Methane and Health-Damaging Air Pollutants From the Oil and Gas Sector: Bridging 10 Years of Scientific Understanding

October 6, 2021

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Acknowledgements

We would like to thank the following individuals for their external review of this report:

Jonathan Buonocore, Sc.D.
Research Scientist
Center for Climate, Health and the Global Environment (C-CHANGE)
Harvard T.H. Chan School of Public Health

Evan D. Sherwin, PhD
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Funding

This report was funded by the High Tide Foundation.

About PSE Healthy Energy

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Executive Summary

The global atmospheric concentration of methane—a potent greenhouse gas that captures 86 times more heat than carbon dioxide (CO^2) over a 20-year time span—is now greater than at any time in the past 800,000 years.[1] Methane emissions must be reduced by almost half during the next decade to avoid the worst effects of climate change.[2] The oil and gas sector—including upstream oil and gas development, midstream oil and gas transmission, and downstream end use—is simultaneously the largest source of anthropogenic methane emissions and volatile organic compounds (VOCs) in the United States, emitting an estimated 196.7 million metric tons of CO^2 equivalent in methane in 2019 and an estimated 2.49 million tons of VOCs annually.[3]

Together, these VOCs and other health-damaging air pollutants (HDAPs)—defined in this report as any airborne pollutant in particulate or gaseous form that is hazardous to human health—emitted from the oil and gas sector degrade air quality and introduce human health hazards, risks, and impacts at local and regional scales. Reducing anthropogenic methane and HDAP emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming, buy time for deeper global decarbonization,[4] and realize air quality and health benefits.

In 2016, for the first time, the United States Environmental Protection Agency (U.S. EPA) finalized new rules to regulate both methane and VOC emissions from the oil and gas industry.[5] While the rules monetized climate-related benefits for methane reductions, the U.S. EPA was unable to calculate the benefits of VOC and other HDAP reductions due to "difficulties in modeling the impacts with the current data available."[6] These data gaps indicate that benefits of oil and gas methane regulations are currently underestimated across the oil and gas industry, and therefore, have ramifications for present and future energy policy.

To better understand the overlap in sources of methane and HDAPs and approaches to prevent, detect, and mitigate emissions, we conducted a systematic review of scientific peer-reviewed literature published between January 2015 and August 2020. Our review focused on primary methane and HDAP data collection efforts pertinent to emissions throughout the oil and gas supply chain, divided into upstream (development and production), midstream (processing and transmission), and downstream (distribution and end-use) sectors, with the following objectives:

- **Summarize Key Themes and Findings:** From our systematic review, we aimed to equip researchers, communities, and decisionmakers with a clear, concise, and informative guide to the state of the science, current research gaps, and priorities on issues of methane and HDAP emissions across the oil and gas sector.

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1 IPCC (2021)

2 UNEP & CCAC (2021)

3 U.S. EPA (2021)

4 UNEP & CCAC (2021)

5 81 FR 35824, June 3, 2016

6 U.S. EPA (2020)

- **Highlight Research and Policy Recommendations:** Based on the findings of the systematic review, we provided recommendations that can be incorporated into actionable climate policy that simultaneously reduces methane emissions and protects public health.

Key Themes, Findings, and Recommendations

We identified 270 unique studies published from January 2015 to August 2020 that met our inclusion criteria. Of this body of literature, 165 articles measured methane emissions alone, 76 articles measured HDAP emissions alone, and 29 articles simultaneously measured both methane and HDAPs (Figure ES-1). We restricted our review to articles that measured emissions from North America (i.e., Canada, the United States, and Mexico). We found more than twice the number of methane studies were published than HDAP studies, and 72% of methane articles and 84% of HDAP articles published during this time focused on some aspect of the upstream oil and gas sector (Figure ES-1). Below we describe key findings, research gaps, and recommendations from our literature review, organized under overarching themes.

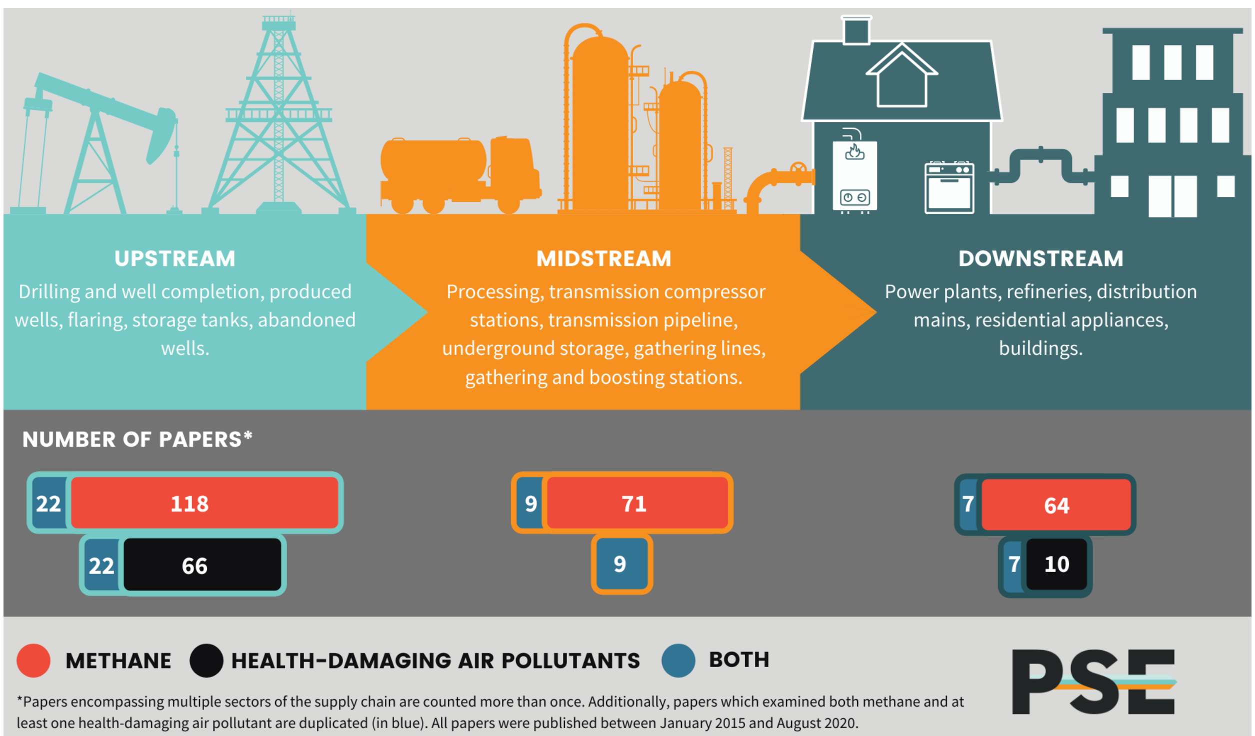

Figure ES-1. Counts of methane and HDAP studies across upstream, midstream, and downstream sectors from the systematic review, 2015–2020. This schematic shows the components from the upstream, midstream, and downstream sectors investigated in this report. The scale bars below each of the sectors indicate the relative weight of evidence available for that sector, as determined by the number of peer-reviewed publications included in our analysis. Papers encompassing multiple sections of the supply chain are counted in each of their respective sectors. Papers which measured methane alone are denoted by red bars, HDAPs alone in black, and both methane and HDAPs in blue.

Theme #1. The composition and magnitude of emissions from oil and gas systems depends on multiple variables.

Finding 1.1. There are two major source-types of air pollutants from oil and gas systems: (1) fugitive emissions from leaks and venting of non-combusted gases that emit relatively high proportions of methane and VOCs and (2) combustion emissions that emit comparatively less methane through incomplete combustion and possibly fewer VOCs, but higher levels of other criteria pollutants as byproducts of combustion such as nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM), among others. In general, sources of methane emissions are nearly always sources of health-damaging air pollutants (HDAPs). However, not all sources of HDAPs are sources of methane.

Finding 1.2. Major equipment sources associated with emissions of unburned fugitive methane and health-damaging VOCs include liquid storage tanks, produced water tanks, dehydrators, pneumatic controllers, and any fugitive leak point that exists from well pad to end-use. HDAPs emitted during fuel combustion to support the oil and gas supply chain include NO_x, CO, PM, VOCs, black carbon, sulfur dioxide, formaldehyde, and ammonia. Major equipment sources of combustion-related emissions include flares, natural gas-fired compressor stations, and diesel fuel-powered equipment typically deployed for drilling and well completion activities.

Finding 1.3. Emissions from oil and gas systems vary by production basin, operator, emission source, emissions process, activity phase and operational status, and emission control technology and measures applied. Temporal aspects of emissions, including intermittent or persistent emissions, also adds complexity and uncertainty in characterizing emissions and subsequently designing mitigation strategies.

Finding 1.4. All supply chain equipment moves through numerous operational phases—including normal functioning, malfunctioning (i.e., abnormal operation), stand-by, and maintenance—emitting both methane and HDAPs at varying intensities and proportions. Operational vs. stand-by status influences the make-up and intensity of emissions, with greater emission rates observed in functional operating status (vs. standby mode) across a host of facility and equipment types. Similarly, different stages of upstream oil and gas development emit HDAPs and methane at varying mixtures and concentrations. For example, emission rates can range by orders of magnitude with different co-pollutant mixtures observed during hydraulic fracturing, flowback, and production stages of well development.

Finding 1.5. A wide range of methane mitigation strategies and monitoring technologies emerged in the past decade. In general, these include engineered emission controls, operational practices such as leak detection and repair programs (LDAR), and various configurations of air-quality monitoring and remote sensing. The general effectiveness of each of these approaches was studied closely and will remain an ongoing area of study. These studies uncovered pros and cons of each of these systems suggesting a future landscape that likely entails tailored mitigation strategies that combine multiple mitigation approaches in a hybridized and redundant form.

Finding 1.6. Despite evidence that methane and HDAPs are emitted from every sector of the oil and gas supply chain, much of the scientific literature tends to evaluate methane and HDAPs as separate issues, resulting in disparate literatures. Only 11% (29) of the studies we reviewed explicitly measured methane and at least one HDAP simultaneously.

Finding 1.7. Certain mitigation measures—such as more frequent upstream leak detection and repair (LDAR)—are not designed to capture non-methane-rich HDAP emissions that contribute to health hazards, risks, and impacts. While methane can be a reasonable indicator for HDAPs when the source is methane-rich (e.g., wellheads, natural gas processing plants, natural gas gathering and transmission infrastructure, household natural gas appliances), methane may be a poor indicator for HDAPs when the source is not typically methane-rich (e.g., flaring, natural gas combustion, heavy oil flashing, produced water management processes, diesel combustion emissions).

Recommendation 1.1. The greatest opportunity to co-reduce both methane and at least one class of HDAPs is by targeting fugitive or vented emissions of natural gas at any point in the oil and gas supply chain. Any efforts to reduce venting and leaks will result in the co-reduction of both methane and certain VOCs, such as benzene, toluene, ethylbenzene, and xylene (BTEX). There is emerging consensus that upstream liquid storage tanks are the single largest fugitive emissions source of both methane and VOCs, and that these emissions are disproportionately underestimated in inventories.

Recommendation 1.2. Additional research is still needed to better understand: (1) the methane to HDAP ratio of emissions from many source-types; (2) the full life cycle of HDAP emissions for many pollutants; and (3) the health impacts associated with HDAP exposures across the oil and gas supply chain. Specifically, more primary research is needed to develop methane to VOC emissions ratios for many source-types. More research is also needed in the downstream sector, specifically for indoor building-level HDAP emissions that can occur very near people, as well as the degree to which widespread distribution leakage affects regional air quality in urban areas. A better understanding of the impacts in these settings could help in quantifying the public health benefits of certain methane emission reduction strategies.

Recommendation 1.3. Four of the most effective emissions controls technologies that simultaneously reduce major sources of methane and HDAPs are: (1) tankless well designs/additional vapor control measures on liquid storage tanks and dehydrators; (2) electrification of compressor engines; (3) preventing the need for flaring through additional separators or vapor-recovery units or improving efficiency of flaring by more accurate monitoring of steam and/or air-assisted flares; and (4) replacement and repair of existing pneumatic devices with zero-bleed devices. Permitting requirements for centralized facilities should include emission control measures, such as the use of low-NO_x or electrified compressor engines, as well as emission rate limitations for NO_x, CO, and VOCs for both compressor engines and all associated process equipment. Moreover, all centralized facilities—including gathering and boosting stations, processing plants, refineries, and natural gas-fired power plants—present opportunities for co-reductions of methane and HDAPs through emissions controls such as engine electrification paired with monitoring systems to verify controls. Additionally, operational best practices that reduce the likelihood of fugitive emissions (for example, open thief hatches) can be very effective forms of emissions control.

Recommendation 1.4. A narrow focus on only controlling emissions from methane-rich sources may lead to a lack of control on other important sources of HDAPs, which can degrade air quality and impact public health. Further development of combustion control technologies should be considered since combustion source-types account for the majority of criteria air pollutant emissions across the life cycle. Examples include: (1) engine electrification where possible and the adoption of new front-end fuel combustion technology, which reduces emissions of NO_x and CO; (2) the implementation of continuous emissions monitoring using more sensitive instruments to capture and adequately mitigate pollutant releases and leaks when they happen; and (3) the implementation of responsive, automatic system controls for specific systems (e.g., combustion, flare control, cooling tower, sulfur recovery unit), which could promote more efficient fuel combustion and reduce process leaks.

Recommendation 1.5. Methane detection and measurement technologies like fixed sensors, mobile laboratories, unmanned aerial vehicles (UAVs), aircraft, and satellites are promising tools that in total meet a range of applications with well-defined tradeoffs related to spatial and temporal sensing resolution and a range of detection/quantification efficacy. Hybridized mitigation strategies or a hierarchy of controls is recommended by multiple research groups. For example, the cost-effectiveness of LDAR programs can be improved by utilizing a multi-platform hybrid screening and confirmation approach, whereby rapid screening technologies—such as vehicle-, aerial-, or satellite-based platforms—can be used to guide ground-based LDAR programs as opposed to routine LDAR sampling regimes (i.e., quarterly). Future mitigation strategies should continue to integrate newer technologies with LDAR programs and should seek to optimize LDAR survey frequency, detection thresholds, and response times.

Recommendation 1.6. On-site stationary monitoring systems were found to be the most capable technology available to simultaneously quantify methane and HDAP emissions. Approaches to on-site air quality monitoring for HDAPs need to first consider the composition of gases emitted from nearby source-types. For instance, components that handle methane-rich gases could benefit from continuous methane monitoring with an auto-trigger VOC-sampling system. These samples can provide speciated VOCs at concentrations suitable for developing better methane:VOC ratio data that is needed for air quality modeling and health impact analysis. These types of stationary monitoring systems can provide routine data that could support the advent of measurement-based inventories over current activity-based inventories. Such inventories could also support the implementation of performance-based regulations that have been applied in other countries and in other U.S. industrial sectors.

Theme #2. Given that sources of methane emissions are nearly always sources of health-damaging air pollutants, prioritizing methane emission reductions near population centers is essential to protect public health and would increase the benefits of methane emission reductions.

Finding 2.1. There is strong evidence that emissions of both methane and HDAPs vary substantially by location, equipment type, production phase, maintenance practices, and many other factors. Therefore, the health benefits per ton of methane reduced will also likely vary substantially by location, and are further mediated by nearby population density, presence or absence of other ambient pollutants, and meteorology.

Finding 2.2. The location of methane emissions does not change their climate impact; however, the location of HDAP emissions determines local and regional air quality and subsequent public health risks. Natural gas leakage studies indicate that all portions of the vast supply chain are prone to leaks, even in the downstream sector where natural gas is delivered to cities and buildings. In these settings, even small concentrations of co-emitted HDAPs may be important due to their proximity to human populations. Downstream emissions contribute to existing urban air quality burdens and in some cases are directly emitted inside of buildings from appliance leaks that can go undetected.

Finding 2.3. The body of scientific evidence indicates that the likelihood of adverse human health outcomes increases as distance decreases between oil and gas development operations and human populations. The risks associated with HDAPs stemming from upstream oil and gas sites can be reduced by establishing larger distances between upstream oil and gas operations and human populations. However, much less is known about the HDAP exposures and adverse human health outcomes associated with midstream and downstream natural gas distribution systems, even though many of these systems are located near human populations. Only 9% of studies in our review examine midstream HDAP emissions and another 16% measure downstream HDAP emissions, while 84% measure upstream HDAP emissions, highlighting a clear gap in the literature when exposures to human health need to be identified.

Recommendation 2.1. Prioritizing methane reductions near population centers can increase the public health and cost-benefit of emissions reductions. Centralized facilities located near population centers such as compressor stations, gathering and boosting facilities, large-scale production pads, and other processing plants should be prioritized for emissions mitigation.

Recommendation 2.2. Regulators and risk managers should consider other risk reduction strategies and safety measures beyond emissions controls and monitoring. These can include implementation of minimum surface setbacks between various types of oil and gas operations—beyond just locations of production wells—and human receptors with additional protections for nearby sensitive populations.

Theme #3. A relatively small proportion of sources are responsible for a disproportionately large fraction of total methane and HDAP emissions. These super-emitters are present in every sector of the oil and gas supply chain and present both the greatest challenge and greatest opportunity for mitigation.

Finding 3.1. A relatively small number of sources located throughout the oil and gas supply chains are responsible for a disproportionately large fraction of methane and HDAP emissions. For methane, these types of sources have been deemed "super-emitters," however, the term and its definition have not been standardized in the scientific literature and are employed differently depending on the context. Attempts have been made to classify sources as super-emitting, such as the "5-50" rule, where the top 5 percent of emitters are responsible for 50 percent of all emissions. However, large intra- and inter-regional variations have been observed for individual components and for regions as a whole.

Finding 3.2. The presence of super-emitters writ large is evidence that substantial emissions reductions are feasible.

Finding 3.3. While the presence of super-emitters is well established in the methane literature, evidence also suggests that super-emitters exist for some fugitive-type VOCs from certain source types and events. These source types include pneumatic controllers, compressor blowdowns, high-emitting flares, and aging wells.

Finding 3.4. The reasons why sources become super-emitters is not entirely clear, although abnormal operational conditions or malfunctions have been identified in some cases. Some evidence suggests that the likelihood of super-emitter events may be more common in idle or stand-by infrastructure, though further research is needed to confirm this observation. Many of the early sampling studies were likely not designed to fully characterize super-emitters and contributed to discrepancies in emissions estimate methods. Bottom-up analyses of individual components typically found much lower emission rates than top-down studies measuring atmospheric methane concentrations, indicating gaps in the bottom-up estimates.

Finding 3.5. While super-emitters are primarily characterized by their emissions relative to other sources, there is strong evidence of substantial temporal intermittency in emission rates, as observed from a few high-frequency sampling campaigns. Some evidence also suggests that the large majority (~90%)[7] of super-emitter events occur as one-offs or at relatively low frequency. While it is unclear if these types of low frequency events indicate that the leak was repaired, it has also been documented that many super-emitter events are easily fixable and preventable issues such as with unlit flares or open thief hatches.

Finding 3.6. Mitigation of super-emitters is not incentivized within the context of the current U.S. EPA Greenhouse Gas Inventory. This is largely due to how emissions factors are used to calculate methane emissions and the use of "regulatory reductions" instead of actual measurements to demonstrate reductions. This has major implications for addressing emissions from super-emitter-type events.

Finding 3.7. While super-emitters are a clear problem for climate and contribute to human health hazards, risks, and impacts, relatively smaller individual emission sources can also cause disproportionate impacts if they are close to and upwind of human populations. Relatedly, large-scale facilities with a multitude of emissions points and source-types may simultaneously exhibit both routine and abnormal emissions events and should be high-priority candidates for deployment of on-site continuous methane and HDAP monitoring systems.

Recommendation 3.1. Efforts to prevent, identify, and mitigate super-emitting sites and equipment should continue to be a top priority due to their disproportionate impact, omnipresence, and elusiveness. However, given the urgency to reduce emissions, focusing solely on equipment control systems or aerial survey technologies will likely have limited effectiveness in preventing and mitigating super-emitter events. A more encompassing approach should entail installed equipment controls, routine preventative maintenance, and multi-platform emissions monitoring to inform a more targeted LDAR program. High-resolution satellites, commercial airborne remote sensing systems, and continuous on-site methane and HDAP monitoring systems can all improve detection capabilities; however, prevention and mitigation steps require other types of management and operational practices to be in place in order to take advantage of these emerging technologies.

Recommendation 3.2. While further component-level root cause study would be valuable, volunteer bias in on-site methane surveys is an unavoidable confounding factor that undoubtedly limits generalizability of findings. Aerial survey technologies and airborne methane remote sensing systems can augment further study of super-emitters and should continue research and development in detecting, quantifying, and apportioning emissions throughout the supply chain.

Recommendation 3.3. If super-emitters are to be explicitly targeted for mitigation, the term "super-emitters" needs to be standardized, whether on a proportional loss or absolute loss basis.

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7 Cusworth et al. (2021)

Theme #4. Over the past decade, the scientific understanding of methane emissions from oil and gas has increased substantially. There is now unequivocal evidence to support swift and aggressive reductions in methane emissions to avoid shorter-term global warming.

Finding 4.1. Using the 20-year global warming potential of methane, dry gas production-normalized emission rates ranging from 2.4-3.9%[8] for methane were calculated to be the breakeven point where the climate impacts of natural gas equal those of coal. The production-normalized methane emission rate for the entire supply chain is estimated to be 2.3%,[9] with individual regions ranging from 0.4% to 17%.[10] Although many studies are close to or lower than the calculated breakeven point, uncertainty in emission estimates remains high. Methane emissions from the upstream sector represent the largest fraction of oil and gas-related methane emissions. As such, uncertainties associated with upstream measurements dominate overall uncertainties for the oil and gas sector as a whole.

Finding 4.2. A persistent issue throughout the past 10 years of scientific study was the lack of agreement between bottom-up and top-down derived methane emission estimates. Studies suggest that component-level, bottom-up estimates routinely underestimate emissions by a factor of 1.6 to 2, compared to top-down studies and site-level bottom-up studies. A few studies have estimated emissions lower than the U.S. EPA Greenhouse Gas Inventory, but these studies were in the minority and were limited to specific parts of the oil and gas supply chain. The disagreement between bottom-up and top-down studies is a result of both the inaccuracy of inventories and the measurement uncertainties in atmospheric studies. Given the generalized assumptions required in bottom-up approaches and the highly variable (and rapidly changing) oil and natural gas industry in the late 2000s, the level of disagreement observed is not surprising.

Finding 4.3. Uncertainties in methane emissions can be expressed relative to the individual sector or source-type alone or relative to the entire supply chain. According to the studies to date, emissions uncertainties relative to individual sector or source-type estimates are most poorly constrained for downstream behind-the-meter sources, upstream orphaned and abandoned wells and other abandoned infrastructure, upstream gathering facility flares, upstream gathering pipelines, dehydrators, still/reboil vents, acid gas removal units, and pneumatic controllers. Emissions uncertainties relative to total estimated supply chain emissions indicate that more information is needed for gathering and boosting stations, pneumatic controllers, and liquid storage tanks. Moreover, important uncertainties remain for emissions between production basins as certain basins have been much more heavily studied compared to others.

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8 Hong & Howarth (2016); Ren et al. (2019); Sanchez & Mays (2015). Analyses by Hong and Howarth (2016) and Sanchez and Mays (2015) are based on generating electricity from natural gas versus coal.

9 Alvarez et al. (2018)

10 See Table 3.1

Finding 4.4. Relative to spatial variability, less is known related to temporal variability of emissions. Most emissions characterization studies have taken place over very short durations (e.g., 2-4 weeks). Shorter duration studies have clear limitations related to generalizability of findings and representativeness of study sample measures, particularly for some source types such as pneumatic controllers, flares, and power plants. Given the large degree of heterogeneity across the North American oil and gas landscape, the presence of long-tailed distributions (i.e., super-emitters), and other temporal variation (e.g., persistent vs. intermittent), this limitation warrants particular attention. The few studies that have assessed temporal aspects of emissions have been particularly informative.

Finding 4.5. Our systematic review indicates that research in the last three years is rapidly accelerating to close major research gaps on methane emissions from oil and gas systems. We identified more methane studies published in 2019 than any of the previous four years. This trajectory is likely to continue. From mid-2020 through August 2021 alone, publication rates were higher than at any other time in the past decade, reflecting the fast-moving pace of the science. While we did not fully review these studies, we incorporated information from select high-priority studies that were identified via external peer review. For example, the first two studies of methane emissions in Mexico were published in the past year (a notable research gap).

Recommendation 4.1. Given current scientific understanding, effective methane and HDAP emissions control technologies and approaches exist today and should be swiftly implemented. Additional scientific study should continue where needed but should not delay deployment of emission controls and monitoring systems for source types that have been well characterized. Rather, the focus of additional study should include targeted campaigns that test the effectiveness of control technologies and validate emerging sensing technologies. These data are critical for supporting policies around continuous monitoring that can underpin a move towards performance-based emissions targets.

Recommendation 4.2. Current component-level bottom-up inventory methods would be improved by incorporating new emissions data from recent studies and revising bottom-up emission modelling approaches. Demonstrating the difference between persistent and intermittent emissions sources and their relative emissions contributions can help constrain emissions discrepancies and design more targeted mitigation approaches.

Recommendation 4.3. In the long term, the most effective strategy to reduce emissions from the oil and natural gas sector is to reduce the overall development, transmission, and use of oil and natural gas. However, as society moves away from oil and natural gas for energy use, the transition must be managed in a way that does not result in degraded operation and maintenance practices and potentially increased emissions.

Conclusion

Feasible approaches to reduce methane emissions have existed for years and could more than halve future anthropogenic methane emissions by 2030 (Clean Air Task Force, 2021). However, widespread deployment of these systems remains a key challenge. The weight of the scientific literature to date indicates there is significant variability in the magnitude and ratios of methane and HDAP emissions across geographic, temporal, and corporate spaces. This degree of variability has challenged the usefulness of both activity-based methane emission inventories, which often rely on outdated emissions factors, and the science aimed at reconciling inventory estimates with real-world observations. While studying emissions from the oil and natural gas sector has its challenges, our analysis found that research in the last five years is rapidly closing major research gaps on both methane and HDAPs and that this trajectory is likely to continue. The likelihood of co-emissions of methane and HDAPs in many, but not all, parts of the oil and gas sector likely means that the cost-benefits of methane mitigation are underestimated, particularly for those sources in proximity to human populations.

In the United States, there is a long history of ambient air quality monitoring and stationary source air monitoring for a multitude of criteria and hazardous air pollutants. These systems have been a critical pillar in identifying HDAP emissions and have played a fundamental role in reducing public health harms from exposures to HDAPs across sectors. Deploying a similar source-focused stationary monitoring network is likely not feasible given the disparate oil and gas landscape. However, centralized facilities located near population centers should exhibit on-site, stationary continuous monitoring systems capable of quantifying both methane and HDAP emissions. On-site continuous monitoring systems can fill data needs for air quality modelling and health impact analysis and would support the development of measurement-based inventories. Such inventories could also support performance-based regulations that would better incentivize prevention of super-emitter type events that currently make up a significant portion of total emissions.

Central to effective air quality monitoring for HDAP emissions from oil and gas systems is improving knowledge of what to monitor for. Our review found that there are two major source-types of air pollutants: (1) fugitive emissions (leaks and venting of non-combusted gases), which emit relatively high proportions of methane and VOCs; and (2) combustion emissions that emit less methane and possibly fewer VOCs, but higher levels of NO_x, CO, and PM. The emission controls that likely provide the greatest opportunity for climate and public health benefits are tankless designs or vapor recovery units on liquid storage tanks, electrification of compressor engines, preventing the need for flaring, and replacement of high-bleed pneumatic devices with zero-bleed devices. Much less is known about the potential health harms associated with downstream fugitive and combustion emissions.

Focusing on emissions controls and monitoring or aerial sensing technologies alone will likely have varied effectiveness in ultimately preventing and mitigating emissions. A more encompassing approach entails installed maximum achievable equipment controls, routine preventative maintenance practices, and multi-platform emissions monitoring to inform a more targeted LDAR program. High-resolution satellites, commercial airborne remote sensing systems, and continuous on-site methane and HDAP monitoring systems can all improve detection capabilities and should continue to be deployed; however, prevention and mitigation activities require other types of operational practices to be in place in order to take advantage of these emerging technologies.

Given the powerful, shorter-term global warming potential of methane–and the fact that no study we reviewed identified methane emissions too small to be of climate concern–it is imperative that methane prevention, detection, and mitigation strategies be swiftly and aggressively deployed. The prospect of future research to refine our understanding of methane and HDAP emission estimates should not preempt swift action, particularly in areas where oil and gas systems are in proximity to human populations.

Lastly, it should be noted that the most effective strategy to rapidly reduce air pollutant emissions from the oil and natural gas sector is to reduce the overall development, transmission, and use of oil and natural gas. However, as society moves away from oil and natural gas for energy use, the transition must be managed in a way that does not result in degraded operation and maintenance practices and potentially increased emissions.

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