in Current Approaches

Direct measurement and verification are essential to accurate and credible emissions quantification. A key challenge in the methane monitoring space in the O&G sector is integrating different measurement and monitoring techniques and approaches to provide accurate, comprehensive, and timely quantification of emissions with source attribution. Multiple research efforts are underway to develop methodologies for integrating bottom-up and top-down approaches to address this challenge (e.g., Energy Emissions Modeling and Data Lab,[26] Veritas[27]). In June, MiQ-Highwood released an index for integrating inventory and direct measurement data for national-level emissions intensity quantification.[28]

Remaining issues for consideration as MRV methodologies and certification schemes are further developed include how emissions associated with well preparation and completion, LNG and transport, and mid-stream emissions are factored in/allocated.

Finally, no path (currently) exists to monitor all facilities at appropriate levels of detection (MDL) and frequency for continuous and comprehensive emissions quantification.

3. WHY ACCURATELY MEASURING METHANE EMISSIONS FROM THE O&G SECTOR IS IMPORTANT

Achieving sustained methane emissions mitigation from the O&G sector requires a strong methane intensity commitment and reducing methane intensity from that commitment over time, combined with credible measurement of methane emission quantification, which depends on effective monitoring, reporting and verification (MRV) systems to ensure sustained mitigation.

Industry voluntary commitments are a starting point for sustained methane emissions mitigation. Examples include the framework established in the Oil and Gas Methane Partnership 2.0 (OGMP 2.0), the Oil and Gas Climate Initiative (OGCI), and the China Oil and Gas Methane Alliance. Launched under the United Nations Environment Programme (UNEP) Climate and Clean Air Coalition (CCAC), OGMP 2.0 member companies commit to setting an upstream methane intensity or absolute reduction target. UNEP promotes the following aspirational goals with respect to these targets:

- 45% reductions in methane emissions overestimated 2015 levels by 2025, leading to 60-75% reductions by 2030;
- or, alternatively, a "near zero" emission intensity, such as the OGCI collective average target for upstream operations of 0.25% by 2025, a target which has been updated to "well below" 0.20% by 2025 in OGCI documentation, as described below.[29]

OGCI requires that its member companies commit to, by 2025, reducing the collective average methane intensity of aggregated upstream oil and gas operations to *well below* 0.20% from a 2017 baseline of 0.30%.[30] This target includes all operated upstream oil and gas assets, annual reporting of collective methane intensity, and the China Oil and Gas Methane Alliance, an association of seven Chinese companies, pledged to reduce members' average gas-production methane emissions intensity to below 0.25% by 2025.[31]

A lack of sustained mitigation may suggest the need for expanded adoption of regulatory approaches, such as those described below.

3.1 Examples of Regulatory Approaches

As mentioned in Section 1, the proliferation of voluntary industry collaborations aimed at reducing methane emissions in the O&G sector and associated performance-rating initiatives reflects the growth of bilateral, multilateral, and plurilateral actions raising awareness of the opportunity to slow warming by cutting methane, the sectors involved, and the level of ambition necessary. Nonetheless, because cutting methane emissions is the single most important action humanity can take to slow warming in the near term, governments are undertaking regulatory actions to drive more comprehensive action. Examples can be found in evolving regulatory and other policy actions in Canada,[32] China,[33] the European Union,[34] Mexico,[35] Nigeria,[36] and the United States.[37] However, in each example, ensuring clarity and scientific and community scrutiny of methane emissions metrics and measurement is critical to ensuring that statutory and regulatory climate goals can be reached. It is therefore important to consider initiatives that focus on the rigour of methane metrics and measurement.

Subnational governments can be "first movers" in terms of environmental action. This is the situation with several U.S. states with respect to methane abatement in the oil and gas sector. Colorado adopted the first methane regulations in the United States in 2014, and has proceeded since that time to adopt improvements. Reflecting the importance of more rigorous methane measurement and the need for an improved regulatory mechanism to enable oil and gas operators to confirm conformity with Colorado's methane emissions requirements, Colorado's Air Pollution Control Division proposed a draft "GHG intensity Verification Rule." Among other important elements, the draft Rule proposes a "State default-intensity verification factor" referring to the "methane factor developed to account for the difference in measured methane emissions and reported methane emissions and used in the calculation of GHG intensity." This default-intensity verification factor is applicable to preproduction and production methane emissions from oil or natural gas wells and associated equipment and activities as further defined in the draft Rule.

4. Current And Emerging Methane Emissions Monitoring System Best Practices For Accuracy And Timeliness

A survey of existing methane policies found that only about 13% of global methane emissions are currently covered by direct methane mitigation policies, with coverage of fossil methane emissions ranging from 5% to 23% depending on geography.[38] Most of the regulations in the O&G sector have focused on prescriptive regulations, such as work practices and standards for LDAR, equipment standards, and restrictions on venting and flaring. Improvements in measurement technologies and approaches are enabling regulations that are based on methane emissions quantification (such as the methane fee in the U.S. Inflation Reduction Act). Achieving compliance and mitigation targets requires extending policy coverage, stringency, and increasingly adopting emissions quantification-based measures, which depend on robust MRV systems.

While most solutions for mitigation methane emissions from the O&G sector are no- or low-cost and involve mature existing technologies, their adoption is lagging due to informational, structural, financial, and regulatory barriers.[39] Below, we highlight examples of best practices for accurate and timely methane emissions monitoring to achieve emissions reductions. For additional details on practical methane policy implementation, see the IEA's methane regulatory roadmap and Environmental Defense Fund resources.[40]

4.1 Work Practice Standards are in Place, Documented, and There is Evidence of Enforcement

Mandated regular LDAR combined with work practice (and technology) standards, as in the example below, are well-established approaches that can deliver methane emissions reductions when properly monitored and enforced.[41] Regulatory agencies should consider what data is required to be reported and on what timeline and frequency and should have the capacity to verify reports and level fines for misreporting and non-compliance to ensure effective enforcement.[42] These prescriptive requirements can precede and complement policies based on emission quantification.

Figure 3. Work practice standards

Requirements
Regular instrument-based monitoring for leaks and abnormal emissions, including at smaller sites, and timely repair of leaks
Transition to zero-emitting pneumatic devices
Prohibition of routine venting and flaring
Control/capture requirements for tank emissions
Reduced emission well completions
Liquids unloading best practices
Emission standards for reciprocating and centrifugal compressors

Figure 3. Table from Lackner M. & Mohlin K. (2022). Certification of Natural Gas With Low Methane Emissions: Criteria for Credible Certification Programs, Environmental Defense Fund.

4.2 Measurement, Reporting and Verification (MRV) Standards for Quantification and Coverage

The key features of a robust MRV framework include an agreed and consistent methodology that: (1) is based on direct measurements that are statistically representative in space and time; (2) integrates top-down and bottom-up measurement data to validate emissions estimates at the facility level and over the reporting period (e.g., the MiQ-Highwood index methodology), and (3) includes associated uncertainty in reported emissions estimates.[43]

The "gold-standard" Level 5 reporting under the OGMP 2.0 framework, as set out in the table below, requires methane emissions reported by detailed source type and direct measurements that characterize site-level emissions for a statistically representative sample.

Figure 4. Reporting levels in the Oil and Gas Methane Partnership 2.0

Figure 4. From Oil and Gas Methane Partnership (OGMP) 2.0, Frequently Asked Questions.

4.3 Pairing Voluntary Standards Certification Schemes with Regulation Captures All Players in the Market

Certification schemes for low-emissivity gas should require and verify that a baseline set of work practice standards is in place and enforced (see Section 4.1). Furthermore, any certification of "differentiated gas" should require reporting consistent with OGMP 2.0 level 5 and meet or exceed the OGCI metric of 0.20% and declines over time.[44]

4.4 Transparency and Timeliness

Best practice reporting would be at the facility scale and on a timeline to enable efficient monitoring and learning cycles to achieve rapid abatement.

5. CONCLUSION

The oil and gas sector is moving from monitoring methane to understand and locate emissions to measuring to eliminate unnecessary emissions. Establishing strong and transparent MRV practices in producing regions, together with regulatory requirements and standards for producers, transporters, and for low methane emission intensity in both producing and importing regions that enable efficient monitoring and learning cycles is key to achieving rapid emissions reductions and meeting climate goals.

The Chair of the OGCI Executive Committee, Bjorn Otto Sverdrup, underscored the need for further action at Global Energy Transition 2023 in June:

> "It's time to move beyond incremental improvement," Sverdrup said, pointing to "zero-tolerance" policies already in place for oil spills and safety incidents. "Let's try to deploy that mindset. All methane emissions can and should be avoided."
>
> As part of that, the industry should look beyond methane in the United States and Europe by offering a "helping hand" to the poorer parts of the world, Sverdrup said. Toward that end, the OGCI has been undertaking a satellite program for 20 months in which it is detecting "super emitters" in places like the Middle East, Central Asia, and North Africa.
>
> "Then we engage in dialogue—knocking on the door, basically saying, 'We see you have a problem. Are you aware of it? Do you know how to fix it? Are you willing to fix it?'" Sverdrup explained, adding that the response to those knocks has been overwhelmingly positive.[45]

International efforts such as IMEO aim to bring together industry-led reporting efforts with satellite and research observations to inform and enable such action to reduce methane emissions. Growing participation from governments, companies, and civil society and support for improved transparency and access to actionable methane information will contribute to achieving needed methane emissions mitigation.

References

[1] Dr. Gabrielle Dreyfus is Chief Scientist at the Institute for Governance & Sustainable Development (IGSD). Richard "Tad" Ferris is Senior Counsel at IGSD. The authors would like to acknowledge assistance from Xiaopu Sun, IGSD Senior China Counsel, particularly on references related to China, Amelia Murphy, IGSD Executive Assistant, and David McCabe, Clean Air Task Force Senior Scientist.

[2] We recommend reporting gas emissions in units of mass and 20-year global warming potential (GWP) when assessing combined methane and CO_2 emissions from the oil and gas sector, as "relying solely on GWP100 can lead to suboptimal policies and priorities by misleading climate actors from the top levels of government (e.g., U.S. NDC) to grassroots organizations. This is because the importance of methane emissions in several sectors is systematically underestimated by GWP100." See Cohen-Shields N., Sun T., Hamburg S. P., & Ocko I. B. (2023) Distortion of sectoral roles in climate change threatens climate goals, FRONTIERS IN CLIMATE: 5.

[3] See, for example, Howarth R. W. (2014) *A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas*, ENERGY SCI. ENG. 2(2): 47–60, Figure 5 shows direct and indirect emissions direct emissions for electricity production.

[4] Alvarez R. A., Pacala S. W., Winebrake J. J., Chameides W. L., & Hamburg S. P. (2012) *Greater focus needed on methane leakage from natural gas infrastructure*, PROC. NAT'L. ACAD. SCI. 109(17): 6435–40, 6436 ("Fig. 2C shows that new natural gas power plants produce net climate benefits relative to efficient, new coal plants using lowgassy coal on all time frames as long as leakage in the natural gas system is less than 3.2% from well through delivery at a power plant. Fig. 2 also shows, for a range of leakage rates, the number of years needed to reach the "cross-over point" when net climate benefits begin to occur after a fuel-technology choice is made."). *See also* Howarth R. W. (2014) *A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas*, ENERGY SCI. ENG. 2(2): 47–60, 57 ("At best, using natural gas rather than coal to generate electricity might result in a very modest reduction in total greenhouse gas emissions, if those emissions can be kept below a range of 2.4–3.2% (based on [40], adjusted for the latest information on radiative forcing of methane [34])."); Schwietzke S., Griffin W. M., Matthews H. S., & Bruhwiler L. M. P. (2014) *Natural Gas Fugitive Emissions Rates Constrained by Global Atmospheric Methane and Ethane*, ENVIRON. SCI. TECHNOL. 48(14): 7714–22, 7720 ("When used for power generation, combined NG CH4 and CO2 emissions break even with coal at 8.6% FER using a 100-year CH4 GWP (including CC FB), but the break-even is only 3.4% over 20 years (Figure 3)."); *and* Gan Y., El-Houjeiri H. M., Badahdah A., Lu Z., Cai H., Przesmitzki S., & Wang M. (2020) *Carbon footprint of global natural gas supplies to China*, NAT. COMMUN. 11(1): 824, 6 ("The increasing average GHG intensity of 2030 is caused by the potential growth of GHG-intensive gas supplies, including supplies from Russia's Urengoi and Nadym fields, Turkmenistan's Galkynysh and Bagtiyarlyk, and domestic shale gas from Fulling field, which all have well-to-city-gate GHG intensities higher than the 75th-percentile level at the supply curve. High well-to-city-gate emissions of gas supply would significantly offset the potential climate benefit of China's coal-to-gas switching.").

[5] Gordon D., Reuland F., Jacob D. J., Worden J. R., Shindell D., & Dyson M. (2023) Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates, ENVIRON. RES. LETT. 18(8): 084008, 6 ("When considering SO_2 aerosol emissions from coal, we find in our scenario analyses that global gas systems that leak over 1% of their methane (when considering a 20 year timeframe) or 3.3% (when considering a 100 year timeframe) have life-cycle emissions intensities that are on par with coal leaking methane at the IPCC emissions rate. And gas with ~0.2% methane leakage rate has higher life-cycle GHGs than coal from low methane coal mines, considering 20 year timeframe effects.").

[6] Intergovernmental Panel on Climate Change (2021) CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge and New York. *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *Benefits and Costs of Mitigating Methane Emissions*, 18; *and* Ferris R., Dreyfus G. & Zaelke D. (2023) A PRIMER ON CUTTING METHANE: *The Best Strategy for Slowing Warming in the Decade to 2030*.

[7] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: *Benefits and Costs of Mitigating Methane Emissions*, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years.").

[8] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *Benefits and Costs of Mitigating Methane Emissions*, 28 ("Fossil fuels: release during oil and gas extraction, pumping and transport of fossil fuels accounts for roughly 23 per cent of all anthropogenic emissions, with emissions from coal mining contributing 12 per cent…. Agriculture: emissions from enteric fermentation and manure management represent roughly 32 per cent of global anthropogenic emissions. Rice cultivation adds another 8 per cent to anthropogenic emissions. Agricultural waste burning contributes about 1 per cent or less…. Waste: landfills and waste management represents the next largest component making up about 20 per cent of global anthropogenic emissions.").

[9] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *Benefits and Costs of Mitigating Methane Emissions*, 20. *See also* Arias et al. (2021) Technical Summary in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York (2021).

[10] David Armstrong McKay et al. (2022) *Exceeding 1.5 ℃ global warming could trigger multiple climate tipping points,* Science 377(6611): eabn7950. *See also* Zaelke D., Picolotti R., Campbell K., & Dreyfus G. (2023) THE NEED FOR FAST, NEAR-TERM CLIMATE MITIGATION TO SLOW FEEDBACKS AND AVOID TIPPING POINTS, 5-15.

[11] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *Benefits and Costs of Mitigating Methane Emissions*, ch. 4. *See also* International Energy Agency (2021) *Curtailing methane emissions from fossil fuel operations*.

[12] *See, for example,* a bill (draft legislation) proposed in California, United States, on natural gas producing low methane emissions. The bill, as of amendments made 1 May 2023, would require, among other things, that the California Air Resources Board (CARB) establish a certification standard for natural gas producing low methane emissions, require CARB to encourage natural gas procurement on behalf of the State to shift to natural gas producing low methane emissions, and require CARB collection of information from utilities and other large gas users regarding any contract for and use of natural gas certified to have at least 80% lower methane emissions than average across the natural gas supply chain, as data are available, or the use of other best practices to minimize methane and greenhouse gases from natural gas supplying California. As of 30 May 2023, the bill passed in the California Senate, and is awaiting reading in the State Assembly.

[13] International Energy Agency (2022) *Global methane tracker*.

[14] Alvarez R A, Zavala-Araiza D, Lyon D R, Allen D T, Barkley Z R, Brandt A R, Davis K J, Herndon S C, Jacob D J, Karion A, Kort E A, Lamb B K, Lauvaux T, Maasakkers J D, Marchese A J, Omara M, Pacala S W, Peischl J, Robinson A L, Shepson P B, Sweeney C, Townsend-Small A, Wofsy S C and Hamburg S P. (2018) *Assessment of methane emissions from the U.S. oil and gas supply chain* *Science* **361** 186–8.

[15] Lackner M. & Mohlin K. (2022) CERTIFICATION OF NATURAL GAS WITH LOW METHANE EMISSIONS: CRITERIA FOR CREDIBLE CERTIFICATION PROGRAMS, Environmental Defense Fund.

[16] *See, for example,* Oil Climate Index plus Gas, OCI+.

[17] Lackner M. & Mohlin K. (2022) CERTIFICATION OF NATURAL GAS WITH LOW METHANE EMISSIONS: CRITERIA FOR CREDIBLE CERTIFICATION PROGRAMS, Environmental Defense Fund.

[18] Clean Air Task Force, *Country Methane Abatement Tool* (last visited 16 June 2023).

[19] Alvarez R. A. *et al.* (2018) *Assessment of methane emissions from the U.S. oil and gas supply chain*, SCIENCE 361(6398): 186–88.

[20] Chen Y., Sherwin E. D., Berman E. S. F., Jones B. B., Gordon M. P., Wetherley E. B., Kort E. A., & Brandt A. R. (2022) *Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey*, ENVIRON. SCI. TECHNOL. 56(7): 4317–23. *See also* Cusworth D. H. … Duren R. M. (2022) *Strong methane point sources contribute a disproportionate fraction of total emissions across multiple basins in the United States*, PROC. NATL. ACAD. SCI. U.S.A. 119(38): e2202338119.

[21] Sherwin E., Rutherford J., Zhang Z., Chen Y., Wetherley E., Yakovlev P., Berman E., Jones B., Thorpe A., Ayasse A., Duren R., Brandt A. & Cusworth D. (2023) Quantifying oil and natural gas system emissions using one million aerial site measurements Online.

[22] Lauvaux T., Giron C., Mazzolini M., d'Aspremont A., Duren R., Cusworth D., Shindell D., & Ciais P. (2022) *Global assessment of oil and gas methane ultra-emitters*, SCIENCE: 375 557–61.

[23] Fox T.A., Barchyn T.E., Risk D., Ravikumar A.P. and Hugenholtz C.H. (2019) *A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas*, ENVIRON. RES. LETT.: 14 053002.

[24] US Department of Energy (4 April 2023) *Joint Statement by the U.S. and EU following the 10th U.S.-EU Energy Council*.

[25] United Nations Environment Programme, *About IMEO* (last visited 16 June 2023).

[26] University of Texas at Austin, Colorado State University, & Colorado School of Mines, *Energy Emissions Modeling and Data Lab* (last visited 16 June 2023)

[27] Veritas, *Home* (last visited 16 June 2023).

[28] MiQ (8 June 2023) *MiQ-Highwood Index Reveals Up-to-Date, Measurement-Informed Estimate of U.S. Average Methane Intensity*, Press Release.

[29] Oil and Gas Methane Partnership (OGMP) 2.0, *Frequently Asked Questions*, "What are the requirements for a company's methane reduction target? ("• Companies that set an upstream **methane intensity target** will report, for example, the sum of all gas marketed or conveyed over the period, to aid in calculation of methane emission intensity. For midstream and downstream segments, other parameters will be used to calculate the emission intensity (e.g., transmitted gas, distributed gas, length of pipeline, regasified gas, withdrawal gas, etc.). Each company is to provide information reflecting the denominator used in their intensity target. • Those companies that set an absolute reduction target should also report their baseline year and reference year for calculating the absolute reduction in methane emissions.") (emphasis in original) (last visited 16 May 2023).

[30] Oil and Gas Climate Initiative (OGCI), *OGCI's 2025 Methane Intensity Target* (last visited 16 May 2023).

[31] China National Petroleum Corporation (CNPC) (19 May 2021) *China Oil and Gas Methane Alliance was inaugurated* ("It has seven members: CNPC, China Petroleum & Chemical Corporation, China National Offshore Oil Corporation, PipeChina, Beijing Gas, China Resources Gas, and ENN Energy, with CNPC serving as its first president. At the conference, the founding members jointly announced their pledge to control methane emissions across the entire industry chain and take practical measures to push for the clean and low-carbon transformation of energy. The China Oil and Gas Methane Alliance is committed to building a high-quality and open platform for technical experience sharing and cooperation, improving methane emissions control, and actively engaging in global climate governance. It will join the global efforts to ensure systematic, regular, standardized and international methane monitoring and measurement, promote and adopt leak detection and repair (LDAR) and other effective emissions control measures throughout the industry chain, from oil and gas production, storage and transportation to sales, increase the recovery and utilization of vented gas during exploration and development, actively develop new energy sources, and reduce dependence on fossil fuels during oil and gas production … Through the China Oil and Gas Methane Alliance, member companies will incorporate methane emissions control into their carbon emissions reduction plan, comprehensively improve methane emissions control, strive to reduce the average methane intensity in natural gas production to below 0.25% by 2025"). Notably, CNPC is also a member of OGCI. *See* OGCI, *Our Members* (last visited 16 May 2023).

[32] *See, for example,* Environment and Climate Change Canada (2019) *Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)* ("Companies must register their facilities before April 30th, 2020, or within 120 days of when the facility begins to be covered by any of the requirements. There are also provisions in the regulations to retain information for record-keeping, inspection purposes, and for on-demand reporting to Environment and Climate Change Canada. Regulatory requirements for fugitive equipment leaks, venting from well completions, and compressors, come into force on January 1, 2020. Regulatory requirements for facility production venting restrictions and venting limits for pneumatic equipment come into force on January 1, 2023.").

[33] *See, for example,* Institute for Governance & Sustainable Development (17 January 2023) *Briefing: China Announces Progress in Methane Monitoring and Evaluation in Preparation for the Release of Its National Action Plan on Methane* ("China's Ministry of Ecology and Environment (MEE) highlighted progress on carbon dioxide and other greenhouse gas monitoring and evaluation pilot projects aimed at answering critical questions on 'what to measure,' 'where to measure,' and 'how to measure.' This includes pilot projects exploring preliminary technical methodologies for methane leakage detection. In particular, MEE noted that the oil and gas industry pilots have established a methane leakage detection mechanism by implementing an integrated "satellite + unmanned aerial vehicle + cruise" monitoring system for tracking methane leakage in production processes. For the coal mining industry pilots, MEE observed that a collaborative methane emissions monitoring technology has been developed using existing coal mine safety monitoring systems. Last but not least, MEE commented that it has established a preliminary understanding of the concentrations and the spatial and temporal distributions of global methane emissions through analysis of satellite remote sensing data."). In this regard, China's MRV efforts are notable and relevant to this study, including:

- Ministry of Ecology and Environment, *Outline of Ecological and Environmental Monitoring Plan (2020-2035)* (2020) ("Following the principle of 'accounting as the main focus and monitoring as a supplement' and under the circumstances that no significant financial investment will be required, the monitoring of greenhouse gases (including CO_2, CH4, SF6, HCFCs, NF3, and N2O, etc.) shall be incorporated into the planning and design of routine monitoring systems");
- Ministry of Ecology and Environment, *14th Five-Year Ecological and Environmental Monitoring Plan* (2021) ("Develop and implement the *Work Plan on Carbon Monitoring and Evaluation Pilot Projects*. Organize enterprises in key industries such as thermal power, iron and steel, oil and gas mining, coal mining and waste disposal to carry out greenhouse gas emissions monitoring pilot projects, including to monitor the emissions of carbon dioxide and methane");
- National Development and Reform Commission, National Bureau of Statistics, and Ministry of Ecology and Environment, *Implementation Plan on Accelerating the Establishment of A Unified and Standardized Carbon Emission Statistics and Accounting System* (2022) ("Promote research on accounting for non-CO_2 greenhouse gas emissions");
- Ministry of Ecology and Environment, *Medium- and long-term Development Plan for Eco-Satellites (2021-2035)* (2022) ("Considering the requirements of promoting synergy in pollution reduction and carbon mitigation as provided in policy

documents including the *Action Plan for Carbon Peaking by 2030*, the main needs for remote sensing monitoring of atmospheric environment include:… remote sensing monitoring for proactive detection of and real-time response to methane emission anomalies in key industries"; "The main needs for remote sensing to support ecological and environmental protection enforcement include:… monitoring of methane emission anomalies in key industries such as oil and gas, and coal"; "During the 14th Five-year period,… develop infrared multispectral satellites so that… greenhouse gas emission source monitoring can identify CH4 emission anomalies above 10-20 ppb"; "During the 14th Five-year period,… further enhance the monitoring accuracy and rapid response capability of satellites through coordinated satellite-ground monitoring and new communication and navigation satellite services in order to provide branded services including … global distribution data of major greenhouse gases (CO2, CH4)"; "Table 4: Technological innovation system of satellite remote sensing monitoring of ecology and environment" includes "Remote sensing technologies for supervision and evaluation of methane emission sources in key industries"; "Table 5: Standard and Norm System of eco-satellite remote sensing for monitoring, inspection and enforcement" includes "Technical specifications for nitrous oxide monitoring by satellite remote sensing" and "Technical specifications for methane monitoring by satellite remote sensing.").

[34] *See, for example,* European Commission (15 December 2022) *Proposal for a Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942*, Art. 12 ("1. By ... [*182 months from the date of entry into force of this Regulation)*], operators shall submit a report to the competent authorities containing **the quantification of** source-level methane emissions estimated using **at least generic** but source-specific emission factors for all sources. **Operators may choose to submit at that stage a report according to the requirements in paragraph 2**. 3. By ... [*36 months from the date of entry into force of this Regulation*] and by *30 March* 31 May every year thereafter, operators shall submit a report to the competent authorities containing *direct measurements* **quantification** of source-level methane emissions for operated assets referred to in paragraph 2, complemented by measurements of site-level methane emissions, thereby *allowing* **improving the** assessment and verification of the source-level estimates aggregated by site…. 4. By ... [*36 months from the date of entry into force of this Regulation*] undertakings established in the Union shall submit a report to the competent authorities **of the Member State where the asset is located** containing *direct measurements* **quantification** of source-level methane emissions for non-operated assets **provided these have not already been reported by an operator in response to the obligation under paragraph 2.** Reporting at such level may involve the use of source-level measurement and sampling as the basis for establishing specific emission factors used for emissions estimation.… 11. The competent authorities shall make the reports set out in this Article available to the public and the Commission, within three months from submission by operators and in accordance with Article 5(4).") (emphasis in original).

[35] *See* Government of Mexico (2022) *Contribución Determinada a Nivel Nacional Actualización 2022*, 14 ("El sector petróleo y gas tiene una meta de 14% de reducción de emisiones y contempla medidas para su cumplimiento que se agrupan en tres ejes de actuación: a) el incremento de la cogeneración, tanto en centros procesadores de gas como en la refinación del petróleo; b) reducción de las emisiones fugitivas del subsector gas y del subsector petróleo, y c) el Programa de Eficiencia Energética en Petróleos Mexicanos y sus empresas productivas. Petróleos Mexicanos ha establecido una meta de aprovechamiento de gas metano del 98%, considerando la producción de campos existentes y nuevos, para lo cual se desarrollará una Estrategia de aprovechamiento de gas en pozos existentes, y se realizarán obras prioritarias en los nuevos desarrollos, con inversiones estimadas en más de 2000 mil millones de dólares.") ("The oil and gas sector has a goal of 14% emissions reduction and contemplates measures to fulfill it that are grouped into three axes of action: a) increased cogeneration, both in gas processing centers and in oil refining; b) reducing fugitive emissions from the gas subsector and the oil subsector, and c) an Energy Efficiency Program for Petróleos Mexicanos and its productive companies. Petróleos Mexicanos has established a methane gas utilization goal of 98%, considering the production of existing and new fields, for which a Gas Exploitation Strategy will be developed in existing wells, and priority works will be carried out in new developments, with investments estimated at more than 2000 billion dollars.") (in Spanish).

[36] *See, for example,* Government of the Federal Republic of Nigeria, Upstream Petroleum Regulatory Commission (November 2022) *Guidelines for Management of Fugitive Methane and Greenhouse Gases Emissions in the Upstream Oil and Gas Operations in Nigeria*. *See also* Clean Air Task Force (11 November 2022) *Nigeria announces rule to reduce methane emissions from the oil and gas sector* ("Nigeria has shown great leadership on methane at COP27, giving the world a concrete example of the kinds of action necessary to slash methane emissions and bend the curve on climate change," said Jonathan Banks, Global Director of CATF's Methane Pollution Prevention program. "Nigeria is turning ambition into action on methane. We sincerely hope that other nations will step up and follow its lead.").

[37] *See for example,* United States Environmental Protection Agency (2 November 2021) *EPA Proposes New Source Performance Standards Updates, Emissions Guidelines to Reduce Methane and Other Harmful Pollution from the Oil and Natural Gas Industry* ("EPA is taking a significant step in fighting the climate crisis and protecting public health through a proposed rule that would sharply reduce methane and other harmful air pollution from both new and existing sources in the oil and natural gas industry. The

proposal would expand and strengthen emissions reduction requirements that are currently on the books for new, modified and reconstructed oil and natural gas sources, and would require states to reduce methane emissions from hundreds of thousands of existing sources nationwide for the first time."). *See also* United States Environmental Protection Agency (11 November 2022) *EPA Issues Supplemental Proposal to Reduce Methane and Other Harmful Pollution from Oil and Natural Gas Operations* ("EPA is taking a significant step in fighting the climate crisis and protecting public health through a proposed rule that would sharply reduce methane and other harmful air pollution from both new and existing sources in the oil and natural gas industry. The proposal would expand and strengthen emissions reduction requirements that are currently on the books for new, modified and reconstructed oil and natural gas sources, and would require states to reduce methane emissions from hundreds of thousands of existing sources nationwide for the first time.").

[38] *See* Figure 4 in Olczak M., Piebalgs A., & Balcombe P. (2023). *A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness*, ONE EARTH 6(5): 519–35.

[39] Mohlin K., Lackner M., Nguyen H., & Wolfe A. (2022) *Policy Instrument Options for Addressing Methane Emissions from the Oil and Gas Sector*, SSRN JOURNAL.

[40] https://www.iea.org/reports/driving-down-methane-leaks-from-the-oil-and-gas-industry/regulatory-roadmap and Mohlin K., Lackner M., Nguyen H., & Wolfe A. (2022) *Policy Instrument Options for Addressing Methane Emissions from the Oil and Gas Sector*, SSRN Journal https://www.ssrn.com/abstract=4136535

[41] Ravikumar A. P., Roda-Stuart D., Liu R., Bradley A., Bergerson J., Nie Y., Zhang S., Bi X., & Brandt A. R. (2020) *Repeated leak detection and repair surveys reduce methane emissions over scale of years*, ENVIRON. RES. LETT. 15(3): 034029, 7–8 ("We find that leaks are persistent and LDAR programs are effective—reducing leaks by 90% between surveys. However, despite high repair efficacy, leak-related emissions only reduced by 22% between the two surveys, indicating the need for rapid, low-cost, and frequent LDAR surveys. More importantly, regulators and operators should focus their efforts on reducing vent-related emissions. In this context, further clarity on the classification of emissions as leaks and vents will aid the repair process and effectiveness of LDAR programs. In this study, vented emissions reduced by 47% between the two surveys, the majority of which can be attributed to lower tank-related emissions in the post-repair re-survey. Finally, we find that tank-related emissions contribute almost two-thirds of total emissions and points to the need for targeted inspection of tanks.").

[42] Mohlin K., Lackner M., Nguyen H., & Wolfe A. (2022) *Policy Instrument Options for Addressing Methane Emissions from the Oil and Gas Sector*, SSRN JOURNAL, 11 ("Relevant considerations for effective enforcement include what data the operator is required to report to the regulatory agency, the capacity of the agency to verify those reports and the level of the fines issued for misreporting and non-compliance"), see Table 1 for a list of LDAR regulations by jurisdiction, coverage, technologies, and frequency, and repair timelines.

[43] Adapted from Mohlin K., Lackner M., Nguyen H., & Wolfe A. (2022) *Policy Instrument Options for Addressing Methane Emissions from the Oil and Gas Sector*, SSRN JOURNAL, 24–26.

[44] Lackner M. & Mohlin K. (2022) *Certification of Natural Gas With Low Methane Emissions: Criteria for Credible Certification Programs*, ENVIRONMENTAL DEFENSE FUND.

[45] Lauren Craft, *OGCI Shifts Methane Focus from Location to Elimination*, 9 June 2023 (Energy Intelligence, Caroline Evans, ed.).