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Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain

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Abstract

Methane emissions from the U.S. oil and natural gas supply chain were estimated 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 Tg/y, equivalent to 2.3% of gross U.S. gas production. This value is ~60% higher than the U.S. EPA 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 CO_2 from natural gas combustion. Significant emission reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems.

One Sentence Summary:

A synthesis of recent measurements shows that methane emissions from the U.S. oil and natural gas supply chain exceed U.S. EPA estimates by ~60%.

Methane (CH_4) is a potent greenhouse gas, and CH_4 emissions from human activities since pre-industrial times are responsible for 0.97 W m^{-2} of radiative forcing, as compared to 1.7 W m^{-2} for carbon dioxide (CO_2) (1). CH_4 is removed from the atmosphere much more rapidly than CO_2, thus reducing CH_4 emissions can effectively reduce the near-term rate of warming (2). Sharp growth in U.S. oil and natural gas (O/NG) production beginning around 2005 (3) raised concerns about the climate impacts of increased natural gas use (4, 5). By 2012, disagreement among published estimates of CH_4 emissions from U.S. natural gas operations led to a broad consensus that additional data were needed to better characterize emission rates (4–7). A large body of field measurements made between 2012 and 2016 (Table S1) has dramatically improved understanding of the sources and magnitude of CH_4 emissions from the industry's operations. Brandt *et al.* summarized the early literature (8); other assessments incorporated elements of recent data (9–11). This work synthesizes recent studies to provide an improved overall assessment of emissions from the O/NG supply chain, which we define to include all operations associated with oil and natural gas production, processing and transport (Section S1.0) (12).

Measurements of O/NG CH_4 emissions can be classified as either top-down (TD) or bottom-up (BU). TD studies quantify ambient methane enhancements using aircraft, satellites or tower networks and infer aggregate emissions from all contributing sources across large geographies. TD estimates for nine O/NG production areas have been reported to date (Table S2). These areas are distributed across the U.S. (Fig. S1) and account for ~33% of natural gas, ~24% of oil production, and ~14% of all wells (13). Areas sampled in TD studies also span the range of hydrocarbon characteristics (predominantly gas, predominantly oil, or mixed), as well as a range of production characteristics such as well productivity and maturity. In contrast, BU studies generate regional, state, or national emission estimates by

aggregating and extrapolating measured emissions from individual pieces of equipment, operations, or facilities, using measurements made directly at the emission point or, in the case of facilities, directly downwind.

Recent BU studies have been performed on equipment or facilities that are expected to represent the vast majority of emissions from the O/NG supply chain (Table S1). In this work we integrate the results of recent facility-scale BU studies to estimate CH_4 emissions from the U.S. O/NG supply chain, and then we validate the results using TD studies (Section S1). The probability distributions of our BU methodology are based on observed facility-level emissions, in contrast to the component-by-component approach used for conventional inventories. We thus capture enhancements produced by all sources within a facility, including the heavy tail of the distribution. When the BU estimate is developed in this manner, direct comparison of BU and TD estimates of CH_4 emissions in the nine basins for which TD measurements have been reported indicates agreement between methods, within estimated uncertainty ranges (Fig. 1).

Our national BU estimate of total CH_4 emissions in 2015 from the U.S. O/NG supply chain is 13 (+2.1/−1.6, 95% confidence interval) Tg CH_4/y (Table 1). This estimate of O/NG CH_4 emissions can also be expressed as a production-normalized emission rate of 2.3% (+0.4%/ −0.3%) by normalizing by gross natural gas production (33 tcf/y, (13) with average CH_4 content of 90 vol%). Roughly 85% of national BU emissions are from production, gathering, and processing sources, which are concentrated in active O/NG production areas.

Our assessment does not update emissions from local distribution and end use of natural gas, due to insufficient information addressing this portion of the supply chain. However, recent studies suggest that local distribution emissions are significant, exceeding the current inventory estimate (14–16), and that end-user emissions might also be important. If these findings prove to be representative, overall emissions from the natural gas supply chain would increase relative to the value in Table 1 (Section S1.5).

Our BU method and TD measurements yield similar estimates of U.S. O/NG CH_4 emissions in 2015, and both are significantly higher than the corresponding estimate in the U.S. Environmental Protection Agency's Greenhouse Gas Inventory (EPA GHGI) (Table 1, Section S1.3) (17). Discrepancies between TD estimates and the EPA GHGI have been reported previously (8, 18). Our BU estimate is 63% higher than the EPA GHGI, largely due to a more than two-fold difference in the production segment (Table 1). The discrepancy in production sector emissions alone is ~4 Tg CH_4/y, an amount larger than the emissions from any other O/NG supply chain segment. Such a large difference cannot be attributed to expected uncertainty in either estimate: the extremal ends of the 95% confidence intervals for each estimate differ by 20% (i.e., ~12 Tg/y for the lower bound of our BU estimate can be compared to ~10 Tg/y for the upper bound of the EPA GHGI estimate).

We believe the reason for such large divergence is that sampling methods underlying conventional inventories systematically underestimate total emissions because they miss high emissions caused by abnormal operating conditions (e.g., malfunctions). Distributions of measured emissions from production sites in BU studies are invariably "tail-heavy", with

large emission rates measured at a small subset of sites at any single point in time (19–22). The difference between the EPA GHGI and BU estimates derived from facility-level measurements is explained if measurements used to develop GHGI emission factors under-sampled abnormal operating conditions encountered during the BU work. Component-based inventory estimates like the GHGI have been shown to underestimate facility-level emissions (23), probably because of the technical difficulty and safety and liability risks associated with measuring large emissions from, for example, venting tanks such as those observed in aerial surveys (24).

Abnormal conditions causing high CH_4 emissions have been observed in studies across the O/NG supply chain. An analysis of site-scale emission measurements in the Barnett Shale concluded that equipment behaving as designed could not explain the number of high-emitting production sites in the region (23). An extensive aerial infrared camera survey of ~8,000 production sites in seven U.S. O/NG basins found that ~4% of surveyed sites had one or more observable high emission-rate plumes (24) (detection threshold of ~3–10 kg CH_4/h was 2–7 times higher than mean production site emissions estimated in this work). Emissions released from liquid storage tank hatches and vents represented 90% of these sightings. It appears that abnormal operating conditions must be largely responsible, because the observation frequency was too high to be attributed to routine operations like condensate flashing or liquid unloadings alone (24). All other observations were due to anomalous venting from dehydrators, separators and flares. Notably, the two largest sources of aggregate emissions in the EPA GHGI – pneumatic controllers and equipment leaks – were never observed from these aerial surveys. Similarly, a national survey of gathering facilities found that emission rates were four times higher at the 20% of facilities where substantial tank venting emissions were observed, as compared to the 80% of facilities without such venting (25). In addition, very large emissions from leaking isolation valves at transmission and storage facilities were quantified using downwind measurement but could not be accurately (or safely) measured using on-site methods (26). There is an urgent need to complete equipment-based measurement campaigns that capture these large emission events, so that their causes are better understood.

Outdated component emission factors and temporal bias are unlikely to explain the difference between our facility-based BU estimate and the GHGI. First, an equipment-level inventory analogous to the EPA GHGI but updated with recent direct measurements of component emissions (Section S1.4) predicts total production emissions that are within ~10% of the EPA GHGI, although the contributions of individual source categories differ significantly (Table S3). Second, we consider unlikely an alternative hypothesis that systematically higher emissions during daytime sampling cause a high bias in TD methods (Section S1.6). Two other factors may lead to low bias in EPA GHGI and similar inventory estimates. Operator cooperation is required to obtain site access for emission measurements (8). Operators with lower-emitting sites are plausibly more likely to cooperate in such studies, and workers are likely to be more careful to avoid errors or fix problems when measurement teams are on site or about to arrive. The potential bias due to this "opt-in" study design is very challenging to determine. We therefore rely primarily on site-level, downwind measurement methods with limited or no operator forewarning to construct our BU estimate. Another possible source of bias is measurement error. It has been suggested

that malfunction of a measurement instrument widely used in the O/NG industry contributes to underestimated emissions in inventories (27); however, this cannot explain the >2× difference in production emissions (28).

The tail-heavy distribution for many O/NG CH_4 emission sources has important implications for mitigation since it suggests that most sources – whether they represent whole facilities or individual pieces of equipment – can have lower emissions when they operate as designed. We anticipate that significant emissions reductions could be achieved by deploying well-designed emission detection and repair systems that are capable of identifying abnormally operating facilities or equipment. For example, pneumatic controllers and equipment leaks are the largest emission sources in the O/NG production segment exclusive of missing emission sources (38% and 21%, respectively; Table S3) with malfunctioning controllers contributing 66% of total pneumatic controller emissions (Section S1.4) and equipment leaks 60% higher than the GHGI estimate.

Gathering operations, which transport unprocessed natural gas from production sites to processing plants or transmission pipelines, produce ~20% of total O/NG supply chain CH_4 emissions. Until the publication of recent measurements (29), these emissions were largely unaccounted by the EPA GHGI. Gas processing, transmission and storage together contribute another ~20% of total O/NG supply chain emissions, most of which come from ~2,500 processing and compression facilities.

Our estimate of emissions from the U.S. O/NG supply chain (13 Tg CH_4/y) compares to the EPA estimate of 18 Tg CH_4/y for all other anthropogenic CH_4 sources (17). Natural gas losses are a waste of a limited natural resource (~\$2 billion/y), increase global levels of surface ozone pollution (30), and significantly erode the potential climate benefits of natural gas use. Indeed, our estimate of CH_4 emissions across the supply chain, per unit of gas consumed, results in roughly the same radiative forcing as does the CO_2 from combustion of natural gas over a 20-year time horizon (31% over 100 years). Moreover, the climate impact of 13 Tg CH_4/y over a 20-year time horizon roughly equals that from the annual CO_2 emissions from all U.S. coal-fired power plants operating in 2015 (31% of the impact over a 100-year time horizon) (Section S1.7).

We suggest that inventory methods would be improved by including the substantial volume of missing O/NG CH_4 emissions evident from the large body of scientific work now available and synthesized here. Such empirical adjustments based on observed data have been previously used in air quality management (31).

The large spatial and temporal variability in CH_4 emissions for similar equipment and facilities (due to equipment malfunction and other abnormal operating conditions) reinforces the conclusion that significant emission reductions are feasible. Key aspects of effective mitigation include pairing well-established technologies and best practices for routine emission sources with economically viable systems to rapidly detect the root causes of high emissions arising from abnormal conditions. The latter could involve combinations of current technologies such as on-site leak surveys by company personnel using optical gas imaging (32), deployment of passive sensors at individual facilities (33, 34) or mounted on

ground-based work trucks (35), and *in situ* remote sensing approaches using tower networks, aircraft or satellites (36). Over time, the development of less failure-prone systems would be expected through repeated observation of and further research into common causes of abnormal emissions, followed by re-engineered design of individual components and processes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments:

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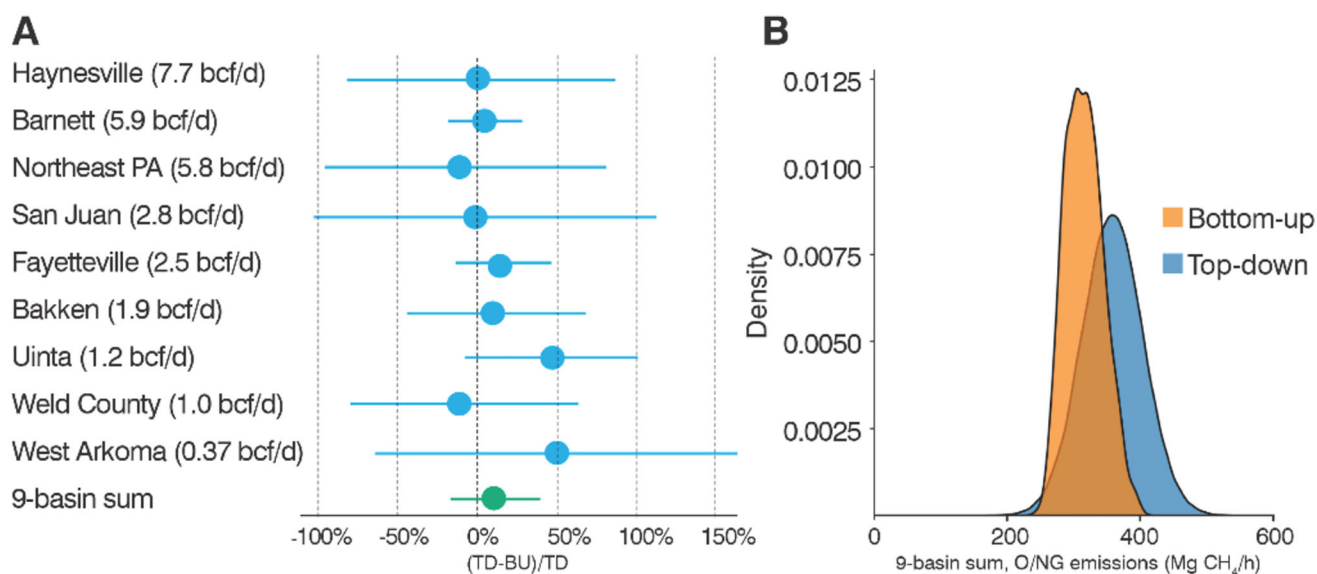
Figure 1.
Comparison of this work's bottom-up (BU) estimates of methane emissions from oil and natural gas (O/NG) sources to top-down (TD) estimates in nine U.S. O/NG production areas. (O/NG) sources to top-down (TD) estimates in nine U.S. O/NG production areas. A: relative differences of the TD and BU mean emissions, normalized by the TD value, rank ordered by natural gas production in billion cubic feet per day (bcf/d, where 1 bcf = 2.8×10^7 m^3). Error bars represent 95% confidence intervals. B: distributions of the 9-basin sum of TD and BU mean estimates (blue and orange probability density, respectively). Neither the ensemble of TD-BU pairs (A) nor the 9-basin sum of means (B) are statistically different (p=0.13 by a randomization test, and mean difference of 11% [95% confidence interval of −17% to 41%]).

Table 1.

Summary of this work's bottom-up estimates of CH4 emissions from the U.S. oil and natural gas (O/NG) supply chain (95% confidence interval) and comparison to the EPA Greenhouse Gas Inventory (GHGI).

Industry segment	2015 CH$_4$ Emissions (Tg/y)	
	This work (bottom-up)	EPA GHGI (17)
Production	7.6 (+1.9/−1.6)	3.5
Gathering	2.6 (+0.59/−0.18)	2.3
Processing	0.72 (+0.20/−0.071)	0.44
Transmission and Storage	1.8 (+0.35/−0.22)	1.4
Local Distribution [*]	0.44 (+0.51/−0.22)	0.44
Oil Refining and Transportation [*]	0.034 (+0.050/−0.008)	0.034
U.S. O/NG total	13 (+2.1/−1.7)	8.1 (+2.1/−1.4)[†]

[*] This work's emission estimates for these sources are taken directly from the GHGI. The local distribution estimate is expected to be a lower bound on actual emissions and does not include losses downstream of customer meters due to leaks or incomplete combustion (Section S1.5).

[†] The GHGI only reports industry-wide uncertainties.