NOWHERE TO HIDE: THE IMPLICATIONS OF SATELLITE-BASED METHANE DETECTION FOR POLICY, INDUSTRY, AND FINANCE

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Introduction

In August 2020, the Trump Administration finalized plans to roll back regulations on oil and gas industry emissions of methane from new and modified infrastructure. In the same month, the European Commission gathered stakeholder comments as part of its process to introduce the first EU-wide methane regulations. Though contradictory in direction, these regulatory processes on opposite sides of the Atlantic highlighted a critical climate protection challenge: How can the oil and gas industry—and the regulators who oversee it—best detect and address methane emissions to protect the environment and the climate in particular?

The answer to this question will drive planning and operational approaches in the oil and gas industry. It could also significantly affect the future role of natural gas. Five years ago, many energy analysts expected natural gas to serve as a bridge fuel that would result in only half as much climate warming as coal, and fewer local air pollutants. Among other roles, gas was seen as a natural complement for variable wind or solar power—a way to provide firm, dispatchable, low-emissions power. Now that it is apparent that our understanding of methane emissions is poor, the climate implications of gas are far less clear.

This poor grasp of methane emissions appears likely to become a thing of the past, however. In roughly the next five years, new satellite detection systems—used in concert with existing systems, aerial monitoring platforms, and ground-based monitors—can increase markedly the transparency surrounding methane leakage. The new wave of satellite monitoring capability has major implications for industry and governments. Our world is rapidly becoming a place in which methane emissions will have nowhere to hide.

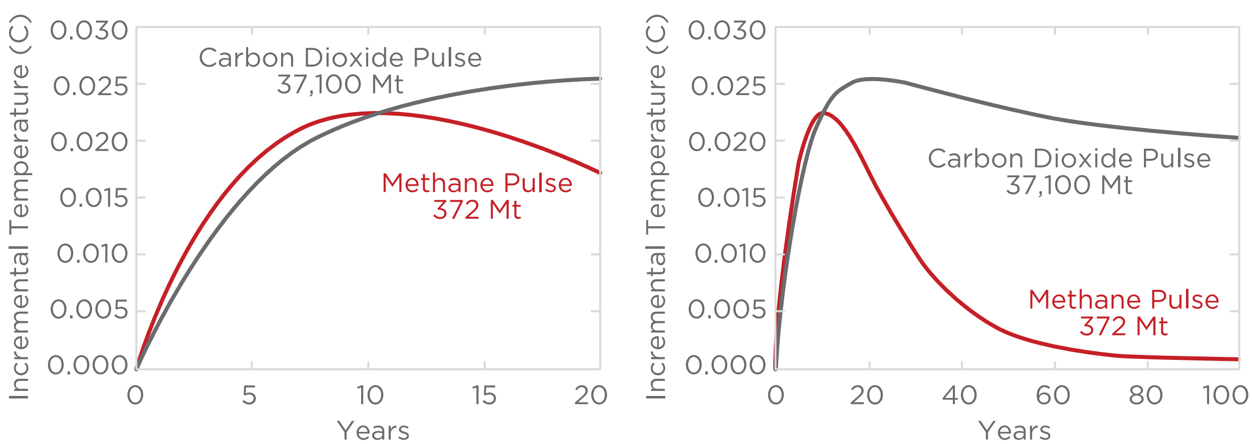
This commentary focuses on detection and response to oil- and gas-related methane emissions, which have been the subject of increasing focus on the part of industry and the public policy community. It addresses the significance of methane emissions for the climate, and the challenges of detecting and accurately quantifying methane emissions. It then explores the evolving capabilities of satellite-based methane detection and monitoring systems, which are expected to advance rapidly in the coming years, and which can be especially powerful when used in concert with aerial and ground-based monitoring systems. It concludes with a discussion of the implications of the changing satellite detection landscape for the oil and gas industry, the finance and investment community, and the realm of public policy.

A Consequential Issue

Methane is often thought of as a second-tier greenhouse gas, but this conventional wisdom misses two critical points. First, methane is pound-for-pound much more potent than the more plentiful carbon dioxide.[1] Carbon dioxide emissions are roughly 100 times greater than methane emissions each year on a mass basis, but methane and carbon dioxide are nonetheless roughly equal culprits in warming the planet over the following decades because methane traps heat so effectively.[2]

A second consideration, however, is that methane remains in the atmosphere for only a few decades, whereas carbon dioxide lingers for centuries. This implies that if methane emissions were reduced today, methane-driven warming would subside rapidly, in contrast to reductions of carbon dioxide emissions, which would have little immediate effect.[3] Methane emissions control is thus a consequential matter, because reducing emissions of this potent and short-lived gas can improve the global warming problem much more quickly than reductions in carbon dioxide emissions. Figure 1 depicts these relationships, showing that in the first 10 years after a single year's emissions of carbon dioxide and methane, the added methane warms the earth by an amount comparable to the warming by a year's worth of carbon dioxide.[4]

Figure 1: Global average temperature rises due to single-year anthropogenic emissions ("pulses") of carbon dioxide and methane



Note: Because of its greater ability to trap heat, during the first 10 years after emission, a year's worth of methane warms the earth by an amount comparable to a year's CO_2.

Source: R.L. Kleinberg, "The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers," preprint (2020), https://www.researchgate.net/publication/344026808_Kleinberg_GWP_Climate_Policy_200901

Atmospheric concentrations of methane have been rising since the start of the industrial era and today are more than twice as high as in the middle of the 18th century. The recent growth of methane concentrations threatens to place out-of-reach the Paris Agreement's goal of limiting global average temperature rise to well below two degrees Celsius.[5] A host of sources contribute to methane emissions, including agriculture, waste management, land use, and permafrost melt.[6] Control of methane from the oil and gas industry, the focus of this essay, is not a simple task, but it represents a relatively straightforward means to respond to the growing atmospheric methane levels.

The Challenge: Detecting and Quantifying Methane Emissions

Given that controlling methane is a consequential objective, logical questions follow: How much methane does the oil and gas industry emit today, and from what aspects of its operations? Regrettably, the answers are not clear nor straightforward.

Methane emissions from the oil and gas industry occur due to either unintentional leaks, or as a result of venting, sometimes in an uncontrolled manner.[7] Because methane is a colorless gas—and odorless until it is spiked with sulfur-containing compounds before commercial distribution—methane can easily escape undetected in the absence of effective monitoring.

The difficulty of detecting oil and gas methane emissions reflects in part the wide range of facilities and components across natural gas production, transmission, storage, and distribution systems, and the vast number of components in each system. In the United States alone, there are more than one million oil and gas wells, millions of miles of natural gas pipelines, and thousands of compressor stations.[8]

In the absence of a comprehensive surveillance regime for methane emissions, regulators may rely on engineering estimates to approximate the amount of methane lost from various oil and gas infrastructure elements and their components[9] In the United States, for example, the Environmental Protection Agency assigns each component type an emission factor, reflecting its use in *normal* operation. Unfortunately, subsequent investigations have shown that these emission factor estimates consistently underestimate the amount of methane lost to the atmosphere—often because the largest emission events are due to *abnormal* process conditions that are not—or are insufficiently—accounted for in the estimation method.[10]

The True Scale of Methane Emissions

All in all, just how bad are current figures for methane emissions from oil and gas? The simple answer is that one does not know for certain, and the answer may vary around the globe. The assessment that arguably constitutes the best overall quantification of emissions from US oil and natural gas production, gathering, processing, transmission, and storage found actual emissions *significantly* higher than levels reported through the official inventory of emissions.[11]

Moreover, methane detection methods that do not employ continuous monitoring can overlook significant emissions in several broad (and overlapping) categories:

- *Vented Emissions:* Certain releases of methane are partly avoidable but permitted, such as the release of methane (venting) resulting from liquid unloading of well bores during production and maintenance activities.[12]
- *Intermittent Emissions:* Some of the most significant sources of emissions are intermittent. They are therefore likely to escape detection when inspections occur infrequently—for example, a few times a year. A successful inspection may give a false sense of security that is only revealed to be false when the next inspection occurs. Egregious examples include oil tanks, which vent volatile organic compounds and methane when temperatures rise.[13]
- *Flaring:* In theory, flaring of gas from oil wells and other installations combusts methane and releases into the atmosphere only carbon dioxide, which captures heat less effectively than methane. In reality, flares are often inefficient and combust methane incompletely. Thus, a significant share of what is meant to be emitted as carbon dioxide is instead emitted as methane.[14] Unlit or malfunctioning flares are even bigger problems.[15] Moreover, flaring is generally underreported.[16]

Compounding the problems arising from these undetected methane emissions is the phenomenon of super-emitters. Some infrastructure elements emit quantities of methane far in excess of the median emitter of that type. For example, a meta study of approximately 20 device types found that 5 percent of leaks typically contribute over 50 percent of total emissions.[17] Similar results are found across infrastructure types, and at all scales.[18] Worse yet, super-emitters tend to be intermittent, which means that they can be both large in scale and hard to detect.

To put the scale of methane emissions in perspective, it is worthwhile to compare the following points: The US Environmental Protection Agency estimated that compliance with its 2016 methane reduction regulations (40 CFR Part 60 Subpart 0000a), with four inspections of covered components per year, would prevent the release into the atmosphere of 220 million kilograms of methane per year, which is equivalent to 25,000 kilograms per hour.[19] The leak from the Aliso Canyon gas storage facility in southern California, by comparison, emitted 100 million kilograms of methane in 112 days (an average rate of 37,000 kilograms per hour).[20] The blowout of a gas well in western Ohio vented 60 million kilograms of methane in 20 days (an average rate of 120,000 kilograms per hour).[21]

On a worldwide basis, incidents on this scale are not rare. Preliminary studies that utilize satellite data along with auxiliary information from a range of other data sources indicate it is possible to find, at any given time, 100 or more super-emitter sources emitting methane at rates exceeding 5,000 kilograms per hour.[22] It is suggested that about half of these super-emitters are associated with oil and gas infrastructure.

Methane Detection from Satellites

Given that methane emissions harm the climate, and at present are not well detected or quantified, new technologies stand to play an important role. Satellites are developing into powerful new tools for this role, especially when used together with traditional ground-based and aerial measurement techniques. Ground-based systems typically provide the most accurate measurements of methane emissions, but they give localized data. Moreover, only a limited amount of ground-based measurement equipment is used for continuous monitoring. Aerial measurements have the ability to cover larger areas, but they are typically only used on the basis of overflight campaigns and are in some countries difficult to implement due to flight permit issues. A key advantage of satellite detection systems is their ability to provide recurring measurements over large, even global, geographies.

There are three broad types of satellite instruments and missions that can be used to measure methane from space (summarized in Table 1). The first category includes instruments that can provide full global coverage, typically on a daily basis. Often such instruments are part of scientific satellite missions that measure a wide range of gases in the atmosphere. Currently the most accurate methane detection system with global coverage is the TROPOspheric Monitoring Instrument (TROPOMI), which orbits aboard the Copernicus Sentinel-5 Precursor of the European Space Agency (ESA). ESA has committed itself to two additional flagship missions in its Copernicus program, each with methane capabilities. These are Sentinel-5 (conventional air pollutants and methane) and CO2M (CO_2 and methane). (See Table 1.)

A second category of space-borne methane sensors are instruments that provide targeted measurements of selected areas. These systems are purpose-built to support emission quantification with good spatial resolution for a limited number of sites.[23] Such systems typically rely on the first category of instruments, those with full global coverage, to identify emission hotspots and/or calibrate sensors.

Examples of the second category of satellites include those operated by GHGSat, a Canadian company that sells its methane data on commercial terms and has attracted investment from the venture fund created by the companies of the Oil and Gas Climate Initiative.[24] In 2016, GHGSat launched its first satellite. The company is launching two follow-on satellites with improved measurement capabilities in 2020 and a larger fleet of satellites in 2022.[25] A second targeted methane monitoring initiative is the Twin Anthropogenic Greenhouse Gas Observers (TANGO) mission, which is currently being evaluated by ESA for potential implementation in 2024. This mission could provide public data of methane and CO_2 emissions and could be used in tandem with the Sentinel-5 and CO2M satellites to provide more detailed examination of specific locations.[26] Another example of this category of satellites is the MethaneSAT system, currently under development by the Environmental Defense Fund (EDF), a major US-based environmental advocacy organization.[27]

A third category of space-based methane sensors are instruments that provide near-continuous measurements of a given part of the planet. These instruments are in a geostationary orbit 35,786 kilometers above mean sea level (compare to typical orbits of 500–800 kilometers for the first and second satellite categories above). For methane observation, the most relevant mission will be the GeoCarb mission, which has been planned by NASA to provide “wall-to-wall” observations over the Americas between 50 degrees North and South latitude—from the southern tip of Hudson Bay to the southern tip of South America.[28]

Table 1: Successive satellite systems enable observation of methane emissions and concentrations

Coverage	Instrument / Mission	Launch	Nominal detection threshold (kg/h)	Pixel size (km x km)
Global	SCIAMACHY	2003	70,000	30 x 60
	TROPOMI	2017	4,000	7 x 7
	Sentinel-5	2022	4,000	7 x 7
	CO2M	2026	1,000	2 x 2
Targeted	TANGO	2024	500–1,000	0.3 x 0.3
	MethaneSat	2022	500–1,000	0.1 x 0.4
	GHGSat	2016	1,000	0.05 x 0.05
		2022	100	0.025 x 0.025
Regional	GeoCarb (only observes the Americas)	2022	4,000	10 x10

Note: "Nominal detection threshold" represents the smallest leak rate a system is expected to detect and quantify. "Pixel size" is a measure of the smallest increment of Earth's surface that the system can observe.
Source: Table by Kleinberg, Leemhuis, and Denier van der Gon based on multiple sources[29]

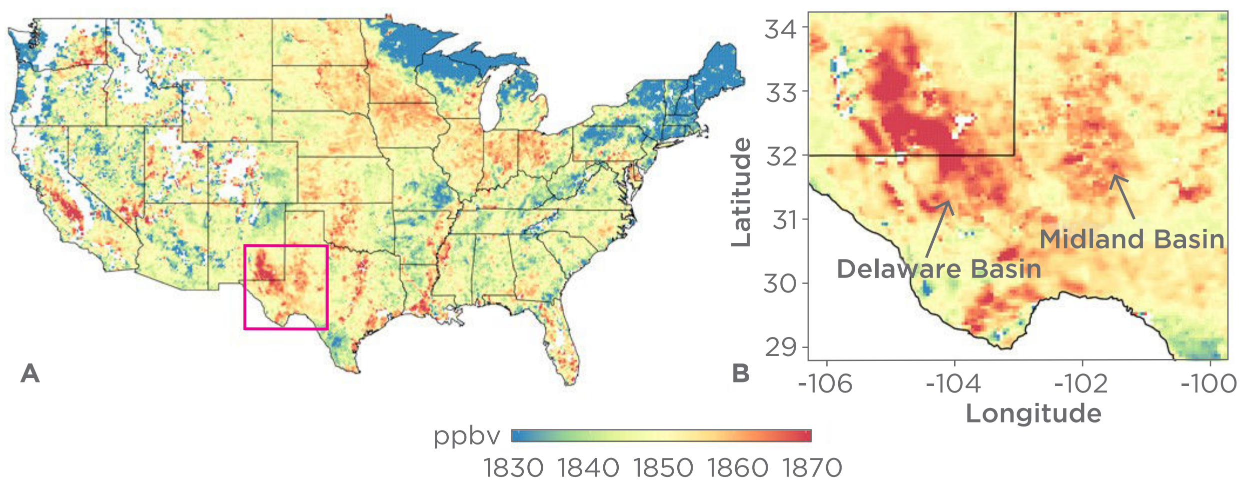
Capabilities of Satellite-borne Sensors

The ability of each satellite instrument to quantify methane emissions depends on its technical specifications (summarized as "detection threshold" in Table 1), its ability to spatially separate neighboring sources, and its ability to produce measurements in different conditions (e.g., the amount of daylight and cloud cover). Offshore methane emissions cannot be measured, or can only partly be measured, from satellite-based systems; instead, on-facility sensors and low-flying aircraft must be used.[30]

Research has shown that satellite data can be used to provide emission assessments at a national level, regional level, or the level of large geographical areas. Satellites can provide valuable insights into emissions from clusters of industrial, agricultural, or waste disposal activities. In the context of the oil and gas industry, a typical example of this concerns emissions on the scale of basins, geographical areas where large numbers of well pads, pipelines, and processing equipment are concentrated to produce hydrocarbons from a subsurface reservoir.

Recently teams of scientists have used the data of TROPOMI to quantify emissions from the Permian Basin in the United States (Figure 2). The Permian accounted for about 35 percent of oil and 16 percent of gas produced in the US in 2019.[31] Reported methane emission rates are about 3 billion kilograms per year.[32] These estimates are more than a factor of two higher than estimates derived from the US Environmental Protection Agency greenhouse gas inventory.[33]

Figure 2: Satellite observations of methane in the atmosphere from TROPOMI



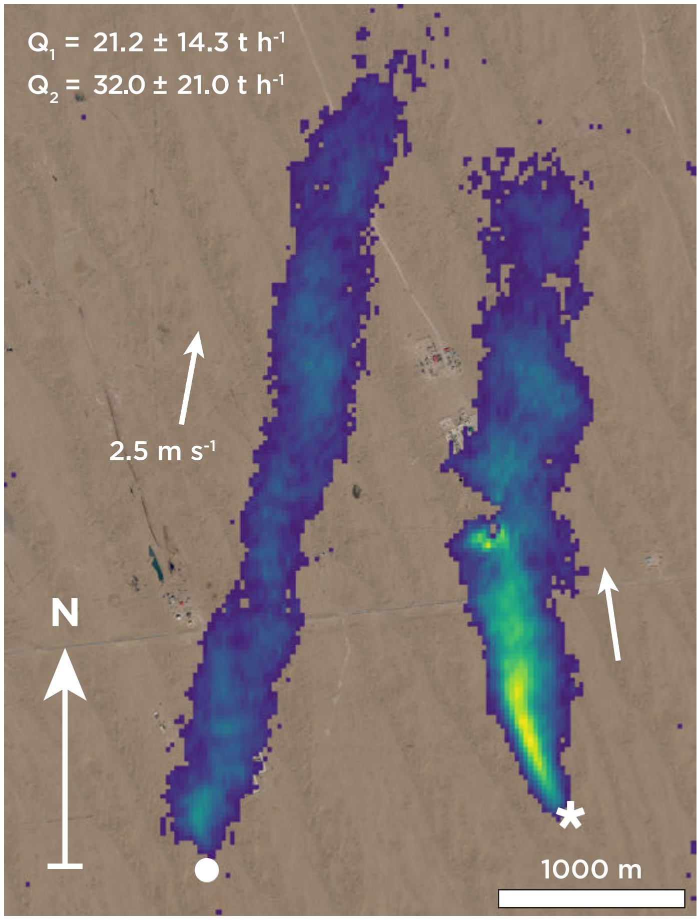
Note: Regions with abnormally high concentrations are shown in red. Researchers use these data to quantify regional emissions of oil and gas basins (such as image B, which magnifies the Permian Basin in Texas and New Mexico).

Source: Y. Zhang et al., "Quantifying Methane Emissions from the Largest Oil-Producing Basin in the United States from Space," Science Advances 6, no. 17 (April 22, 2020), https://advances.sciencemag.org/content/6/17/eaaz5120

National and basin-level assessments can be used by policy makers and other stakeholders to assess methane emission reduction potential, and compare reported and actual emissions. Such assessments do not at present allow owners and operators of facilities to detect individual leaks in order to take specific remedial action. The precision of satellite-based assessments is expected to improve with successive generations of satellites. Moreover, the national and basin-level assessments can serve as a tool to help identify methane hotspots, thus enabling the use of detailed ground or airborne measurements to find leaks and identify mitigation steps. Furthermore, national and basin assessments can help policy makers and investors assess the likely extent of emissions in areas from which little other emission data is available.

Satellites have recently become an increasingly valuable tool for quantifying individual emission sources, and they will improve further as technical capabilities evolve. Figure 3 shows an example of how the targeted measurements of GHGSat were used to monitor emissions from a pipeline leak in the Korpezhe oil and gas field in Turkmenistan. GHGSat data enabled identification of a leak at a gas compressor station, which was assessed to be 10,000 to 43,000 kilograms of methane per hour. Other nearby leaks were also identified, with strengths ranging from 4,000 to 32,000 kilograms per hour (see e.g., Figure 3, left plume). Archived TROPOMI data showed large Korpezhe emissions persisted for at least 14 months.[34]

Figure 3: Targeted emission assessments



Note: GHGSat-D pinpoints the location and scale of plumes in Korpezhe, Turkmenistan, January 13, 2019. Data from TROPOMI did not allow identification as two distinct leaks.

Source: D.J. Varon et al., "Satellite Discovery of Anomalously Large Methane Point Sources From Oil/Gas Production," Geophysical Research Letters 46, no. 22 (October 25, 2019), https://doi.org/10.1029/2019GL083798

The ability to quantify emissions data from space is a recent development, and is gaining momentum. Further technological advancements can be expected. To date, nearly all emission assessments have been undertaken through scientific studies. A major task lies ahead to translate scientific knowledge into operational systems, validate them, and ensure frequent and reliable streams of emission data become available for use by facility operators, investors, and policy makers.

New Pathways for Space-based Methane Information

Access to publicly available satellite methane data from TROPOMI, and in the future other platforms such as those being planned by the ESA Copernicus missions, is animating interest from for-profit companies and not-for-profit advocacy groups that are interested in using methane data to advance these organizations' missions. For example, the Paris-based company Kayrros produces and seeks to sell insights on methane emissions that fuse publicly available satellite imagery with other data sources and market information.

On the nonprofit side, the Environmental Defense Fund will soon launch MethaneSAT. Working in collaboration with scientific advisors, satellite constructors, and other specialist organizations, EDF aims to start producing data from MethaneSAT in 2023. MethaneSAT will offer the possibility of targeted measurements as well as measurements across larger areas such as oil and gas producing regions.[35] Soon after launch, EDF will begin a stream of near real-time data that will be made available to the public for free.

Thus, in roughly the next five years, data about atmospheric methane emissions will be significantly more plentiful, less reliant on estimates, and more widely available outside the scientific community than in the past. One can classify the different streams of methane data and their availability in accordance with the three pathways shown in Table 2: public information, a hybrid of public and private information, and proprietary information.

Table 2: Methane emissions data will follow three pathways to user communities

Pathways for methane satellite data utilization			
	1. Publicly available	2. Public-private	3. Proprietary
Examples	Copernicus missions (Sentinel-5p, Sentinel-5, TANGO and CO2M) and MethaneSAT	Kayrros products, using Copernicus data	GHG-Sat
Access to raw data	Yes	Yes	No, privately owned spacecraft and instruments
Emission products and methods publicly available	Yes, part of scientific studies and planned monitoring programs	No, sold in products/ services	No, sold in products/ services

Several implications are worthy of note:

- *The availability of services:* An increasing range of paid services is expected that will give consumers access to methane emissions information without bearing the cost and burden of developing extensive scientific and technical expertise.

- *Different levels of analytical transparency:* Methane information gained through the public route can be expected to be more transparent and verifiable. By contrast, proprietary and hybrid sources will be likely to generate commercially marketed information, such as satellite data that are fused with big data from non-satellite sources and observations; comparing data from alternative channels will enable verification of emissions data.
- *No "one-size-fits-all" solution:* Different users will be served best by information products made available through different sources. An industrial end-user that requires detailed and confidential information on its facilities will have different needs than advocacy groups trying to encourage effective policy or responsible industrial field operations, or a national government seeking to verify emission in the context of an international treaty.

Implications of Emerging Satellite Systems

The emergence of new satellites will in roughly the next five years radically increase the amount of methane emissions data available, with greater accuracy, spatial detail, quantification, and timeliness. Moreover, those data can be expected to enable—and in some cases to force—decision-making and action by the oil and gas industry, by the finance world, and by the public policy community.

Implications for the Oil and Gas Industry

At present, companies engaged in the production, processing, transportation and distribution of oil and gas often engage in self-reporting of methane emissions. This is generally true even for those companies that are engaging in voluntary emissions-reduction programs.[36] Consequently, results from the voluntary efforts are difficult to verify for outside parties. Those companies not inclined to engage on a voluntary basis have only limited incentives. Some companies see these efforts as core to good business practice; others view them as a strategic effort to sustain their industry's social license to operate. Many companies seek to reduce the wastage of methane as a potentially valuable resource, as industry advocates are quick to stress.

Nonetheless, in a situation in which official emissions figures are calculated using engineering estimates that appear to systematically underreport actual emissions levels, as discussed above, there is little if any external stimulus for transparency, precision, or remediation of true emissions. The decline in global demand for oil and natural gas this year, which pushed many oil and gas producers into survival mode, may have resulted in temporary reductions in emissions but only makes it more challenging for companies that have not been addressing methane emissions from their facilities to begin doing so now. Companies have slashed capital expenditure budgets[37] and some experts worry that deferring investments to reduce methane emissions may result.[38] The oil and gas industry is also confronting a significant loss of trust from many members of the general public.[39] As public awareness of actual emissions levels grows, the environmental bona fides of natural gas are now subjected to more skeptical evaluation.[40]

With the arrival of progressively improving satellite-based methane emissions information, the oil and gas industry will face far more scrutiny from stakeholders who will be armed with far more accurate and timely information. This scrutiny translates into good news for the climate: It will be directed along the entire value chain of the industry—from exploration and production all the way through to local distribution.[41] It will apply no less to non-operated assets and joint ventures—even those in jurisdictions where there has been little or no transparency, less attention to environmental standards, and little ability to engage in aerial or ground-based monitoring. It is likely to exacerbate significant controversies over new developments, and continuing operations. Improving satellite-based emissions information may also enable comparison of companies in different jurisdictions; it will make it much easier to assess company performance—whether the company is a publicly traded "major" or a smaller independent company or a state-owned entity.

The arrival of new satellite capabilities will not only bring new challenges for natural gas—it will also bring new opportunities. Companies that move aggressively to quantify their true methane emissions and reduce them may have a window of opportunity to differentiate themselves from less-proactive competitors. Companies that seek to reduce their methane emissions as a matter of strategic priority may benefit from their ability to employ the range of new emission-detection and quantification tools that are emerging at a much lower cost than in the past. These satellite technologies may help facilitate the development of a market in which end users can opt to buy what might be called "certified low-emission natural gas"—a differentiated commodity akin to structures that now allow electricity consumers to buy carbon-free "green" power.

Implications for Investors

The financial and investment community is increasingly focused on understanding and mitigating its vulnerabilities arising from the causes and impacts of climate change. At present, many investors who wish to base their investment decisions on assessments of environmental risks and opportunities lack the data to accurately evaluate companies' performance. Such investors often look to environmental, social, and governance (ESG) ratings of the companies they may invest in. But today's ESG ratings can confront investors with more complexity and confusion than clarity and definitive insight. With over 600 ESG ratings and rankings available, the ESG landscape is fragmented.[42] Different ratings schemes often employ non-transparent methodologies—"black boxes"—with little or no standardized scoring methodology. Compounding the problem is the fact that ESG ratings firms must depend on unreliable public data when it comes to emissions. It is therefore hardly surprising that a given company's rating can vary wildly from one ratings agency to the next.[43]

Many in the investment community conclude that they cannot rely on either ESG ratings or the oil and gas companies' own measurements of emissions.[44] What is needed instead are reliable and impartial data of actual performance. In regard to environmental attributes (the "E" in "ESG"), satellite data on methane emissions can provide badly needed, uniformly applied, authoritative verification. Investors can be expected to see the new satellite-based methane information as a tool to press for real-time and accurate disclosures of methane emissions. The financial community will also be likely to face growing divestment pressures in regard to those oil and gas companies that fail to reduce and prevent methane emissions.

Implications for Public Policy

The public policy impacts of more accurate and timely understanding of methane emissions could prove especially significant.

This better understanding may well reverberate through national and international structures whose mission it is to maintain inventories of greenhouse gas emissions and craft policies to respond adequately to them—including national-level environment agencies, scientific entities like the Intergovernmental Panel on Climate Change, and the parties to the UN Framework Convention on Climate Change. If it turns out that global emissions of oil-and-gas-related methane are significantly greater than previously understood, national and international priorities for climate change mitigation may need to be reordered.[45]

The availability of improved methane emissions data could encourage countries to demand that their companies detect and respond to methane emissions. The new data could drive efforts to introduce strict regulation of gas production or imports or to accelerate abandonment of fossil fuel usage. The new data could also facilitate emissions pricing schemes. The corollary to this thought is that, because of methane's potency and short atmospheric lifetime, addressing methane emissions with a much greater sense of urgency may help to foster badly needed climate progress. Reducing and eliminating methane emissions, after all, should enable easier and faster climate mitigation than alternative options such as significantly reducing emissions from heavy industry or replacing internal combustion engines with electric vehicles.[46]

Other impacts in public policy will arise in regard to current legal and regulatory structures. Policy makers, regulators, the general public, and environmental advocacy groups that seek to speak on the public's behalf will have a much better understanding than was historically the case of how much methane is being emitted, where, by whom, and for how long. This information may be employed to identify ineffective regulatory oversight or to "name and shame" individual companies whose operations result in methane emissions. The data may be introduced into facility-level approvals as well as long-term policy planning. In this sense, the new information may assist regulators in enforcing emissions standards, penalizing laggards or, conversely, creating greater incentives for stronger environmental stewardship.

Last, the new availability of methane emissions data may be used to exert influence on policy makers and regulators themselves. The environmental community has historically criticized those officials perceived as defending the interests of companies rather than the general public. The availability of accurate, near real-time methane emissions data can be expected to exert pressure for a new degree of public accountability. If lawmakers and regulators fail to set and enforce sufficiently rigorous standards and mandates, the public will be able to see the proof in new, clear detail.

Conclusions

Methane emissions pose a serious threat to global climate, and therefore to the oil and gas industry. They result from faults in design and operation of complex industrial systems that reach from the wellhead in oil and gas producing regions to the burner tip in industrial installations, residential kitchens, and other end-use locations. Methane emissions can come in the form of routine, low-level leakage, but also as intermittent super-emissions, which often go undetected for a period of time due to the pernicious combination of inadequate methane emissions detection systems and inadequate regulatory and/or financial incentives.

The power of methane as a greenhouse gas, and methane's comparatively short atmospheric lifetime, mean that it is vital to eliminate—or at least control much more effectively—methane emissions. The climate benefits of doing so are compelling.

The emergence of new generations of space-based methane emissions detection and quantification systems can and should drive change in the treatment of methane in the oil and gas industry, the financial community, and the public policy arena. More plentiful and accurate data on methane emissions will soon be available through a variety of channels and in a variety of forms—some designed for speedy remediation of leaks by industry, others available to be used by investors or public interest groups to enable accountability, regulatory action, and perhaps legal change. Companies that fail to act now and reduce emissions will suffer the consequences at the hands of investors, governmental decision-makers, and the general public. There will be nowhere to hide methane emissions.

Notes

1. R.L. Kleinberg, "The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers," preprint (2020) https://www.researchgate.net/publication/344026808_Kleinberg_GWP_Climate_Policy_200901.

2. Ibid.

3. D. Shindell et al., "Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security," *Science* 335 (2012): 183-189, https://science.sciencemag.org/content/335/6065/183.

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5. E.G. Nisbet et al., "Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement," *Global Biogeochemical Cycles* 33, no. 3 (2019) https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GB006009.

6. Quirin Schiermeier, "Global methane levels soar to record high," *Nature* (July 14, 2020), https://www.nature.com/articles/d41586-020-02116-8 (accessed August 17, 2020).

7. D. Zavala-Araiza et al., "Super-emitters in natural gas infrastructure are caused by abnormal process conditions," *Nature Communications* 8 (2017), https://www.nature.com/articles/ncomms14012.

8. R.A. Alvarez et al., "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science* 13 (July 2018), Supplementary Material, https://science.sciencemag.org/content/361/6398/186.

9. EPA, "Methane Emissions from the Natural Gas Industry," EPA/600/R-96/080a through EPA/600/R-96/080o (15 volumes) (1996).

10. Examples of such abnormal conditions include: failures of tank control systems, stuck pressure-relief valves that result in venting of methane from tanks into the atmosphere, design failures, excessive operating pressures, and malfunctioning or improperly operated equipment (Zavala-Araiza, "Super-emitters").

11. Alvarez et al. found actual emissions from production, gathering, processing, and transmission to be 1.7 times larger than reported via the official inventory and did not assess emissions from natural gas distribution, oil refining or transportation. See: Alvarez, "Assessment of methane emissions" and note the references therein. For comparison to the official inventory, see: EPA, "Inventory of Greenhouse Gas Emissions and Sinks, 1990-2018," US Environmental Protection Agency, 430-R-20-002 (2020a).

12. EPA, "EPA's Voluntary Methane Programs for the Oil and Natural Gas Industry," US Environmental Protection Agency (2020b), https://www.epa.gov/natural-gas-star-program.

13. D. Lyon et al., "Aerial Surveys of Elevated Hydrocarbon Emissions from Oil and Gas Production Sites," *Environmental Science and Technology* 50 (2016): 4877-4886, https://pubs.acs.org/doi/10.1021/acs.est.6b00705.

14. R.L. Kleinberg, "Greenhouse Gas Footprint of Oilfield Flares Accounting for Realistic Flare Gas Composition and Distribution of Flare Efficiencies," preprint (2019), https://doi.org/10.1002/essoar.10501340.1.

15. EDF, "Flaring: Aerial Survey Results," PermianMAP, https://www.permianmap.org/flaring-emissions/ (accessed September 9, 2020).

16. C. Leyden, "Satellite data confirms Permian gas flaring is double what companies report," EDF (2019), http://blogs.edf.org/energyexchange/2019/01/24/satellite-data-confirms-permian-gas-flaring-is-double-what-companies-report/.

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