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January 2017
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IDA Paper P-8315
Log: H 17-000001

IDA SCIENCE & TECHNOLOGY POLICY INSTITUTE
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About This Publication
This work was conducted by the IDA Science and Technology Policy Institute under contract NSFOIA-0408601 (DE-DT0011794), project EA-20-4270 "Federal Priorities for Research on Energy Sector Methane Emissions," for the Department of Energy. The views, opinions, and findings should not be construed as representing the official position of either the National Science Foundation or the sponsoring office.

Acknowledgements
The report was informed heavily by input from workshop participants, including experts from the Department of Energy (DOE), the national laboratories, other Federal agencies, and the private sector, several of whom also served as reviewers for this report. Their time and effort to attend the DOE workshop and provide valuable insights and feedback is deeply appreciated. Within the DOE community, special thanks go to James Bradbury, Judi Greenwald, and Colin Cunliff of DOE's Office of Energy Policy and Systems Analysis; Neelesh Nerurkar and Christopher Freitas of DOE's Office of Fossil Energy, and Lynn Orr, DOE Under Secretary for Science and Energy.

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Executive Summary

Effective sensing and mitigation of methane emissions can reduce the effect of oil and gas operations on the environment while improving safety, enhancing operational efficiency, and enabling potentially increased revenue in the production segment through the sale of recovered natural gas. While cost-effective mitigation methods are already employed, additional monitoring and measurement technologies are required to take advantage of new leak-reduction opportunities that may reduce the cost of mitigation and further increase operational efficiency. These technologies detect methane emission sources and provide sufficient information to prioritize operational modifications, repairs, or replacements as needed. Recent research has suggested that existing national- and regional-scale estimates of oil and gas methane emissions may not fully capture the spatial and temporal distribution of emissions across the oil and gas sector. Continuous improvements in the development and deployment of emission measurement and monitoring technology, including the assimilation and analysis of measurements, are needed to identify, prioritize, and implement necessary actions to mitigate emissions.

To better understand opportunities for improving methane detection and measurement capabilities, the Department of Energy's Office of Energy Policy and Systems Analysis, hosted a workshop in October 2016 that was supported by the IDA Science and Technology Policy Institute (STPI). The *Workshop on Research Strategies to Address Oil and Gas Sector Methane Emissions* assembled researchers, industry representatives, technology companies, and government officials to identify oil and natural gas sector methane measurement research opportunities, to inform oil and gas sector methane measurement and monitoring research priorities, and to share recent progress in advancing methane measurement science.

STPI subsequently considered the workshop presentations, discussions, and participant input in the context of existing research efforts to synthesize a set of recommendations intended to inform Federal methane measurement and monitoring research planning. The resulting workshop recommendations are organized around the three policy-relevant methane emission goals articulated during the workshop: (1) supporting the U.S. annual Environmental Protection Agency (EPA) *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (referred to as the U.S. Greenhouse Gas Inventory or GHGI), (2) enabling methane emissions abatement, and (3) broader methane monitoring opportunities. The research recommendations and opportunities discussed within this report are derived from input from workshop participants and stakeholders, and STPI's analysis of the workshop proceedings. A summary of key research recommendations is provided in the following sections.

Supporting the EPA's U.S. Greenhouse Gas Inventory

The EPA publishes its annual GHGI to meet the United Nations Framework Convention on Climate Change inventory reporting requirements. For natural gas and petroleum systems, the inventory is a bottom-up accounting of emissions based on activity data and estimated emissions factors. (A *bottom-up* method refers to the process of estimating emissions from the aggregation of site- or component-level direct measurements or activity data and emission factors, whereas a *top-down* method refers to atmospheric measurements of emission concentrations and employing mathematical models to compute the emissions that typically include sources from a large geographic area.) The EPA uses the best data available to estimate actual emissions and continually updates underlying assumptions based upon newly available scientific evidence that is applicable.

STPI analyzed input from workshop participants to develop the following recommendations that could inform the data needs and development process of the EPA's U.S. GHGI. Based on feedback from workshop participants, these opportunities follow three overarching sets of potential research activities:

1. Improving the EPA's estimates of poorly characterized components of U.S. GHG emissions, including (a) gathering pipelines, (b) condensate storage tanks, (c) underground vaults and meters, (d) associated gas wells, (e) facilities not covered by the EPA GHG Reporting Program, and (f) sources that are considered to be super-emitter sources, which represent a small population of sources that emit a disproportionately large fraction of total emissions within the sample size of concern.
2. Characterizing methane sources currently absent from the U.S. GHGI due to limited information on activity data or emissions factors, including (a) abandoned wells and (b) beyond-the-meter emissions.
3. Improving the usability of the U.S. GHGI by (a) improving uncertainty reporting in the GHGI, (b) enhancing the usability and accessibility of the underlying inventory data and assumptions, (c) developing an annual spatially resolved (gridded) GHGI product, and (d) establishing a common process for obtaining and integrating research data to support the GHGI.

Enabling Methane Emissions Abatement

Technologies, strategies, and systems for enabling methane mitigation within oil and natural gas operations is essential for reducing environmental impact, increasing safety, and enhancing operational efficiency. Opportunities for cost-effective leak detection would enable operators to (1) find and mitigate typical equipment leaks from components like valves and flanges to equipment like controllers, pumps, and compressors, (2) rapidly identify atypical or unexpected emissions events, (3) better characterize the temporal characteristics of leaks, and (4) readily comply with state and national regulations and standards.

The current portfolio of technologies and tools for operational methane emissions detection and measurement meets existing site-level monitoring regulatory requirements. However, advances in technologies, technology applications, data analytics, and other support measures would better incentivize and facilitate improved operational emissions reductions. Workshop discussions informed recommendations to advance emissions measurement technology to support operational mitigation in the following ways:

1. *Research and development to advance measurement technology in support of cost-effective leak detection*. This could include (1) developing capabilities, such as autonomous detection, continuous monitoring, *super-emitter* source detection, and simultaneous detection and measurement, as well as increasing the reliability and resilience of field-deployed technologies. These advances could improve operational efficiencies, including deployment of staff to repair or replace leaking components.
2. Efforts to enable the operational demonstration and deployment of experimental measurement technology should include the integration of multiple monitoring technologies with existing decision-support systems. These research opportunities include demonstrating the efficacy and capabilities of new technologies, integrating multiple measurement approaches across spatial- and temporal-scales and integration of measurement data into operator asset management systems.
3. Research that quantifies the emissions avoided as a result of operational leak detection and repair can demonstrate the technical feasibility and reliability of new methods and technologies. These performance data are needed to support a business case for mitigation efforts. Related research priorities include developing approaches to validate leak repair activities and performance, and methods to determine measurement technology equivalence for regulatory purposes and to inform industry investments.
4. Research efforts can help connect commercial deployment of measurement technologies to leak repair and broader emission mitigation efforts. Measurement technology vendors, industry, and researchers could collaborate to develop analytical decision support tools and foster a culture of coordination among the scientific and industry communities, which can support robust methane quantification research and sustain mitigation efforts, over time.

Broader Methane Monitoring Opportunities

Beyond improving U.S. GHGI estimates or detecting leaks at a site scale, there are broader research opportunities to make significant advances in detection of emission sources, quantification of emissions, and support for mitigation decisions. Workshop discussions informed the following three areas for advancing research:

1. Optimizing multi-scaled observations and measurements such that multiple tiers of observations can be integrated and advanced in order to meet three potential end-use goals: (1) leak detection, (2) emissions quantification (flux estimation), and (3) mitigation support.
2. Improving atmospheric transport modeling to better enable methane emissions quantification, including examining and identifying optimal modeling approaches for investigation of energy sector emission by source or region, and fundamental research to improve the application of models and for simulation of nighttime boundary layer dynamics.
3. Improving source attribution approaches or guidelines on how to consistently attribute emissions to specific sources. This would help to improve emissions quantification efforts, in part by enabling better coordination between the application of top-down and bottom-up emissions measurement methodologies.

Contents

1. Introduction

A. Background

Methane is a powerful greenhouse gas (GHG) with a global warming potential (GWP) 36 times greater than carbon dioxide (CO_2) over a 100-year time horizon.[1] Development of accurate methane emissions detection and measurement technology is driven in part by the ongoing need to demonstrate progress towards national and international GHG reduction goals. The United Nations Framework Convention on Climate Change in 1992 and the recent Paris Agreement represent two significant global commitments to reduce GHG emissions. To support these global commitments and domestic policy goals, the White House issued the *Climate Action Plan: Strategy to Reduce Methane Emissions* in 2014 (White House 2014). The strategy emphasizes methane measurement as an administration priority and sets forth a plan to reduce methane emissions in the United States across all sectors, setting goals for "improving the bottom-up emissions data relevant for mitigation, and advancing the science and technology for monitoring and validating atmospheric concentrations."

The energy sector is a significant source of methane in the United States, accounting for 45% of total U.S. methane emissions in 2014, according to the Environmental Protection Agency (EPA) annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (referred to as the U.S. Greenhouse Gas Inventory or GHGI) (EPA 2016d). Of methane emitted from the energy sector, current estimates suggest 74% is derived from natural gas or petroleum systems (EPA 2016d). While these emissions occur throughout the petroleum and natural gas supply chain, the majority of emissions derive from production activities (e.g., using well-pad equipment, gathering and boosting venting and leaks, completions and workovers, tank vents, and blowdowns). According to the Energy Information Administration (EIA), production of natural gas and petroleum is projected to increase beyond 2020 (EIA 2016), indicating that the sector will continue to be a significant potential source of methane emissions in the future.

Recent research suggests that challenges persist in ensuring that the underlying data and assumptions used to calculate U.S. oil and gas sector GHG estimates are representative of actual emissions (Brandt et al. 2014). Activities are currently being undertaken across

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[1] This citation for 100-year GWP with climate-carbon feedbacks and CO_2 released from methane oxidation: other GWP values provided in; from Intergovernmental Panel on Climate Change (IPCC) (2006, Chapter 8, Table 8.7).

the scientific community, U.S. Government agencies, and oil and gas companies to better understand and characterize these emissions, develop and deploy technology to find and more accurately characterize the highest emitting sources, and provide information necessary to design and implement strategies for mitigating emissions (Clavin and Ressler 2016).

B. Project Scope

The Department of Energy (DOE) Office of Energy Policy and Systems Analysis asked the IDA Science and Technology Policy Institute (STPI) to help DOE convene a workshop that could inform recommendations for future Federal research efforts to improve methane emission sensing and quantification from the energy sector. DOE's policy objectives for future methane emission detection and monitoring research efforts are include: (1) help to improve the EPA's U.S. GHGI, (2) enable operational methane emissions abatement activities, and (3) advance the development of technologies and methods that would enable broader methane monitoring opportunities that are not currently deployed in operations.

C. Data Collection Methodology

Workshop on Research Strategies to Address Oil and Gas Sector Methane Emission was held on October 13–14, 2016. The workshop convened Federal researchers and program managers, State agencies, oil and gas sector companies, methane sensing technology development companies, and members of academia and private organizations that are involved with researching methane emissions from the energy sector.

To support the workshop's overall goal of collecting stakeholder feedback on research opportunities associated with DOE's three policy objectives, three sessions were held that reflected those objectives:

- Session 1: Energy Sector Methane Emissions Measurement for National Climate Goals—Supporting the U.S. GHGI
- Session 2: Enabling Methane Emissions Abatement
- Session 3: Broader Energy Sector Methane Monitoring Opportunities—Translating Research to Operational Capabilities

Workshop facilitators and organizers did not seek consensus on research questions and recommendations from workshop participants. The workshop was held under Chatham House Rule to stimulate candid discussion among workshop participants from all stakeholder perspectives. Specifically, participants were asked to:

- Identify stakeholder-specific requirements for the use of methane measurement and monitoring data and technology;

- Share recent progress in methane measurement and monitoring science;
- Discuss potential applications for research findings to advance operational methane emissions measurement and detection capabilities;
- Identify methane monitoring opportunities for the oil and gas sector to achieve discrete national and subnational government policy and industry emissions abatement goals; and
- Specify research investments necessary to meet these distinct objectives, including detection parameters (e.g., thresholds and spatial resolution) and data management requirements (e.g., discoverability, usability, and accessibility).

Over the course of the workshop, participants were split up into three breakout groups tasked with developing potential research activities to address technical measurement and monitoring challenges associated with maintaining an accurate, national, U.S. GHGI; improving the detection and measurement of operational leaks; and improving the detection and measurement of super-emitter sources. Through facilitated discussions, each group was asked to identify unmet technical needs and challenges, propose potential programmatic objectives that could be met in a timeframe of 5–10 years through increased research and development efforts that address the unmet needs and challenges, and propose research activities that could achieve these programmatic objectives.

The recommendations described in this report are STPI's analysis of the workshop proceedings regarding energy sector methane emission measurement, monitoring, and quantification.

D. Report Structure

This report is structured around the proceedings and participant input provided in the workshop. The next three chapters of this report (Chapters 2–4) correspond to the research opportunities identified at the workshop that correspond to DOE's policy objectives.

- Chapter 2—Supporting the U.S. GHGI
- Chapter 3—Enabling Methane Emissions Abatement
- Chapter 4—Translating Research to Operational Capabilities

Each of these chapters follows a structure that provides an introduction to the policy goals for each session of the workshop, describes the current state or practice of employing methane measurement, sensing, or monitoring technologies to meet the associated policy objectives, discusses research opportunities and recommendations informed by the workshop outcome, and describes related existing Federal and non-governmental research activities. Chapter 5 briefly describes considerations for the future, and Appendix A provides a concise summary of the recommendations provided in the report.

2. Research Opportunities—Supporting the U.S. Greenhouse Gas Inventory

A. Introduction

The EPA publishes the GHGI to meet the United Nations Framework Convention on Climate Change inventory reporting requirements. Within the energy sector, methane emissions are estimated from natural gas systems, petroleum systems, coal mining, stationary combustion, abandoned underground coal mines, mobile combustion, and incineration of waste. Published every year in April, each edition of the GHGI includes data from 1990 through the most recent available year of data. For example, the GHGI published in 2016 reports emissions from 1990 through 2014 (EPA 2016d).

The EPA annually updates its emissions estimates based on new or revised input data, calculation methods, and research. Recent studies have typically found higher levels of methane emissions from the oil and natural gas sector than those published in the official GHGI estimates from Brandt et al. (2014). Additionally, certain emission sources or specific equipment estimates may use emission factors and activity data that are outdated or incomplete. Because of the relevance for informing policy, it is a shared goal among Federal agencies, academic researchers, and industry stakeholders to generate data and research that contributes to the continuous improvement of the GHGI.

B. State of Knowledge or Practice

Given current technological and operational challenges of directly measuring all emission sources, GHGI estimates for emissions from natural gas and petroleum systems are typically calculated using activity data and emission factors.[2] This bottom-up approach uses best available data to estimate actual emissions.

1. Data Sources

Assumptions for activity data and emission factors are derived from a variety of sources. For methane emissions from the energy sector, sources of activity factor data include energy statistics such as oil and gas production data from the Energy Information

[2] *Activity data* refers to equipment counts or activity frequency, such as miles of pipeline. *Emission factors* are estimates of emissions per unit of equipment or activity, such as emissions per mile of pipeline. Data for some sectors, including onshore natural gas production, are estimated at a regional level and then compiled to determine national estimates.

Administration (EIA), industry association reports, and other Federal and State organizations. Sources for energy sector emission factors include the EPA Greenhouse Gas Reporting Program (GHGRP); EPA studies; Bureau of Ocean Energy Management, Regulation, and Enforcement data; academic journals; and industry peer review panels.

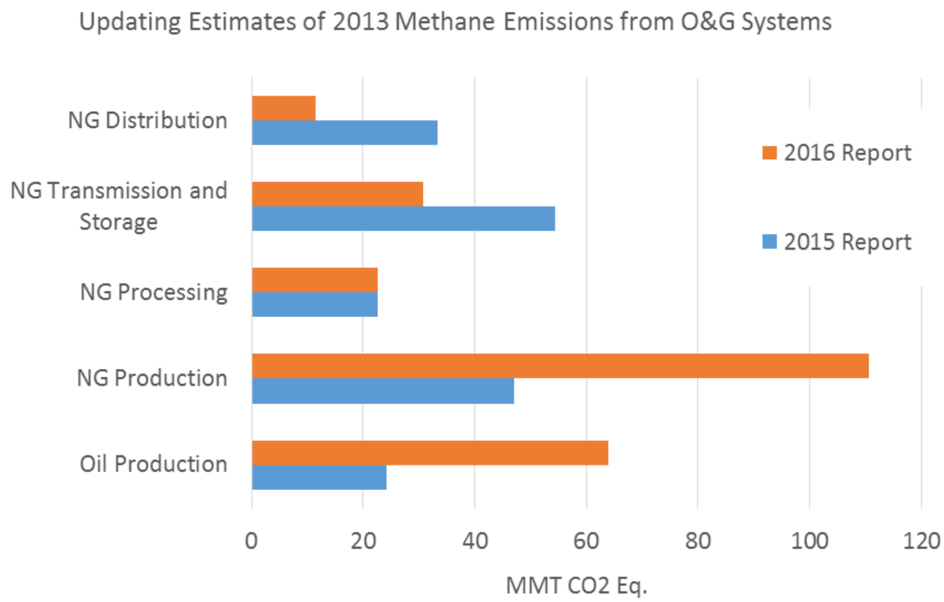
The GHGRP requires large U.S. sources to annually report GHG emissions to the EPA annually. GHGRP data are generally reported at the facility level and typically require that any facility that emits over 25,000 metric tons of CO_2-eqivalent per year must report to the program. Over 2,000 petroleum and natural gas reports are submitted to the GHGRP annually. These reports include emissions estimates, activity data, and other operational information (Title 40 CFR 2010).

2. Inventory Updates

When EPA's annual updates are incorporated into the GHGI, they are applied to all data in the time series, as appropriate, by recalculating and revising data for previous years. This approach is designed to preserve trends over time and ensure that fluctuations in emissions are due to underlying factors represented in the data, rather than changing calculation methods.

Methane emission estimates from the petroleum and natural gas sector were last updated in 2016 using newly available data and EPA's public input and peer review process. The revision increased emissions about 30% higher than 2015 GHGI estimates published in the previous year. (As noted above, updates are applied to all data in the time series to the extent possible by recalculating and revising data for previous years, so the petroleum and natural gas sector emissions increased throughout the time series in the 2016 GHGI as opposed to only for the most recent year.) Due to the recalculations, net emission estimates increased; however, as shown in Figure 1, the emission estimates of some segments of the petroleum industry decreased (e.g., natural gas transmission and storage and natural gas distribution), and some increased (e.g., natural gas production and petroleum production).[3] The higher production sector estimates in the 2016 inventory do not necessarily represent increased emissions over time or an upward trend, but rather indicate improvements in understanding of the distribution and magnitude of emissions across the petroleum and natural gas supply chain.

[3] The 2014 GHGI estimates increased from 1.0 teragram (Tg) of methane (CH_4) to 2.6 Tg CH_4 (+157%) for petroleum systems and from 6.3 Tg CH_4 to 7.0 Tg CH_4 (+12%) for natural gas systems compared to 2013 GHGI estimates.



Sources:. EPA (2015, 2016d).

Note: The GHGI evaluates CO_2 equivalence based on the methane GWP estimate of 25 in the IPCC's Fourth Assessment Report (AR4) versus the GWP estimate of 36 (for fossil methane, assuming climate carbon feedbacks) in the IPCC's Fifth Assessment Report (AR5).

Figure 1. Comparison between 2016 and 2015 GHGI Reports for 2013 Estimates of Methane Emissions from Natural Gas and Petroleum Systems Supply Chains

3. Discrepancies between Regional Measured Emissions and GHGI Estimates

Since 2011, multiple regional studies scaled up to national estimates, and national/continental modeling studies have indicated a potential discrepancy between measured or modeled methane emissions and GHGI estimates. Many of these studies are included in a 2014 meta-study that synthesized 20 years of technical literature on natural gas emissions and found a range of estimates for different spatial scales that suggest the GHGI has consistently underestimated natural gas system emissions at varying degrees and at different spatial scales (Brandt et al. 2014). Studies published since this meta-study continue to investigate the discrepancies it described, attempting to identify potential component-, regional-, or operational practice-specific reasons for these differences in estimates.

More recent studies suggest that the disagreement between the GHGI's estimates of methane emissions from the petroleum and natural gas sector and results of the atmospheric modeling studies may be largely due to *super-emitters*—a small number of sources in the petroleum and gas sector that emit a disproportionately large fraction of total methane emissions (Allen et al. 2013; Harriss et al. 2015; Zavala-Araiza et al. 2015). Super-emitters may consistently emit large quantities of emissions, or they may be ephemeral high-volume sources. In fact, the exact definition of a super-emitting source is debated often within the methane measurement community, but the key feature of disproportionately high methane emissions is that their distribution does not follow a Gaussian model. In fact, the evidence strongly suggests that their probability distribution is statistically heavy-tailed (Brandt, Heath, and Cooley 2016). Given that a large percentage of methane emissions come from a relatively small number of oil and gas sector facilities or equipment, the resulting long-tail distribution of methane emissions and temporal variability make it difficult to representatively sample these emission sources. As a result, undersampling of the long tail of such a distribution results in underestimating true emissions, because emission factors determined from sampling typically do not sufficiently account for the high-emitting sources (Brandt, Heath, and Cooley 2016).

4. Recent Efforts to Bridge Measurement Methodology Results

In addition to research attempting to understand discrepancies between regional- and national-scale estimates and the GHGI estimates, other research is underway to spatially resolve the GHGI's emission estimates. The European-based Emissions Database for Global Atmospheric Research (EDGAR) is a publicly available, widely used, spatially resolved global emissions data set; however, EDGAR may not be representative of current estimates and distribution of U.S. methane emissions. A spatially resolved, U.S.-specific emissions database would likely improve the accuracy of atmospheric models and provide an annual benchmark to validate bottom-up estimates aggregated or extrapolated to subnational levels. Researchers at Harvard University, in collaboration with EPA, have spatially resolved the GHGI's 2012 methane emission data at a 10 kilometer × 10 kilometer resolution (Maasakkers et al. 2016). This project may provide useful input to support atmospheric modeling studies, specifically inverse models, in attributing inferred methane emissions to ground sources.

Environmental Defense Fund (EDF) researchers investigated methane emissions in the Barnett Shale region in Texas using multiple measurement approaches applied to the same area sources simultaneously during a 2-week field campaign in 2013. The researchers attempted to characterize area emissions using top-down approaches (e.g., mass balance flight studies and isotopic and hydrocarbon enhancement for attribution to sources) and bottom-up approaches (e.g., aggregation of site- and component-level measurements and inclusion of sampling of super-emitter sources). The two methodological approaches yielded statistically similar results, supporting the compatibility of the two measurement approaches; however, they estimated higher levels of emissions when compared to a production-based, scaled-down GHGI estimate for the Barnett region (Harriss et al. 2015; Smith et al. 2015; Karion et al. 2015).

These studies, and similar research investigating discrepancies between inventory estimates and measured or modeled emissions estimates, highlight research topics that could help improve the GHGI. These topics include reducing and determining sources of uncertainty related to data needs and, more broadly, enhancing understanding of the distribution of methane emission sources from the petroleum and natural gas sector.

C. Research Opportunities and Recommendations

1. Improving GHGI Emissions Estimates of Poorly Characterized Components

The GHGI is continually updated to incorporate new information and data to improve its accuracy. However, there remain some important components and emissions sources in the petroleum and natural gas sector that could be improved through additional measurements, which could be used to inform updates to the GHGI. Measurement information needs to better characterize oil and gas sector emissions discussed in this section are potential candidate sources for measurement projects and campaigns, such as through investments from the DOE's Methane Emission Mitigation Midstream Infrastructure research programs (DOE 2016). Research opportunities discussed in this section are potential candidate sources for measurement projects and campaigns, such as DOE's Methane Emission Mitigation Midstream Infrastructure research program (DOE 2016). Specifically, the components and systems described in the following subsections are known areas where improved emissions estimates would result from additional research and data.

a. Gathering Pipelines

Within the GHGI, onshore natural gas production and natural gas gathering systems, which include gathering pipelines and the small compressor stations (boosting stations) along the pipeline, are reported together in one segment. For the 2016 GHGI, the EPA updated the data used for the gathering systems estimates with the data from Marchese et al. (2015), while at the same time acknowledging that new activity data would be provided by the GHGRP in future years. Gathering pipelines and booster facilities (compressor stations) were added as an emissions source in the GHGRP for 2016, which means that the first data on gathering and booster system will be submitted to the EPA in March 2017. This data includes information on miles of gathering pipeline by material for each facility that must report.

This new data for gathering pipelines will help to improve activity data for this source, but it will not address improved emissions factors. Currently in the GHGRP, gathering pipeline equipment leak emissions estimates are based on emission factors for distribution main pipelines.[4] Workshop participants called into question the accuracy of applying these

[4] Current emission factors for Subpart W (Petroleum and Natural Gas Systems of the GHGRP can be found in Tables W-1A through W-7 of 40 CFR Part 98 (http://www.ecfr.gov/cgi-bin/text-idx?SID=b100800b080c25b1839cc831cf059b6e&mc=true&node=sp40.23.98.w&rgn=div6#_top).

factors for gathering pipelines, since distribution main pipelines and gathering pipelines transfer vastly different quantities of product and have significant differences in materials, pressures and diameters.

To develop emission factors that are specific to gathering pipelines, a coordinated research campaign targeted at gathering pipeline operations in a variety of geologies and conditions would need to be examined.[5] One model is that used by Lamb et al. to examine, sample and measure distribution main pipeline emissions under different operational conditions. Workshop participants suggested that an expanded version of the Lamb study (Lamb et al. 2015) that focused on gathering pipelines specifically could yield enough data and information to develop gathering pipeline emission factors, which could then be used in both the GHGI and GHGRP.

b. Atmospheric Pressure Storage Tanks

In the natural gas sector, condensate storage tanks are primarily used during the production stage. Once a well begins producing, fluids brought to the surface are composed of a mixture of natural gas, water, hydrocarbons, and other gases. Operators use separator units to isolate the natural gas from the liquids. These liquids, called *condensate*, are collected and stored in tanks before they are transported to refineries to be incorporated into liquid fuels (Armendariz 2009).

Depending on the engineering and control strategies, storage tanks can be a significant source of emissions and can be challenging to measure (Hendler, Nunn, and Lundeen 2009; Chambers et al. 2006; Gidney and Pena 2009). Tank emissions can result from four main incidences: (1) thief hatches leaking or accidentally left open at controlled tanks; (2) tank breathing losses, resulting from daily temperature changes; (3) tank flashing losses, resulting from pressure drop during transfer of liquid; and (4) tank working losses, resulting from vapors being displaced while filling the tank (Modrak et al. 2012). Because the GHGI calculates tank emissions based on an estimated emission factor, it does not capture these episodic events. Workshop participants provided feedback that in addition to these four pathways, , emissions from other components and processes, such as dump valves that are stuck open or liquids unloading events, may be routed through tanks, which can create complicated accounting issues to avoid double-counting emissions from both the originating source as well as the tank.

Even with direct measurements, however, it is often challenging to locate and quantify this type of large, short-term emissions (Brantley et al. 2014). As a result of this

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[5] A forthcoming series of studies on basin-scale top-down and bottom-up methane measurements from onshore oil and gas development funded by the Research Partnership to Secure Energy for America is expected to include research findings that may be relevant to multiple GHGI oil and gas sources, including gathering pipelines.

intermittency and spatial variability, the current methods may significantly underestimate tank related annual methane emissions. Of these emissions, researchers believe tank flashing losses are larger than the other three tank related emissions during a single event. However, measurement campaigns have found that leaking thief hatch seals on controlled tanks were among the most frequently observed emission category on production pads (Brantley, Thoma, and Eisele 2015).

In the 2016 GHGI, tank emissions are calculated by multiplying throughput of each category (with and without control devices) by an estimated average emissions factor for each category. The GHGRP does not require industry to report all tank emissions, so there are limited direct measurements to inform the GHGI estimates (Title 40 CFR 2010). Two different emissions factors are used, depending on whether the tanks have control devices or not. Control devices, such as vapor recovery units (VRUs), capture vapors, consisting of methane, VOCs, and other pollutants, rather than allow them to be vented to the atmosphere (EPA 2016d). While the GHGI estimates that control devices reduce 80% of tank emissions, actual emissions reductions could be lower depending on operating conditions and how the systems were installed.

The rate and composition of tank emissions can also vary over time, requiring long-term measurements in varying operating conditions. Workshop participants noted that research is needed to develop an understanding of the root cause of high methane emissions rates from tanks. A key consideration is also whether or not the researcher is able to communicate with the operator and inquire about operational changes when they see large emission increases. This communication is key to understanding tank emissions and furthering the scientific understanding of methane emissions related to tanks.

Beyond the needs for communication with the operator and spatial variability, there are additional research considerations for this emissions source. Physical access to tanks (i.e., tall tanks) by operators and researchers is a simple but important complexity to studying these sources, and the emissions from these sources present complex attribution issues (i.e., several co-located tanks, tanks in close proximity to other emissions sources). Tanks also vary significantly in their design, and distinct designs may have distinct root causes for malfunctions.

c. Underground vaults and meters

Emissions from underground vaults and meters in the natural gas distribution sector are currently approximated using default factors from the 1996 GRI/EPA study in the current GHGI for earlier time series years, and applied Lamb et al. (2015) for later time-series years (EPA 2016e). Linear interpolation of emission factors was used for intermediate years. Activity data for 2011–2014 was recently revised in 2016 GHGI to use GHGRP data that is scaled up to national-level representation, with prior years (1990–

2010) not requiring activity data updates because year-to-year variation in station counts would not differ with currently best available data sources.

Workshop participants discussed the representativeness and accuracy of the original default factors and stressed the need for a measurement campaign to directly measure these underground sources with the goal of revising the existing factors. Underground testing in confined spaces raises safety concerns that would have to be considered and mitigated. Provided safety of the researcher can be assured, a research campaign could be conducted that includes sampling from underground systems at different companies, including variations in infrastructure age and operating pressure. As noted previously, active and rapid communication between researchers and operators would be essential to the success of such a research study.

Another possible approach is to mine the GHGRP data for company-specific emissions factors for meter and regulating (M&R) stations, which are developed from targeted measurements done by each company, and use the same emissions factors for underground vaults. If implemented, the validity of M&R station emission factors for the underground equipment would need to be verified for some portion of sites to prove comparability above and below ground.

d. Wells with associated gas emissions

Workshop participants highlighted the importance of casinghead gas as a significant portion of associated gas emissions. Workshop participants stated that the current GHGI methods assume that casinghead gas emissions predominately occur at stripper wells, but some participants questioned that assumption. The current GHGI accounts for emissions from stripper well production by applying an oil tank emission factor to 20% of throughput, and applying a well venting/casinghead gas emission factor to the remaining 80% of throughput. When considering the application of GHGRP data for associated gas emissions, definitional issues exist between the GHGRP and GHGI. The GHGRP associated gas venting and flaring data is most comparable to the GHGI's stripper well venting category, however GHGRP associated gas venting includes emissions from both stripper and non-stripper wells (EPA 2016f).

To account for the concern that casinghead gas emissions occur at a wider set of wells with associated gas emissions than only stripper wells, the GHGI is considering using associated gas venting and flaring data from GHGRP to update the GHGI. The GHGRP data could be extrapolated to the full population of wells with associated gas emissions in the GHGI to create a more accurate accounting of associated gas emissions that is inclusive of casinghead gas emissions (EPA 2016f).

Another potential solution is a coordinated research campaign to measure wells with associated gas sources to provide updated, directly-measured methane data to inform emission factors. Considerations for such a research campaign include:

- Geographic and geological variation and representativeness
- Cataloging associated gas emissions sources to ensure complete accounting of what is included in each measurement
- Capturing operational variation in wells investigated to inform analysis of emissions sources under different operations (such as investigating if certain operational configurations produce increased casinghead gas emissions)
- Differentiating data gathered from what is provided in the GHGRP, including an evaluation of how the two data sets could complement each other

e. Non-GHGRP facility emissions

The GHGRP only requires facilities to report emissions if they produce over 25,000 metric tons of CO_2-equivalent per year. As a result, sectors containing facilities that are estimated to be smaller or lower emitting facilities are not fully represented in the GHGRP data. This includes a lack of information on whether the emission rates or distributions of sources is similar to or different from higher emitting sources. For example, only about 1/3 of total U.S. natural gas transmission and storage facilities are reported. The reporting threshold for GHGRP facilities limits the information available on non-reporting facilities. This leads to research questions regarding the representativeness of the distribution of GHGRP emissions data related to a population that also includes non-reporting facilities.

Additionally, for upstream facilities (for onshore production and gathering systems), recent data indicate that only about 30% of operational wells are included in the GHGRP (EPA 2016f). To identify the remaining facilities and their emissions, some researchers have considered analyzing State data; however, State permits typically have reporting thresholds as well, therefore limiting coverage of below-threshold data. While limited additional data on below-threshold facilities may be available through the EPA's upcoming petroleum and natural gas Information Collection Request, workshop participants noted that more information will be needed to comprehensively represent below-threshold facilities (EPA 2016c). Operational parameter data from the Information Collection Request could be used to identify the appropriate cross-section of smaller facilities (or lower emission facilities) that should be included in an examination and comparison between emissions from below- and above-threshold facilities, which would include comparisons between specific emissions sources, operational conditions and spatial and temporal cross-sections for these two groups.

f. Super-emitter sources

Emission sources that are disproportionally large or emission sources that have a long-tailed distribution remain difficult to capture in measurement campaigns (Brandt, Heath, and Cooley 2016). Workshop participants discussed the difficulty in ensuring measurements contain a representative sample when a large percentage of methane emissions actually come from a relatively small number of super-emitter point sources. In particular, research campaigns must be able to fully characterize the distribution of the source in question and ensure that the long tail of such a distribution is being appropriately sampled and accounted for. Future research campaigns should include strategies for sampling full emissions distributions, including the long tail, and ensure an adequately large sample size.

2. Characterizing Methane Sources Currently Absent from the GHGI

In addition to the areas of the GHGI where certain components and emissions sources in the petroleum and natural gas sector could be improved, beyond-the-meter emissions from leaks and abandoned oil and natural gas wells are absent from the petroleum and natural gas sector calculations in the GHGI all together. This is typically due to a lack of any reliable emissions or activity data for these sources as well as a lack of research demonstrating that they represent methane emissions on a scale that can be quantified. Both an activity data collection campaign and significant research efforts would be needed to measure these emissions sources in a representative way.

a. Beyond the meter emissions

Workshop participants also voiced concern that the GHGI currently does not account for natural gas leaks that occur beyond the meter. The GHGI does account for residential and industrial customer meter emissions, which are derived from emissions factors based upon a 2009 GTI study and 2011 Clearstone study (Williamson, Hall, and Harrison 1996; EPA 2016d) and activity data derived from EIA data (EIA 2015c, 2015a, 2015b).

Beyond-the-meter emissions refer to leaked or uncombusted natural gas after transfer to individual buildings (homes and businesses) or to industrial facilities. The GHGI does account for uncombusted natural gas used beyond the meter in the fossil fuel combustion category and may also account for a fraction of the methane emissions that result from natural gas leaks beyond the meter (IPCC 2006). Once the natural gas is transferred beyond the meter, custody and responsibility for the natural gas rests with the user or building owner, instead of the natural gas distribution company. Leaks within building pipes can vary significantly depending on the age and level of maintenance of the building, piping material, volume and pressure of natural gas used, equipment used for combustion, and any human error considerations. Natural gas leaks in homes or buildings, when they exist, can be dangerous and typically fall within the purview of building codes and safety standards. More common, low-concentration natural gas leaks, although not causing a safety hazard, may represent a non-negligible source of emissions when aggregated across the U.S. commercial and residential building stock. Additionally, industrial facilities may have a higher potential leak rate for beyond the meter emissions, as their natural gas piping may operate at significantly higher pressures than residential or commercial buildings. The number of potential emission sources suggests that an estimate of beyond the meter emissions could be determined if sufficient data was available to calculate an emissions factor for buildings based on total natural gas used, size of building, length of pipeline, types of combustion-related equipment, and relative infrastructure maintenance level.

b. Abandoned Wells

Some abandoned oil and natural gas wells are a consistent source of methane emissions (Boothroyd et al. 2015; Townsend-Small et al. 2016). Abandoned well emissions occur for several reasons. Unplugged wells vent readily to the atmosphere, while others are plugged but designed to vent methane as a safety measure in coal-producing regions. A recent study reviewing abandoned wells in Pennsylvania found that methane from abandoned wells contribute 5–8% of total State-wide methane emissions. Researchers also found that a small number of high-emitting abandoned wells accounted for the majority of emissions, and that these emissions tend to persist over multiple years (Kang et al. 2016).

Although abandoned oil and gas wells are known to be sources of methane, they are not included in the GHGI. Workshop participants discussed one primary difficulty with including abandoned oil and gas wells in the GHGI: no comprehensive database details the number of abandoned wells in the United States. For example, while a Pennsylvania database maintained by the Pennsylvania Department of Environmental Protection identifies approximately 31,700 abandoned wells in the State, researchers estimate that the actual number of abandoned wells ranges from 470,000 to 750,000 (Kang et al. 2016). Previous studies have investigated magnetic detection from helicopters as a tool to locate abandoned wells (Hammack and Veloski 2016). Additionally, county- and State-level oil and gas permitting records may contain information that identifies the location of abandoned wells. While a systematic synthesis of data on wells that have been abandoned in individual counties may yield a better estimate of total abandoned wells in the United States than exists today, extracting and synthesizing these data may be resource- and time-intensive.

In addition to a lack of activity data, another challenge workshop participants discussed related to inclusion of abandoned wells in the GHGI is the lack of a nationally representative emission factor. Not all abandoned wells leak appreciable quantities of methane, and for those that do, the correlation between abandoned well characteristics and associated methane leakage is not well understood. Therefore, workshop participants noted that additional research is needed to be able to predict which abandoned wells might be high emitters, and to estimate those emissions based on specific types of wells, locations, or other characteristics; it has not yet been demonstrated that such clear correlations or patterns exist (Miller 2015).

In addition to comprehensive efforts to locate abandoned wells in order to develop the necessary activity data, efforts to develop emission factors for inclusion in the GHGI would require a research campaign evaluating field emissions from an appropriate cross-section of particular wells, followed by extensive statistical analysis. If activity data and emission factors were determined to be impractical for such a varied methane emissions source, other methods would need to be developed to estimate the contribution to national emissions, potentially informed from data collected through top-down quantification methods or periodic direct measurements of abandoned wells. Potential investments from DOE's Methane Emissions Mitigation from Midstream Infrastructure research program could develop methods to improve upon activity data collection, such as exploring the use of innovative measurement and monitoring technologies, or research to generate a representative sample of abandoned wells in multiple oil and gas producing basins.

3. Opportunities to Improve GHGI Processes

Workshop participants noted where GHGI processes, communications, or information could be improved and streamlined to assist the larger GHG science community with access to relevant and accurate information.

a. Research approach to improve uncertainty reporting within the GHGI

Some workshop participants suggested a need to develop approaches and methods for coordinating measurement studies for comparison and aggregation of research findings with the GHGI was identified. The concern is that different studies appear to be using common nomenclature for emissions from sources that may not be directly comparable. Many regional or local studies have attempted to verify GHGI emissions estimates and address the question regarding the uncertainty within the GHGI only to discover that they either do not have enough data for appropriate source attribution (regional) or were not using the same equipment and operational definitions in the GHGI during their study (local).

To solve the definitional issue, workshop participants suggested the development of a taxonomy for petroleum and natural gas leak sources that can be consistently used by future measurement studies. This could be developed by the EPA, by a standard-setting group such as the American National Standards Institute or by a petroleum and natural gas association such as the American Petroleum Institute. For regional studies, top-down measurements can be used to inform where the GHGI may be over- or underestimating emissions; however, one common disconnect is the level of uncertainty between studies.

One approach to verification could be to leverage existing modeling and statistical analysis to inform regional studies regarding the amount and variations of data needed to inform the GHGI (Brandt, Heath, and Cooley 2016). Applying rigorous statistical analysis on existing data could also be used to extract information from previous studies that may allow the data to further inform the GHGI. Another approach is to develop a standard protocol for all studies to ensure similar variables, key parameters, and definitions are used so these studies results will be better positioned to inform the level of uncertainty in the GHGI.

b. Enhancing the usability and accessibility of GHGI data and reports

The main goal of the GHGI is to meet the international requirement to submit United States GHG emissions to the United Nations Framework Convention on Climate Change annually. However, workshop participants discussed that the GHGI is also a repository of meaningful data, information, resources, and references regarding GHG emissions. Researchers also use the GHGI to gather detailed information related to GHG emissions and trends. Given the scope and length of the annual GHGI, users of GHGI information can sometimes have difficulty finding the information they need in a concise format. A potential solution is to develop key, concise products that provide the information targeted for specific user communities, such as petroleum and natural gas sector researchers, without requiring them to sift through volumes of information to find key data or trends. While the EPA has published many fact sheets and trend plots to date, they primarily focus on the public user with some information / knowledge of the GHGI and GHGRP. They do not focus on the researcher looking for key information in a targeted area. If additional GHGI-derived products were to be developed, a first step is to survey the target population to understand what key products are missing from EPA publications and information currently and how the information in the GHGI could be streamlined to meet their needs. Employing a survey of a broad and meaningful cross-section of participants could be an approach to identify unique and overlapping user needs associated with GHGI output.

c. Streamline process for annual release of a spatially resolved GHGI

Recent efforts have focused on how to spatially resolve the GHGI into a regional grid of U.S. methane emissions (Maasakkers et al. 2016). This research will provide a key tool for regional research campaigns to use that will assist with the resolution of top-down and bottom-up GHGI data. Workshop participants suggested that this work is immensely helpful for research purposes and should be continued annually for U.S. methane emissions and expanded to other GHGs going forward. If pursued, this research could build on existing efforts to generate a streamlined, annual gridded CH_4 inventory (EPA 2016b) that could inform regional research campaigns, companies, state and local regulators and policy makers, and the public.

d. Establish and communicate a common process for obtaining and using research data for the GHGI

As part of the annual GHGI report, EPA develops a list of potential future updates for each chapter in the GHGI, which often includes identification of data needs for the sector or sectors. Researchers at the workshop expressed frustration over the lack of specific information on necessary research parameters and collected data to allow incorporation of their study into the GHGI. This report aims to help shed light on current gaps and areas for improvement in the GHGI. However, a potential long-term solution could be to develop a common process for incorporation of studies into the GHGI. This would likely require including both a pre-study review of the collection methods and types of information and data being collected in the research campaign as well as a post-study analytical review of results. There are a number of considerations to account for in developing a common process, but a few opportunity areas include:

- Establishing specific criteria for data standards, such as level of representativeness, quality assurance, and appropriate statistical analysis.
- Ensuring GHGI data publication does not impede or precede any scheduled publications on the same data
- Collaborative communication between researchers and the EPA (or other body EPA appoints to execute the process) before, during and after the research campaign

3. Research Opportunities—Enabling Methane Emissions Abatement

A. Introduction

Mitigating methane emissions at the operational level requires the development of operationally-relevant mitigation strategies, technologies, methods and tools. Such opportunities for cost-effective leak detection could help the private sector prioritize investments in methane emissions mitigation technology and equipment. Broadly speaking, operational monitoring objectives fall into three categories, each with unique challenges and requirements. Leak detection at all operations along the oil and natural gas supply chain is necessary (1) to find typical equipment leaks from valves, pumps, and compressors, (2) to rapidly identify super-emitters, and (3) to comply with state and national regulations, and voluntary performance standards.

Current commercially available emissions measurement and sensing technologies allow oil and gas owners and operators to detect emissions and employ mitigation measures for a portion of their activities and to meet basic monitoring needs. These current measurement technologies and monitoring approaches have limitations that could be addressed by new technologies and technology applications, which could enable more consistent, comprehensive, and higher-frequency monitoring. Additionally, decision support tools, data analytics, cooperative agreements, and other support measures could facilitate operational emission reductions.

B. State of Knowledge or Practice

Through the implementation of the *Climate Action Plan: Strategy to Reduce Methane Emissions* (White House 2014), Federal agencies have established voluntary programs, promulgated new regulations and increased investments in technology research, development, demonstration and deployment (RDD&D). Advancements in measurement and monitoring technologies create opportunities to reduce the cost of methane mitigation, and this remains a priority goal for RDD&D efforts. For example, the DOE Advanced Research Projects Agency–Energy (ARPA-E) program called Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) aims to develop technically innovative and cost-effective solutions that can locate and measure methane emissions from the natural gas sector (ARPA-E 2015). Projects within MONITOR must demonstrate both a low cost per facility installation and technical accuracy and robustness when deployed. Another RDD&D effort is the Environmental Defense Fund (EDF)

Methane Detectors Challenge, which focuses on developing new, low-cost, continuous methane detection technology (EDF 2016). Both of these programs have included test and pilot facility demonstrations for successful technology. Finally, in 2016 the DOE Office of Fossil Energy invested $13 million in projects targeting methane quantification and mitigation. More information on these programs is provided in Section C.

While companies currently implement emissions mitigation measures using commercially available methane detection technology, there are opportunities to improve the state of the art beyond existing RDD&D efforts. Advances in methane detection/measurement technologies, sensing platforms, and integrated monitoring systems could help develop cost-effective, continuous monitoring tools to more effectively address oil and gas sector methane emissions. These research efforts require stakeholder collaboration between government agencies, non-governmental organizations, the academic community, and private industry. A discussion of research opportunities beyond the current commercially available technology is provided in the following sections.

C. Research Opportunities and Recommendations

1. Improve Technologies to Support Cost-Effective Methane Leak Detection

Detection needs and monitoring challenges can vary by geographic location, supply chain segment, cost, and other factors. As a result, no single leak detection technology is optimal for all situations. Best practices recommended by the EPA and state regulators currently promote the use of hand held monitoring tools, such as portable analyzers and optical gas imaging (OGI) cameras based on infrared (IR) imaging. Portable analyzers are intended to locate and classify leaks by providing a reading for the concentration of gas leaked in parts per million. Portable analyzers need to be calibrated to a reference gas at a known concentration in the atmosphere. OGI cameras provide a real-time visual image of gas leaks and can therefore be used to monitor more components on a per hour basis than portable analyzers (EPA 2016d). However, detection capability depends on gas characteristics of the leak, optical depth of the plume, and temperature differential between the gas and atmosphere (Ravikumar, Wang, and Brandt 2016).

Midstream pipeline leak detection is currently driven by efforts to improve safety rather than to address climate change. The Federal pipeline safety program is overseen by the Department of Transportation’s Pipeline and Hazardous Materials Safety Administration. Current methods for pipeline leak detection include internal monitoring through computational models that assess flow parameters within the pipeline, and external monitoring using helicopters or manually surveying pipelines with OGI cameras and IR imaging tools.

These commercial technologies and others have successfully helped reduce methane emissions across the natural gas supply chain. For example, U.S. partner companies participating in the voluntary EPA Natural Gas STAR program reported reducing methane emissions by a total of 52 billion cubic feet in 2014 using these and other technologies and practices (EPA 2016d).

a. Current State of Monitoring Technology

Despite the emissions reductions attributed to the use of these measurement and monitoring technologies, technical and operational limitations prevent cost-effective application in some circumstances. For example, they require manual operation, thereby enabling only intermittent monitoring. Another challenge limiting adoption of these technologies is that they can only detect leaks directly in the sensor's path or in the line-of-sight of the camera, which makes site-surveying more time and labor intensive. These operational burdens combined with their high capital costs limit the net economic benefits of adopting existing technologies for more frequent use or more geographically extensive monitoring regimes. Additionally, most hand-held sensors and basic OGI technologies typically only measure concentration (or a proxy for concentration) and do not quantify methane leakage rates. However, quantification of mass leakage rate is an important capability for prioritizing leak repair and benchmarking and GHGI development. Some algorithms have been developed to translate estimated concentrations from portable analyzers to mass leakage rate estimates, but this continues to be an area of research.

While not officially recognized as an EPA best practice, many researchers and industry groups are increasingly using mobile monitoring approaches to identify emissions sources (EPA 2016h). For example, a vehicle can be equipped with sensing or measuring equipment and driven around a site. Mobile leak detection can cover a large area, however it is generally less accurate than on-site source measurements. Additionally, it requires vehicle access to areas downwind of the site and wind conditions favorable to estimating and tracing emission plumes.

b. Current Programs and Opportunities to Advance Methane Monitoring Technologies

New developments in methane detection and measurement tools are focusing on reducing the cost and operational/administrative burden so they can be easily incorporated into comprehensive monitoring strategies. Current pilot to development phase research activities have generally focused on developing technologies that would enhance operators' ability to employ more cost effective leak detection and repair programs. Development of these technologies could also have broader utility to the research community.

The Environmental Defense Fund (EDF) and eight oil and gas partner companies tested novel cutting edge methane monitoring technologies at Southwest Research Institute through the Methane Detectors Challenge (MDC) (EDF 2016). The specifications of the MDC were to be able to detect the leaks responsible for the majority of emissions within hours, be weatherized and solar powered, automatically conduct data analysis and alert operators of a leak, and effectively differentiate between on-site and off-site methane emissions. The challenge began in 2013 and after two phases of testing, the two most promising technologies are currently at the pilot deployment stage. Industry partners plan to use the tools across a range of geographies and facilities.

The Advanced Research Projects Agency–Energy (ARPA-E) Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) program is supporting the development of new methane detection and measurement technologies for the oil and gas sector (ARPA-E 2015). MONITOR is providing up to $30 million to 11 research teams to deliver high sensitivity, low cost, innovative approaches to sense methane emissions, characterize leakage rates, identify leak sources, and effectively communicate data to operators. Examples of innovative approaches used by the 11 projects funded through the program include remote sensing, advanced dispersion models, UAVs, and low-cost print manufacturing. As part of the MONITOR Program, ARPA-E funded Colorado State University to develop a test site facility where project teams can evaluate their sensing technologies. The test site includes facilities that simulate a range of production, transmission, compression, and distribution equipment. The test site's controlled emission releases are designed to simulate real emissions scenarios that account for variations in emission location, frequency, duration, composition, and volume.

A third notable research program is organized by the DOE Office of Fossil Energy. In September 2016, the Office of Fossil Energy announced it awarded $13 million to 12 multi-year research projects to address methane emissions from natural gas infrastructure (DOE 2016). Five of these projects are specifically intended to advance quantification research to better measure methane emissions across different segments of the supply chain.

Finally, another recently developing research area is the use of unmanned aerial vehicles (UAVs) as a sensor platform for IR imaging cameras to detect methane in the midstream sector where manual leak detection of pipelines is challenging. The Federal Aviation Administration (FAA) reauthorization bill passed by congress in 2016 includes an amendment permitting UAV use by the oil and gas industry (Public Law 114–190 2016). Prior to this amendment, individual companies could apply for exemptions in order to use UAVs to aid in infrastructure inspections, so several companies have already been testing UAVs for monitoring pipelines and production platforms. Some advantages of UAVs over aircraft operations include increased safety, potential for reduced operating costs, and reduced weather-related flying limitations.

c. Research Priorities to Advance Methane Monitoring Technology

When developing methane monitoring and measurement equipment, researchers must meet several objectives. While some design parameters, such as detection threshold and spatial resolution may complement each other, they may be in direct competition with important implementation parameters such as cost-effectiveness and temporal resolution (the number of measurements taken per given time period). Additionally, different sectors across the oil and natural gas supply chain have unique priorities and needs, which are further individualized depending on the specific geography surrounding the operations, state regulation requirements, and type of operating equipment in use.

While the technology development programs funded by EDF, ARPA-E, and DOE Office of Fossil Energy via the Methane Emissions Mitigation from Midstream Infrastructure research program described above have made great strides towards advancing the field of measurement technology, continued efforts will allow further development of cost-effective, resilient, and robust technologies for operators.

In the case of methane emissions measurement and mitigation, there are several challenges to demonstrating cost-effectiveness of detection technology. The first challenge is that the value of the methane emissions mitigated to an operator depends on the quantity and price that would be obtained for the sellable methane captured. Predicting emissions avoided by any given technology is complex, because emissions vary widely across operations, location, and time. Additionally, if a leak is detected and promptly mitigated, there is no counterfactual to benchmark the emissions avoided due to the technology having been in place, as opposed to how long the leak may have persisted under standard operating procedures. A second challenge to demonstrating cost-effectiveness of a technology is that the cost depends on how accurate and robust a technology is, which is difficult to predict outside of a controlled testing environment. If a device constantly requires operator attention, repairs, or calibration, there is a high operational cost in addition to the initial capital investment.

The following technology development research priorities were discussed by workshop participants to address these challenges.

1) Autonomous detection

Currently, leak detection that requires operator interaction is expensive. In addition to the cost of the operator's time in the field designated to detection, there is an opportunity cost associated with the work the operator otherwise could have been doing during that time. Furthermore, the spatial and temporal resolution, accuracy, and consistency of measurements are likely to decrease the more human interaction a device requires due to natural human error and response times compared to autonomous operation. As a result, designing autonomous leak detection technologies is an important priority for reducing operational cost, increasing the quality of emissions data for regulators and researchers, and avoiding environmental impact by quickly identifying leaks for mitigation.

2) Continuous monitoring

One of the primary benefits of automatic technology would be the capability for frequent or continuous monitoring. Because emissions can be episodic in nature, it is possible that they would not be detected by a periodic measurement survey. In determining the cost-effectiveness of a technology, an important factor is how many leaks are detected. Continuous monitoring would ensure that any time a leak occurs, it is detected, thereby increasing the likelihood of a technology to add value to oil and gas operations. Frequent or continuous monitoring would also allow operators to observe potential patterns in operational fugitive emissions. This could serve as a reliable framework for predictive maintenance, asset management, reduced waste, and an increase in overall safety. These ancillary benefits of frequent or continuous monitoring could further contribute to the cost-effectiveness of a methane monitoring technology.

3) Super-emitter detection

Rapid super-emitter detection has benefits both to the environment and to industry because, in addition to avoiding the release of methane to the atmosphere, the detected natural gas can, in many cases, be retained and sold. Because emissions from super-emitters are so large, super-emitter detection is more likely to be cost-effective than the monitoring and detection of smaller operational leaks. Due to the unpredictable nature of super-emitters, technology targeting super-emitter leaks has different requirements than other operational methane detection technology. To overcome the spatially diffuse nature of these sources, super-emitter-focused detection and measurement technologies would need to be able to regularly scan a broad spatial scale. However, the detection threshold and spatial resolution would not need to be as fine as other detection or quantification focused technology solutions targeted toward smaller operational leaks.

4) Simultaneous detection and quantification

Traditional operational methane detection devices such as hand held sensors and OGI cameras are designed to identify the occurrence of a methane leak, rather than to determine the specific emission source or quantify the emissions flux. Alternatively, some devices quantify leaks by measuring the concentration of methane (which is influenced by atmospheric conditions), rather than by estimating the mass flow rate of the leak (which is a property of the leak size itself). Current concentration-based measurement tools require operations to identify the source and size of a leak before repairs can take place. This additional labor burden requires operator time to measure the leak post-detection, thereby increasing abatement costs. Advancements in technology to simultaneously quantify the emissions flux and identify the specific source of the leak, rather than only detecting the occurrence of a leak, would reduce operator time and help prioritize and streamline repair work.

5) Reliability and Resilience

An important feature of methane leak detection technology is that it should perform reliably and be resilient to a wide range of operating conditions. In the context of oil and gas operations, this requires measurement technology to continuously deliver accurate measurements over an extended period of time without the need for constant calibration or cleaning, while withstanding exposure to harsh weather conditions. This long-term robustness increases the life time of the technology, thereby reducing the cost for each detected leak. Additionally, the less calibration, maintenance, and repair a technology requires, the lower the operating costs are likely to be. While the reliability and resilience of a technology can be assessed based on simulations and lab testing, it is important to understand how the technologies respond in uncontrolled, real world environments. Given these considerations, the ARPA-E test site presents an opportunity to provide transparent, objective, and real-world performance results that can be used to benchmark and compare the reliability of different measurement technology approaches. To demonstrate resiliency, technology developers could collaborate with industry partners to evaluate the long-term performance of methane detection technologies in pilot tests.

2. Translating Technologies from Research and Development (R&D) to Operations

Individual technologies are currently under development that have the potential to increase the effectiveness of leak detection, reduce cost for operators, and improve the ease of implementation. However, systems may need to be developed to integrate different measurement technological approaches into existing operational systems, such as operators' asset management systems. Opportunities exist to leverage Federal technology transfer programs to coordinate research activities that move applied research findings into demonstration projects.

a. Multi-Scaled Monitoring and Observing Systems Integration

To complement technology advancements and enhance technology effectiveness, new networks and integrated systems are under development to facilitate continuous, cost-effective monitoring and data communication. Proposals for a 'tiered observing' approach capitalize on the concept that multiple scales of observations and measurements could be integrated together, in a contextually optimized configuration, to meet a variety of operational and research objectives (Duren et al. 2016). For example, a basic operational multi-tiered measurement system could be two stage leak detection system that first uses mobile monitoring to detect a leak, and then relies on more advanced technologies to identify the source and quantify the leakage rate.

b. Current Programs and Opportunities to Advance Systems Integration

One pilot project for integrated methane emissions measurement program is the Indianapolis Flux Experiment (INFLUX), which is deploying a set of observational capabilities to develop a comprehensive urban greenhouse gas monitoring network using Indianapolis as a case study (Shepson Atmospheric Chemistry Group 2016). Additionally, the Megacities Carbon Project is also pursuing an integrated approach to monitoring urban greenhouse gas emissions (JPL 2015). In particular, this project is working towards the development of integrated measurement systems that can collectively reduce emissions estimate uncertainty through simultaneous measurement approaches and characterize emissions within a complex urban environment that would be not be feasible with a single measurement approach. Pilot activities are underway in Los Angeles, California, and Paris, France, and activities are planned to begin in São Paulo, Brazil, in the future.

c. Research Opportunities to Advance Systems Integration

1) Leverage multiple scales of observational capabilities for rapid, cost-effective emissions detection

Integrating multiple scales of technologies, each with different capabilities and strengths, into a unified tiered system could be a cost-effective methane leak detection implementation strategy. This could be implemented by relying upon measurements with lower spatial resolution that are continuous in nature, and then employing more precise measurements where further investigation is needed. This concept would aim to reduce the application of high-cost, high-precision measurements only to locations where lower-cost measurement technology provide evidence that a leak may exist. For example, an operator may install leak detection on towers at strategic locations around a production site. Once a tower identifies an area of elevated emissions, an operator can then drive in a car with a mobile sensor to refine the source location and measure the site-level leak flux. Finally, an operator can be deployed with a hand-held sensor to locate the precise location of the leak and perform maintenance as necessary.

In addition to reducing the cost of leak detection, a tiered system approach can provide continuous monitoring while increasing operator safety and reducing the likelihood of false positive leak reports. Further cost reductions could be achieved if the tiered observation system concept could be implemented by multiple co-located oil and gas operators. Existing programs such as the INFLUX project are currently demonstrating the value of tiered system within the distribution sector. However, there are opportunities to implement these processes for cost-effective monitoring at oil and gas production facilities as well. In order to encourage industry adoption of tiered monitoring systems, networks and system architecture facilitating such technology integration should be developed to fully operationalize the approach.

2) Integrate technologies with owner and operator asset management systems

In addition to integrating technologies operating at different scales into a single effective tiered system, workshop participants noted that research is needed to design systems that integrate methane detection technologies with owner and operator asset management systems. Asset management systems for oil and gas operations consolidate input from sensors, controls, tools, and equipment in the field into a decision-relevant output that enables streamlined oversight and management decisions. These systems collect data and track operations to provide key information in a structured, meaningful manner, thereby reducing labor, costs, and operational risk.

Integrating methane detection technology with asset management systems could take several different forms. For example, a rapid-repair, alert-based approach could link methane detection sensors to the system such that an operator in the control room could be automatically alerted of a methane leak and be able to visualize on a screen which component is responsible for the leak. In a leak detection and repair optimization configuration, asset management decision-support systems would analyze patterns and trends in operations and leaks to identify the most cost-effective mitigation options. These systems could be used to observe patterns and trends in operational oversight and identify equipment malfunctions.

3. Enable the Business Case for Leak Detection and Support Regulatory Compliance

There are several potential ancillary benefits realized by oil and gas owners and operators that implement methane detection technologies. In addition to reducing environmental impact of oil and gas operations and complying with regulations, leak detection could improve operations, increase safety, and reduce waste. These benefits contribute to a long-term asset management advantages and cost savings. However, monetizing these benefits to demonstrate the business case for leak detection implementation is challenging because there is no counterfactual (i.e., no benchmark of what would have happened without implementing leak detection for comparison). There are several independent factors all influencing these outcomes, such as the price of natural gas and operator error.

a. Drivers for Emissions Measurement, Monitoring, and Mitigation

Methane emissions mitigation represents a potential revenue source for the upstream oil and natural gas industry. Potential operational efficiency improvements are dependent upon the ability of facility operators to detect emissions, attribute those emissions to specific sources or practices, and take action to reduce or eliminate leaks. Improvements in methane measurement science and technology could help identify previously unknown emission sources, provide enhanced attribution capabilities, and enable more cost-effective monitoring. This could further incentivize voluntary mitigation actions by industry.

In addition to the potential to improve operational efficiency and general additional revenue, oil and gas owners and operators may need to mitigate emissions to comply with regulations. In June 2016, the EPA issued updates to New Source Performance Standards (NSPS) to reduce methane and volatile organic compound emissions from new and modified sources in the oil and natural gas industry (EPA 2016i). These regulations identify best practices for leak detection and repair on fixed schedules. The NSPS also initiated an approval process to allow operators to use new and innovative leak detection technologies to meet the regulatory requirements. In addition to the updates to the NSPS for new and modified methane sources, the EPA also announced plans in 2016 to propose regulation for existing sources of methane emissions from the oil and natural gas sector.

A handful of states have also established regulations for the oil and natural gas sector. These often require more frequent monitoring than do Federal regulations and designate their own best practices in addition to the EPA recommendations. In 2014, Colorado became the first state to adopt rules targeting methane emissions from the oil and gas industry, followed by additional oil and gas producing States such as California and Pennsylvania. Other states, including Wyoming and Ohio, indirectly regulate oil and gas sector methane emissions by targeting reductions in volatile organic compound (VOC) emissions. VOCs are toxic gases emitted from natural gas and oil leaks, therefore reductions in VOC emissions indirectly target methane emissions as well.

b. Current Programs

One program helping to identify the business case for methane detection is the EPA Natural Gas STAR Methane Challenge Program. The Methane Challenge Program is a voluntary program that serves as a platform for companies to showcase their efforts to reduce methane emissions, improve air quality, and capture and monetize natural gas. The program enables information sharing, technology transfer, peer networking, voluntary record of reductions, and public recognition. By participating, companies reduce operational risk, increase efficiency, and demonstrate commitments to reduce methane emissions. In exchange, partner companies agree to perform methane mitigation activities in accordance with a set of allowable commitment options and must transparently report their actions to reduce methane emissions (EPA 2016g). Recently, the EPA approved an option for Industry to follow ONE Future methods and data submission as a compliance pathway in the voluntary Methane Challenge Program (EPA 2016a).

A second voluntary collaboration is Our Nation's Energy (ONE) Future Coalition. ONE Future Coalition is a group of companies across the natural gas industry focused on identifying policy and technical solutions to support emissions management. The goal of the coalition is to "demonstrate an innovative, performance-based approach to the management of methane emissions directed toward a concrete goal: to achieve an average rate of methane emissions across the entire natural gas value chain that is 1% or less of total (gross) natural gas production" (ONE Future Coalition 2016). These investments in methane abatement technologies will both reduce environmental impacts and enhance supply chain efficiency. As such, successes demonstrated by the participating companies will help demonstrate the business case for broader adoption of methane mitigation practices.

c. Research to Support the Business Case for Leak Detection and Support Regulatory Compliance

1) Repair validation: Develop means to validate repairs and estimate emissions avoided through detection and mitigation efforts

As discussed in previous sections, the business case for leak detection implementation depends on the quantity of methane recovered as a sellable product. However, there are currently no standard methods for evaluating emissions avoided through detection and mitigation efforts. Additionally, for episodic emission events that occur sporadically and without an identifiable pattern, there is no standard method for demonstrating if a repair or change in operations was successful at mitigating emissions. Measurement approaches that could verify and quantify the reduction in episodic emissions due to repairs would provide evidence for the business case of methane leak detection.

2) Emissions reporting: Streamline emissions reporting process by integrating reporting format with technology output data formats

Better integration of technology outputs and reporting formats could streamline the emissions reporting process. By coordinating the reporting format with the technology output format, workshop participants noted that the reporting process could be effectively streamlined. In addition to reducing compliance costs for owners and operators, this streamlined process would improve the quality of the reported data by eliminating manual transcription errors and other data quality concerns. This restructuring would first require coordination between Federal, state, and local regulators to establish consistent data reporting and data format requirements. Additionally, it would require collaboration between the technology development companies, industry standard setting organizations, and government oversight to harmonize the output data format.

3) **Performance based approach: Develop analytical approaches to validate performance equivalence of measurement technology options**

Existing regulations prescribe approved leak detection technologies and best practices that owners and operators can use to comply with detection requirements. While the EPA's New Source Performance Standards and some state regulations provide a pathway for new technologies to be introduced and approved for leak detection, it continues to be challenging for new technologies to be widely integrated into oil and gas methane monitoring and to break into the leak detection technology market.

To transition to a performance based regulatory approach rather than prescribing approved detection technologies, workshop participants noted that protocols would need to be developed for establishing equivalency of monitoring technologies. There are currently some efforts to begin to provide a framework for technology comparison. For example, the Interstate Technology & Regulatory Council has a team dedicated to establishing a consensus for evaluating and comparing the effectiveness of methane-detection and characterization technologies (Interstate Technology and Regulatory Council 2016). Additionally, researchers at Stanford University developed a model called Fugitive Emissions Abatement Simulation Testbed that allows users to compare the cost and environmental benefits of various methane leak detection programs by simulating leaks over time on a virtual gas field and determining the rate at which each technology would identify the leaks (Kemp, Ravikumar, and Brandt 2016). Because leak detection needs vary by operation, being able to evaluate and compare the effectiveness of monitoring technologies under different conditions is essential. In addition to supporting flexible and adaptive regulatory compliance pathways, owners and operators could use the systems and tools to ensure they are investing in the most cost-effective technology for their unique operations, thereby supporting the broader business case for monitoring implementation.

4. Additional Commercial Opportunities for Enabling Operational Methane Mitigation

Adoption of these measurement technologies by a large segment of industry requires the development of commercial technology solutions. Currently, standard operating procedures include practices that aim to detect leaks and repair and replace the leaking equipment, depending on the context and magnitude of the leak. Monitoring information supporting these operational decisions is limited. Improving owner and operator emission monitoring information and decision tools could integrate with existing operator safety and leak detection protocols, help prioritize these efforts, and increase the efficiency of existing operator leak detection and repair programs.

Workshop participants identified potential commercial tools that would aid owners and operators in planning and implementing methane emission measurement strategies. These opportunities include the development of decision support tools to automatically translate data into actionable output, the ability to distinguish between leak types, and predictive analytic capabilities to prioritize repairs and improve asset management. Improving industry engagement through public recognition of mitigation efforts, the formation of public private partnerships, and industry collaboration with academic researchers would help facilitate the commercial development of these tools.

1) **Decision support: Coordinate with industry owners and operators to develop tools to verify leaks and prioritize mitigation actions**

An important benefit of methane emissions data discussed by workshop participants is that it can inform the development of decision support tools for oil and gas owners and operators. The data could serve as a framework for predictive maintenance tools that could prioritize mitigation actions across all operations within a given site. Additionally, such tools could support asset management decisions by identifying when replacing a component would likely be a more cost-effective solution than repairing it. Using data collected from methane monitoring equipment in a way that supports industry goals of increased safety, reduced waste, and enhanced operational efficiency increases the value of integrating methane monitoring with oil and gas operations. Specific needs of operations vary by location, oil and gas properties, and age of facility. Incorporating site-specific data into operator-tailored decisions support and analytical tools would enable operators to more accurately assess the value of where and how to incorporate monitoring infrastructure in their systems.

2) **Reported emissions vs. leaks: Conduct statistical studies to identify what types of emission events are considered typical or atypical**

As methane monitoring technology continues to advance, technical measurement capabilities are enabling the detection of smaller and smaller leaks. For example, ARPA-E's MONITOR Program has a detection threshold requirement of 0.1 standard cubic feet per minute (scfm). However, in order to continue to be cost-effective and beneficial for oil and gas operators and to maintain focus on prioritizing leak repair, the detection technology would need to be supported with information to further characterize the detected emissions.

Workshop participants noted that operators must be able to distinguish between when a small emission source is indicative of a potential future component failure or when such emissions are representative of typical operating conditions and do not require additional investigation. This differentiation is especially important in the distribution segment where owners and operators have legal liability associated with detected leaks, but is also important for prioritization and planning in upstream segments. For example, in the distribution sector, every detected leak remains on file regardless of its leak classification. Therefore, a small Grade 3 leak which is non-hazardous at the time of detection and expected to remain non-hazardous in the future could remain on a potential list of repairs for several years. Data analytics and modeling could be used to help differentiate between expected and typical and atypical emission events, unintentional leaks and operational emissions, which would be important to support the business case for advanced, continuous leak detection.

3) **Predictive analytics: Use predictive analytics to identify potential mitigation opportunities and increase cost-effectiveness of leak repairs**

As previously discussed, methane detection can provide an advantage for asset management, which translates into long-term cost savings for a company. One avenue for asset management discussed by workshop participants is to use collected data from methane monitoring tools to perform predictive analytics. Predictive analytics uses techniques such as data mining, statistics, and machine learning to extract information from data in order to forecast trends and behaviors. In an operations context, predictive analytics could help prioritize component repairs, manage component replacement schedules, and improve overall efficiency of operations.

4) **Constructive industry engagement: Improve energy sector participation in measurement studies**

Maintaining a comprehensive and accurate methane emissions inventory and effectively reducing methane emissions form oil and gas operations are supported by meaningful collaboration across stakeholders, including the Federal, state, and local government, oil and gas owners and operators, academic researchers, and NGOs. Trusted relationships across this wide array of stakeholders is essential to facilitate information sharing, transparency, and cooperation to meet mutual environmental and economic goals. In particular, constructive industry engagement is key to both improving the GHGI and implementing effective emissions mitigation efforts. Opportunities for enhancing industry engagement include public recognition of mitigation efforts, formation of public-private partnerships, and facilitating collaboration between industry and academic researchers.

Public recognition of beneficial actions. Workshop participants noted that recognition of operator best practices could lead to broader adoption of measurement technology leading to mitigation actions. Best practices could be highlighted through public recognition options such as features in news articles, journal articles, and elsewhere in the media. The EPA Methane Challenge Program provides an existing platform to publicly recognize industry partner organizations and works to help partners communicate their achievements to shareholders, customers, and the public

Public-private partnerships. Public-private partnerships (PPPs) could be an influential pathway for collaboration between the Federal government and the oil and gas industry. For industry, the benefits of a PPP might include shared/reduced risk of investing in methane detection technologies, while government agencies could benefit from increased transparency of industry data and/or activities.

Facilitate collaboration between industry and academic researchers. To date, the most successful example of an organized, multi-sector, spatially diverse methane emissions measurement campaign was coordinated by EDF. In collaboration with over 125 academic researchers and industry experts, EDF conducted a series of 16 projects designed to quantify methane emissions across the natural gas supply chain. The success of this collaboration demonstrates the importance of industry access and expertise on improving fundamental understanding of emission rates and sources to enhance the GHGI and advance methane detection technology. Future research efforts should encourage forming partnerships between academic researchers and industry as a prerequisite. Furthermore, a streamlined common framework could be developed to expedite establishing confidentiality agreements and anonymizing data that would aid researchers and industry partners who wish overcome legal hurdles with participating in scientific studies.

4. Research Opportunities—Broader Methane Monitoring Opportunities

A. Introduction

Atmospheric measurements, including sustained atmospheric observations of greenhouse gas concentrations, have increasingly been used to investigate anthropogenic GHG emission patterns associated with oil and natural gas sources at continental- and regional-scales (Turner et al. 2016; Turner et al. 2015; Duren 2016; Miller et al. 2013). These research efforts provide a tangible demonstration of potential observation, detection, and quantification capabilities that could be further developed. Sustained atmospheric observations collected by NOAA through the GHG Reference Network, state agency partners such as the California Air Resources Board, and international partners provide a critical monitoring and data service that makes up the foundation for what could be developed into a multi-scaled monitoring system.

Currently, the concept of developing multiple tiers of observing capabilities to support multiple emission goals (i.e., detection, quantification, mitigation support) is explored as a research topic. Research activities include fundamental research to improve and apply atmospheric transport modeling to better understand and characterize GHG emissions, applied research to develop and validate in-situ measurement or remote sensing technologies, and technology development efforts that have the goal of developing operational capabilities that use aircraft-mounted remote sensing to detect large emission sources. The application of these research activities broadly could be applied to support multiple end-uses categories, which for the purposes of this report section are defined as: (1) detection of emission sources, (2) quantification of emissions, and (3) information supporting mitigation decisions. Current research activities support all three of these end-use goals, however, the technical challenges and associated research challenges with meeting each of these specific goals will differ.

This chapter will focus on describing three potential research pathways and applications: (1) conducting research and analysis to understand how multiple scales of GHG and methane sensing and observations could be integrated to provide capabilities to aid multiple observational goals, (2) the improvement and use of atmospheric modeling to detect and quantify methane emission rates from different sources, and (3) identifying approaches to resolve differences between top-down and bottom-up methodology results through improvements in source attribution of atmospheric in-situ measurements, remote sensing, and modeling results.

B. State of Knowledge or Practice

Platforms for atmospheric measurements can be categorized as either sub-orbital (vehicles, towers, aircraft) or orbital (satellites), and the instruments can either utilize direct sampling (in-situ) or indirect measurement (remote sensing)[6]. Sustained atmospheric measurements are largely maintained by the National Oceanic and Atmospheric Administration (NOAA) through the Global Monitoring Division of Earth System Research Laboratory (NOAA 2016b). The Global Greenhouse Gas Reference Network is an example of these programs, and consists of approximately 70 atmospheric sampling sites across the world, primarily concentrated in the United States (NOAA 2016a). These sites are a combination of tall tower in-situ measurements, aircraft measurements, and AirCore atmospheric sampling.[7] Another important measurement network is the DOE Atmospheric Radiation Measurement (ARM). The ARM program records greenhouse gas concentrations from in-situ measurements and remote observations on a long-term, continuous basis at fixed locations around the globe (Conley et al. 2016).

Other suborbital sensors and all satellites use indirect approaches to estimate methane concentrations. These methods are primarily based on IR spectroscopy, which exploits the three strong absorption bands in the IR spectrum that make up methane's spectral signature.[8] An example of a remote sensing approach is the Japanese Greenhouse Gas Observing Satellite (GOSat) project(GOSAT Project), a satellite that quantifies greenhouse gas emissions at a resolution of 10 kilometers × 10 kilometers. It uses solar backscatter-based spectroscopy, which observes infrared light reflected and emitted from the Earth's surface and atmosphere. International efforts to coordinate comprehensive global observing systems for monitoring and verification of methane emissions are currently underway through the Committee on Earth Observation Satellites (CEOS) *Strategy for Carbon Observations in Space* (COES Committee on Earth Observation Satellites (CEOS)), and the World Meteorological Organization (WMO) Integrated Global Greenhouse Gas Information System (IG3IS) (WMO World Meteorological Organization (WMO)).

The combined application of these different measurements and monitoring infrastructure remains an active area of scientific research. In general, individual source emissions estimates derived from atmospheric measurements have a higher degree of

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[6] Remote sensing techniques collect data by detecting the energy that is reflected from Earth, such as recording energy reflected by natural sunlight, thermal imagers, or measuring the time it takes for a projected laser beam to reflect back to its sensor.

[7] AirCore sampling consists of long tubing that preserves the profile of methane in the atmosphere.

[8] The two most common methods are: (1) solar backscatter in which instruments measure solar radiation backscatter by the Earth and its atmosphere (identifies short-wave infrared absorption band), and (2) thermal emissions in which instruments measure blackbody terrestrial radiation absorbed and re-emitted by the atmosphere (identifies thermal infrared).

uncertainty and error than ground measurements due to the complexity of meteorological conditions, estimated modeling parameters, and simplifying assumptions. In particular, estimating emissions can be challenging if atmospheric conditions change during a coordinated flyover program or between satellite observations. However, atmospheric measurements also have benefits over ground based measurements. Due to the continuity in measurements and wider spatial coverage, well-placed aircraft campaigns and tall tower observations can specifically target a region of interest to identify and quantify point- or area-source emitters. Satellite technologies provide global, dense, continuous coverage, but resulting data tend to be of lower spatial resolution than sub-orbital measurements, and observations taken by solar backscatter spectroscopy can be limited by clouds and can only be taken during the day when there is sunlight.

C. Research Opportunities and Recommendations

Efforts to-date to combine and advance in-situ and remote sensing approaches for emissions monitoring have primarily been focused on supporting scientific missions. The discussion in the following sub-sections highlights research recommendations that aim to advance active research fields of atmospheric science to support both scientific and operational methane monitoring and mitigation goals.

1. Optimizing Multi-Tiered Observation and Measurements to Support Multiple End-Use Goals

Broader methane monitoring goals, including developing observation and modeling capabilities to characterize large emission sources (including super-emitting sources), require multiple tiers of observations deployed in a coordinated manner. Workshop participants recommended investment to establish a study to inform the design of a multi-tiered observation campaign, which would provide further guidance for optimized observation strategies to improve multiple end-goals in emissions monitoring.

a. Ongoing research activities

Several ongoing research activities use multiple scales of atmospheric observations and in-situ measurements to investigate methane and other GHG emissions. Notable examples include efforts by the NASA Jet Propulsion Laboratory (JPL)to quantify the Aliso Canyon natural gas storage facility leak through multiple observation approaches, which included observation infrastructure from the Megacities Carbon Project (i.e., stationary remote sensing, tower in-situ measurements, aircraft-mounted spectrometer, satellite observations), research studies such as Atmospheric Carbon and Transport–America (ACT-America) that aim to improve atmospheric inversion systems through the combined and coordinated deployment of multiple scales of observations, and city- and region-based studies such as the Indianapolis Flux Experiment and the National Institute of Standards and Technology (NIST) Urban Test Bed projects where multiple measurement and modeling approaches are deployed simultaneously to examine and improve GHG measurement strategies and modeling efforts in urban locations (NASA 2015; JPL 2015; NASA 2016; Thompson et al. 2016; NIST 2016).

In addition to integrated observational studies, there is ongoing technology R&D in sensor technology deployment, remote sensing advancements, improved modeling capabilities, and integrated monitoring systems. Scientific advances are leading to new sensor technology which could be deployed on a range of platforms (hand-held devices, towers, aircraft, unmanned aerial vehicles, and satellites) to monitor at various temporal scales (intermittent, frequent, or continuous) across different points in the oil and gas supply chain. Furthermore, these observational studies are being implemented at different spatial scales (component-scale, site-level, area-level, or continental-scale resolution) at differing detection thresholds to help characterize methane emission sources.

b. Research recommendations: designing a research study to translate research activities to operational capabilities for multiple end-uses

The research activities discussed in the previous subsection and the operational research activities discussed in section 4.B. present a set of discrete activities that are not optimally designed to meet specific user-needs in an operational context. Multiple research activities aim to advance scientific knowledge on how these methods could be applied, often in specific locations for limited durations. However, they have not been examined in an integrated manner to understand how different methane sensing and modeling techniques could be optimized for multiple end-use goals. In summary, there is currently no observation approach that would meet all end-use goals.

Workshop participants discussed the value of developing a research study that could inform the development of a multi-tiered observation strategy. This research would enable the scientific community and private sector to understand how existing and future observation capabilities could be optimized to meet a variety of stakeholder end-use goals. Considerations for the design of a study include:

- **Defining the end-use goals**. Optimal design of a multi-tiered observation strategy requires participant researchers and operators to identify the end-uses that observations and modeling results would inform. These end-use requirements would identify the spatial resolution, sampling frequency, and acceptable levels of uncertainty associated with an observation strategy. Three potential end-use goals are:
  - Leak Detection End-Use Goal: Technical requirements associated with this goal include specifying the distribution of sources of emissions, their expected spatial and temporal distribution, the range of the magnitude of

emissions, and understanding the underlying root cause of the emission (e.g., malfunction, maintenance). Capabilities to attribute the emission to certain sources, within acceptable levels of uncertainty, are needed.

  - Leak Quantification End-Use Goal: This end-use goal requires reduced uncertainty in attributing the observed emission to a certain source or set of sources. Atmospheric transport and inversion modeling considerations will be included in the design of a study that aims to quantify methane emission flux.
  - Mitigation Support End-Use Goal: This end-use goal follows on from the leak detection end-use goal, and takes into consideration the level of uncertainty in terms of spatial and temporal resolution, temporal resolution/frequency, and attribution needed by a set of operators. Considerations such as how the output data would be integrated with existing oil and gas asset management systems and decision-support tools to prioritize leak repair activities would be factored into this observation strategy.
- Establish study design principles: Rather than establish a set of requirements for this study, a set of concepts should be considered for adoption as underlying principles or considerations for any end-use goal(s).
  - Ensure the duration of the study is sufficient to understand measurement challenges associated the intended end-use observation strategy.
  - Coordinate across multiple investigators and researchers conducting research on their respective set of observations. All tiers of observations should identify how the output from one tier of observations could augment another tier, or how modeling improvements could aid the deployment and design of observations.
  - Establish the types of emission sources that would be examined, and their known characteristics. Emission sources may vary in terms of the type of equipment, type of leak (i.e., malfunction, maintenance, routine operational venting), and operational context of the leak (i.e., continuous operational emission, unplanned emission event, intermittent). Study design should examine whether sources that are considered to be super-emitters are to be included, and if so, a common definition of super-emitters should be employed across the study or studies.
  - Common agreements for data sharing should be incorporated across the study. This includes data on known source types within the region of study

and their emission characteristics, and meteorological data which is important for modeling efforts.

- Establish common research objectives and outcomes: A study of multi-tiered observations will have multiple stakeholder goals, and the outcomes or output from the study would be equally diverse. The results from this type of study could form the basis for measurement and data-driven prioritization of operator leak detection and repair activities. Common principles for the output of the study include:
  - Ensuring observation data is available for sharing across study participants and outside of the study group. Technology developers, scientists, oil and gas producers, and non-profit organizations would be interested in the technical results of the study, and efforts should be taken to ensure the results and outcomes are shared across interested groups.
  - Development of potential analytical tools and analytical outcomes should be considered in the development of the study. The study should result in improved understanding of how to optimize multiple tiers of observations for specified end-use goals, but also should inform the design or development of analytical results that could be used to meet those end-use goals in other locations or for other sources.

A potentially important analytical data service discussed by workshop participants was the concept of a publicly available data stream of emission sources at multiple spatial scales. The concept was considered a *methane weather map*, where a collaboration of organizations or government agencies provides a public service where emissions magnitude, location, and their spatial distribution is published periodically. This data service could foster a common understanding of emissions activity across stakeholders, and provide a basis for planning future research and mitigation efforts.

Efforts to ensure the design of such a multi-tiered study could meet multiple interested stakeholder considerations for methane detection, quantification, and mitigation goals would increase the utility of future multi-tiered observation systems. The cooperative efforts required to convene the stakeholders necessary to design this type of study could also foster continued coordination across research and operational stakeholders, and ensure that public R&D investments have broad appeal across a large set of scientific, non-governmental, and private sector interests.

2. Improving Atmospheric Modeling to Quantify Methane Emissions and Communicating Modeling Limitations

Research that aims to quantify the emission flux from a set of sources using atmospheric measurements or indirect measurements from remote sensing faces challenges when attempting to employ the limited set of methods, emissions, and meteorology data currently available. Once data on atmospheric methane concentrations are obtained through either direct or indirect methods, emission fluxes are estimated using modeling methods that are appropriate for the spatial scales being examined. Inversion systems, using atmospheric transport models, are applicable across multiple spatial scales from regional to global scales. However, for smaller spatial scales that aim to provide information associated with a specific process, site, or set of sites of emission sources, inverse models tuned with site-specific tracer release and meteorology data provide a different approach to estimate emissions flux (Vogel 2016). All estimation methods rely upon user input, such as prior observations, wind speed, and other meteorological parameters, and incorporate it with atmospheric chemistry models to estimate the origin of the emission source.

a. Ongoing research activities

A broad array of Federal agencies support scientific research that aim to use atmospheric modeling to study GHG emissions from various sources, including oil and gas systems. These efforts include NASA's efforts to develop light detection and ranging (lidar) technology-based approaches to measure aerosols and GHGs from aircraft, NIST's urban test bed projects, and NOAA's multiple projects, such as Shale Oil and Natural Gas Nexus (SONGNEX) 2015 and Twin Otter Projects Defining Oil/Gas Well Emissions (referred to as TOPDOWN) 2015, that aim to employ airborne methods and atmospheric models to estimate emissions flux from oil and gas sources (Clavin and Ressler 2016). There is currently limited Federal research activity aiming to improve atmospheric transport and dispersion models for the purposes of estimating methane emissions.

b. Research recommendations

Potential roles for increased focus on research that would advance the application of atmospheric modeling, with a focus on applying inversion modeling approaches for validating bottom-up emissions, were explored. Workshop participants' input helped identify the following potential areas for additional research:

- Improve understanding of model limitations: Research studies that compare multiple methodologies in an attempt to validate the results of two different approaches (e.g., comparing top-down and bottom-up results) are currently conducted on a spatially-limited and ad hoc basis. Studies are performed where data exist or where researchers are capable of acquiring sufficient funding to collect new data for a limited duration. This practice of conducting model comparison in a limited data environment has not led to a well-structured examination of modeling results, and has hindered the communication of the strengths and shortcomings in modeling approaches.

Workshop participants described how future research could aim to employ a standardized set of modeling efforts, over a duration sufficient to explore multiple emission flux quantification challenges with a variety of meteorological and emission sources. Coordinated model intercomparison research that characterizes underlying causes of difference between modeling results and observations data could provide the basis for planning where modeling can be appropriately applied to energy sector emission sources, and the basis to plan modeling improvements.

- Advance modeling capabilities to augment studies where data collection or observations are difficult: Modeling advances could supplement where emission reporting is not required, or where poor meteorological conditions are present. Fundamental research efforts that improve atmospheric transport and dispersion modeling options across multiple scales is an area of on-going research opportunities. Efforts could include exploring approaches to incorporate nighttime data into atmospheric transport models, research to improve fundamental understanding or simulation of boundary layer dynamics, and continued research into how to more fully account for experimental conditions in models.

  Atmospheric modeling, in particular inversion systems that rely upon atmospheric transport models, provide a promising approach to expand the tool set available to operators and policymakers who are interested in verifying other methodological emission estimates and connecting site- and regional-scale emissions estimates to the continental or global scale context. Outstanding research remains to improve models, and communicate the limitations associated with the model, input data, and modeling results to appropriately compare between different emission estimation methodologies.

3. Improving Source Attribution of Modeling Results

A final step in using atmospheric models is to determine whether the quantified emissions originated from fossil or biogenic sources and to distinguish between different segments or sectors using source attribution techniques. There are three primary means of source attribution. If it is known that the measurements are being taken from a region, and time period dominated by a single emissions source, attribution can be done by subtracting estimated bottom up inventories of other sources from the total. For more complex scenarios, emissions can be attributed to fossil or biogenic sources using either a molecular tracer or isotopic footprints. A molecular tracer is a molecule that accompanies methane emissions from a given source. For example, ethane can be used as a tracer for oil and gas operations, such that the ratio of methane to ethane in the emissions flux suggests a fossil-based emissions source. Isotopic footprints are the relative abundance of deuterium and

^{13}C in the emissions flux, which vary by methane source. Chemical mass balance (CMB) methods can also be used in conjunction with bottom up inventories, molecular tracers, and isotope ratios to further attribute the quantified methane emissions to distinct sectors.

a. Ongoing Research Activities

The application of source attribution methods is well-demonstrated in recent studies using aircraft- or vehicle-based atmospheric measurements for methane emission flux estimation at a site- or area-scale (Smith et al. 2015; Karion et al. 2015; Petron et al. 2012; Petron et al. 2014; Peischl et al. 2015). At a global scale, isotopic measurements have been demonstrated as being useful in estimating trends and changes in relative contribution of different sources of emissions to the global methane budget (Schwietzke et al. 2016). Focused Federal research efforts to improve attribution methodologies for site- to global-scales includes NOAA ESRL's CarbonTracker methane project, NOAA's TOPDOWN and SONGNEXT studies, individual projects under NASA's Carbon Monitoring System, and individual research projects funded by the National Science Foundation examining GHG emissions from a variety of source types.

b. Research Recommendations

Source attribution remains a topic of fundamental research; however, for energy sector and oil and gas source emission quantification studies, the choice of which method to use for source attribution is often related to the method that is most cost-effective. Use of hydrocarbon ratios in observations often provide the most cost-effective approach for source attribution in limited duration site-scale studies; however, isotopic measurements have been demonstrated to be useful over longer timescales and over larger spatial scales. For energy sector sources, attribution is needed to disaggregate emissions signals associated with energy and non-energy sector sources, emissions originating from natural and anthropogenic sources, and within the energy sector, separating coal, oil, and gas sources.

Approaches to improve source attribution discussed within the workshop include the coordination of top-down and bottom-up methods to aid source attribution and consistent application and reporting of source attribution methods across studies. Coordination of component- or site-scale studies that are using bottom-up methodologies to statistically sample known emissions sources within a specified site or region could provide needed emissions profile data to support attribution of atmospheric measurements. Coordinated studies could aim to collect samples at similar time periods and from both known emission sources and potentially confounding sources (i.e., landfills, urban centers). Across these studies, consistently applying and reporting results from the use of common attribution approaches (i.e., tracer releases, hydrocarbon ratios, isotopic measurements) would increase the ability to compare source attribution methods across studies and examine the performance of each method.

5. Future Considerations

Mitigating methane emissions from energy systems, particularly from oil and natural gas sources, remains a persistent environmental and economic opportunity. Scientific consensus remains elusive regarding overall global methane trends and contributions of oil and gas emissions toward global methane concentration; however, recent progress in measurement technology and data analysis capabilities has enabled measurement science to help identify cost-effective mitigation opportunities and address known data needs. (Schwietzke et al. 2016; Nisbet et al. 2016) Lower-cost sensor development has enabled cost-effective leak detection at site and regional scales. To date, these applications have been primarily for scientific purposes; however, recent activity within the private sector suggests the emergence of new commercial options to employ integrated measurement and monitoring technology solutions that can lead to more cost-effective and efficient mitigation operations.

Measurement science and technology to support identification and mitigation of oil and natural gas system methane emissions continues to have scientific and industry interest given the projections that U.S. production is likely to increase in the coming decades. (EIA 2016) Advances in measurement and monitoring technology from the oil and gas sector present opportunities to apply these lessons to other emission sources. According to the GHGI, emissions from coal mining and abandoned underground coal mines collectively represent the fourth largest anthropogenic methane emission sources nationally (EPA 2016d). Ensuring that measurement technologies and strategies developed for oil and gas sources have applicability to coal emission sources and the broader energy sector could enable new mitigation opportunities that were either previously unknown or not cost-effective without the application of integrated monitoring systems.

Successful implementation of nearly all of the research recommendations within this report depend upon coordination across multiple scientific fields, stakeholder groups, industry partners, and governmental organizations. Efforts to improve data sharing, standards, and communication of scientific results among all those involved (academic researchers; non-governmental organizations; governmental researchers and program managers; and private sector owners, operators, and measurement technology developers) are critical to ensuring these measurement technologies yield tangible benefits. Successful translation of research findings to operational capabilities rely upon a robust series of efforts where multiple stakeholders are jointly working to ensure that scientific research findings inform future energy sector mitigation strategies.

Appendix A.
Summary of Research Needs and Recommendations

DOE Policy Topic	Research Opportunity Areas	Research Suggestions Communicated by Workshop Participants
Supporting the U.S. Greenhouse Gas Inventory (GHGI)	Improve emissions estimates for components known to be under- or overestimated by the GHGI	Improve emission factor and activity data for the following sources: • Gathering pipelines & Booster facilities • Condensate storage tanks • Underground vaults and meters • Associated gas well emissions • Non-Greenhouse Gas Reporting Program facility emissions • Super-emitter sources
	Characterize methane sources currently absent from the GHGI	Develop emission factor assumptions and collect activity data for the following sources: • Abandoned wells • Beyond the meter emissions
	Improving GHGI Processes	Improve GHGI processes, communication and information products, associated with the following topics: • Uncertainty reporting • Enhancing usability, accessibility of GHGI data and reports • Streamline annual release of spatially resolved GHGI • Establish and communicate a common process for obtaining and using research data for the GHGI

DOE Policy Topic	Research Opportunity Areas	Research Suggestions Communicated by Workshop Participants
Enabling Methane Emissions Abatement	Improve technologies to support cost-effective methane leak detection	Improve measurement technology to include the following: • Autonomous detection • Continuous monitoring • Super-emitter detection • Simultaneous detection and measurement • Reliability and resilience
	Translating Technologies from R&D to Operations	Improve tiered observing systems to enable timely detection of methane leaks Integrate detection with asset management systems
	Support the business case for leak detection and regulatory compliance	Develop a system to validate leak repairs and estimate emissions avoided Streamline emissions reporting to reduce costs of compliance Develop a method to systematically validate technology performance equivalency
	Develop data analysis, modeling, or other analytical methods to inform effective leak detection	Develop support tools that can inform decisions about leak repair and augment industry standard operating practices Distinguish between typical emissions versus leaks Develop predictive analytics to identify potential mitigation opportunities and increase cost-effectiveness of leak repairs
	Promote constructive industry engagement	Expand public recognition programs and opportunities Develop public-private partnerships Encourage industry collaboration with academic researchers and set up framework for confidentiality agreements

DOE Policy Topic	Research Opportunity Areas	Research Suggestions Communicated by Workshop Participants
Broader Methane Monitoring Opportunities	Design a multi-scaled measurement study that identifies potential capabilities supported by integration of multiple tiers and scales of measurement technologies	Research study design should take into consideration: • Defined end-use goals – leak detection, leak quantification (flux measurement), and mitigation decision support • Study design considerations: duration of measurements; diversity of emission sources, meteorological conditions; coordination across investigators • Coordination of outcomes: implement data sharing agreements, stakeholder end-uses and analytical requirements considered in study design, consideration of research to operations pathway for emissions data distribution
	Improving atmospheric modeling to quantify methane emissions and communicating modeling limitations	Improve communication of model limitations within scientific community Employ standard set of modeling efforts to understand root cause for differences between modeled and observed results Improve atmospheric transport and dispersion modeling results where observations are difficult or prohibitive to collect
	Improve source attribution for top-down studies and remote measurements	Coordinate component-, site-scale studies with atmospheric measurement campaigns to improve attribution methodologies (e.g., tracer releases, hydrocarbon ratios, isotopic measurements)

References

Advanced Research Projects Agency–Energy (ARPA-E). 2015. *MONITOR (Methane Observation Networks with Innovative Technology to Obtain Reductions).* Available from http://arpa-e.energy.gov/?q=arpa-e-programs/monitor.

Allen, D. T., V. M. Torres, J. Thomas, D. W. Sullivan, M. Harrison, A. Hendler, S. C. Herndon, C. E. Kolb, M. P. Fraser, A. D. Hill, B. K. Lamb, J. Miskimins, R. F. Sawyer, and J. H. Seinfeld. 2013. "Measurements of Methane Emissions at Natural Gas Production Sites in the United States." *Proceedings of the National Academy of Sciences* 110 (44):17768–17773. doi: 10.1073/pnas.1304880110.

Armendariz, A. 2009. Emissions from Natural Gas Production in the Barnett Shale Area and Opportunities for Cost-Effective Improvements. Austin, Texas: Environmental Defense Fund.

ARPA-E. 2015. *MONITOR (MethanFe Observation Networks with Innovative Technology to Obtain Reductions).* Available from http://arpa-e.energy.gov/?q=arpa-e-programs/monitor.

Boothroyd, I. M., S. Almond, S. M. Qassim, F. Worrall, and R. J. Davies. 2015. "Fugitive Emissions of Methane from Abandoned, Decommissioned Oil and Gas Wells." *Science of the Total Environment* 547:461–469. http://www.sciencedirect.com/science/article/pii/S0048969715312535.

Brandt, A. R., G. Heath, E. A. Kort, F. O'Sullivan, G. Petron, S. Jordaan, P. Tans, J. Wilcox, A. Gopstein, D. Arent, S. C. Wofsy, N. Brown, R. Bradley, G. D. Stucky, D. Eardley, A. Patrinos, and R. Harriss. 2014. "Methane Leakage from North American Natural Gas Systems: Sources, Uncertainties, and Policy Implications " *Science* 343 (6172):733–735. doi: 10.1126/science.1247045.

Brandt, A. R., G. A. Heath, and D. Cooley. 2016. "Methane Leaks from Natural Gas Systems Follow Extreme Distributions." *Environmental Science & Technology* 50 (22):12512–12520. doi: 10.1021/acs.est.6b04303.

Brantley, H. L., E. D. Thoma, and A. P. Eisele. 2015. "Assessment of Volatile Organic Compound and Hazardous Air Pollutant Emissions from Oil and Natural Gas Well Pads Using Mobile Remote and on-Site Direct Measurements." *Journal of the Air & Waste Management Association* 65 (9):1072–1082. doi: 10.1080/10962247.2015.1056888.

Brantley, H. L., E. D. Thoma, W. C. Squier, B. B. Guven, and D. Lyon. 2014. "Assessment of Methane Emissions from Oil and Gas Production Pads Using Mobile Measurements." *Environmental Science & Technology* 48 (24):14508–14515. http://pubs.acs.org/doi/full/10.1021/es503070q.

Chambers, A., M. Strosher, T. Wootton, J. Moncrieff, and P. McCready. 2006. "Dial Measurements of Fugitive Emissions from Natural Gas Plants and the Comparison with Emission Factor Estimates."

Clavin, C., and A. Ressler. 2016. *Review of Federal and Non-Governmental Methane Measurement and Monitoring*. Alexandria, VA: IDA. Document D-8029. https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2016/D-8029.ashx.

Committee on Earth Observation Satellites (CEOS). 2014. *CEOS Strategy for Carbon Observations from Space. The Committee on Earth Observations Satellites (CEOS) Response to the Group on Earth Observations (GEO) Carbon Strategy*. Japan: JAXA and I&A Corporation.

Conley, S., G. Franco, I. Faloona, D. R. Blake, J. Peischl, and T. B. Ryerson. 2016. "Methane Emissions from the 2015 Aliso Canyon Blowout in Los Angeles, CA." *Science*. doi: 10.1126/science.aaf2348.

Department of Energy (DOE). 2016. *DOE Announces $13 Million to Quantify and Mitigate Methane Emissions from Natural Gas Infrastructure*. Washington, DC: DOE.

Duren, R. 2016. California Methane Monitoring for Climate Action and Public Safety.

Duren, R. M., A. K. Thorpe, R. O. Green, C. Frankenberg, D. R. Thompson, A. D. Aubrey, C. E. Miller, K. R. Gurney, L. Guanter, H. Bovensman, K. Gerilowski, I. Aben, A. Butz, C. Sweeney, and E. A. Kort. 2016. *Understanding Anthropogenic Methane and Carbon Dioxide Point Source Emissions*.

Energy Information Administration (EIA). 2015a. *Number of Natural Gas Consumers–Commercial*. Available from http://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN5_Count_a.htm.

———. 2015b. *Number of Natural Gas Consumers–Industrial*. Available from http://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN7_Count_a.htm.

———. 2015c. *Number of Natural Gas Consumers–Residential*. Available from http://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN3_Count_a.htm.

———. 2016. *Annual Energy Outlook 2016*. Washington, DC: EIA.

Environmental Defense Fund (EDF). 2016. *Methane Detectors Challenge*. Available from https://www.edf.org/energy/natural-gas-policy/methane-detectors-challenge.

Environmental Protection Agency (EPA). 2015. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013*.

———. 2016a. EPA Announces First One Future Commitments under Methane Challenge Program.

———. EPA 2016b. *Gridded 2012 Methane Emissions*. Available from https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions.

———. 2016c. *Information Collection Request Supporting Statement: Information Collection Effort for Oil and Gas Facilities,*. Washington, D.C.: EPA.

———. 2016d. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014*. Washington, D.C.: EPA.

———. 2016e. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: Revisions to Natural Gas Distribution Emissions*. Washington, DC: EPA. https://www.epa.gov/sites/production/files/2016-08/documents/final_revision_ng_distribution_emissions_2016-04-14.pdf.

———. 2016f. Inventory of U.S. Greenhouse Gas Emissions and Sinks: Revisions under Consideration for Natural Gas and Petroleum Production Emissions. Washington, DC: EPA. https://www.epa.gov/sites/production/files/2017-01/documents/2017_ghgi_ngpetro_revunderconsid-production_and_gb_1.10.17.pdf.

———. 2016g. *Natural Gas STAR Program*. Available from https://www.epa.gov/natural-gas-star-program/natural-gas-star-program.

———. 2016h. *Natural Gas STAR Program: Recommended Technologies to Reduce Methane Emissions*. Available from https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions.

———. 2016i. "Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources." Proposed rule in *Federal Register* 40 (107): 35824–35941.

Gidney, B., and S. Pena. 2009. Upstream Oil and Gas Storage Tank Project Flash Emissions Models Evaluation. Texas Commission on Environmental Quality.

GOSAT Project. 2016. *GOSAT Project*. National Institute for Environmental Studies. Available from http://www.gosat.nies.go.jp/en/.

Hammack, R. W., and G. Veloski. 2016. Methods for Finding Legacy Wells in Residential and Commercial Areas. Pittsburg, PA: U.S. Department of Energy, National Energy Technology Laboratory.

Harriss, R., R. A. Alvarez, D. Lyon, D. Zavala-Araiza, D. Nelson, and S. P. Hamburg. 2015. "Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas." *Environmental Science & Technology* 49 (13):7524–7526. doi: 10.1021/acs.est.5b02305.

Hendler, A., J. Nunn, and J. Lundeen. 2009. Voc Emissions from Oil and Condensate Storage Tanks. The Woodlands, TX: Texas Environmental Research Consortium.

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Hayama, Japan: Institute for Global Environmental Strategies. http://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Interstate Technology and Regulatory Council. 2016. *Evaluation of Innovative Methane Detection Technologies*. Available from http://www.itrcweb.org/Team/Public?teamID=77.

Jet Propulsion Laboratory (JPL). 2015. *Megacities Carbon Project*. Available from https://megacities.jpl.nasa.gov/portal/pages/about.

Kang, M., S. Christian, M. A. Celia, D. L. Mauzerall, M. Bill, A. Miller, B. Y. Chen, M. Conrad, T. Darrah, and R. B. Jackson. 2016. "Identification and Characterization of High Methane-Emitting Abandoned Oil and Gas Wells." *Proc. Natl. Acad. Sci. U. S. A.* 113 (48):13636–13641. http://www.pnas.org/content/113/48/13636.full.

Karion, A., C. Sweeney, E. A. Kort, P. B. Shepson, A. Brewer, M. Cambaliza, S. A. Conley, K. Davis, A. Deng, M. Hardesty, S. C. Herndon, T. Lauvaux, T. Lavoie, D. Lyon, T. Newberger, G. Pétron, C. Rella, M. Smith, S. Wolter, T. I. Yacovitch, and P. Tans. 2015. "Aircraft-Based Estimate of Total Methane Emissions from the Barnett Shale Region." *Environmental Science & Technology* 49 (13):8124–8131. doi: 10.1021/acs.est.5b00217.

Kemp, C., A. Ravikumar, and A. R. Brandt. 2016. "Comparing Natural Gas Leakage Detection Technologies Using an Open-Source "Virtual Gas Field" Simulator." *Environmental Science & Technology* 50 (8):4546–4553. doi: DOI: 10.1021/acs.est.5b06068.

Lamb, B. K., S. L. Edburg, T. W. Ferrara, T. Howard, M. R. Harrison, C. E. Kolb, A. Townsend-Small, W. Dyck, A. Possolo, and J. R. Whetstone. 2015. "Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States." *Environmental Science & Technology* 49:5161–5169. doi: 10.1021/es505116p.

Maasakkers, J. D., D. J. Jacob, M. P. Sulprizio, A. J. Turner, M. Weitz, T. Wirth, C. Hight, M. DeFigueiredo, M. Desai, R. Schmeltz, L. Hockstad, A. A. Bloom, K. W. Bowman, S. Jeong, and M. L. Fischer. 2016. "Gridded National Inventory of U.S. Methane Emissions." *Environmental Science & Technology*. doi: 10.1021/acs.est.6b02878.

Marchese, A. J., T. L. Vaughn, D. Zimmerle, M. D. M., L. L. Williams, A. L. Robinson, A. L. Mitchell, R. Subramanian, D. S. Tkacik, J. R. Roscioli, and S. C. Herndon. 2015. "Methane Emissions from United States Natural Gas Gathering and Processing." *Environmental Science & Technology* 49 (17):10718–10727. http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02275.

Miller, A. 2015. *Methane Emissions from Abandoned Oil and Gas Wells: New Measurements and Analysis of Temporal Variations and Land Cover*, Civil and Environmental Engineering, Princeton University.

Miller, S. M., S. C. Wofsy, A. M. Michalak, E. A. Kort, A. E. Andrews, S. C. Biraud, E. J. Dlugokencky, M. L. Fischer, G. Janssens-Maenhout, B. R. Miller, S. A. Montzka, and C. Sweeney. 2013. "Evidence for a Large Fossil Fuel Methane Source over the South-Central US." *Proceedings of the National Academy of Sciences of the United States of America* (Submitted).

Modrak, M., M. Shahrooz, J. Ibanez, C. Lehmann, B. Harris, D. Ranum, E. D. Thoma, and W. C. Squier. 2012. Understanding Direct Emission Measurement Approaches for Upstream Oil and Gas Production Operations. U.S. Environmental Protection Agency.

National Aeronautics and Space Administration (NASA). 2016. *ACT-America*. Available from https://act-america.larc.nasa.gov/science.html.

National Institute of Standards and Technology (NIST). 2016.*Urban Test Bed Measurements*. Available from https://www.nist.gov/topics/greenhouse-gases/urban-test-beds.

National Oceanic and Atmospheric Administration (NOAA). 2016a. *Global Greenhouse Gas Reference Network*. Available from http://www.esrl.noaa.gov/gmd/ccgg/index.html.

———. 2016b. *Global Monitoring Division*. Available from http://www.esrl.noaa.gov/gmd/.

Nisbet, E. G., E. J. Dlugokencky, M. R. Manning, D. Lowry, R. E. Fisher, J. L. France, S. E. Michel, J. B. Miller, J. W. C. White, B. Vaughn, P. Bousquet, J. A. Pyle, N. J. Warwick, M. Cain, R. Brownlow, G. Zazzeri, M. Lanoisellé, A. C. Manning, E. Gloor, D. E. J. Worthy, E. G. Brunke, C. Labuschagne, E. W. Wolff, and A. L. Ganesan. 2016. "Rising Atmospheric Methane: 2007–2014 Growth and Isotopic Shift." *Global Biogeochemical Cycles* 30 (9):1356–1370. doi: 10.1002/2016GB005406.

ONE Future Coalition.2016. *FAQs*. ONE Future Coalition. Available from http://www.onefuture.us/faqs/.

Peischl, J., T. B. Ryerson, K. C. Aikin, J. A. de Gouw, J. B. Gilman, J. S. Holloway, B. M. Lerner, R. Nadkarni, J. A. Neuman, J. B. Nowak, M. Trainer, C. Warneke, and D. D. Parrish. 2015. "Quantifying Atmospheric Methane Emissions from the Haynesville, Fayetteville, and Northeastern Marcellus Shale Gas Production Regions." *Journal of Geophysical Research: Atmospheres* 120 (5):2119–2139. doi: 10.1002/2014JD022697.

Pennsylvania State University. 2015. *Indianapolis Flux Experiment (INFLUX).* Available from http://sites.psu.edu/influx/.

Petron, G., G. Frost, B. R. Miller, A. I. Hirsch, S. A. Montzka, A. Karion, M. Trainer, C. Sweeney, A. E. Andrews, L. Miller, J. Kofler, A. Bar-Ilan, E. J. Dlugokencky, L. Patrick, C. T. Moore, T. B. Ryerson, C. Siso, W. Kolodzey, P. M. Lang, T. Conway, P. Novelli, K. Masarie, B. Hall, D. Guenther, D. Kitzis, J. Miller, D. Welsh, D. Wolfe, W. Neff, and P. Tans. 2012. "Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study." *Journal of Geophysical Research-Atmospheres* 117. doi: 10.1029/2011jd016360.

Petron, G., A. Karion, C. Sweeney, B. R. Miller, S. A. Montzka, G. Frost, M. Trainer, P. Tans, A. Andrews, J. Kofler, D. Helmig, D. Guenther, E. Dlugokencky, P. Lang, T. Newberger, S. Wolter, B. Hall, P. Novelli, A. Brewer, S. Conley, M. Hardesty, R. Banta, A. White, D. Noone, D. Wolfe, and R. Schnell. 2014. "A New Look at Methane and Non-Methane Hydrocarbon Emissions from Oil and Natural Gas Operations in the Colorado Denver-Julesburg Basin." *Journal of Geophysical Research: Atmospheres*:2013JD021272. doi: 10.1002/2013JD021272.

Public Law 114–190. 2016. Title 2, Subtitle B—UAS Safety (FAA Extension, Safety, and Security Act of 2016).

Ravikumar, A. P., J. Wang, and A. R. Brandt. 2016. “Are Optical Gas Imaging Technologies Effective for Methane Leak Detection?” *Environmental Science & Technology*. doi: 10.1021/acs.est.6b03906.

Schwietzke, S., O. A. Sherwood, L. M. P. Bruhwiler, J. B. Miller, G. Etiope, E. J. Dlugokencky, S. E. Michel, V. A. Arling, B. H. Vaughn, J. W. C. White, and P. P. Tans. 2016. “Upward Revision of Global Fossil Fuel Methane Emissions Based on Isotope Database.” *Nature* 538 (7623):88–91. doi: 10.1038/nature19797.

Shepson Atmospheric Chemistry Group. 2016. *Indianapolis Flux Experiment*. Purdue University. Available from https://www.science.purdue.edu/shepson/research/BiosphereAtmosphereInteractions/influx.html.

Smith, M. L., E. A. Kort, A. Karion, C. Sweeney, S. C. Herndon, and T. I. Yacovitch. 2015. “Airborne Ethane Observations in the Barnett Shale: Quantification of Ethane Flux and Attribution of Methane Emissions.” *Environmental Science & Technology* 49 (13):8158–8166. doi: 10.1021/acs.est.5b00219.

Thompson, D. R., A. K. Thorpe, C. Frankenberg, R. O. Green, R. Duren, L. Guanter, A. Hollstein, E. Middleton, L. Ong, and S. Ungar. 2016. “Space-Based Remote Imaging Spectroscopy of the Aliso Canyon Ch4 Superemitter.” *Geophysical Research Letters* 43 (12):2016GL069079. doi: 10.1002/2016GL069079.

Title 40 CFR. 2010. Part 98, Subpart W - Petroleum and Natural Gas Systems.

Townsend-Small, A., T. W. Ferrara, D. Lyon, A. Fries, and B. K. Lamb. 2016. “Emissions of Coalbed and Natural Gas Methane from Abandoned Oil and Gas Wells in the United States.” *AGU Geophysical Research Letters* 43:2283–2290. http://onlinelibrary.wiley.com/doi/10.1002/2015GL067623/pdf.

Turner, A. J., D. J. Jacob, J. Benmergui, S. C. Wofsy, J. D. Maasakkers, A. Butz, O. Hasekamp, and S. C. Biraud. 2016. “A Large Increase in U.S. Methane Emissions over the Past Decade Inferred from Satellite Data and Surface Observations.” *Geophysical Research Letters* 43 (5):2218–2224. doi: 10.1002/2016GL067987.

Turner, A. J., D. J. Jacob, K. J. Wecht, J. D. Maasakkers, A. E. A. E. Lundgren, H. B. S. C. Biraud, K. W. Bowman, N. M. Deutscher, M. K. Dubey, D. W. T. Griffith, A. K. F. Hase, J. Notholt, H. Ohyama, R. Parker, V. H. Payne, R. Sussmann, C. Sweeney, V. A. Velazco, T. Warneke, P. O. Wennberg, and D. Wunch. 2015. “Estimating Global and North American Methane Emissions with High Spatial Resolution Using GOSAT Satellite Data.” *Atmospheric Chemistry and Physics* 15:7049–7069. doi: 10.5194/acp-15-7049-2015.

Vogel, F. 2016. Towards a Global Science on Natural Gas Leakage, "10 Largest Research Gaps". Paper read at Stanford University Natural Gas Initiative Workshop on "Natural gas leakage: Moving the science forward", at Stanford, CA.

White House. 2014. Climate Action Plan, Strategy to Reduce Methane Emissions. Washington, DC: The White House.

Williamson, H. J., M. B. Hall, and M. R. Harrison. 1996. *Methane Emissions from the Natural Gas Industry, Volume 4: Statistical Methodology*. Research Triangle Park, NC: Gas Research Institute (GRI)/Environmental Protection Agency (EPA). https://www.epa.gov/sites/production/files/2016-08/documents/4_statisticameth.pdf.

World Meteorological Organization (WMO). 2015. *Implementing and Integrated, Global Greenhouse Gas Information System (IG3IS)*. https://www.wmo.int/pages/prog/arep/gaw/ghg/documents/GHGIGIS2015.pdf.

Zavala-Araiza, D., D. Lyon, R. A. Alvarez, V. Palacios, R. Harriss, X. Lan, R. Talbot, and S. P. Hamburg. 2015. "Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites." *Environmental Science & Technology* 49 (13):8167–8174. doi: 10.1021/acs.est.5b00133.

Abbreviations

ACT-America	Atmospheric Carbon and Transport–America
ARM	Atmospheric Radiation Measurement
ARPA-E	Advanced Research Projects Agency–Energy
CEOS	Committee on Earth Observation Satellites
CFR	Code of Federal Regulation
CH_4	methane
CO_2	carbon dioxide
DOE	Department of Energy
EDF	Environmental Defense Fund
EDGAR	Emissions Database for Global Atmospheric Research
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
GEO	Group on Earth Observation
GHG	greenhouse gas
GHGI	Greenhouse Gas Inventory
GHGRP	Greenhouse Gas Reporting Program
GWP	global warming potential
IDA	Institute for Defense Analyses
IG3IS	Integrated Global Greenhouse Gas Information System
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
JPL	Jet Propulsion Laboratory
MDC	Methane Detectors Challenge
MONITOR	Methane Observation Networks with Innovative Technology to Obtain Reductions
NASA	National Aeronautics and Space Administration
NIST	National Institute for Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
OGI	optical gas imaging
ONE	Our Nation's Energy
R&D	research and development
RDD&D	research, development, demonstration, and deployment
STPI	Science and Technology Policy Institute
Tg	teragram
UAV	unmanned aerial vehicle
VOC	volatile organic compound
WMO	World Meteorological Organization

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
XX-01-2017

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
Jul 2016 - Jan 2017

4. TITLE AND SUBTITLE
Research Strategies for Detection and Measurement of Oil and Gas Sector Methane Emissions

5a. CONTRACT NUMBER
NSFOIA-0408601 (DE-DT0011794)

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
EA-20-4270

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311-1882

8. PERFORMING ORGANIZATION REPORT NUMBER
IDA Paper P-8315

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of Energy
Office of Energy Policy and Systems Analysis
1000 Independence Ave., SW
Washington, D.C. 20585

10. SPONSOR/MONITOR'S ACRONYM(S)
DOE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited (17 January 2017).

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Development of accurate methane emissions detection and measurement technology is driven in part by the ongoing need to demonstrate progress towards national and international GHG reduction goals. The energy sector is a significant source of methane in the United States, accounting for 45% of total U.S. methane emissions in 2014. The Department of Energy held a subject-matter expert workshop in October 2016 that could inform recommendations for future Federal research efforts to improve methane emission sensing and quantification from the energy sector. The report describes research opportunities and recommendations to develop and deploy methane measurement and monitoring technologies to support the Environmental Protection Agency’s U.S. Greenhouse Gas Inventory, enable methane emissions abatement opportunities from the oil and natural gas sectors, and identify broader methane monitoring opportunities using tools such as remote sensing, unmanned aerial vehicles, and atmospheric modeling.

15. SUBJECT TERMS
atmospheric science, climate change, greenhouse gas (GHG), methane, natural gas, oil

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Bradbury, James
Unclassified	Unclassified	Unclassified	Same as Report	63	19b. TELEPHONE NUMBER *(Include area code)* 202-586-0683