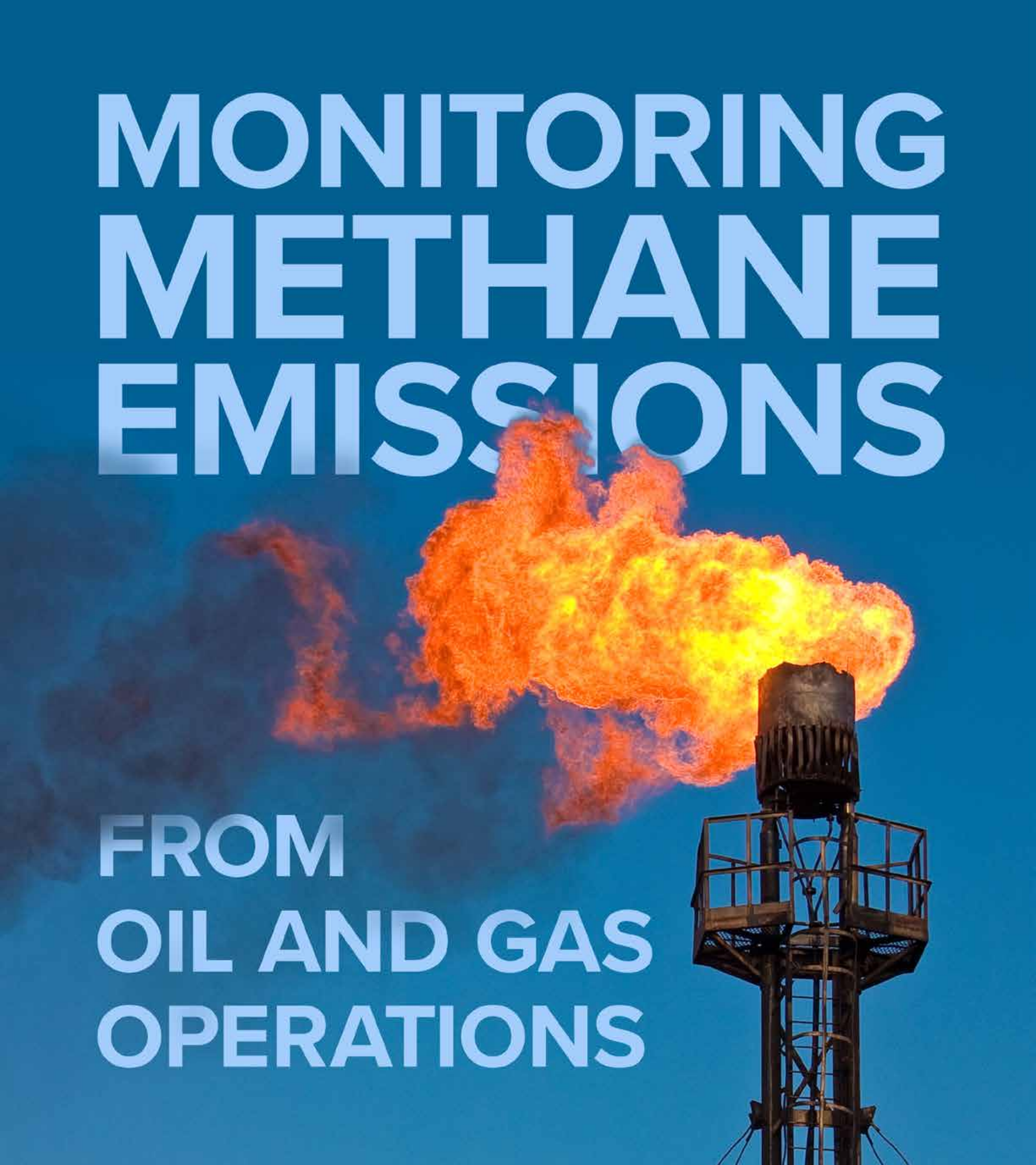
MONITORING METHANE EMISSIONS FROM OIL AND GAS OPERATIONS



A SCIENCE POLICY REPORT ISSUED BY
the American Physical Society and Optica

MAY 2022

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ACKNOWLEDGEMENTS

We acknowledge the help and support from APS and Optica staff and leadership, as well as the contributions made by the external reviewers and members of the community that made themselves available to the report committee.

PUBLICATION DATE: MAY 2022

Cover and report designed by Travis Frazer.

For additional information, including the participant bios and the workshop charge and agenda, please visit: https://www.aps.org/policy/reports/popa-reports

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I. EXECUTIVE SUMMARY

Methane (CH_4) is the second-most-abundant anthropogenic (human-created) greenhouse gas and significantly contributes to global warming. Consequently, there is an urgent need to reduce methane emissions to help reduce temperature increases from anthropogenic greenhouse gases. An essential part of any strategy to mitigate methane emissions is the ability to accurately measure and monitor the amount and location of methane released by various sectors. This report identifies several policy recommendations that can substantially enhance the detection of methane released by the oil and gas sector. These recommendations could strengthen measures already taken by that sector to manage methane and enhance worker safety.

The atmospheric concentration of methane has risen rapidly since the start of the industrial revolution in the 18th century, from 730 parts per billion (ppb) in 1750 to 1866 ppb in 2019, due primarily to human activities. The recent increases in methane concentrations appear to be equally contributed by the fossil-fuel sector and by a combined contribution from agricultural activity and waste sources.

Quantifying emissions from the fossil-fuel sector has led to three consequences. First, companies that are losing a valuable commodity to the atmosphere have begun using the latest technology for leak detection and repair (LDAR). Second, with the global community moving toward regulation of greenhouse gas emissions, the question of how to verify emission decreases from the oil and gas industry has arisen. Lastly, the scientific community has started to form a picture of how these emissions are distributed and how different components, sites, and processes contribute. It has become clear that a small portion of methane sources (such as leaks) are contributing a significant fraction of the total emitted natural gas. Identifying and mitigating these large leaks quickly can potentially reduce production costs while alleviating a large percentage of the emission problem.

For methane emission regulation to be most effective, it should specifically target the small portion of leaks that are major emitters. Additionally, data should be publicly available and with high enough spatial resolution to determine the source of the emissions, especially in regions where well pads owned by different companies are spatially collocated. Domestically, ground and aircraft measurements offer sensitive and cost-effective approaches for frequent or continuous monitoring of individual assets. At the same time, limiting methane emissions will need to be done globally. Satellite measurements are uniquely capable of supporting international collaborations to identify significant sources worldwide and informing international agreements to mitigate emissions.

Three scientific and technological advances across several fields would appreciably improve our ability to measure and monitor methane emissions. The first would be the construction of improved high-resolution spectroscopic databases for methane, especially for its near-infrared spectral bands commonly used for remote sensing. The second would be the invention of improved methods for remote sensing of carbon isotopes, which would greatly facilitate identifying fuel source type. The third would be the development of high quantum efficiency detectors to support methane LIDAR (light detection and ranging instruments), which would be particularly advantageous for resolving the three-dimensional distribution of methane in the Earth's atmosphere.

To support emerging national and international efforts to mitigate emissions of methane, three areas of policy development would be beneficial:

Methane emissions detection:

- The federal government should invest in research that seeks to improve the emission detection limits for satellite instruments and to develop capabilities to resolve the spatial structure and isotopic composition of methane.
- The federal government should require and/or incentivize a system of 24/7 continuous monitoring and quantification of methane emissions for U.S. oil and gas operations based on the latest generation of methane monitoring technologies.
- The federal government should establish national facilities for testing new technologies and intercalibrating methane measurements that would support a tiered and federated observational network.

Reliable and systematized data and models to support mitigation measures:

- A unified national repository of observations of methane concentrations and emissions open to the international climate community would help monitor progress towards mitigation targets.
- A national operational methane hindcast and forecast model, especially in conjunction with such a repository, would help identify the emergence of new significant sources of methane as well as project the long-term efficacy of policies to reduce its emission.

Effective regulation:

- The federal government should equip agencies with adequate and appropriate methane measurement capabilities, empowering them to partner with the private sector as well as state and local public sectors on methane monitoring. The government should support federal agencies to improve the fidelity and increase the frequency of updates of their anthropogenic methane emissions databases, particularly from the oil and natural gas sectors.
- In partnership with public- and private-sector stakeholders, the federal government should design a regulation structure for a high-impact and cost-effective approach to reducing methane emission from oil and gas operations.

This report is deliberately focused on methane emissions from oil and natural gas operations. While agriculture and agricultural waste constitute the dominant sources of emissions worldwide, the measures to mitigate emissions from agricultural and fossil-fuel sectors can be quite different. The authors also recognize that the methane emissions from the leaks in the U.S. oil and gas supply chain are as much as 60% higher than official inventory estimates. However, to focus on emissions that can be readily addressed by targeted measures at significant point sources, this study is intentionally delimited to methane released to the atmosphere from the production of fossil fuels.

II. Monitoring Methane Emissions and Flaring from Oil and Gas Operations is Necessary

This report focuses on the gaps in our quantitative observations of the fossil-fuel sector's methane emissions. These gaps need to be addressed with advanced physics-based methods to fully characterize their highly spatially heterogeneous and temporally intermittent point sources. Meaningful progress to reduce anthropogenic methane emissions requires the ability to monitor sources for years to decades in a scalable manner.

2.1 Methane Emissions are a Large and Addressable Component of Anthropogenic Climate Change

Methane is the second-most-abundant and important anthropogenic greenhouse gas (GHG). Methane has a global warming potential nearly 30 times greater than that of carbon dioxide on centennial timescales [45, Appendix 8.A]. Addressing anthropogenic sources of methane is a central part of current approaches to address Earth's changing climate, including international pledges like the ones made at the 2021 Conference of the Parties (COP26) conference in Glasgow.

Anthropogenic methane emissions account for half of all methane emissions to the atmosphere. Methane atmospheric concentrations have been rising rapidly since the start of the industrial revolution in the late 18th century, including recent years [63]. Today, the concentration of methane is at its highest in the last 800,000 years, as confirmed by comparison against relic methane trapped in air bubbles in ice cores from the Greenland and Antarctic ice sheets [9]. In the last decade, anthropogenic emissions represent more than half of all methane emissions [59][9].

Decisive actions on methane emissions can have short- and long-term benefits. During the early 2000s, when global atmospheric concentrations of methane temporarily ceased increasing, researchers demonstrated that methane concentrations can respond rapidly to reductions in emissions [63]. Methane's high global warming potential and its short atmospheric lifetime of roughly a decade [46] imply that reductions in methane emissions should be included as part of an overall mitigation strategy to measurably reduce temperature increases from anthropogenic GHGs [49]. Currently, methane is the largest reason for departures from the idealized pathways to constraining global warming below 2°C discussed in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) [63]. The more ambitious limit of 1.5°C requires reductions in methane emissions by nearly 2% per year over the next 20 years, a target unfortunately contravened by the current increases in emissions by approximately 0.5% per year [63].

2.2 The Methane Emissions from the Oil and Gas Industry Present a Significant Opportunity for Swift Action

Oil and gas account for 30% of anthropogenic emissions in the U.S. Globally, the anthropogenic emissions of methane are contributed by three principal source categories: agriculture and agricultural waste (approximately 59% of global human emissions), the production and transport of fossil fuels (33%), and biomass and biofuel combustion (8%) [9]. Increases in the last decade in methane concentrations appear to be equally contributed by the fossil-fuel sector and by a combined contribution from agricultural activity and waste sources [21] [33] [63].

Oil and gas emissions are localized, frequently intermittent, and dominated by a relatively small number of super-emitters. There is compelling evidence of a long-tail distribution of emission sources, indicating that methane emissions across the natural gas (NG) supply chain are dominated by a relatively small number of super-emitters; in numerous instances 1–10% of potential sources contribute more than half the methane emissions [77] [5] [80] [40]. The 2016–2018 California Methane Survey [20] [21] observed the same behavior across all methane point source emission sectors. These studies were spatially extensive and provided an indication of stochastic activity. However, they lacked the continuous, high-frequency sampling necessary to constrain the distribution of intermittent emission processes as well as diffuse area sources. These uncertainties and limitations pose barriers to providing relevant and timely information to guide mitigation efforts—with implications for state and local agencies, businesses, communities, and NG ratepayers. Identifying and monitoring methane super-emitters can be an efficient way to enable mitigation efforts in the short term if individual sources can be identified to the relevant stakeholders in a timely fashion.

2.3 Flaring is an Important Contributor of Methane Emissions

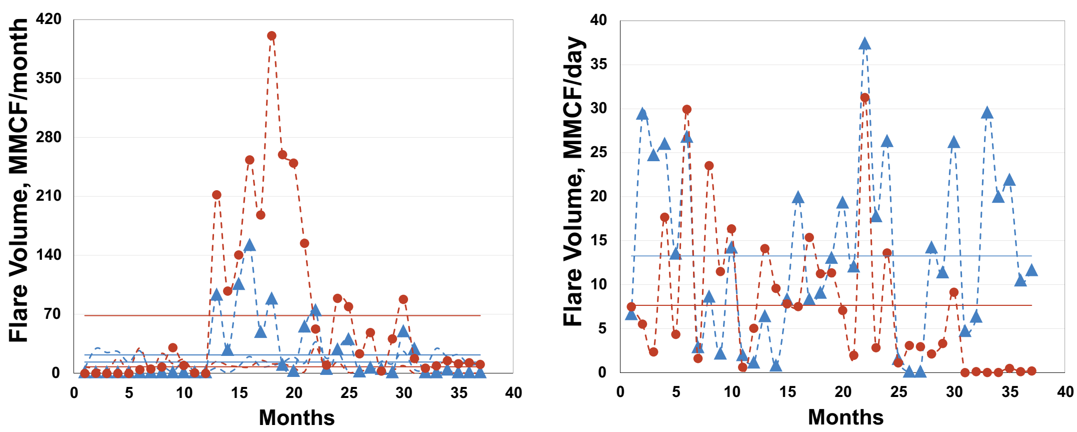
Flaring is the controlled burning of natural gas, a common practice in oil and gas exploration and production. The issue of flaring of natural gas (and other volatile compounds) is worth examining separately from other emission source types for several reasons.

Flaring contributes up to one-fifth of methane emissions in oil and gas operations. Flaring produces atmospheric carbon dioxide (CO_2) under complete combustion and methane from incomplete combustion. The combustion of CH_4 to CO_2 during flaring is supposed to operate at an efficiency of 97% or greater. While most flare efficiencies are in the high 90 percent range, the sheer volume of flared gas results in significant methane emissions. Moreover, observations suggest that many flares burn with <90% efficiency, resulting in significant unintended releases of methane. Recent studies using aircraft-based instruments show that flaring can represent as much as 20% of the methane released from oil and natural gas wells [30] and arises from the long tail of the flare efficiency distribution. Continuous monitoring of flaring can provide critical verification that the desired efficiency is being maintained [18].

Flaring is a waste of a nonrenewable natural resource. Flared natural gas is a completely viable fuel provided there is an infrastructure able to transport it.

Flaring is poorly monitored. It is challenging to measure the amount of methane combustion from flares, as well as the issue of flare burning efficiency. This has led monitoring stakeholders to rely on self-reporting from producers. Moreover, the satellite observations of flares available today are episodic: they only can take pictures of the same site a few times per month. Discrepancies from these two available data sets (self-reporting and satellite data) reflect the incomplete nature of both approaches. An example is shown in Figure 1, where observations from the visible infrared imaging radiometer suite (VIIRS) flown on the NASA/NOAA (National Oceanic and Atmospheric Administration) Sumo National Partnership satellite are compared with self-reported flaring data at two representative sites in the Texas Permian Basin.

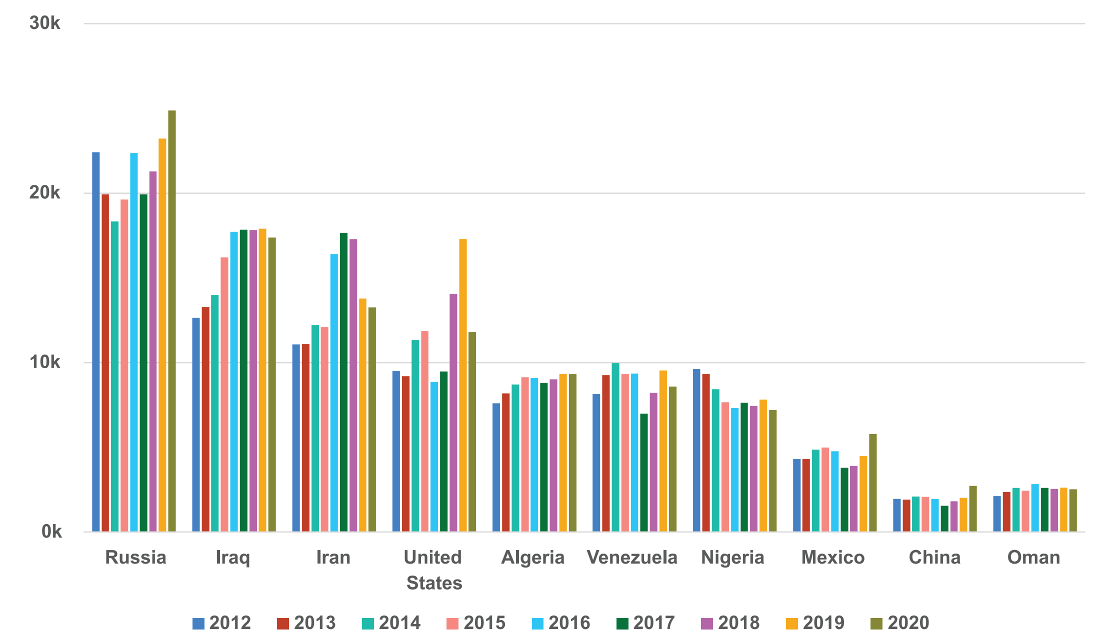
Figure 1. Monthly flare volumes for two representative sites in the Permian Basin for the three-year period from February 2018 to February 2021, as reported by satellite observations (blue triangles) [64] [24] [22] and by the state regulator based on self-reported data from the operator to the state regulating agency (red circles). The overall averages are marked with solid horizontal lines, using the same color code. For the right-hand site, the overall satellite flare volume is nearly twice the operator-reported volume, while the reverse is true for the left-hand site. The dashed lines are guides to the eye. There is considerable scatter in the data, and it would be helpful to have a finer mesh to explore the relationship of the relative measurements.



Monitoring flaring volume is complementary to the imaging spectrometers currently used by most methane monitoring missions. Satellites can observe flaring with visible spectrometers during nighttime hours, providing a complementary approach to daytime observations using other technologies.

Flaring is visible from space-based observations, providing a path to global monitoring. Flaring is not just an issue of concern for the United States. On a global scale, the U.S. ranks only fourth in comparison to satellite-observed flaring from other countries, as shown in Figure 2. Satellites make global monitoring of flaring possible,

Figure 2. The top 10 countries by satellite-retrieved volume of flared gas, 2012–2020. The World Bank [28] reports that Russia, Iraq, Iran, the United States, Algeria, Venezuela, and Nigeria remain the top seven gas-flaring countries for nine years running. These seven countries produce 40% of the world's oil each year, but account for 65% of global gas flaring.



although this methodology still faces technical challenges due to large uncertainties in the volumes of flared gas retrieved from satellite imagery. The need to complement satellites with lower-cost ground-based networks to enable continuous monitoring of methane is elaborated on in §7.1.

2.4 Our Current Ability to Monitor Methane Does Not Match Present Needs

Current bottom-up emission inventories systematically underestimate true emissions. Regulatory agencies need accurate methane inventories before they can determine if methane emissions have decreased. Multiple studies have identified significant underestimation of methane emissions from the fossil-fuel sector reported by greenhouse gas inventories for the U.S., California, and other domains [71] [54] [44] [34] [35]. For example, emissions in California are up to 1.8 times higher than inventories constructed by the California Air Resources Board [71] [34]. To determine accurate emissions and changes in these emissions, regulatory agencies must either take the measurements themselves, employ outside contractors, or rely on sporadic peer-reviewed literature.

Methane's global warming potential was recently demonstrated to be greater than previously thought. Recent studies have shown that the absorption of near-infrared sunlight by methane augments its infrared greenhouse effect by 25% [27] [12], an effect omitted in all Assessment Reports (ARs) of the IPCC prior to the sixth AR, completed in 2021. According to climate models, methane further warms the climate by increasing its own residence time in the atmosphere; increasing the production of ozone and stratospheric water vapor, two other GHGs; and increasing the lifetimes of hydrochlorofluorocarbons and hydrofluorocarbons both of which are families of potent GHGs [46] [45] [50].

2.5 Our Current Ability to Model Methane Does Not Match Present Needs

Existing models do not agree on the causes for observed regional and global trends in methane concentrations. As stated by the team that constructed a global methane budget for 2000 to 2017 [59], to date no consensus has been reached in explaining the observed trends in atmospheric methane concentrations since 2007. Present-day simulations from state-of-the-art models also do not agree on emissions from the oil and natural gas sector. Estimates of annual emissions from this sector using global models constrained by observations are uncertain to roughly 25% worldwide. The spread between the 5th to 95th percentile estimates is 66% for the U.S., and the corresponding spread in the latitude band of 30–60°N that includes most of the heavily industrialized countries exceeds 40% [59 and sources therein]. The large range in these top-down estimates using methane models complicates interpretation of current and future observations as well as projections of methane reduction from possible mitigation measures.

2.6 Methane Emissions Impose a High Societal Cost

The social cost of methane per metric ton far exceeds that of carbon dioxide. Policymakers use economic metrics to guide their decision-making process toward reducing greenhouse gas emissions. The Social Cost of Carbon (SCC), an estimate of the total future economic damage resulting from the present-day emission of one ton of CO_2 into the atmosphere, is one such metric. Similarly, one can construct an analogous Social Cost of Methane. The social costs of CO_2 and methane temporarily adopted by the Biden administration are $51 and $1,500 per ton, respectively, and, like global warming potential, are separated by a factor of roughly 30 on a 100-year timescale [4]. The SCC on a time horizon of 2050 is much smaller than that of methane, ranging from $26 to $95 per metric ton [48]. It should be noted that these metrics have large uncertainties because social costs are inherently functions of a variety of societal factors, including socioeconomic projections, estimates of future benefits and costs, and discount rates relating present to future financial benefits. The fact that harms and costs are likely to be highly heterogeneous worldwide leads to even larger estimates of the social cost of methane for the United States than those used by the federal agencies [26].

2.7 Lessons Learned from Observing Methane Emissions from Oil and Natural Gas Operations are Transferable

It is worth noting that while we focus here on upstream oil and gas emissions, there are other significant global sources of methane. Landfills and the agricultural sector will be important to consider in the future, and both present a range of challenges and opportunities for monitoring and mitigation. Agricultural methane emitters are particularly diverse. They include diffuse sources, such as rice production or extensive livestock husbandry, and intense point sources, such as feedlots, dairy farms, and manure digesters. The observational approaches described in this report have clear applications to agricultural and landfill point sources and super-emitters, and remote sensing has been used to detect and quantify such emissions [21]. Other principles articulated in the report are generally applicable to monitoring agricultural methane; for example, the need for well-calibrated and precise yet deployable instruments, the need for enhanced knowledge of methane spectroscopy for remote detection, and the need for careful and systematic observations tuned to the emitter characteristics of the sector. Therefore, while some outcomes of this report are quite specific to the energy sector, there is considerable potential for application in other important sectors as well.

III. Current Capabilities for Measuring Methane Emissions

3.1 Brief History of Methane Monitoring Technology

The U.S. Environmental Protection Agency (EPA) has published a GHG inventory, which includes a methane inventory, each year since the 1990s [25] under the United Nations Framework Convention for Climate Change (UNFCCC).

Commercial instrumentation for the measurement of methane improved significantly during the 2000s. Current in situ instrumentation for measuring methane is borrowed from the success of the telecommunications industry. With advancements in near- and mid-infrared lasers [72], by the mid-2000s this technology led to commercialized instruments using integrated-cavity-output spectroscopy (ICOS) [52][3], cavity ring-down spectroscopy (CRDS) [51][16], and other multi-pass absorption techniques [76]. These instruments significantly improved quantitative measurement of atmospheric methane concentration, both in intensity and in geographical location with high spatial resolution. The instruments were easily installed aboard aircraft and flown to oil- and gas-producing regions of the U.S., where the mass balance technique was used to quantify emissions [73]. These advances led to measurements during the 2010s [38][55] that made evident the disparity between the methane inventory maintained by the EPA and measured methane emissions. However, although those flights cover large geographical areas, they only collect measurements at short, specific times during the day and can miss intermittent methane sources.

Additional studies and a decade of quantification in the 2010s of oil and gas methane emissions from the component level up to regional scale have shown that oil and gas companies are losing a valuable commodity to the atmosphere, that there are significant discrepancies between methane inventory estimates and actual methane emissions, and that the distribution of the leaks have a "fat tail," i.e., a handful of large leaks at the high end of the distribution contribute a significant fraction of the total emitted methane (as shown in Figure 3).

3.2 Challenges Facing Effective Methane Monitoring

Methane monitoring technologies for oil and gas operations must be tailored to the needs of the industry and the public regulators. The following topics are critical to consider for a successful adoption of monitoring technologies and systems.

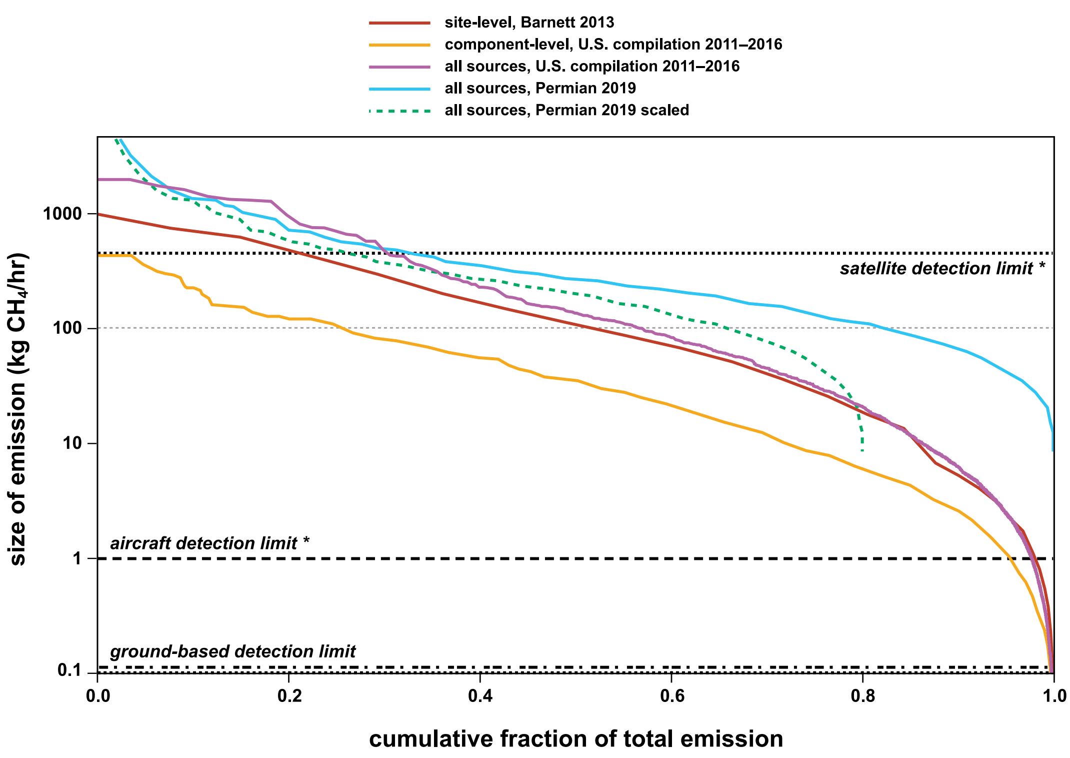
Methane emissions in oil and gas operations are dominated by a relatively small number of super-emitters. Methane emissions from oil and gas operations originate from many different sources of various sizes. The amount of methane released in the atmosphere is most commonly measured in kilograms per hour (kg/hr), with the following somewhat arbitrary definitions [78] [21]:

- Small leaks: <3 kg/hr
- Medium leaks: 3–30 kg/hr
- Large leaks (i.e., super-emitters): >30 kg/hr

Many studies of methane emissions in oil and gas operations have shown that a few emitters are the source of a large quantity of methane released into the atmosphere. Figure 3 shows a summary of existing literature results on the cumulative emission of methane as a function of size of the source (often, leaks). It shows that large leaks, often referred to as super-emitters, are the source of 60% to 80% of all methane emissions in important oil and natural gas production regions. For example, in the Permian Basin of West Texas and New Mexico, super-emitters associated with just 37 plumes in a 30,000-square-kilometer area contribute between **one-third** and **one-half** of the estimated emissions [32]. One must be careful when interpreting the data as, in some studies, observed "super-emitters" correspond to complete facilities where the emission is likely made up of contributions from many sources. However, even studies that have focused on individual components find a similar distribution, as seen in the orange curve of Figure 3. Based on the component data, targeting leaks greater than 30 kg/hr for repair would reduce emissions by ~70–90% while keeping the number of leaks at an actionable level for industry.

Oil and gas operations operate in low density, over very large areas. Any monitoring approach needs to be **scalable** in cost and operation to go from a single well to a large basin area. This makes **field-of-view** and **spatial resolution** key parameters to consider in order to detect and attribute a leak to a specific site or component.

Figure 3. Component and facility emissions and measurement detection threshold. Magnitude of oilfield methane emissions is plotted vs. the cumulative emission, i.e., the fractional contribution of all leaks of a given size or larger. Four distributions of emissions are plotted from published studies representing Barnett emissions in 2013 (red trace) [78 Figure 2c], a compilation of published emissions between 2011 and 2016 (component-level: yellow trace [6, Figure 5]; all sources: purple trace [6, Worksheet S1]), and Permian emissions in late 2019 (blue trace) [18, Figure 2B]. Also plotted is a scaled distribution of the Permian emissions (green dashed trace) to approximately correct for the higher detection limit of the Cusworth et al. method, which may not fully account for medium-sized leaks. For comparison, approximate detection limits for satellite-, aircraft-, and ground-based emission quantification are shown. Where the detection limit lines cross the emission distribution traces indicates the fraction each method can detect of the total emission. We note that some of these studies occurred several years ago and may not reflect emissions under current regulatory or infrastructure regimes.



** The aircraft detection limit is for LIDAR at wind speeds <2 m/s. The detection limit increases with wind speed [37]. Detection limits are higher for mass balance (3–5 kg/hr) and airborne imaging spectrometers (10–30 kg/hr). The satellite detection limit of 500 kg/hr is that stated by Irakulis-Loitxate et al. [32], although the detection limit of 100 kg/hr, stated by Jervis et al. [36] for the latest GHGSat detection limits, is shown for comparison. As of the writing of this report, the lower detection limit has not been verified in the peer-reviewed literature.*

It is standard practice that oil and gas emission monitoring is performed by personnel from local industry or local regulating agencies. Any monitoring approach needs to be available to, and usable by, personnel currently on the ground. Although collected information on leaks is currently proprietary and not readily shared with all stakeholders, it should be quantitative, location-specific, and timely to integrate effectively into industry LDAR.

Methane fugitive emissions from the oil and gas sector are episodic in nature. Leaks can start at any point and vary in their leak rate significantly over the course of hours or even minutes. Any robust monitoring approach cannot rely on flybys and noncontinuous monitoring.

Accurate methane source apportionment is critical for LDAR and emissions inventories. Observing platforms with adequate spatial resolution and field-of-view can identify the physical origin of methane releases. Chemical approaches that measure the abundance of carbon isotopes (e.g., ^{13}C) [15] or other species (e.g., ethane) can be employed to disentangle emissions from oil and gas production sites from those originated at other nearby sources, such as, for example, agricultural lands [39].

The current understanding of the methane absorption spectrum is incomplete. The ICOS, CRDS, and multi-pass absorption techniques, typically used for in situ measurements, have avoided this issue by focusing on a single absorption feature, allowing for high-precision measurements. As for remote sensing, our lack of knowledge of methane's absorption features, and hence some of the uncertainties in our calculations of methane shortwave forcing, is due to the remarkable complexity of methane spectroscopy [7]. Its current derivation from laboratory measurements and theory is known to be deficient[7][11][19]. This limits the sensitivity of spectroscopy techniques, which are the main airborne and spaceborne methane-sensing methodologies.

Based on current technology, global fugitive emissions of methane cannot be monitored effectively with a single observing platform. As illustrated by Figures 3 and 4, different platforms (space-based, airborne, ground-based) have different sensitivities to the leak rate of methane emissions. Furthermore, the different platforms also offer different fields-of-view, different spatial resolution, local versus global coverage, and different time resolutions. A tiered approach combining multiple types of sensors and platforms is necessary to both provide the information necessary to mitigate leaks locally (in particular the super-emitters) and understand global emissions.

3.3 Importance of Transparency in Monitoring

Private companies have a financial incentive to reduce methane emissions from oil and gas operations. However, public interest and private interest may not be perfectly aligned. There is little incentive for companies of any size to share methane emission information with competitors or the public. At the same time, there are significant advantages to this data being publicly available. For example, the industry's understanding of fugitive emissions is evolving as scrutiny by stakeholders and monitoring technologies improve and provide more insight. Requiring companies to share information on LDAR responses (currently proprietary) could greatly accelerate the industry-wide understanding of best practices regarding leak mitigation.

Similarly, public trust in the oil and gas industry and the ability of public institutions to regulate the sector should be a high priority. For greenhouse gas emission regulation to be effective, data should be validated, be publicly available, and have high enough spatial resolution to determine the source of the emissions, especially in regions where well pads owned by different companies may be as close as 50 meters (m) apart. Although ground- and aircraft-based measurement techniques are effective ways to monitor and quantify emissions within the United States, they are predicated on access to either the ground or airspace. If binding international accords were ever to be implemented, satellite measurements may be an invaluable method for verification, even given their limited sensitivity and intermittent observation times as compared to ground and aircraft measurements as discussed/highlighted in Section IV.

IV. Current State and Future Directions of Methane LDAR

Fully understanding methane emission sources and location at oil and natural gas sites in a production basin is a nontrivial problem. On top of the complexity and physical distribution (covering very large areas of land) of the methane sources, the episodic nature of the emissions requires 24/7 sensing and monitoring. It is critical to catch super-emitters that are responsible for large fractions of the emissions from drilling sites as fast as possible to guide LDAR efforts.

Effective national or global continuous monitoring cannot rely on a single technology. Instead, it is necessary to use a combination of ground, aircraft, and satellite platforms that together can allow the rapid detection of fugitive methane emissions.

4.1 Critical Parameters for Methane LDAR

While there are numerous approaches for methane LDAR, effective detection methods should share the following qualities:

- **Full or partial autonomy:** One of the biggest cost drivers in conventional monitoring—often based on optical gas imaging (OGI) cameras—is the need for an inspector to drive to each well. The U.S. alone has over 1 million active wells, most in remote locations. Sending a ground crew to each site is unscalable.
- **Low or zero false positive rate:** The background concentrations of methane at an oil and gas production site can vary significantly and rapidly. Sensors will need to identify leaks while rejecting these background fluctuations. The cost of a false positive resulting in sending a LDAR crew to a remote site is a deterrent for industry.
- **Leak quantification:** As noted in Figure 3, most emissions come from only a small percentage of leaks. Conversely, if a production company is repairing all leaks, it is spending most of its resources addressing a negligible fraction of the problem. Systems that allow rapid prioritization of large leaks will greatly improve efficiency.

- **Leak localization:** Oil and gas systems are complex. Once a leak is detected, LDAR crews will still likely have to search for the exact leak location. Localizing the leak to within a few meters will decrease search time and may limit the need for expensive OGI cameras.

- **Continuous monitoring and low latency:** Natural gas leaks can be highly episodic in nature and may last only days or hours. Infrequent monitoring can easily miss even very large leaks. Significant latency in identifying these leaks could lead an LDAR crew to mistakenly assume a false positive.

- **Oil patch integration:** While this is not strictly speaking a sensor quality, it bears mentioning that industry management and LDAR teams will be critical to any large-scale leak mitigation. A successful sensor will be far more effective in its purpose if the data are easily digestible and integrate with existing industry workflow. Moreover, tight integration with industry will be necessary to differentiate standard process emissions, to speed leak repair of fugitive emissions, and to spur development of better industry practices.

Table 1 lists attributes of common sensing modalities and Figure 4 shows the detection limits of each type of LDAR method, compared to the measured emission rates from various components of natural gas production in the Barnett Shale region of Texas [78]. The following sections will further detail the measurement capabilities and use cases.

Table 1. Key attributes of common sensing modalities (ground-based, airborne, and spaceborne).

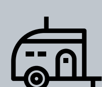
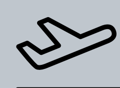
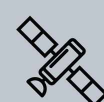
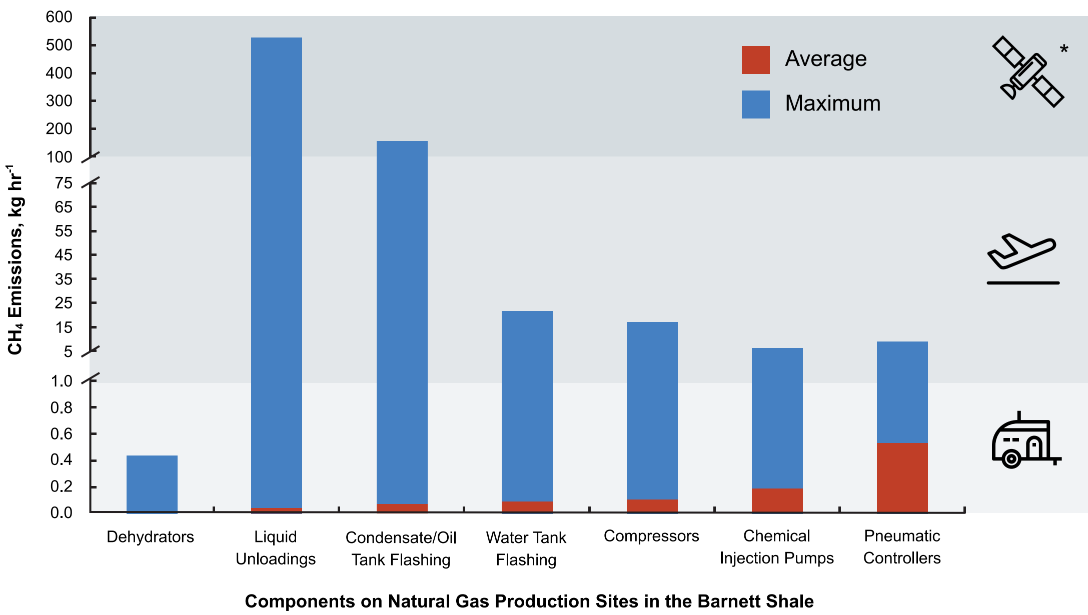
Key Attributes			
Autonomous	✓	✗	✓
Continuous	✓	✗	✗
Leak Quantification	Component Scale	Component-Scale/ Pad-Scale	Facility-Scale
Leak Localization	1 – 10 Meters	1 – 50 Meters	25 Meters – 7 Kilometers
Cost	$-$$	$$-$$$	$$$$

Figure 4. Component emissions and measurement detection threshold. Single-source methane emissions are plotted for various components of natural gas production in the Barnett Shale region of Texas [78]. The average emissions are shown with red bars; the maximum expected emissions are shown with blue bars. Overlaid are the detection limits for emissions using ground-, airborne-, and satellite-based technologies. Note the breaks in the scale of the y-axis. Detection limits are determined from peer-reviewed literature for ground-based [1], airborne [2] [61] [37] and spaceborne [36] emission detection.

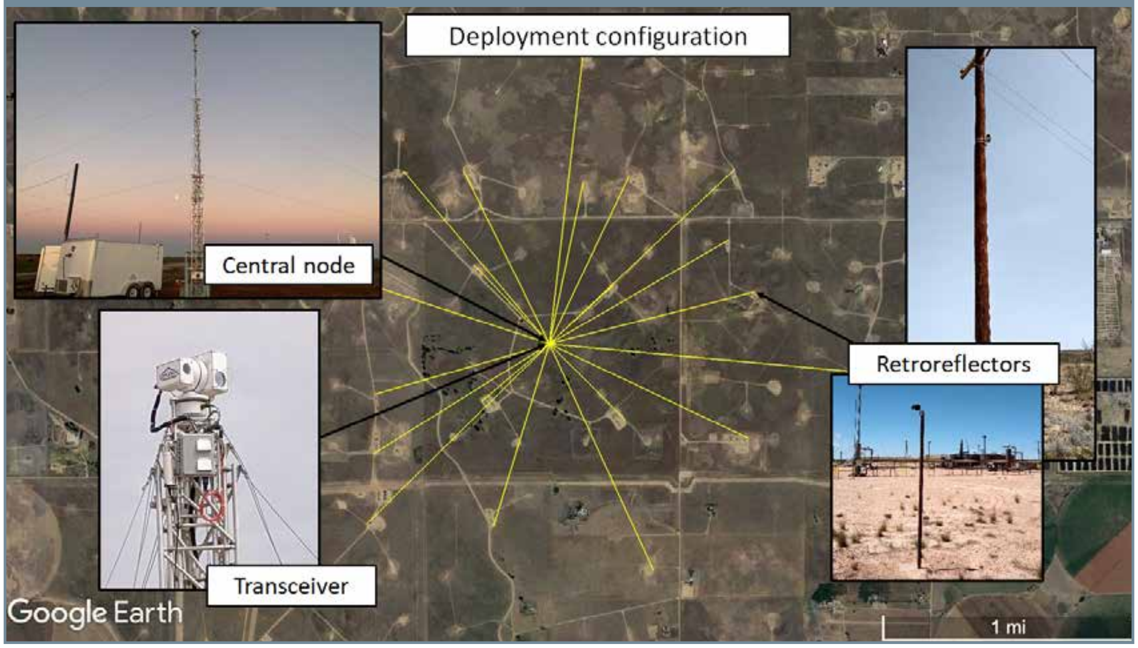


** Note that the spaceborne detection limit shown here is based on predicted capabilities of next generation GHGSat systems. The current detection limit demonstrated in practice is 500 kg/hr [32].*

4.2 Automated Ground-Based Monitoring

The most sensitive way to detect fugitive methane emissions from oil and gas sites is at ground level. Ground-based platforms are capable of high spatial resolution, 24/7 operation, and electronic data transmission to mobile or stationary receivers. The cost of ground-based detection arrays has dropped, and large-scale trials in both industry and academia are beginning [56]. Ground-based monitoring is likely the only solution for truly continuous monitoring of infrastructure. The sensitivity of ground systems easily exceeds monitoring needs, and sub-pad localization of leaks is often possible. While these systems do have installation costs, the associated sensors are also easier to make autonomous, and it is likely that in the future, operating costs will be competitive. An example of ground-based monitoring is illustrated in Figure 5.

Figure 5. Example of the standoff ground-based emissions monitoring approach (image provided by LongPath Technologies). A single laser spectrometer sequentially measures along several kilometer-scale beam paths to look for leaks in an oil and gas region. Cost reduction is achieved by the fact that a single system can sensitively monitor many assets in a 1- to 2-mile radius [1].



Ground sensor design and measurement approaches vary greatly. At one extreme are low-cost chemical point sensors which are prone to drift and have limited sensitivity, but this can be overcome by employing dense networks of these devices around possible sources. Laser-based detection systems are generally more expensive per device, but also more stable and sensitive, allowing them to be deployed in smaller numbers for the same coverage. An extreme example is shown in Figure 5, where a single laser system can monitor assets in a 2-mile radius. It is not clear yet which approach would operate at a lower cost per well in the long term, but all seem to be garnering industry interest.

In combination with measurements of local wind data and an atmospheric transport model, these ground-based instruments can give a good estimation of both leak size and location. Evaluations at the Methane Emissions Technology Evaluation Center (METEC) have shown that these systems can reliably detect small leaks and identify leak location within 1–5 m (3–15 feet) [1][70][79].

4.3 Airborne Monitoring

Airborne sensing for leak detection has recently garnered considerable attention. An instrumented aircraft can be deployed relatively quickly (within days to weeks) with modest cost, and can achieve better sensitivity than satellite measurements. While not autonomous, a single aircraft can observe many wells in a short period of time and can enable more frequent revisit times. However, as with satellites, they represent a single "snapshot in time" for each well that limits the detection of intermittent emissions. Low-flying drones, helicopters, and planes have illuminated a great deal of information about methane releases through measurements of methane plumes in oil and natural gas production regions, especially those not easily accessible by ground-based sensors.

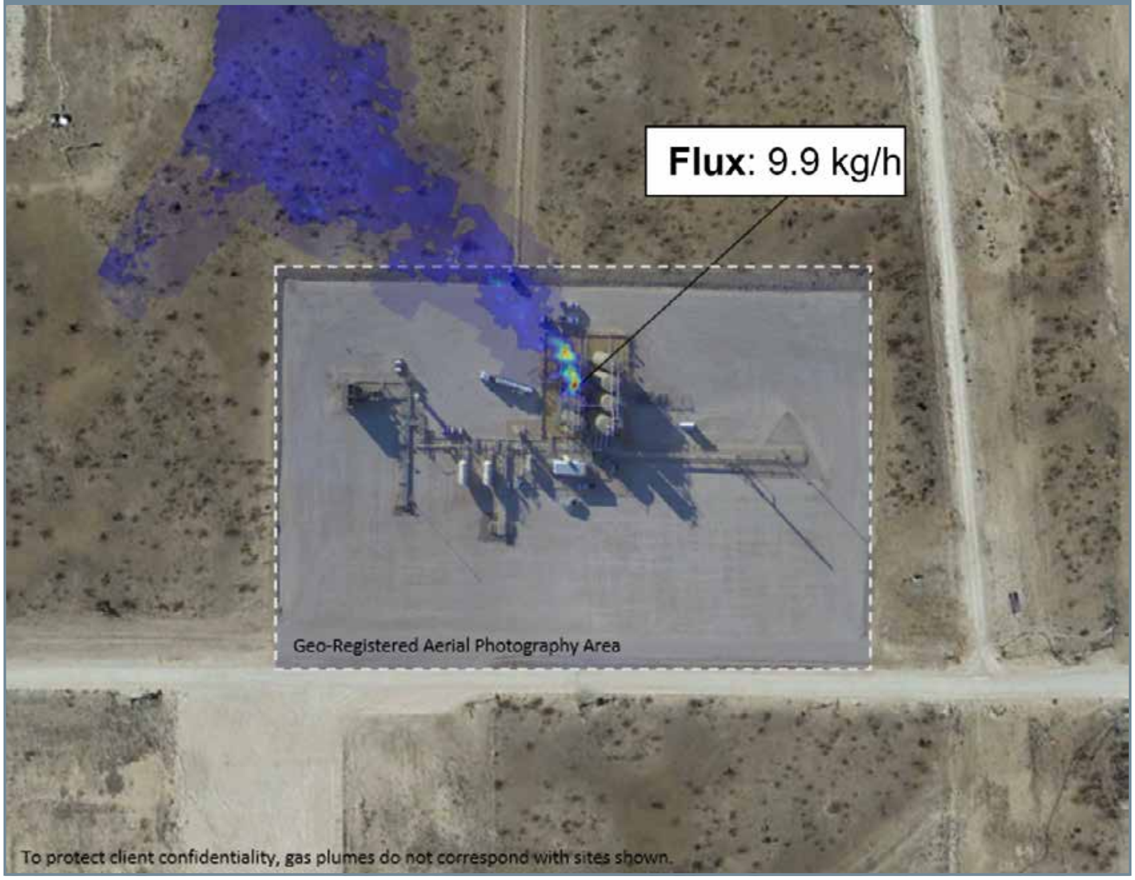
Currently, three main airborne sampling approaches are widely used:

- **Mass balance measurements,** where an instrumented aircraft records methane concentrations as it flies through a plume. Flight patterns and local meteorology are combined with the data to determine an emission rate and location. The mass balance approach is attractive in its ability to identify local small leaks as well as recover facility-scale leak rates [60]. Such measurements informed much of the early understanding of methane emissions. The downside of this approach stems from the fact that the aircraft must pass through the emission plumes, requiring low-altitude flights as well as the right meteorological conditions to loft the plume. Night-time and cold weather operation is often difficult or impossible. Leak location at the sub-pad level is also impractical, though it may be possible with unmanned aerial systems (UAS).

- **Airborne imaging spectrometers** use reflected sunlight to measure a column-integrated methane concentration. Much like similar satellite instruments, this provides a top-down view of the emission plume, with the additional advantage that the airplane is much closer to the plume than a satellite. This relative proximity allows for greater sensitivity and higher spatial resolution. Compared to mass balance, this approach relaxes the constraints on meteorology and can be performed at higher flight altitudes. The sensitivity is lower, however, at around 10 kg/hr [66] [60]. This approach was recently shown to enable repeated, high-resolution mapping of large areas with large methane emission sources. Including an example where a campaign detected 3,067 plumes of methane above the 10 kg/hr detection limit in a 50,000 kilometers-squared (km^2) area [17] [10]. Spatial resolution is also often on the order of 3–10 m (10–30 feet). Sub-pad leak localization is possible at the low end of this range but is difficult at 10 m.

- **Light detection and ranging (LIDAR)** is the most recent emerging technology in methane detection. Like imaging spectrometers, LIDAR provides a bird's-eye view of an emission source (Figure 6). Methane absorbs in an eye-safe wavelength of 1.65 microns, greatly relaxing eye safety concerns that can be a problem at other wavelengths for LIDAR. LIDAR systems have detection sensitivities similar to mass balance approaches (1–3 kg/hr, depending on wind speed) and very fine ~1 m spatial resolution. This high spatial resolution allows precise leak location [37] [57], though this does come at the cost of a narrower viewing swath (100 m) and may require more complex aircraft flight patterns. Additionally, these systems can be used from higher flight altitudes, like the imaging spectrometer. At the same time, they are not reliant on sunlight, which allows for their operation at night or days with high clouds.

Figure 6. Example leak detected from an airborne gas mapping LIDAR system provided by Bridger Photonics. High spatial resolution and overlaid aerial photography greatly simplify the process of identifying the leak source [37].



- **Autonomous systems:** Virtually all the methane detection technologies employed by aircraft are also being considered for UAS. The potential advantages are obvious. Such systems could in principle fly much closer to facilities, offering improved sensitivity to leaks and improved spatial resolution for leak location. Additionally, UASs are often envisioned as being fully autonomous, flying pre-programmed inspection routes and alleviating the expense of a pilot.

  Unfortunately, there are also significant hurdles faced by this technology that make it hard to know when it will be practical. On the technological side, UAS platforms often struggle with limited battery lifetime, greatly limiting range and up-time, which in turn impacts the economics of this approach. Regulation is also a challenge. In much of the U.S. these systems cannot operate autonomously and must be flown by a qualified pilot with line-of-sight to the aircraft, further impacting the costs. There are also some practical concerns. A UAS flying close to oil and gas infrastructure would likely have to meet strict safety criteria such as not producing sparks, even in the event of a crash. Lastly, most upstream oil and gas infrastructure is in remote areas where the security of an unattended and inherently visible UAS system is a potential concern.

4.4 Spaceborne Monitoring

Spaceborne methane monitoring is an active and growing field. There are two relevant spaceborne methods for monitoring methane emissions from oil and gas operations: 1) infrared imaging spectrometers for direct measurement of methane through its distinct absorption of specific electromagnetic frequencies, and 2) visible and infrared imaging of flaring at night. For flaring observations, the principal instrument of interest is the VIIRS visible infrared imaging radiometer suite. As discussed in Section II, there are challenges associated with flaring retrievals, but these measurements do provide a global picture of flaring, which would be challenging to collect by other means. The PRISMA satellite has also been used to simultaneously retrieve carbon dioxide and methane concentrations, which is an interesting new approach allowing one to derive emissions and quantify the combustion efficiency of the flared blowout [18].

There is an increasing abundance of direct measurements of methane using imaging spectrometers as well. Satellites such as GOSAT, GOSAT-2, TROPOMI, and SCIAMACHY [65][79][8] paved the way for satellite remote sensing of methane, but in general, these satellites provide too coarse a picture for monitoring individual wells. TROPOMI, for instance, provides column atmospheric methane measurements with 7 km × 7 km spatial resolution but near-daily global coverage with its large 2,600-km-wide swath [79]. This is well suited for understanding regional methane emissions but poorly suited for resolving 10 m × 10 m well pads. Near-term follow-ons to GOSAT and TROPOMI satellites as well as the new Copernicus Carbon Dioxide Monitoring (CO_2-M) and MERLIN will offer further enhancements but not well pad imagery. CO_2-M, for instance, is expected to reach an image resolution of 2 km × 2 km. MERLIN, a satellite-based LIDAR instrument, is expected to have a minimum image resolution of 150 m × 150 m but a 28-day revisit time.

Where the picture starts to get interesting for leak detection is with a handful of private-sector missions. In 2016, a privately funded satellite, GHGSat, was launched with the purpose of monitoring methane emissions from space [36]. The imaging spectrometer aboard this satellite measures backscattered solar radiation with a high spectral resolution (0.1 nanometers [nm] at 1650 nm) and with a spatial resolution of 50 × 50 m^2 in a 12 km × 12 km region. Oil and gas emissions were one of the key targets of this satellite. Similarly, the DigitalGlobe land imaging satellite WorldView-3 was recently shown to be sensitive to methane plumes from oil and gas [58], as was the European Sentinel-2 satellite [23], both at high spatial resolution. The ability to observe emissions from these land imaging satellites is particularly exciting since they are often well funded and widely deployed, helping ensure the long-term availability of this data.

The challenges for oil and gas monitoring with satellites. Observing the world from space has obvious advantages for identifying global emission irrespective of borders. However, there are also downsides to observing sources from several hundred kilometers away. First, the sensitivity of these systems is much poorer than aircraft and ground systems, which limits them to detecting only large and super-emitter sources (30%–50% of emissions, as illustrated in Figure 3). Second, satellites provide a single snapshot in time and long delays between overpasses, making it hard to locate intermittent sources. The problem is worsened by the fact that the imaging spectrometers require clear sky and may be frequently blocked by clouds in certain parts of the world. On the plus side, there seems to be some commercial appetite for deploying constellations of these systems, which should relax the revisit time concerns. The ability to fold in land imager data will further help in this regard.

Global monitoring challenges for satellites. Understanding the global and regional methane concentration is also desirable with satellite systems, though the accuracy requirements are challenging. Typically, one would track methane changes at the 0.1% level (2 ppb), but intercomparisons between satellites looking at CO_2 (for which the spectroscopy is better understood than methane) show variations on the 1% level [41]. Better calibrations of these systems will be needed as we seek to track smaller changes in methane.

4.5 Understanding Both the Well Pad and the Global Picture

While we focus heavily on observing and mitigating oil and natural gas infrastructure emissions, it is worth noting that there are two separate questions that we need to address to solve this problem. Specifically, there is the little picture (e.g., is a given well pad leaking?) and the big picture (e.g., is a given basin/region/nation improving?). The little picture addresses the immediate problem of leaking infrastructure, but the big picture is also critical in identifying missed sources and understanding climate impact. As such, it may be helpful to consider how different technologies address both pictures and how such systems can be combined.

- **Satellite systems** can uniquely monitor the global picture. Methane is a global problem, and verification will necessarily transcend national boundaries. Satellites would be a critical piece to any "trust but verify" approach to international methane emission reduction. Additionally, different satellites observe at different length scales. A tiered approach combining measurements from multiple satellites will allow both global identification of super-emitters and observation of regional methane enhancements.

- **Airborne monitoring** offers a relatively sensitive means to detect leaks over a broad region, though it is also a snapshot in time. While aircraft and pilots drive up the cost, this is balanced by the fact that aircraft are a very versatile measurement approach. These systems work well to fill gaps in ground systems or for large-scale verification of ground-based deployments. Additionally, their low cost of redeployment makes them ideal for rapidly addressing new monitoring challenges as they come up. Lastly, aircraft can be instrumented to measure regional emissions with high accuracy.

- **Ground-based monitoring** currently offers the only option for truly autonomous, continuous monitoring that can provide rapid feedback to industry partners. They are well suited for monitoring upstream oil and natural gas (O/NG) infrastructure. However, while ground-based sensors are sensitive, they are necessarily tuned to the specific asset they monitor and tend to “tune out” the surrounding environment. These systems will likely be less useful in understanding the regional picture. While not discussed here, there also exists an important array of ground-based sensors (e.g., The Total Carbon Column Observing Network (TCCON) [75]) tuned specifically to the regional and global methane picture. These sensors provide critical long-term accuracy, allowing observation of multi-year trends and also calibrating many satellite missions.

V. Summary of Identified Needs

Sections II through IV uncover several areas of need in the monitoring of methane emissions from oil and gas operations. A number of policy-related and physics- and optics-based research needs are summarized here, and recommendations to address them are presented in sections VI and VII.

Research needs:

1. **Improved high-resolution spectroscopic databases to support methane sensing.** Both passive and active remote sensing of methane are reliant on accurate, laboratory-validated databases of near-infrared methane absorption lines, which are currently incomplete (§3.2).

2. **Sensors for remote sensing and in situ measurement of carbon isotopes and remote sensing of ethane**. The ability to measure methane isotopes and ethane, especially from satellite-borne instrumentation, would help differentiate between fossil-fuel-derived and biogenic emissions of methane, thereby reducing the risk of “false positive” attributions to nonnatural sources (§3.2 and §4.1).

3. **High-quantum efficiency photodetectors to support methane LIDAR and other methane detection technologies.** LIDAR systems are preferable for measuring lateral transects and vertical profiles of methane. Such detectors could greatly reduce the cost and size of these systems, and would help close gaps between satellite, airborne, and ground-based observational platforms (§3.2 and §4.3).

Policy-related needs:

1. **Currently, many state and federal regulatory agencies lack adequate and appropriate methane measurement capabilities.** Existing inventories of O/NG emissions developed by state and federal regulatory agencies systematically underestimate emissions because they fail to capture the distribution of sources that includes super-emitters. Robust studies have consistently found that state and federal bottom-up methane emissions inventories routinely and appreciably underestimate real emissions by a factor of 1.6 or more (§2.4).

2. **The absence of a purpose-built network for measuring methane emissions from the comprehensive range of anthropogenic sources is hindering the ability to detect and repair leaks, including those of super-emitters.** As described in Sections 3 and 4, no single detection platform is capable of supporting effective monitoring of methane emissions.

3. **There is no national test bed for developing and calibrating methane sensors.** Measurements between different monitoring platforms and even between different technologies of the same platform are not directly comparable, making it extremely challenging to build an accurate assessment of methane emissions at the state or country scale (§4.2, §4.3, and §4.4).

4. **There is no central national repository of methane emissions data from O/NG collected from in situ, airborne, and satellite sensor networks**. The lack of a centralized repository of methane emissions observations adds additional difficulty to assessing and monitoring emissions (§3.3).

5. **There is no national methane emissions hindcast and forecast model.** It is difficult to quantify the efficacy of current (and project the impact of future) regulatory frameworks for methane emissions reduction without accurate measurement data and a robust methane hindcast and forecast model (§3.3).

6. **A disproportionately large fraction of methane emissions from oil and gas operations originates from a few sources.** This finding should inform cost-effective approaches to methane emission reduction (§3.2).

VI. Research Recommendations

This report has detailed the importance of monitoring methane emissions and flaring from oil and gas operations (Section II), listed our current capabilities for measurement (Section III), and described the current state of methane leak detection and repair (Section IV). Together, they identify promising physics-based research opportunities (Section V) that can both advance the state of the art and lead to reduction in methane concentrations in the atmosphere. This section identifies three areas of research, well suited to the APS and Optica communities, that can significantly address gaps in our current knowledge and practice.

6.1 Improved High-Resolution Spectroscopic Databases to Support Methane Sensing

High-resolution spectroscopic databases enable accurate modeling of light transmission through the atmosphere. These models are used to evaluate data retrieved from in situ and remote sensing platforms across observing scales (i.e., ground-based, airborne, and spaceborne platforms highlighted in §4.2, §4.3, and §4.4). Studies over the lifetime of satellite-based observing systems have shown that uncertainties or biases in data products can be quantitatively linked to retrieval algorithm inputs, including spectroscopic reference data [13][14][31].

For the Orbiting Carbon Observatory (OCO) satellite missions, where column-averaged, dry air mole fraction of CO_2 (XCO_2) is a primary product, analysis algorithms rely on accurate spectroscopic parameters (e.g., line strength, pressure, temperature, and collisional effects) of CO_2, O_2, and H_2O to minimize retrieval error and bias. Absorption coefficient (ABSCO) tables used in the OCO retrieval algorithm are routinely updated to reflect improvements in laboratory spectroscopic data and theoretical models. The latest update (ABSCO 5.1 [53]) highlighted the impact of current and future advances in O_2 and H_2O spectroscopy on XCO_2 and surface pressure retrievals. Additionally, a recent study of the sensitivity of XCO_2 retrievals to perturbation of spectroscopy inputs, including environmental parameters and physical model assumptions used in analysis of laboratory reference data, showed errors on par with, or larger than, expected measurement noise alone [31]. These observations continue to motivate advanced laboratory measurements and physics-based theoretical models to minimize spectroscopic contributions to the overall OCO uncertainty. These calculations also suggest that improving spectroscopy would lead to reduced seasonal and regional biases currently present in OCO data products [31].

The need for highly accurate and precise spectroscopic parameters extends to, and is amplified for, methane sensing. Not only are accurate parameters of H_2O, O_2, and other trace gases still critical for remote sensing retrievals, but methane presents a more complex measurement challenge due to its large number of vibrational degrees of freedom and spectral bands that possess a high level of degeneracy. This leads to a dauntingly large array of overlapping spectroscopic transitions requiring precise measurement. A recent study evaluating TROPOMI data using different spectroscopic databases found significant differences in resulting biases in XCH4 retrievals [42], which further highlights the need for additional studies to constrain relevant parameters.

6.2 Remote Sensing and in Situ Measurement of Carbon Isotopes and Remote Sensing of Ethane

Source apportionment is a critical aspect to successfully identifying and mitigating fugitive methane emissions in oil and gas infrastructure. Current efforts frequently rely on leak localization using imaging spectrometers or laser-based instrumentation coupled with atmospheric transport models. These instruments can pinpoint the physical origin of leaks and guide LDAR efforts.

A complementary approach, independent of leak rate and wind speed, involves examining the elemental signature of methane and by quantifying the relative abundance of naturally occurring isotopes, especially for regions where O/NG production encroaches upon urban and agricultural sources. In particular, carbon isotopes are regularly used to determine from where (or when) a sample originated, thus providing the ability to distinguish fossil-fuel-derived methane from biologically produced methane, since biogenic methane is typically ~5–20% more depleted in methane isotopes than fossil fuel, and even geographical origin, where fossil methane isotopes may vary on the order of 10% [67] [62].

The need for high sensitivity to reveal tiny differences in isotopic signatures, on the order of 20 parts per million (1% of ~1.1% of ~2000 ppb) to reach the World Meteorological Organization and literature-based [e.g., 43] targets for stable carbon isotopes of methane, limits the existing scope of field measurements in both time and space. Additionally, state-of-the-art instrumentation based on mass spectrometry or cavity-enhanced laser spectroscopy can require extractive sampling, long averaging times in situ, and routine calibration against known reference materials.

To advance measurement capabilities and incorporate this isotopic analysis into an idealized panoptic observing network, measurement rates would need to approach 1 Hz for airborne measurements while maintaining the parts-per-thousand sensitivity required for stable carbon isotope analysis. For example, this would enable sufficiently rapid aircraft observations resulting in km-scale regional isotopic maps. There is also a critical need for nonconsumable and stable reference materials, which allow for accurate calibration of relative abundance scales across instrumentation. Extending optical sensing capabilities to include radiocarbon isotopes, in particular $^{14}CH_4$, would also be highly valuable because fossil-fuel methane is fully depleted of ^{14}C, whereas biogenic sources are not [e.g., 29].

Similarly, ethane is a tracer for fossil-fuel-derived methane sources, where its abundance can range from a few percent to 30% of natural gas, but it is not emitted by biological species. This makes it a valuable tracer for oil and gas emissions, especially in regions with confounding biogenic methane sources, such as cattle, landfills, or wetlands. In situ measurements of ethane are currently adequate for use as a fossil methane tracer, but satellite-borne measurements face a challenge similar in scale to methane isotopes. The background level of ethane is around 1 ppb, and enhancements in oil and gas regions may range from several ppb to 10s of ppb.

6.3 High Quantum Efficiency Photodetectors to Support Methane Lidar

Current LIDAR systems are often required to rely on indium gallium arsenide (InGaAs) avalanche photodiode detectors, which can have painfully low quantum efficiency (<10%) at methane sensing bands around 1.65 micrometers (μm). High quantum efficiency could be a powerful enabling technology for this approach. An ideal detector would have the following properties:

- Close to unity quantum efficiency at 1.65 μm
- At or close to single photon sensitivity
- Moderate to high response times (<0.1 microseconds [μs]) to allow for separation of returns from multiple targets
- Six orders of magnitude of dynamic range to support daytime operation
- Wide availability outside of defense industries

Similarly, the development of novel laser gain media at 1.65 μm could greatly accelerate methane LIDAR systems. Currently, many of these systems are based on optical parametric oscillator resonators, which are cumbersome and must be very carefully assembled to ensure robust operation. High-power-gain media in this region, ideally based on optical fiber or semiconductor gain for low size, weight and power operation, would greatly reduce the costs and size of these systems. Improvements such as these would benefit both existing airborne LIDAR systems discussed in Section 4.3 and emerging ground and satellite LIDAR systems.

VII. Policy Recommendations

We note that regulating methane emissions is a shared responsibility of state and federal agencies. While both levels of government agencies are responsible for oversight, monitoring and enforcing regulations are primarily a local and state function. Though jurisdictions may have different requirements and enforcement procedures regarding production and air quality, federal rulemaking provides overall guidance. Thus, in this section, we make policy recommendations for the federal government to address the needs identified by this report (Section V), and these recommendations can in turn inform state and local agencies. Given the global importance of methane emissions from the agricultural sector, and the fixed-point sites that represent some of its dominant sources, ideally policies and measures would be applicable to both oil and natural gas operations and to agriculture (§2.6, §8).

7.1 Detection

- **Develop a national approach to 24/7 continuous monitoring of methane.**
  In concert with the private sector, the federal government should require and incentivize a system of 24/7 continuous monitoring and quantification of methane emissions from oil and natural gas production, transmission, and processing sites in the U.S. It should establish requirements for monitoring revisit times, monitoring sensitivity, and production normalized acceptable emission rates. The U.S. and Canada are already beginning to adopt methane monitoring systems, and it would be in the public interest to speed this process with federal subsidies of such systems. In return, the federal government should require access to the data from these systems, allowing the public the ability to ensure compliance.

- **Support development of new methane sensing technologies.**
  In partnership with the private sector, the federal government—including EPA, NOAA, the National Institute of Standards and Technology (NIST), the Department of Energy (DOE), and NASA—should continue to provide robust and sustained support for the development of new sensing technologies and strategies as outlined in Section VI. Support should be provided for a broad range of proof-of-principle instrument research as well as for translational work to develop working prototypes that could be scaled to be field-operational.

- **Develop national facilities for testing and intercalibration of methane measurements.**
  A national test bed for methane sensors would greatly accelerate the development and deployment of new generations of accurate yet affordable methane sensors. This test bed should build off the successes of existing DOE programs, such as the Colorado State University METEC effort, and should be expanded to test for a greater range of leak sizes, a greater range of geographic diversity (e.g., forests, urban settings, etc.), and new industry practices as they evolve.

For space-based monitoring in particular, it is critical to establish accessible, robust testing of the calibration and accuracy of space-based sensors operated by the U.S. and international space agencies as well as by a rapidly growing constellation of private companies. Instruments like NASA's upcoming CLARREO (Climate Absolute Radiance and Refractivity Observatory) Pathfinder (CPF) mission [47] slated for deployment on the International Space Station (ISS), are ideally suited for this purpose. CLARREO will measure sunlight reflected by the Earth five to ten times more accurately than existing sensors and is designed to maintain this accuracy throughout its mission [47]. Using CLARREO to calibrate existing and future space-based sensors will increase the accuracy of other satellite sensors, like those used to remotely sense methane concentrations.

7.2 Data and Models

- **Support development of a unified national repository of methane observations open to the international climate community.**
  The creation of a unified national repository of methane observations would support national and international efforts to mitigate its emissions [74][69]. Collaboration with or participation in the United Nations Environmental Programme's (UNEP) new International Methane Emissions Observatory [68] could facilitate attainment of these objectives. A national repository of methane observations, products, inventories, and geographic information systems of associated infrastructure would allow scientists to improve existing emissions inventories, develop a national methane model, identify opportunities to close gaps in current observational networks, and support observing system simulation experiments. Inventories based on outdated methods of calculation must be updated by the current state of the science.

- **Support development of a national operational methane hindcast and forecast model.**
  The federal government, through agencies including NASA and NOAA, should support an operational national methane hindcast and forecast modeling facility. This would strongly affect our ability to better understand, and therefore monitor, methane. First, the model could be used to project the benefits of emission mitigation measures on reducing methane concentrations, indirect effects on other short-lived climate pollutants (ozone in particular), and greenhouse effect warming. Second, the model could be used to check the consistency of improved emissions databases against the unified national repository of methane observations as a key test of the fidelity and completeness of the databases. Third, onset of large differences between

model hindcasts and the observational repository could be used to detect, and ideally identify, the location and time of onset of significant accidental methane releases or emergence of significant new anthropogenic methane emissions.

7.3 Regulation

- **Equip federal regulatory agencies with adequate and appropriate methane measurement capabilities.**
  The federal government should support methane monitoring and ensure regulatory stakeholders have access to adequate and appropriate methane measurement capabilities. This includes access to relevant data from space-based monitoring, as well as support for the implementation of airborne and ground-based tools that will enable a continuous 24/7 monitoring of methane emissions, including production, storage, processing, and transportation sites. As noted above, collaboration with or participation in UNEP's new International Methane Emissions Observatory [68] would allow the U.S. to attain these objectives. Appropriate on-the-ground monitoring capabilities are critical for accurate detection of super-emitters, an accurate national inventory of methane emissions, and an accurate assessment of the implementation of new regulations or technologies.

- **Design a regulation structure for a high-impact and cost-effective approach to reducing methane emissions from oil and gas operations.**
  Current regulations seeking to reduce fugitive emission from oil and gas are often written at the component level and dictate inspection schedules and performance for these components. This is no longer appropriate, as we now know that it is just a handful of leaks, roughly 1 component in 1,000, that contribute to the majority of the problem. Continuous basin-wide monitoring focused on rapidly detecting large leaks to address them in a timely manner has great potential to reduce oil and gas emissions. Regulations mandating repair of all leaks regardless of size are likely counterproductive. Given the host of proven new technologies to detect and quantify leaks, the federal government should consider an approach in the short term that identifies an acceptable leak rate, then ensure that leaks above that threshold be detected and addressed rapidly by both public and private actors. This structure should reflect input from industry, academia, and environmental groups. Consultation could help yield a clear, consistent set of requirements, goals, and objectives that are predictable and would enable industry to meet these goals without changing requirements, policy, etc. A goal would be a consensus-driven "roadmap" that would bring fugitive emissions down to levels that are negligible for climate change, health, and safety.

VIII. Closing Summary

This report is intended to summarize for both researchers and policymakers the current capabilities of monitoring methane emissions from oil and natural gas production, distribution, and processing. While there are many other sources of methane emissions (e.g., agriculture, landfills, melting tundra), this report focuses on oil and natural gas industry sources. The "lessons learned" from reduction of methane emissions from these sources may be helpful in addressing other, more distributed sources. The report also identifies avenues to match current needs. It focuses on identifying the gaps in our ability to quantify methane emissions and proposes concrete actions to fill those gaps.

The report details the importance of monitoring methane emissions and flaring in Section II, lists our current capabilities for measurement in Section III, and describes the current state of methane leak detection and repair in Section IV. These sections together identify scientific gaps, detailed in section V, as well as promising research opportunities, detailed in Section VI, that can enhance quantitative measurements of methane emissions into the atmosphere from oil and natural gas production sites. Section VII addresses the opportunities and responsibilities of the federal government, which can also inform local and state agencies, for effective monitoring of methane emissions. Included are detection, data and models, and regulation, all supporting this crucial enterprise.

Atmospheric methane concentrations continue to rise, but methane's short lifetime (approximately 10 years) means that addressing these corrective actions can lead to meaningful changes within the space of a few decades. It is time to act if we are to reduce global warming to a level consistent with life on Earth as we now know it.

IX. Acronyms

$^{14}CH_4$	Radiocarbon Isotope of Methane
ABSCO	Absorption Coefficient
AR	(IPCC) Assessment Report
AR5	Fifth (IPCC) Assessment Report
CH_4	Methane
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CO_2	Carbon Dioxide
COP26	26th Conference of the Parties (of the United Nations Framework Convention on Climate Change)
CRDS	Cavity Ring-Down Spectroscopy
DOE	Department of Energy
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GHGSat	Greenhouse Gas Satellite (Inc.)
GOSAT	Greenhouse gases Observing SATellite
H_2O	Water
ICOS	Integrated-Cavity-Output Spectroscopy
IPCC	Intergovernmental Panel on Climate Change
ISS	International Space Station
LDAR	Leak Detection and Repair
LIDAR	Light Detection and Ranging
MERLIN	Methane Remote Sensing LIDAR Mission
METEC	Methane Emissions Technology Evaluation Center
NASA	National Aeronautics and Space Administration
NG	Natural Gas
NIST	National Institute of Standards and Technology
NOAA	National Oceanographic and Atmospheric Administration
O_2	Oxygen
OCO	Orbiting Carbon Observatory
OGI	Optical Gas Imaging
O/NG	Oil and Natural Gas
ppb	Parts per Billion
PRISMA	PRecursore IperSpettrale della Missione Applicativa
SCC	Social Cost of Carbon
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY
TCCON	Total Carbon Column Observing network
TROPOMI	TROPOspheric Monitoring Instrument
UAS	Unmanned Aerial Systems
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
VIIRS	Visible Infrared Imaging Radiometer Suite
XCH_4	Column Dry Air Mole Fraction of CH_4
XCO_2	Column Dry Air Mole Fraction of CO_2

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