Methane References Summary

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Introduction

This is a reference summary for methane that shows by example that the Part 496 Regulatory Impact Statement does not provide a comprehensive set of references because most of these references are not included. It contains a set of references that I believe should be considered for the New York emission inventories required by the Climate Leadership and Community Protection Act. For each reference I include a link to the paper and, where available, the abstract and other supporting information.

In my opinion, M. Saunois et al.2020: The Global Methane Budget 2000–2017 necessarily has to be included as a reference in any inventory report that purports to represent the "best available science and methods of analysis". The paper was authored by 87 authors representing 72 organizations. Their short summary states:

> "Understanding and quantifying the global methane (CH_4) budget is important for assessing realistic pathways to mitigate climate change. We have established a consortium of multidisciplinary scientists under the umbrella of the Global Carbon Project to synthesize and stimulate new research aimed at improving and regularly updating the global methane budget. This is the second version of the review dedicated to the decadal methane budget, integrating results of top-down and bottom-up estimates."

If one were to read the Part 496 Regulatory Impact Statement (RIS) without reading Saunois et al. you could easily conclude that methane inventories are without controversy. However, this clearly is not the case. Saunois et al. notes in the abstract: "The relative importance of CH4 compared to CO2 depends on its shorter atmospheric lifetime, stronger warming potential, and variations in atmospheric growth rate over the past decade, the causes of which are still debated. Two major challenges in reducing uncertainties in the atmospheric growth rate arise from the variety of geographically overlapping CH4 sources and from the destruction of CH4 by short-lived hydroxyl radicals (OH)". This is important because the treatment of methane emissions is the main reason that the proposed Part 496 emission inventory nearly doubled from previous inventories.

In order to document the evolving nature of methane emission inventory development I provide summaries for the papers referenced in the following two quotes, my emphasis added.

M. Saunois et al.: The Global Methane Budget 2000–2017 p. 1573

> The shale gas contribution to total dry natural gas production in the United States reached 62 % in 2017, growing rapidly from 40 % in 2012, with only small volumes produced before 2005 (EIA, 2019). **The possibly larger emission factors from the shale gas compared to the conventional ones have been widely debated** (e.g. Cathles et al., 2012; Howarth, 2019; Lewan, 2020). **However, the latest studies tend to infer similar emission factors in a narrow range of 1 %–3 %** (Alvarez et al., 2018; Peischl et al., 2015; Zavala-Araiza et al., 2015), different from the widely spread rates of 3 %–17 % from previous studies (e.g. Caulton et al., 2014; Schneising et al., 2014).

The following quote lists studies that obviously should be included in a comprehensive set of references. Moreover, the reference to Zavala-Araiza et al. highlighted below provides valuable information for the interpretation of methane emissions from the oil and gas industry.

M. Saunois et al.: The Global Methane Budget 2000–2017 p.1574

> Most studies (Alvarez et al., 2018; Brandt et al., 2014; Jackson et al., 2014b; Karion et al., 2013; Moore et al., 2014; Olivier and Janssens-Maenhout, 2014; Pétron et al., 2014; Zavala-Araiza et al., 2015), albeit not all (Allen et al., 2013; Cathles et al., 2012; Peischl et al., 2015), suggest that methane emissions from oil and gas industry are underestimated by inventories and agencies, including the USEPA. Zavala-Araiza et al. (2015) showed that **a few high-emitting facilities, i.e., super-emitters, neglected in the inventories, dominated US emissions. These high-emitting points, located on the conventional part of the facility, could be avoided through better operating conditions and repair of malfunctions.** As US production increases, absolute methane emissions almost certainly increase. US crude oil production also doubled over the last decade and natural gas production rose more than 50 % (EIA, 2019). However, global implications of the rapidly growing shale gas activity in the United States remain to be determined precisely.

Also included are additional references that I think need to be highlighted. Lan et al. use long term monitoring data to show that “there is no large increase of total methane emissions in the United States in the past decade” and “there is a modest increase in oil and gas methane emissions, but this increase is much lower than some previous studies suggest”. Grubert and Brant discuss life cycle assessments of methane from natural gas systems that are another aspect of the documentation that is necessary but lacking at this time. I included Jackson et al. 2020 that showed that the natural gas systems are not the only cause of the observed methane increases. Howarth (2020) is included because it directly references the CLCPA. Miller et al. is a reference used by Howarth (2020). Finally, I included Plant et al because it was used in the RIS.

The global methane budget 2000-2017

https://essd.copernicus.org/articles/12/1561/2020/

Saunois et al., 2020, The global methane budget 2000-2017, Earth Syst. Sci. Data, 12, 1561–1623, 2020
https://doi.org/10.5194/essd-12-1561-2020

Understanding and quantifying the global methane (CH_4) budget is important for assessing realistic pathways to mitigate climate change. We have established a consortium of multidisciplinary scientists under the umbrella of the Global Carbon Project to synthesize and stimulate new research aimed at improving and regularly updating the global methane budget. This is the second version of the review dedicated to the decadal methane budget, integrating results of top-down and bottom-up estimates.

Abstract

Understanding and quantifying the global methane (CH4) budget is important for assessing realistic pathways to mitigate climate change. Atmospheric emissions and concentrations of CH4 continue to increase, making CH4 the second most important human-influenced greenhouse gas in terms of climate forcing, after carbon dioxide (CO2). The relative importance of CH4 compared to CO2 depends on its shorter atmospheric lifetime, stronger warming potential, and variations in atmospheric growth rate over the past decade, the causes of which are still debated. Two major challenges in reducing uncertainties in the atmospheric growth rate arise from the variety of geographically overlapping CH4 sources and from the destruction of CH4 by short-lived hydroxyl radicals (OH). To address these challenges, we have established a consortium of multidisciplinary scientists under the umbrella of the Global Carbon Project to synthesize and stimulate new research aimed at improving and regularly updating the global methane budget. Following Saunois et al. (2016), we present here the second version of the living review paper dedicated to the decadal methane budget, integrating results of top-down studies (atmospheric observations within an atmospheric inverse-modelling framework) and bottom-up estimates (including process-based models for estimating land surface emissions and atmospheric chemistry, inventories of anthropogenic emissions, and data-driven extrapolations).

For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH4 yr−1 (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH4 yr−1 or ∼ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH4 yr−1 or 50 %–65 %). The mean annual total emission for the new decade (2008–2017) is 29 Tg CH4 yr−1 larger than our estimate for the previous decade (2000–2009), and 24 Tg CH4 yr−1 larger than the one reported in the previous budget for 2003–2012 (Saunois et al., 2016). Since 2012, global CH4 emissions have been tracking the warmest scenarios assessed by the Intergovernmental Panel on Climate Change. Bottom-up methods suggest almost 30 % larger global emissions (737 Tg CH4 yr−1, range 594–881) than top-down inversion methods. Indeed, bottom-up estimates for natural sources such as natural wetlands, other inland water systems, and geological sources are higher than top-down estimates. The atmospheric constraints on the top-down budget

suggest that at least some of these bottom-up emissions are overestimated. The latitudinal distribution of atmospheric observation-based emissions indicates a predominance of tropical emissions (∼ 65 % of the global budget, < 30◦ N) compared to mid-latitudes (∼ 30 %, 30–60◦ N) and high northern latitudes (∼ 4 %, 60–90◦ N). The most important source of uncertainty in the methane budget is attributable to natural emissions, especially those from wetlands and other inland waters.

Some of our global source estimates are smaller than those in previously published budgets (Saunois et al., 2016; Kirschke et al., 2013). In particular wetland emissions are about 35 Tg CH4 yr−1 lower due to improved partition wetlands and other inland waters. Emissions from geological sources and wild animals are also found to be smaller by 7 Tg CH4 yr−1 by 8 Tg CH4 yr−1, respectively. However, the overall discrepancy between bottom-up and top-down estimates has been reduced by only 5 % compared to Saunois et al. (2016), due to a higher estimate of emissions from inland waters, highlighting the need for more detailed research on emissions factors. Priorities for improving the methane budget include (i) a global, high-resolution map of water-saturated soils and inundated areas emitting methane based on a robust classification of different types of emitting habitats; (ii) further development of process-based models for inland-water emissions; (iii) intensification of methane observations at local scales (e.g., FLUXNET-CH4 measurements) and urban-scale monitoring to constrain bottom-up land surface models, and at regional scales (surface networks and satellites) to constrain atmospheric inversions; (iv) improvements of transport models and the representation of photochemical sinks in top-down inversions; and (v) development of a 3D variational inversion system using isotopic and/or co-emitted species such as ethane to improve source partitioning.

“The possibly larger emission factors from the shale gas compared to the conventional ones have been widely debated”

Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane?,

Howarth, R. W.: Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane?, Biogeosciences, 16, 3033–3046, https://doi.org/10.5194/bg-16-3033- 2019, 2019

Abstract

Methane has been rising rapidly in the atmosphere over the past decade, contributing to global climate change. Unlike the late 20th century when the rise in atmospheric methane was accompanied by an enrichment in the heavier carbon stable isotope (13C) of methane, methane in recent years has become more depleted in 13C. This depletion has been widely interpreted as indicating a primarily biogenic source for the increased methane. Here we show that part of the change may instead be associated with emissions from shale-gas and shale-oil development. Previous studies have not explicitly considered shale gas, even though most of the increase in natural gas production globally over the past decade is from shale gas. The methane in shale gas is somewhat depleted in 13C relative to conventional natural gas. Correcting earlier analyses for this difference, we conclude that shale-gas production in North America over the past decade may have contributed more than half of all of the increased emissions from fossil fuels globally and approximately one-third of the total increased emissions from all sources globally over the past decade.

Commentary on Howarth

Cathles, L., Brown, L., Taam, M., and Hunter, A.: A commentary on “The greenhouse-gas footprint of natural gas in shale formations” by R .W. Howarth, R. Santoro, and Anthony Ingraffea, Clim. Change, 113, 525–535, https://doi.org/10.1007/s10584-011-0333-0, 2012.

Abstract

Natural gas is widely considered to be an environmentally cleaner fuel than coal because it does not produce detrimental by-products such as sulfur, mercury, ash and particulates and because it provides twice the energy per unit of weight with half the carbon footprint during combustion. These points are not in dispute. However, in their recent publication in Climatic Change Letters, Howarth et al. (2011) report that their life-cycle evaluation of shale gas drilling suggests that shale gas has a larger GHG footprint than coal and that this larger footprint “undercuts the logic of its use as a bridging fuel over the coming decades”. We argue here that their analysis is seriously flawed in that they significantly overestimate the fugitive emissions associated with unconventional gas extraction, undervalue the contribution of “green technologies” to reducing those emissions to a level approaching that of conventional gas, base their comparison between

gas and coal on heat rather than electricity generation (almost the sole use of coal), and assume a time interval over which to compute the relative climate impact of gas compared to coal that does not capture the contrast between the long residence time of CO2 and the short residence time of methane in the atmosphere. High leakage rates, a short methane GWP, and comparison in terms of heat content are the inappropriate bases upon which Howarth et al. ground their claim that gas could be twice as bad as coal in its greenhouse impact. Using more reasonable leakage rates and bases of comparison, shale gas has a GHG footprint that is half and perhaps a third that of coal.

Comment on Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? by Robert W. Howarth (2019)

Lewan, M. D.: Comment on Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? by Robert W. Howarth (2019), Biogeosciences Discuss., https://doi.org/10.5194/bg-2019-419, in review, 2020.

Abstract.

The ideas and perspectives presented by Howarth (2019) on shale gas being a major cause of recent increases in global atmospheric methane are based on his notion that stable carbon isotopes of methane ($\delta^{13}C_1$) of shale gas are lighter than that of conventional gas based on a meager and unrepresentative data set. A plethora of publicly available data show that the $\delta^{13}C_1$ values of shale gas are typically heavier than those of conventional gas. This contradiction renders his ideas, perspectives, and calculations on methane emissions from shale gas invalid.

Conclusion

Sources and magnitude of methane emissions are important considerations in understanding the intricacies of climate change. In this regard, it is critical that objective and cognizant science be presented on the issue. Howarth (2019) does not use representative shale-gas isotopic data, excludes a plethora of publicly available shale-gas data, does not acknowledge shale gas and conventional gas on a global basis cannot be readily distinguished based solely on $\delta^{13}C_1$ values, speculates contrary to field observations and laboratory experiments that migration causes conventional gases to have heavier $\delta^{13}C_1$ values than shale gas, does not consider the effects of thermal maturation on shale-gas $\delta^{13}C_1$ values, and neglects $\delta^{13}C_1$ data showing major shale-gas production is heavier and not lighter than conventionally produced gas. These numerous and significant shortcomings render his conclusions on global methane emissions from shale gas invalid.

“The latest studies tend to infer similar emission factors in a narrow range of 1 %–3 %”

Assessment of methane emissions from the U.S. oil and gas supply chain

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., Shepson, P. B., Sweeney, C., Townsend-Small, A., Wofsy, S. C., and Hamburg, S. P.: Assessment of methane emissions from the U.S. oil and gas supply chain, Science, 361, 186–188, https://doi.org/10.1126/science.aar7204, 2018.

> Considerable amounts of the greenhouse gas methane leak from the U.S. oil and natural gas supply chain. Alvarez et al. reassessed the magnitude of this leakage and found that in 2015, supply chain emissions were ~60% higher than the U.S. Environmental Protection Agency inventory estimate. They suggest that this discrepancy exists because current inventory methods miss emissions that occur during abnormal operating conditions. These data, and the methodology used to obtain them, could improve and verify international inventories of greenhouse gases and provide a better understanding of mitigation efforts outlined by the Paris Agreement.
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> Abstract
> Methane emissions from the U.S. oil and natural gas supply chain were estimated by using ground-based, facility-scale measurements and validated with aircraft observations in areas accounting for ~30% of U.S. gas production. When scaled up nationally, our facility-based estimate of 2015 supply chain emissions is 13 ± 2 teragrams per year, equivalent to 2.3% of gross U.S. gas production. This value is ~60% higher than the U.S. Environmental Protection Agency inventory estimate, likely because existing inventory methods miss emissions released during abnormal operating conditions. Methane emissions of this magnitude, per unit of natural gas consumed, produce radiative forcing over a 20-year time horizon comparable to the CO2 from natural gas combustion. Substantial emission reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems.

Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions

Peischl, J., Ryerson, T. B., Aikin, K. C., de Gouw, J. A., Gilman, J. B., Holloway, J. S., Lerner, B. M., Nadkarni, R., Neuman, J. A., Nowak, J. B., Trainer, M., Warneke, C., and Parrish, D. D.: Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions, J. Geophys. Res.-Atmos., 120, 2119–2139, https://doi.org/10.1002/2014jd022697, 2015.

Abstract
We present measurements of methane (CH4) taken aboard a NOAA WP-3D research aircraft in 2013 over the Haynesville shale region in eastern Texas/northwestern Louisiana, the Fayetteville shale region in Arkansas, and the northeastern Pennsylvania portion of the Marcellus shale region, which accounted for the majority of Marcellus shale gas production that year. We calculate emission rates from the horizontal CH4 flux in the planetary boundary layer downwind of each region after subtracting the CH4 flux entering the region upwind. We find 1 day CH4 emissions of (8.0 ± 2.7) × 107 g/h from the Haynesville region, (3.9 ± 1.8) × 107 g/h from the Fayetteville region, and (1.5 ± 0.6) × 107 g/h from the Marcellus region in northeastern Pennsylvania. Finally, we compare the CH4 emissions to the total volume of natural gas extracted from each region to derive a loss rate from production operations of 1.0–2.1% from the Haynesville region, 1.0–2.8% from the Fayetteville region, and 0.18–0.41% from the Marcellus region in northeastern Pennsylvania. The climate impact of CH4 loss from shale gas production depends upon the total leakage from all production regions. The regions investigated in this work represented over half of the U.S. shale gas production in 2013, and we find generally lower loss rates than those reported in earlier studies of regions that made smaller contributions to total production. Hence, the national average CH4 loss rate from shale gas production may be lower than values extrapolated from the earlier studies.

Reconciling divergent estimates of oil and gas methane emissions

Zavala-Araiza, D., Lyon, D. R., Alvarez, R. A., Davis, K. J., Harriss, R., Herndon, S. C., Karion, A., Kort, E. A., Lamb, B. K., Lan, X., Marchese, A. J., Pacala, S. W., Robinson, A. L., Shepson, P. B., Sweeney, C., Talbot, R., Townsend-Small, A., Yacovitch, T. I., Zimmerle, D. J., and Hamburg, S. P.: Reconciling divergent estimates of oil and gas methane emissions, P. Natl. Acad. Sci. USA, 112, 15597–15602, https://doi.org/10.1073/pnas.1522126112, 2015.

Significance
Past studies reporting divergent estimates of methane emissions from the natural gas supply chain have generated conflicting claims about the full greenhouse gas footprint of natural gas. Top-down estimates based on large-scale atmospheric sampling often exceed bottom-up estimates based on source-based emission inventories. In this work, we reconcile top-down and bottom-up methane emissions estimates in one of the country's major natural gas production basins using easily replicable measurement and data integration techniques. These convergent emissions estimates provide greater confidence that we can accurately characterize the sources of emissions, including the large impact that a small proportion of high-emitters have on total emissions and determine the implications for mitigation.

Abstract
Published estimates of methane emissions from atmospheric data (top-down approaches) exceed those from source-based inventories (bottom-up approaches), leading to conflicting claims about the climate implications of fuel switching from coal or petroleum to natural gas.

Based on data from a coordinated campaign in the Barnett Shale oil and gas-producing region of Texas, we find that top-down and bottom-up estimates of both total and fossil methane emissions agree within statistical confidence intervals (relative differences are 10% for fossil methane and 0.1% for total methane). We reduced uncertainty in top-down estimates by using repeated mass balance measurements, as well as ethane as a fingerprint for source attribution. Similarly, our bottom-up estimate incorporates a more complete count of facilities than past inventories, which omitted a significant number of major sources, and more effectively accounts for the influence of large emission sources using a statistical estimator that integrates observations from multiple ground-based measurement datasets. Two percent of oil and gas facilities in the Barnett accounts for half of methane emissions at any given time, and high-emitting facilities appear to be spatiotemporally variable. Measured oil and gas methane emissions are 90% larger than estimates based on the US Environmental Protection Agency's Greenhouse Gas Inventory and correspond to 1.5% of natural gas production. This rate of methane loss increases the 20-y climate impacts of natural gas consumed in the region by roughly 50%.

Widely spread rates of 3 %–17 % from previous studies

Toward a better understanding and quantification of methane emissions from shale gas development

Caulton, D., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Anthony R, Ingraffea, A. R., Cambaliza, M. O. L., Sweeney, C., Karion, A., Davis, K. J., Stirm, B. H., Montzka, S. A., and Miller, B. R.: Toward a better understanding and quantification of methane emissions from shale gas development, Proc. Natl. Acad. Sci. USA, 111, 6237–6242, https://doi.org/10.1073/pnas.1316546111, 2014

Significance

We identified a significant regional flux of methane over a large area of shale gas wells in southwestern Pennsylvania in the Marcellus formation and further identified several pads with high methane emissions. These shale gas pads were identified as in the drilling process, a preproduction stage not previously associated with high methane emissions. This work emphasizes the need for top-down identification and component level and event driven measurements of methane leaks to properly inventory the combined methane emissions of natural gas extraction and combustion to better define the impacts of our nation's increasing reliance on natural gas to meet our energy needs.

Abstract

The identification and quantification of methane emissions from natural gas production has become increasingly important owing to the increase in the natural gas component of the energy sector. An instrumented aircraft platform was used to identify large sources of methane and quantify emission rates in southwestern PA in June 2012. A large regional flux, 2.0–14 g CH4 s−1 km−2, was quantified for a ∼2,800-km2 area, which did not differ statistically from a bottom-up inventory, 2.3–4.6 g CH4 s−1 km−2. Large emissions averaging 34 g CH4/s per well were observed from seven well pads determined to be in the drilling phase, 2 to 3 orders of magnitude greater than US Environmental Protection Agency estimates for this operational phase. The emissions from these well pads, representing ∼1% of the total number of wells, account for 4–30% of the observed regional flux. More work is needed to determine all of the sources of methane emissions from natural gas production, to ascertain why these emissions occur and to evaluate their climate and atmospheric chemistry impacts.

Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations

Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., and Bovensmann, H.: Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, Earths Future, 2, 548–558, https://doi.org/10.1002/2014EF000265, 2014.

Abstract

In the past decade, there has been a massive growth in the horizontal drilling and hydraulic fracturing of shale gas and tight oil reservoirs to exploit formerly inaccessible or unprofitable energy resources in rock formations with low permeability. In North America, these unconventional domestic sources of natural gas and oil provide an opportunity to achieve energy self-sufficiency and to reduce greenhouse gas emissions when displacing coal as a source of energy in power plants. However, fugitive methane emissions in the production process may counter the benefit over coal with respect to climate change and therefore need to be well quantified. Here we demonstrate that positive methane anomalies associated with the oil and gas industries can be detected from space and that corresponding regional emissions can be constrained using satellite observations. On the basis of a mass-balance approach, we estimate that methane emissions for two of the fastest growing production regions in the United States, the Bakken and Eagle Ford formations, have increased by 990 ± 650 ktCH4 yr−1 and 530 ± 330 ktCH4 yr−1 between the periods 2006–2008 and 2009–2011. Relative to the respective increases in oil and gas production, these emission estimates correspond to leakages of 10.1% ± 7.3% and 9.1% ± 6.2% in terms of energy content, calling immediate climate benefit into question and indicating that current inventories likely underestimate the fugitive emissions from Bakken and Eagle Ford.

Methane emissions are under-estimated

Methane Leaks from North American Natural Gas Systems

Brandt, A. R., Heath, G. A., Kort, E. A., O'Sullivan, F., Pétron, G., Jordaan, S. M., Tans, P., Wilcox, J., Gopstein, A. M., Arent, D., Wofsy, S., Brown, N. J., Bradley, R., Stucky, G. D., Eardley, D., and Harriss, R.: Methane Leaks from North American Natural Gas Systems, Science, 343, 733–735, https://doi.org/10.1126/science.1247045, 2014.

The Environmental Costs and Benefits of Fracking

Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H., O'Sullivan, F., and Pétron, G.: The Environmental Costs and Benefits of Fracking, Annu. Rev. Environ. Resour., 39, 327–362, https://doi.org/10.1146/annurev-environ-031113-144051, 2014b.

Abstract

Unconventional oil and natural gas extraction enabled by horizontal drilling and hydraulic fracturing (fracking) is driving an economic boom, with consequences described from "revolutionary" to "disastrous." Reality lies somewhere in between. Unconventional energy generates income and, done well, can reduce air pollution and even water use compared with other fossil fuels. Alternatively, it could slow the adoption of renewables and, done poorly, release toxic chemicals into water and air. Primary threats to water resources include surface spills, wastewater disposal, and drinking-water contamination through poor well integrity. An increase in volatile organic compounds and air toxics locally are potential health threats, but the switch from coal to natural gas for electricity generation will reduce sulfur, nitrogen, mercury, and particulate air pollution. Data gaps are particularly evident for human health studies, for the question of whether natural gas will displace coal compared with renewables, and for decadal-scale legacy issues of well leakage and plugging and abandonment practices. Critical topics for future research include data for (a) estimated ultimate recovery (EUR) of unconventional hydrocarbons, (b) the potential for further reductions of water requirements and chemical toxicity, (c) whether unconventional resource development alters the frequency of well integrity failures, (d) potential contamination of surface and ground waters from drilling and spills, (e) factors that could cause wastewater injection to generate large earthquakes, and (f) the consequences of greenhouse gases and air pollution on ecosystems and human health.

Methane emissions estimate from airborne measurements over a western United States natural gas field

Karion, A., Sweeney, C., Pétron, G., Frost, G., Michael Hardesty, R., Kofler, J., Miller, B. R., Newberger, T., Wolter, S., Banta, R., Brewer, A., Dlugokencky, E., Lang, P., Montzka, S. A., Schnell, R., Tans, P., Trainer, M., Zamora, R., and Conley, S.: Methane emissions estimate from airborne measurements over a

western United States natural gas field, Geophys. Res. Lett., 40, 4393–4397, https://doi.org/10.1002/grl.50811, 2013

Abstract
Methane (CH4) emissions from natural gas production are not well quantified and have the potential to offset the climate benefits of natural gas over other fossil fuels. We use atmospheric measurements in a mass balance approach to estimate CH4 emissions of 55 ± 15 × 103 kg h−1 from a natural gas and oil production field in Uintah County, Utah, on 1 day: 3 February 2012. This emission rate corresponds to 6.2%–11.7% (1σ) of average hourly natural gas production in Uintah County in the month of February. This study demonstrates the mass balance technique as a valuable tool for estimating emissions from oil and gas production regions and illustrates the need for further atmospheric measurements to determine the representativeness of our single-day estimate and to better assess inventories of CH4 emissions

Air impacts of increased natural gas acquisition, processing, and use: a critical review

Moore, C. W., Zielinska, B., Pétron, G., and Jackson, R. B.: Air impacts of increased natural gas acquisition, processing, and use: a critical review, Environ. Sci. Technol., 48, 8349–8359, https://doi.org/10.1021/es4053472, 2014.

Abstract
During the past decade, technological advancements in the United States and Canada have led to rapid and intensive development of many unconventional natural gas plays (e.g., shale gas, tight sand gas, coal-bed methane), raising concerns about environmental impacts. Here, we summarize the current understanding of local and regional air quality impacts of natural gas extraction, production, and use. Air emissions from the natural gas life cycle include greenhouse gases, ozone precursors (volatile organic compounds and nitrogen oxides), air toxics, and particulates. National and state regulators primarily use generic emission inventories to assess the climate, air quality, and health impacts of natural gas systems. These inventories rely on limited, incomplete, and sometimes outdated emission factors and activity data, based on few measurements. We discuss case studies for specific air impacts grouped by natural gas life cycle segment, summarize the potential benefits of using natural gas over other fossil fuels, and examine national and state emission regulations pertaining to natural gas systems. Finally, we highlight specific gaps in scientific knowledge and suggest that substantial additional measurements of air emissions from the natural gas life cycle are essential to understanding the impacts and benefits of this resource.

Part III: Total Greenhouse Gas Emissions, of CO2 Emissions from Fuel Combustion

Olivier, J. G. J. and Janssens-Maenhout, G.: Part III: Total Greenhouse Gas Emissions, of CO2 Emissions from Fuel Combustion (2014 edn.), International Energy Agency, Paris, ISBN-978-92-64-21709-6., 2014

Abstract:

CO2 emissions from fuel combustion represent the majority of anthropogenic GHG emissions. However, comprehensive analysis of emission trends considers other sources of CO2 as well as other gases, knowing that data on gases and sources other than CO2 from fuel combustion are much more uncertain. Country-specific estimates of CO2 from biomass burning and F-gas emissions are particularly difficult to ascertain. To complement work regarding the emissions of CO2 from fuel combustion, the IEA also included EDGAR data on other CO2 sources and on five other greenhouse gases; methane (CH4), nitrous oxide (N2O) and the fluorinated gases (or "F-gases") HFCs, PFCs and SF6, all gases addressed by the Kyoto Protocol.The Main changes in this edition are that CO2 emissions from carbon released in fossil fuel use, labelled in the sectoral energy balance as 'non-energy use' or 'chemical feedstock', in addition to CO2 emissions of fugitive nature are now taken from the EDGAR4.3.2 dataset.The information in Part III (with the exception of CO2 emissions from fuel combustion) has been provided by Jos G.J. Olivier from the PBL Netherlands Environmental Assessment Agency and Greet Janssens-Maenhout from the Joint Research Centre (JRC) of the European Commission, using the EDGAR database (version 4.3.2 for CO2 emissions and 4.2FT2010 for other gases) developed jointly by JRC and PBL. Please note that the GHG emissions totals presented here will differ from those shown in countries' official national inventory submissions to the UNFCCC. This is primarily due to differences in coverage for the cat-egory Other. However, this may also occur due to differences in allocation, methodologies, and underlying data sources for activities and emission factors, as specified in Part III, chapter Sources and Methods. Details on possible differences between IEA and UNFCCC CO2 emissions from fuel combustion estimates can be found in Part I. Details on causes of differences in other GHG emissions can also be found in Part III.

A new look at methane and nonmethane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin

Pétron, G., Karion, A., Sweeney, C., Miller, B. R., Montzka, S. A., Frost, G. J., Trainer, M., Tans, P., Andrews, A., Kofler, J., Helmig, D., Guenther, D., Dlugokencky, E., Lang, P., Newberger, T., Wolter, S., Hall, B., Novelli, P., Brewer, A., Conley, S., Hardesty, M., Banta, R., White, A., Noone, D., Wolfe, D., and Schnell, R.: A new look at methane and nonmethane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin, J. Geophys. Res.-Atmos., 119, 6836–6852, https://doi.org/10.1002/2013jd021272, 2014.

Abstract

Emissions of methane (CH4) from oil and natural gas (O&G) operations in the most densely drilled area of the Denver-Julesburg Basin in Weld County located in northeastern Colorado are estimated for 2 days in May 2012 using aircraft-based CH4 observations and planetary boundary layer height and ground-based wind profile measurements. Total top-down CH4 emission estimates are 25.8 ± 8.4 and 26.2 ± 10.7 t CH4/h for the 29 and 31 May flights, respectively. Using inventory data, we estimate the total emissions of CH4 from non-O&G gas-related sources at 7.1 ± 1.7 and 6.3 ± 1.0 t CH4/h for these 2 days. The difference in emissions is attributed to

O&G sources in the study region, and their total emission is on average 19.3 ± 6.9 t/h, close to 3 times higher than an hourly emission estimate based on Environmental Protection Agency's Greenhouse Gas Reporting Program data for 2012. We derive top-down emissions estimates for propane, n-butane, i-pentane, n-pentane, and benzene from our total top-down CH4 emission estimate and the relative hydrocarbon abundances in aircraft-based discrete air samples. Emissions for these five nonmethane hydrocarbons alone total 25.4 ± 8.2 t/h. Assuming that these emissions are solely originating from O&G-related activities in the study region, our results show that the state inventory for total volatile organic compounds emitted by O&G activities is at least a factor of 2 too low for May 2012. Our top-down emission estimate of benzene emissions from O&G operations is 173 ± 64 kg/h, or 7 times larger than in the state inventory.

Methane Emissions are not underestimated

Measurements of methane emissions at natural gas production sites in the United States

Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., Herndon, S. C., Kolb, C. E., Fraser, M. P., Hill, A. D., Lamb, B. K., Miskimins, J., Sawyer, R. F., and Seinfeld, J. H.: Measurements of methane emissions at natural gas production sites in the United States, P. Natl. Acad. Sci. USA, 110, 17768–17773, https://doi.org/10.1073/pnas.1304880110, 2013.

Significance

This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States. The measurements indicate that well completion emissions are lower than previously estimated; the data also show emissions from pneumatic controllers and equipment leaks are higher than Environmental Protection Agency (EPA) national emission projections. Estimates of total emissions are similar to the most recent EPA national inventory of methane emissions from natural gas production. These measurements will help inform policymakers, researchers, and industry, providing information about some of the sources of methane emissions from the production of natural gas, and will better inform and advance national and international scientific and policy discussions with respect to natural gas development and use.

Abstract

Engineering estimates of methane emissions from natural gas production have led to varied projections of national emissions. This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers). For well completion flowbacks, which clear fractured wells of liquid to allow gas production, methane emissions ranged from 0.01 Mg to 17 Mg (mean = 1.7 Mg; 95% confidence bounds of 0.67–3.3 Mg), compared with an average of 81 Mg per event in the 2011 EPA national emission inventory from April 2013. Emission factors for pneumatic pumps and controllers as well as equipment leaks were both comparable to and higher than estimates in the national inventory. Overall, if emission factors from this work for completion flowbacks, equipment leaks, and pneumatic pumps and controllers are assumed to be representative of national populations and are used to estimate national emissions, total annual emissions from these source categories are calculated to be 957 Gg of methane (with sampling and measurement uncertainties estimated at ±200 Gg). The estimate for comparable source categories in the EPA national inventory is ∼1,200 Gg. Additional measurements of unloadings and workovers are needed to produce national emission estimates for these source categories. The 957 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with EPA national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emissions from natural gas production (0.42% of gross gas production).

Correction for Allen et al., Measurements of methane emissions at natural gas production sites in the United States

Correction for “Measurements of methane emissions at natural gas production sites in the United States,” by David T. Allen, Vincent M. Torres, James Thomas, David W. Sullivan, Matthew Harrison, Al Hendler, Scott C. Herndon, Charles E. Kolb, Matthew P. Fraser, A. Daniel Hill, Brian K. Lamb, Jennifer Miskimins, Robert F. Sawyer, and John H. Seinfeld, which appeared in issue 44, October 29, 2013, of *Proc Natl Acad Sci USA* (110:17768–17773; first published September 16, 2013; 10.1073/pnas.1304880110).

The authors note that upon publication their conflict of interest statement was not complete. The updated disclosure statement is as follows, “Jennifer Miskimins holds a joint appointment with Barree & Associates and the Colorado School of Mines. She has also served as an advisor to Nexen in 2012. David T. Allen served as a consultant for the Eastern Research Group and ExxonMobil in 2012, and is the current chair of the Science Advisory Board for the EPA. John H. Seinfeld has served as a consultant for Shell in 2012. David T. Allen, Matthew Harrison, Charles E. Kolb, and Robert F. Sawyer variously serve as members of scientific advisory panels for projects supported by Environmental Defense Fund and companies involved in the natural gas supply chain. These projects are led at Colorado State University (on natural gas gathering and processing), Washington State University (on local distribution of natural gas), and the University of West Virginia (on CNG fueling and use in heavy duty vehicles).”

Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions

Peischl, J., Ryerson, T. B., Aikin, K. C., de Gouw, J. A., Gilman, J. B., Holloway, J. S., Lerner, B. M., Nadkarni, R., Neuman, J. A., Nowak, J. B., Trainer, M., Warneke, C., and Parrish, D. D.: Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions, J. Geophys. Res.-Atmos., 120, 2119–2139, https://doi.org/10.1002/2014jd022697, 2015.

Abstract

We present measurements of methane (CH4) taken aboard a NOAA WP-3D research aircraft in 2013 over the Haynesville shale region in eastern Texas/northwestern Louisiana, the Fayetteville shale region in Arkansas, and the northeastern Pennsylvania portion of the Marcellus shale region, which accounted for the majority of Marcellus shale gas production that year. We calculate emission rates from the horizontal CH4 flux in the planetary boundary layer downwind of each region after subtracting the CH4 flux entering the region upwind. We find 1 day CH4 emissions of (8.0 ± 2.7) × 107 g/h from the Haynesville region, (3.9 ± 1.8) × 107 g/h from the Fayetteville region, and (1.5 ± 0.6) × 107 g/h from the Marcellus region in northeastern Pennsylvania. Finally, we compare the CH4 emissions to the total volume of natural gas extracted from each region to derive a loss rate from production operations of 1.0–2.1% from the Haynesville region, 1.0–2.8% from the Fayetteville region, and 0.18–0.41% from the

Marcellus region in northeastern Pennsylvania. The climate impact of CH4 loss from shale gas production depends upon the total leakage from all production regions. The regions investigated in this work represented over half of the U.S. shale gas production in 2013, and we find generally lower loss rates than those reported in earlier studies of regions that made smaller contributions to total production. Hence, the national average CH4 loss rate from shale gas production may be lower than values extrapolated from the earlier studies.

Long-term measurements show little evidence for large increases in total U.S. methane emissions over the past decade.

Lan, X., Tans, P., Sweeney, C., Andrews, A., Dlugokencky, E., Schwietzke, S., et al. (2019). Long-term measurements show little evidence for large increases in total U.S. methane emissions over the past decade. *Geophysical Research Letters*, *46*, 4991–4999. https://doi.org/10.1029/2018GL081731

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018GL081731

Abstract

Recent studies show conflicting estimates of trends in methane (CH4) emissions from oil and natural gas (ONG) operations in the United States. We analyze atmospheric CH4 measurements from 20 North American sites in the National Oceanic and Atmospheric Administration Global Greenhouse Gas Reference Network and determined trends for 2006–2015. Using CH4 vertical gradients as an indicator of regional surface emissions, we find no significant increase in emissions at most sites and modest increases at three sites heavily influenced by ONG activities. Our estimated increases in North American ONG CH4 emissions (on average approximately 3.4 ± 1.4 %/year for 2006–2015, ±σ) are much smaller than estimates from some previous studies and below our detection threshold for total emissions increases at the east coast sites that are sensitive to U.S. outflows. We also find an increasing trend in ethane/methane emission ratios, which has resulted in major overestimation of oil and gas emissions trends in some previous studies.

Plain Language Summary

In the past decade, natural gas production in the United States has increased by ~46%. Methane emissions associated with oil and natural gas productions have raised concerns since methane is a potent greenhouse gas with the second largest influence on global warming. Recent studies show conflicting results regarding whether methane emissions from oil and gas operations have been increased in the United States. Based on long-term and well-calibrated measurements, we find that (i) there is no large increase of total methane emissions in the United States in the past decade; (ii) there is a modest increase in oil and gas methane emissions, but this increase is much lower than some previous studies suggest; and (iii) the assumption of a time-constant relationship between methane and ethane emissions has resulted in major overestimation of an oil and gas emissions trend in some previous studies.

Three considerations for modeling natural gas system methane emissions in life cycle assessment

https://www.sciencedirect.com/science/article/abs/pii/S0959652619307875#!

Grubert, E.A. and A.R. Brant, 2019: Three considerations for modeling natural gas system methane emissions in life cycle assessment. Journal of Cleaner Production, Volume 222, 10 June 2019, Pages 760-767.

Abstract
Natural gas is a fossil fuel accounting for about 30% of US primary energy consumption. Climate change is one of the primary environmental issues associated with natural gas use: natural gas combustion releases carbon dioxide. A less emphasized issue is that natural gas is mostly methane, a potent greenhouse gas (GHG). The climate impact of natural gas use is thus sensitive to the amount of methane that escapes from the natural gas system unburned. We call attention to three considerations for modeling natural gas-related methane emissions in life cycle assessment (LCA). First, natural gas system methane leakage is inconsistently characterized and likely systematically underestimated by commonly used life cycle inventory (LCI) databases. Second, studies are often imprecise in assumptions about process boundaries. This matters because not all natural gas uses rely on the same infrastructure and induce the same methane leakage. Third, there is not yet a stable estimate for the global warming potential (GWP) of methane. Newer estimates tend to be larger, which further exacerbates the underestimation of GHG impacts from natural gas systems. Data uncertainty is common in LCA, but natural gas-related methane emissions deserve special attention due to their influence on a decision-relevant parameter (GHG intensity) in product systems across the economy.

Three considerations for modeling natural gas system methane emissions in life cycle assessment
Natural gas is a fossil fuel accounting for about 30% of US primary energy consumption. Climate change is one of the primary environmental issues associated with natural gas use: natural gas combustion releases carbon dioxide. A less emphasized issue is that natural gas is mostly methane, a potent greenhouse gas (GHG). The climate impact of natural gas use is thus sensitive to the amount of methane that escapes from the natural gas system unburned. We call attention to three considerations for modeling natural gas-related methane emissions in life cycle assessment (LCA). First, natural gas system methane leakage is inconsistently characterized and likely systematically underestimated by commonly used life cycle inventory (LCI) databases. Second, studies are often imprecise in assumptions about process boundaries. This matters because not all natural gas uses rely on the same infrastructure and induce the same methane leakage. Third, there is not yet a stable estimate for the global warming potential (GWP) of methane. Newer estimates tend to be larger, which further exacerbates the underestimation of GHG impacts from natural gas systems. Data uncertainty is common in LCA, but natural gas-related methane emissions deserve special attention due to their influence on a decision-relevant parameter (GHG intensity) in product systems across the economy.

Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources

https://doi.org/10.1088/1748-9326/ab9ed2,

Jackson, R. B., Saunois, M., Bousquet, P., Canadell, J. G., Poulter, B., Stavert, A. R., Bergamaschi, P., Niwa, Y., Segers, A., and Tsuruta, A.: Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources, Environ. Res. Lett., in press, https://doi.org/10.1088/1748-9326/ab9ed2, 2020.

Conclusions

Methane emissions have continued to rise over the past decade and are tracking concentrations most consistent with the warmest marker scenario of the Intergovernmental Panel on Climate Change (RCP8.5, a representative concentration pathway) that yields an estimated global warming of 4.3 °C by year 2100 (Saunois et al 2016b, 2020, Nisbet et al 2019). Current trajectories in socioeconomic development also suggest the world is likely to follow IPCC Shared Socioeconomic pathways (SSP) leading to relatively higher emission trajectories over the next decade (Saunois et al 2020). Estimates for 2018 and 2019 show increases in atmospheric methane of 8.5 and 10.7 ppb, respectively, two of the four highest annual growth rates since 2000 (Dlugokencky 2020).

Increased emissions from both the agriculture and waste sector and the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner et al 2019), atmospheric chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.

Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York

https://doi.org/10.1080/1943815X.2020.1789666

Robert W. Howarth (2020): Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York, Journal of Integrative Environmental Sciences, DOI: 10.1080/1943815X.2020.1789666

Abstract

In 2019, New York State passed aggressive new climate legislation to reduce greenhouse gas (GHG) emissions and laid out major changes for how emissions are reported. One change is the inclusion of emissions from outside of the boundaries of the State if they are associated with energy use within NY; the traditional inventory considered emissions only within the State. The new legislation also mandated that methane emissions be compared with carbon dioxide over a 20-year time frame rather than the 100-year time frame previously used by NY and still used by virtually all other governments globally. This reflected the desire of NY's policymakers for a tool that evaluates emissions from the standpoint of energy consumption and that more heavily weighs the role of methane as an agent of warming over the next few decades. This paper compares emissions based on the new approach for GHG reporting with the traditional inventory. The traditional inventory is driven almost entirely by carbon dioxide emissions. As of 2015, these carbon dioxide emissions had declined by 15% since 1990 due to an 88% decrease in coal consumption and a 27% decrease in consumption of petroleum products, although consumption of natural gas had increased by 57%. Methane emissions increased by almost 30% between 1990 and 2015, largely due to the increased consumption of natural gas. According to the new GHG reporting rules, methane contributed 28% of all fossil-fuel emissions in 1990 and 37% in 2015. Total GHG emissions remained virtually unchanged from 1990 to 2015.

Anthropogenic emissions of methane in the United States

https://www.pnas.org/content/110/50/20018

Miller SM, Wofsy SC, Michalak AM, Kort EA, Andrews AE, Biraud SC, Dlugokencky EJ, Janusz Eluszkiewicz J, Fischer ML, Janssens-Maenhout G, et al. 2013. Anthropogenic emissions of methane in the United States. Proceedings of the National Academy of Sciences. 110:20018–20022. doi:10.1073/pnas.1314392110

Significance

Successful regulation of greenhouse gas emissions requires knowledge of current methane emission sources. Existing state regulations in California and Massachusetts require ∼15% greenhouse gas emissions reductions from current levels by 2020. However, government estimates for total US methane emissions may be biased by 50%, and estimates of individual source sectors are even more uncertain. This study uses atmospheric methane observations to reduce this level of uncertainty. We find greenhouse gas emissions from agriculture and fossil fuel extraction and processing (i.e., oil and/or natural gas) are likely a factor of two or greater than cited in existing studies. Effective national and state greenhouse gas reduction strategies may be difficult to develop without appropriate estimates of methane emissions from these source sectors.

Abstract

This study quantitatively estimates the spatial distribution of anthropogenic methane sources in the United States by combining comprehensive atmospheric methane observations, extensive spatial datasets, and a high-resolution atmospheric transport model. Results show that current inventories from the US Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research underestimate methane emissions nationally by a factor of ∼1.5 and ∼1.7, respectively. Our study indicates that emissions due to ruminants and manure are up to twice the magnitude of existing inventories. In addition, the discrepancy in methane source estimates is particularly pronounced in the south-central United States, where we find total emissions are ∼2.7 times greater than in most inventories and account for 24 ± 3% of national emissions. The spatial patterns of our emission fluxes and observed methane–propane correlations indicate that fossil fuel extraction and refining are major contributors (45 ± 13%) in the south-central United States. This result suggests that regional methane emissions due to fossil fuel extraction and processing could be 4.9 ± 2.6 times larger than in EDGAR, the most comprehensive global methane inventory. These results cast doubt on the US EPA's recent decision to downscale its estimate of national natural gas emissions by 25–30%. Overall, we conclude that methane emissions associated with both the animal husbandry and fossil fuel industries have larger greenhouse gas impacts than indicated by existing inventories.

Large fugitive methane emissions from urban centers along the U.S. East Coast

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL082635

Plant, G., Kort, E. A., Floerchinger, C., Gvakharia, A., Vimont, I., & Sweeney, C. (2019). Large fugitive methane emissions from urban centers along the U.S. East Coast. Geophysical Research Letters, 46, 8500–8507. https://doi.org/ 10.1029/2019GL082635

Abstract

Urban emissions remain an underexamined part of the methane budget. Here we present and interpret aircraft observations of six old and leak-prone major cities along the East Coast of the United States. We use direct observations of methane (CH4), carbon dioxide (CO2), carbon monoxide (CO), ethane (C2H6), and their correlations to quantify CH4 emissions and attribute to natural gas. We find the five largest cities emit 0.85 (0.63, 1.12) Tg CH4/year, of which 0.75 (0.49, 1.10) Tg CH4/year is attributed to natural gas. Our estimates, which include all thermogenic methane sources including end use, are more than twice that reported in the most recent gridded EPA inventory, which does not include end-use emissions. These results highlight that current urban inventory estimates of natural gas emissions are substantially low, either due to underestimates of leakage, lack of inclusion of end-use emissions, or some combination thereof.

Plain Language Summary

Recent efforts to quantify fugitive methane associated with the oil and gas sector, with a particular focus on production, have resulted in significant revisions upward of emission estimates. In comparison, however, there has been limited focus on urban methane emissions. Given the volume of gas distributed and used in cities, urban losses can impact national-level emissions. In this study we use aircraft observations of methane, carbon dioxide, carbon monoxide, and ethane to determine characteristic correlation slopes, enabling quantification of urban methane emissions and attribution to natural gas. We sample nearly 12% of the U.S. population and 4 of the 10 most populous cities, focusing on older, leak-prone urban centers. Emission estimates are more than twice the total in the U.S. EPA inventory for these regions and are predominantly attributed to fugitive natural gas losses. Current estimates for methane emissions from the natural gas supply chain appear to require revision upward, in part possibly by including end-use emissions, to account for these urban losses.