# U.S. Methane Leakage from Natural Gas Systems: A Literature Review

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## Introduction

Here we present a review and short summary of the literature on methane leakage over the natural gas lifecycle. The review includes journal articles, government reports, NGO reports, and industry reports. The review generally focuses on research and data collected after 2010, with some exceptions for important earlier papers.

Over the past 20 years, EPA has been active in attempting to determine the source of methane emissions from different industry sectors, the impact of methane emissions to the climate and how to characterize methane emissions from known industrial processes. EPA does not currently regulate methane, but does require reporting from industry in order to comply with its mandate to report total US greenhouse gas (GHG) emissions to the United Nations on a yearly basis. In addition, EPA is quickly moving to control GHGs. As part of this effort, EPA is attempting to characterize the emissions from different processes and stages of the natural gas lifecycle using emissions factors and possibly other methods. Currently most of the disagreement is about the extent of methane emissions and the impact this will have on the climate. Most of the papers below address the extent of leakage during the natural gas lifecycle. There are two main approaches that scientists and engineers take. The first approach is a bottom up modeling of the different processes in the natural gas lifecycle using, usually EPA, emissions factors. Significant concern has begun to arise, however, that the data in the bottom-up approach is based on engineering calculations and/or approximately measured volumes, and has not been comprehensively measured to verify emissions from a wide variety of wells. As such, there has been increasing attention paid to top-down modeling, which takes aggregated data, such as atmospheric methane measurements, and uses models to determine the sources of these gases. In many cases, the top-down measurements have revealed methane concentrations near gas basins that are several orders of magnitude higher than official estimates based on the bottom up approach.

The other major source of disagreement is whether it is important to consider climate change on a 20-year scale or a 100-year scale. Methane has a much greater impact over a 20-year period than a 100-year period due to its relatively short life in the atmosphere. IPCC reports impacts from climate gases on a 100-year time scale but clearly states that this does not mean that other time scales are unimportant. In their latest report, they say that "there is no scientific argument for selecting 100 years compared with other choices…The choice of time horizon is a value judgment because it depends on the relative weight assigned to effects at different times." Many researchers and policy makers, however, believe that the 20-year time period is more important than the 100-year time period for policy purposes. Given the fact that the IPCC also warned in their latest report that global GHG emissions will have to fall between 40 to 70 percent within the first half of this century to avoid irreversible climate “tipping points,” there is a compelling scientific rationale for using the 20-year timeframe when setting emissions reduction goals.

Nearly all of the researchers from industry, government and academia agree that more data is necessary from all stages of the natural gas lifecycle (except during combustion) and that no one is quite sure how much methane is leaking. Few direct measurements have been made, but the few that have emerged recently from academic and government bodies suggest that official estimates may be substantially underestimating leakage in many cases. EPA has already began the next step in updating their inventory, which is to develop more accurate emission factors and to consider better measurement techniques.

## <u>Section I: Unpublished Sources</u>

**Search Term: "natural gas" methane emissions -news_tracker -"funding opportunity" -coalbed -"coal bed" -hydrates**

### Greenhouse Gas Emissions Reporting From The Petroleum And Natural Gas Industry[1]

“First update on emission factors by the agency since 1996 (Harrison et al.1996). The earlier report served as the basis for the national GHG inventory for the past decade. However, that study was not based on random sampling or a comprehensive assessment of actual industry practices, but rather only analyzed facilities of companies that voluntarily participated (Kirchgessner et al. 1997). The new EPA (2010) report notes that the 1996 “study was conducted at a time when methane emissions were not a significant concern in the discussion about GHG emissions” and that emission factors from the 1996 report “are outdated and potentially understated for some emissions sources.” Indeed, emission factors presented in EPA (2010) are much higher, by orders of magnitude for some sources.”

### EPA: White Papers on Methane and VOC Emissions

Published by EPA in April 2014 for external peer review. White papers include five technical white papers on potentially significant sources of emissions in the oil and gas sector. The papers are guidelines for estimating emissions from the following sources:

- Compressors
- Emissions from completions and ongoing production of hydraulically fractured oil wells
- Leaks
- Liquids unloading
- Pneumatic devices

Input on the papers is due by June 16, 2014.

### Characterizing Pivotal Sources of Methane Emissions from Unconventional Natural Gas Production Summary and Analysis of API and ANGA Survey Responses[2]

Published by the American Natural Gas Association and the American Petroleum Institute on the website of the American Petroleum Institute website on June 1, 2012 by consultants from the URS Corporation and the Levon Group. Industry produced report on methane emissions during 2010 based on data from surveys responses from 20 companies covering nearly 91,000 wells. The companies self-reported emissions aggregates for regions within which wells were located. ANGA distributed two surveys. The first survey asked for "high-level information on the total number of operating gas wells, the number of gas well completions, and the number of gas well workovers with hydraulic fracturing". The second survey requested data on "more detailed well information about key activities" such as liquid unloading rates, venting times, gas pressure, etc. All information was sent to the consultant who indicated that they would keep the information confidential including from their clients, the API and ANGA. The paper was not peer-reviewed, there were no checks on the accuracy of the survey data submitted and there was no mention of methods used to keep data confidential from the client or the public other than stating in the survey that "company confidential information will be protected " and that "neither API nor ANGA will review member data sent as a response to this request". The survey results suggest that the methane emissions for 2010 from liquid unloading were about 86% less than the emissions reported by EPA, the number of re-fractures for unconventional wells was overestimated by EPA and the true methane emissions were 72% less than the emissions reported by EPA, and the total methane emissions for the natural gas industry are 50% lower than the methane emissions reported by EPA.

**Life Cycle Greenhouse Gas Inventory of Natural Gas Extraction, Delivery and Electricity Production[3]**

Published online by the National Energy and Technology Laboratory in 2011. The study relies on 2011 EPA emissions factors and EIA resource data to perform an ISO 14040 compliant bottom up natural gas LCA of methane emissions. The study considers two endpoints: 1) cradle-to-gate, which includes acquisition and transport; and 2) cradle-to-grave, which includes cradle-to-gate as well as energy conversion and product transport. The study results suggest that cradle-to-gate GHG emissions of conventional and unconventional natural gas are nearly equal to one another at about 33 lbs.$CO_2e$/MMBtu for the IPCC 100-year GWPs and 81 lbs.$CO_2e$/MMBtu for the IPCC 20-year GWPs . This corresponds to fugitive and vented or flared emissions of 2.3% of total production for unconventional natural gas and just under 1% for conventional natural gas when factoring in EURs. The authors point out that "losses of … methane to the atmosphere during the extraction, transmission, and delivery of natural gas to end users made up 32 percent of U.S. 2009 total methane emissions, and 3 percent of all greenhouse gases". The authors also show that "compared on an upstream energy basis, natural gas has higher GHG emissions than coal …, natural gas is nominally 116 percent more greenhouse gas intense [on an upstream basis] than coal." However, the paper ends up concluding that under most scenarios natural gas will have a lower GWP than coal on 20-year or 100-year basis, but that there are exceptions depending on the combustion and carbon capture technology employed in the two plants under comparison. The report recommends that emissions can be reduced by improving compressor efficiency during transportation, reducing fugitive emissions during transportation, improved power plant efficiency, and implementing carbon capture technology. The report also suggests flaring to reduce methane emissions.

Estimate: EPA overestimates total LCA emissions, but underestimates upstream emissions
Method: BU
Citations: 16

**Life Cycle Greenhouse Gas Emissions from Shale Gas Compared to Coal: An Analysis of Two Conflicting Studies**[4]

An article published by the Post Carbon Institute compares the NETL study to the 2011 study by Howarth, et al. The article concludes that the two studies end up with similar results if the NETL model accounts for the increased use of shale gas and uses the same data for Estimated Ultimate Recoveries (EURs), provided by EIA, for both studies and the same 2009 EPA fugitive emissions inventories. The article points out that the NETL study is not peer-reviewed and it is not clear where the authors obtain their input factors for calculating fugitive emissions. The only way the author of this analysis was able to compare the two studies was by using a "a slide deck (i.e., a PowerPoint presentation) that has not been peer-reviewed, includes many input parameters of conventional and unconventional gas (slides 21-23); yet the sources of the values assigned are mostly not cited in the presentation". Another criticism is that NETL assumed a high EUR for shale gas wells that is over twice the EUR estimated by the EIA, reducing underestimated unconventional leakage percentages by up to one half. The author adjusts NETLs calculations to the same EIA EURs for shale gas wells used by Howarth, et al. (1.24 bcf average lifetime production for Barnett Shale) and the resulting emissions are 4.40%, when also adjusting for EPA's 2009 emission inventory to calculate fugitive emissions the leakage rate goes up to 6.35% of total emissions. These estimates are in line with the study by Howarth, et al., which estimated leakage rates at between 3.6% and 7.9% of total production. The author also found that NETL "used a higher average efficiency of gas-fired electricity generation of 47.1% by excluding plants with a capacity factor of less than 40%". Adjusting NETLs model to account for lower efficiencies of natural gas power plants (the plants we have, not the plants we want to build), the existing natural gas power plants would "exceed the existing U.S. coal fleet emissions by 9% to 27%" on a 20-year time frame. When comparing the most efficient natural gas plants to the most efficient coal power plants, the natural gas power plants produce between 17% and 34% higher GHG emissions. "When compared on the basis of the average efficiency of the U.S. gas- and coal-fired electricity generation fleets, and on the basis of most-efficient-technology gas and coal, shale gas clearly has higher emissions over a 20-year timeframe and lower emissions over a 100-year timeframe."

**Methane emissions from natural gas systems**[5]

Published online in 2012 as a background paper prepared for the National Climate Assessment by researchers from Cornell University, NASA Goddard Space Institute, Boston University, and the University of Cincinnati. The paper summarizes the literature pertaining to methane emissions from natural gas systems and their effect on climate. The authors explain why short-term methane emissions can drive a positive feedback in climate change potential. A 1.8$^{o}$ C increase in temperature from the baseline established at the end of the 19$^{th}$ century would melt ice caps that would then, in turn, release methane producing an accelerated warming trend. The paper points out that natural gas accounts for 40% of the anthropogenic U.S. methane emissions. The authors explain that EPA (2011) assumes that on average methane extracted from a particular well will leak 2.6% of the total methane that the well will produce over the entire lifecycle of the fuel. Of this, only 0.9% comes from downstream emissions [transmission and distribution]. The authors then summarize estimates of downstream natural gas emissions from various studies and point out that "recent estimates in the peer-reviewed literature for downstream emissions of methane from natural gas systems range from 0.07% to 10% of the methane produced over the lifetime of a well". Estimate for upstream and midstream emissions [here this refers to emissions from the well site and the processing facility] are "fairly [close] to the new EPA estimate of 1.6%" for conventional wells and "vary from 0.6% to 4.0%" for unconventional wells. The authors note that most of these estimates are based on "sparse and poorly documented data" and that only the Pétron et al. (2012) study measured emissions from a production field. The authors recommend "the Petron et al. (2012) study should be repeated in other unconventional gas fields". Finally, the authors explain why a 20-year GWP is important because we may "reach critical tipping points in the climate system, on the time scale of 18 to 38 years".

**Leaking Profits: The U.S. Oil and Gas Industry Can Reduce Pollution, Conserve Resources, and Make Money by Preventing Methane Waste[6]**

Published online in March 2012 by the Natural Resource Defense Council by researchers from Harvey Consulting and the Natural Resource Defense Council. This report attempts to catalogue the total potential for emissions reductions using EPA's Natural Gas STAR Program. The report looks at each of ten control technologies in the STAR program and the emission source that it is designed to control. The report then estimates the emissions from each phase of the natural gas lifecycle and the STAR technology (ies) that could be used to control emissions from that phase and the percentage of emissions that can be captured and controlled through the STAR program. The report finds that 88% of fugitive and vented methane emissions can be captured and controlled with the largest gains from Green Completions and plunger systems. The report then goes on to point out that there is a lot of uncertainty around fugitive and vented emissions. The authors explain how EPA initially vastly underestimated fugitive and vented emissions from the wellpad with industry reports of reduced emissions using green completions showing "gas recovery estimates more than 1,000 times higher than the 3 Mcf of gas per well estimated in the *2008 Greenhouse Gas Inventory*". At that time, companies that reported these large emissions reductions include BP ("green completions at 106 wells and reported 3,300 Mcf of gas recovered per well"), "Devon Barnett Shale employed green completions at 1,798 wells between 2005 and 2008 and reported 6,300 Mcf of gas recovery per well", and "Williams [who] employed green completions at 1,064 wells in the Piceance Basin and reported 23,000 Mcf of gas recovered per well". The report recounts how EPA has continued to make adjustments in their methane emissions estimates, usually adjusting upwards. "Revised emissions estimates range from 11 times higher for well venting from liquids unloading, to 36 times higher for gas well venting from conventional well completions, to 3,540 and 8,800 times higher for gas well venting during well workovers and completions of unconventional wells, respectively." The report performs an economic analysis on all of the STAR technologies and determines a potential profit and time for payout. Timescales for turning a profit on a particular technology range from less than 6 months to 3 years. The report has descriptions of each of the ten technologies with flow diagrams, photographs, emissions reduction potential and profitability. Finally, the authors make policy and regulatory recommendations including that EPA should regulate methane directly, provide a more detailed breakdown of emissions reduction achieved through the STAR program, and make the STAR program mandatory. The Federal Bureau of Land Management should "exercise their authority and responsibility to control methane waste from oil and gas lease operations on federal lands." States should follow the examples of Colorado, Wyoming and Montana and require the use of methane control technologies.

**U.S. Natural Gas System Methane Emissions: State of Knowledge from LCAs, Inventories, and Atmospheric Measurements**[7]

Presented in April 2014 as a lecture in a mechanical engineering seminar at Colorado State University by a researcher from the National Renewable Energy Laboratory. It is unclear if this is a paper in progress. The presentation summarizes the debate on natural gas leakage and analyzes the results of previous studies. Three main results are that 1) "total U.S. [methane] emissions are larger than those estimated by EPA inventory," 2) "national-scale atmospheric studies suggest that [methane] emissions are 50% [25% - 75%] higher than EPA estimates," and 3) "excess [methane] emissions from the natural gas industry are very likely to contribute to the total excess". The author looked at all studies that generated original observations and computed an emissions flux that was then compared to a published inventory. Plots were generated comparing the magnitude of emissions (log scale) to the ratio of observed to expected emissions [measured emissions / inventory emissions] for each source in each study. Any observation with a ratio to published inventory data over 1 meant more methane was measured than expected. Anything less than one meant less methane was measured than expected. Because various studies compared results to various inventories or baselines, the author modified the results to compare them to the 2013 EPA Greenhouse Gas Inventory (GHGI) for regions and sectors. Normalized results "suggest overall emissions of [methane] of ~1.5 (1.25-1.75) times those of EPA estimates". Natural gas specific studies also find that both "top-down and bottom-up tend [to have a ratio greater than 1]", although it is unclear how much of this "overall excess is due to the NG system". The analysis of the data suggests from bottom up studies that most systems do not leak, that a small fraction of devices do leak, and that a "very small fraction (<<1%) leak a large amount". These "super-emitters" account for a large fraction of the total leakage. One example of this result was that "50 out of 75,000 source points (0.06%) resulted in 60% of all emissions." It is unclear from the slides what the source is in this summary.

## Section II: Academic Sources

**Search Term: leakage shale "natural gas" production "methane emissions" -rice**
**541 results – Results were reviewed and the following list was developed.**
**The review included all papers that cite papers on this list.**
**Key: [EPA Estimate (LT, EQ, GT )], [Method (Bottom Up (BU)/Top Down (TD))], [Journal Impact Factor (JIF) (number)], [Citations (number)]**

Key Definitions

**Estimate** states whether the authors believe EPA underestimated, overestimated or accurately assessed emissions in their latest annual report. If the paper does not make a comparison or if it is not applicable, the field contains "NA".

**Method.** Bottom Up and Top Down refer to whether the paper attempts to determine leakage through process engineering calculations and direct measurements at the site of the activity (bottom up) or through measuring ambient levels of methane and relating these measurements to leakage at activity sites (top down).

**Journal Impact factor (JIF)** is a measurement of the impact of a journal and is calculated by dividing the number of citations for papers in a journal by the number of citable papers published in a journal over the prior two year period. The impact factor included in this paper is the 2012 impact factor from www.impactfactorsearch.com.
**Citations** refers to the number of academic papers that cite the paper in question.

**Estimate of Methane Emissions from the US Natural Gas Industry**[8]
Published in the journal *Chemosphere* in 1997 by researchers from the Environmental Protection Agency, the Gas Research Institute and the Radian Corporation. The attempted to estimate methane emissions from the natural gas industry to within an accuracy of ± 0.5% of production using1992 as a "base year" to calibrate the model developed by the team. The bottom up model developed by the researchers estimates emissions from all phases of the natural gas lifecycle upstream of consumption including production, processing, transmission and distribution. However, not all segments of each phase of the lifecycle were included in the model and the authors acknowledge that "some high emission rate items of equipment … have been excluded". As part of the study emissions factors for leakage were determined using three different methods for steady sources with constant emissions. The first was by screening nearly 200,000 components at 33 facilities throughout the country measuring total hydrocarbons and correlating that to methane. The second method was to use a high-flow sampler to take air samples and then to directly measure methane within the air samples. The third method was used at metering and pressure regulating stations and employed a tracer gas. The gas was monitored downwind and correlated with emissions. For unsteady sources, estimates were calculated using related parameters and taking into account differences in these parameters between various sites. Two examples of unsteady sources were blowdown events and maintenance activities. The results for the baseline year (1992) were that 1.42% ± 0.47 of total production was leaked as emissions.

Table 3: Summary of Methane Emissions (Transposed)

| **Segment** | **Emissions Bscf ($10^9$ $M^3$)** | **Percent of Total Emissions (%)** | **Emissions as a Percent of Gross National Production (1992)**[a] |
|---|---|---|---|
| Production | 84.4 ± 37.0[b] (2.39 ± 1.05) | 26.8 ± 11.8 | 0.38 ± 0.17 |
| Processing | 36.4 ± 20.6 (1.03 ± 0.58) | 11.6 ± 6.6 | 0.16 ± 0.09 |
| Transmission/Storage | 116.5 ± 58.0 (3.30 ± 1.64) | 37.1 ± 18.5 | 0.53 ± 0.26 |
| Distribution | 77.0 ±53.6 (2.18 ± 1.52) | 24.5 ± 17.1 | 0.35 ± 0.24 |
| **Total** | **314 ± 105**[c] **(8.89 ± 2.97)** | **100.0 ± 33.4** | **1.42 ± 0.47** |

a 1992 Gross national production = 22,132 Bscf (626.8 x $10^9$ $m^3$).
b Precision is based on a 90% confidence interval, assuming a normal distribution.
c Total precision is based on a 90% confidence interval, with more conservative assumptions.

When these emission factors were developed the authors point out that "Our emission estimate … is approximately twice the two previous estimates for the U.S. gas industry". The authors focus on previous underestimates of fugitive emissions due to lack of data, which was not a problem for this study.

| | |
|---|---|
| Estimate: | EPA estimate of total LCA emissions |
| Method: | BU |
| JIF: | 3.137 |
| Citations: | 50 |

**Methane Leaks from North American Natural Gas Systems[9]**
Published in the journal *Science* in February 2014 by researchers from Stanford University, Harvard University, MIT, the National Oceanic and Atmospheric Administration, the National Renewable Energy Laboratory, University of Michigan, Ann Arbor, University of Colorado, Boulder, University of Calgary, Lawrence Berkley National Laboratory, University of California, Santa Barbara, and the Environmental Defense Fund. The report reviewed 20 years of technical literature on natural gas emissions in the United States and Canada. The authors estimated that regional atmospheric studies with very high emissions rates are unlikely to be representative of typical natural gas system leakage rates, but goes on to say that EPA is probably underestimating gas sector methane emissions by 50%. This corresponds to emissions of 3.6 to 7.1 of total production. The authors conclude that "improved inventory validation is crucial to ensure that supplied information is timely and accurate," and that "diligence will be required to ensure that leakage rates are low enough to achieve sustainability goals"

| | |
|---|---|
| Estimate: | 3.6 – 7.1% EUR |
| Estimate: | EPA underestimates emissions |
| Method: | NA |
| JIF: | 31.027 |
| Citations: | 9 |

**Air Impacts of Increased Natural Gas Acquisition, Processing, and Use: A Critical Review[10]**
Published in the journal *Environmental Science and Technology* in March 2014 by researchers from the Desert Research Institute, University of Colorado, Boulder, National Oceanic and Atmospheric Administration, Stanford University and Duke University. This paper summarizes the literature on air quality impacts from natural gas extraction, production and use. The summary includes various air contaminants associated with natural gas including methane. The literature review for methane covers methane leakage during the entire natural gas lifecycle for both conventional and non-conventional extraction techniques. The authors show that there is a lot of disagreement within the scientific community about the extent of methane emissions from the natural gas lifecycle. They suggest that the EPA is relying on "limited, incomplete, and sometimes outdated emission factors and activity data" to compile their annual emission inventories. They conclude by stating, "A review of 20 years of literature on methane leaks has found that the extent of leakages from North American natural gas systems may be larger than [EPA estimates]". They recommend direct air quality measurements "prior to oil and gas development", acquisition of "independent scientific data" on the "true extent" of nationwide methane leaks, compilation of an inventory of abandoned and orphaned wells to help estimate

emissions, and, finally, more "collaboration between scientists, regulators and operators" to ensure access to appropriate measurement areas.

| | |
|---|---|
| Estimate: | EPA underestimates emissions |
| Method: | NA |
| JIF: | 5.257 |
| Citations: | 0 |

**Methane and the greenhouse-gas footprint of natural gas from shale formations[11]**
Published in the journal *Climate Change Letters* in June 2011 by researchers from Cornell University. This study relied primarily on a 2010 technical greenhouse gas reporting document submitted by the petroleum and natural gas industry to the EPA and a 2010 report from the Government Accountability Office about federal oil and gas leases. The paper attempts to estimate total greenhouse gas emissions over the lifecycle of conventional and unconventional natural gas production, including production, processing, transportation and electricity and heat generation. The authors calculate that emissions are 3.6% to 7.9% of production for shale gas and 1.7% to 6% of production for conventional gas. The authors conclude that "compared to coal, the footprint of shale gas is at least 20% greater and perhaps more than twice as great on the 20-year horizon and is comparable when compared over 100 years." The authors conclude by recommending technologies to reduce methane leakage rates including plunger lifts, flash-tank separators or vapor recovery units for dehydrators, Reduced Emission Completions (RECs), better storage tanks and compressors, better leakage monitoring, and use of low-bleed pneumatics.

| | |
|---|---|
| Estimate: | 3.6 – 7.9% conventional EUR and 1.7 – 6% unconventional EUR |
| Estimate: | EPA underestimates emissions |
| Method: | BU |
| JIF: | 3.634 |
| Citations: | 319 |

**A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea[12]**
Published in the journal *Climate Change Letters* in July 2012 by researchers from Cornell University and New York based Electric Software, Inc. The authors question the results of Howarth, et al. on grounds that they overestimate the fugitive emissions from unconventional gas extraction, undervalue emissions associated with "green technologies," compare gas and coal on a heat rather than electricity producing basis and use an inappropriate time interval to compare gas to coal. The paper estimates that Howarth et al.'s assertion that natural gas has a greater climate impact than coal is only correct if "a very high methane leakage rate of 7.9% and a short global warming impact period of 20 years are selected" and concede that they "agree with Howarth et al. … that there is an obvious need for better estimates." This corresponds to a leakage rate of the total gas a well will produce of 0.7% for downstream (transmissions, storage and distribution) and 0.9% for both conventional gas wells and unconventional gas wells for upstream and midstream (well site and processing plant) (Howarth et al. 2012). They also suggest that industry flares more of the vented methane than accounted for in the

paper. The authors also point out that "scientific assessments are … encumbered by accounting conventions that relate to how gas transmission is charged to pipeline users. The results of most studies should not be considered accurate estimates that can be used for climate studies." The authors conclude by acknowledging that "It is of course possible, although we consider it highly unlikely and find no evidence to that effect, that methane emissions from wells and pipelines might be as large as Howarth et al. aver" and agree that "these leaks could be economically and relatively easily fixed."

Estimate: 1.6% EUR (0.7% transmission, storage and distribution and 0.9% production and processing)
Estimate: EPA correctly estimates or overestimates emissions
Method: NA
JIF: 3.634
Citations: 59

**Venting and leaking of methane from shale gas development: response to Cathles et al.**[13]
Published in the journal *Climate Change Letters* in July 2012 by researchers from Cornell University. Howarth et al. defend their initial paper and each of its conclusions. They point out that EPA released new estimates for lifecycle methane emissions from conventional and unconventional natural gas that are more in line with the conclusions in their paper and within the range of their estimates. They give EPA statistics asserting that less than 15% of vented gas is currently flared. Even though EPA has adjusted most of their emission factors for climate gases upward, the authors suggest that that EPA underestimates fugitive emissions from transmission, storage and distribution because "they continue to rely on the 1996 EPA study for downstream emissions." They point out that the 1996 EPA study, which EPA is planning to update, is "not based on random sampling or a comprehensive assessment of actual industry practices, but…emissions from model facilities" that voluntarily participated in the study. The authors admit that their estimates are "highly uncertain" and acknowledge that there is an "urgent need for better measurements … from all parts of the natural gas industry," but particularly during completion of unconventional wells and during storage, transmission and distribution. The authors also state that " considering methane's global warming effects on the decadal time scale is critical" and give evidence to support that statement including the need to avoid "critical tipping points in the earth's climate system".

Estimate: EPA underestimates emissions
Method: NA
JIF: 3.634
Citations: 319

**Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum**[14]
Published in the journal *Environmental Science and Technology* in November 2011 by researchers from Argonne National Laboratory. This study uses published data and estimates to determine lifecycle methane emissions from different fuel sources including coal, conventional natural gas and unconventional natural gas. The authors create a stochastic model (called

GREET) to estimate statistical ranges of emissions in order to compare the GHG emissions from different fuels to one another. The authors found that the lifecycle GHG emissions from shale gas have a 6% lower 100-year GWP than conventional gas and 33% lower than coal, but acknowledge that there is overlapping "statistical uncertainty" to their analysis. This corresponds to a leakage rate of the total gas a well will produce of 0.6% for downstream (transmissions, storage and distribution) and 2.0% for conventional gas wells and 1.3% for unconventional gas wells for upstream and midstream (well site and processing plant) (Howarth et al. 2012). However, their results agree with Howarth et al. that the 20-year GWP of natural gas is similar to coal, even using a lower GWP for methane than the one used by Howarth et al.

Estimate: 2.6% conventional wells EUR (0.6% transmission, storage and distribution and 2.0% production and processing) and 1.9% unconventional EUR (0.6% transmission, storage and distribution and 1.3% production and processing)
Estimate: EPA estimates emissions accurately
Method: BU
JIF: 5.257
Citations: 80

**Modeling the Relative GHG Emissions of Conventional and Shale Gas Production**[15]
Published in the journal *Environmental Science and Technology* in November 2011 by researchers from Shell Global Solutions based in the UK. This study is similar to the Burnham et al. study above and published in the same issue of the same journal. The authors use EPA emission factors to create a model to compare potential emissions from conventional versus nonconventional natural gas lifecycles. The model focuses on three cases, the base case for "typical" production, distribution and use for shale and convention natural gas, a sensitivity analysis varying certain parameters and a worst-case scenario. The study also makes use of the 2009 API Compendium to calculate fugitive emissions during the production, processing and transmission stages of the lifecycle; however, it is important to realize that the API Compendium is an industry resource (American Petroleum Institute) and contains lower emissions estimates than the estimates based on EPA data (provided by the authors for some phases of the lifecycle). The study estimates convention gas emissions from 487.5 to 490.2 gCO2e/kWh, of which 2.7–3.2% is methane. The estimate for shale gas is 499.2 gCO2e/kWh, of which 4.3% is methane. This corresponds to a leakage rate of the total fuel that will be extracted from a particular well of 0.07% for downstream (transmissions, storage and distribution) and 0.4% for conventional wells and 0.6% for unconventional wells for upstream and midstream (well site and processing plant) (Howarth et al. 2012). The study only uses the 100-year GWP for calculating carbon dioxide equivalent emissions and relies on IPCC 2007 estimates for methane equivalency discounting the 20-year GWPs. The authors concede, "The largest unknown is the amount of fugitive emissions". The study includes a worst case analysis which predicts that the rate of methane flaring and emissions during well completions have the largest impact on the calculation of total GHG emissions. The sensitivity analysis also predicts that ultimate recovery (EUR) of a well has a large impact on the percent of emissions when calculating emissions against the total production of a given well.

Estimate: 0.47% conventional wells EUR (0.07% transmission, storage and distribution and 0.4% production and processing) and 0.67% unconventional EUR (0.07% transmission, storage and distribution and 0.6% production and processing)
Estimate: EPA overestimates emissions
Method: BU
JIF: 5.257
Citations: 29

**Life cycle greenhouse gas emissions of Marcellus shale gas[16]**
Published in the journal *Environmental Research Letters* in August 2011 by researchers from Carnegie Mellon. This study is similar to the Stephenson study above and compares natural gas lifecycle GHG emissions from shale, and particularly Marcellus shale, to natural gas lifecycle GHG emissions from conventional wells. The authors use EPA emission factors to create a model to compare potential emissions from conventional versus nonconventional natural gas lifecycles and then perform a monte carlo analysis to estimate the emissions of the various activities in the model. The model focuses on three cases, the base case for "typical" production, distribution and use for shale and convention natural gas, a sensitivity analysis varying certain parameters and a worst-case scenario. The study only uses the 100-year GWP for calculating carbon dioxide equivalent emissions and relies on IPCC 2007 estimates for methane equivalency. The lifecycle boundaries include preproduction, production, processing, transportation and combustion. The paper acknowledges a wide range of methane emissions during the well completion stage with the preproduction estimates subject to wide variability that range from 0.1 to 9.2 g $CO_2$e/MJ (approximately 0% to 18%), nearly two orders of magnitude. The paper goes on to point out that in all cases preproduction makes up less than 15% of the lifecycle emissions. The paper also compares both forms of natural gas to coal. The study found shale gas to have 11% higher GHG emissions than conventional gas, but 20% to 50% lower GHG emissions than coal. The corresponding emissions from leakage of natural gas from unconventional wells over the total lifecycle of a well are 0.4% from downstream (transmissions, storage and distribution) and 2.0% from upstream and midstream (well site and processing plant) (Howarth et al. 2012). The authors state that in general natural gas has lower emissions, but that "when advanced technologies are used with CSS [carbon capture and storage] then the emissions are similar and coal provides slightly less emissions … imply[ing] that the upstream emissions for natural gas life cycle are higher than the upstream emissions from coal".

Estimate: 2.4% (0.4% transmissions, storage and distribution; and 2.0% production and processing)
Estimate: EPA estimates emissions accurately
Method: BU
JIF: 3.582
Citations: 82

**Measurements of methane emissions at natural gas production sites in the United States[17]**
Published in the journal *Proceedings of the National Academies of Science* in September 2013 by a study team led by University of Texas, URS, and Aerodyne Research in collaboration with an the Environmental Defense Fund and nine natural gas producers – Environmental Defense Fund (EDF), Anadarko Petroleum Corporation, BG Group plc, Chevron, Encana Oil & Gas (USA)

Inc., Pioneer Natural Resources Company, SWEPI LP (Shell), Southwestern Energy, Talisman Energy USA, and XTO Energy, an ExxonMobil subsidiary. This paper studied the production stage of fracking through direct measurements of methane emissions at 190 onshore natural gas sites in the United States. Most of the participating companies also participate in EPA's voluntary Natural Gas STAR Program to reduce methane emissions, the measured sites were selected by the participating companies, and the researchers took measurements at times when the companies granted them access. The study team concluded that "Estimates of total emissions are similar to the most recent EPA national inventory of methane emissions from natural gas production." This corresponds to emissions of 0.42% of total downstream production.

Estimate: EPA estimates emissions accurately
Method: BU
JIF: 9.737
Citations: 26

**Shale gas production: potential versus actual greenhouse gas emissions[18]**
Published in the journal *Environmental Research Letters* in November 2012 by researchers from Massachusetts Institute of Technology. The paper attempts to characterize the fugitive and vented emissions from 3,948 horizontally drilled shale wells that underwent preproduction during 2010. The methodology in this paper is to simply assume an average of 9 days of venting per well and to use the peak production rates of wells in a given shale formation to determine the total potential emissions. The result is that venting alone could potentially account for 17% of upstream fugitive emissions accounted for in the EPA annual GHG inventory. They seem to directly compare their results for flowback with the EPA results for all upstream fugitive and vented emissions:

> "Aggregating the data … for the total number of wells brought online in 2010 yields an overall estimate of hydraulic fracturing-related potential fugitive emissions from the five [shale] plays of 902 Gg CH4... For comparison, the EPA GHG inventory for the upstream gas sector estimates total 2010 fugitive emissions of 6002 Gg CH4."

The authors describe the difficulty of estimating true fugitive emissions stating that "significant opaqueness surrounds real world gas handling practices in the field". The authors then go on to reduce their emissions stating that "an industry survey of unconventional gas producers has suggested that reduced emission completions are being used on more than 90% of shale wells completions, and that in the case of those wells not subject to a reduced emissions completion, the duration of flowback is rarely more than 3 days". The authors settle for "70% of potential fugitives are captured, 15% vented, and 15% flared". The study concludes that "in 2010 the total fugitive GHG emissions from US shale gas-related hydraulic fracturing amounted to 216 Gg $CH_4$". The study only accounts for venting during the flowback stage of well completion and does not include all the other sources of fugitive emissions and venting during the preproduction stage of the fuel lifecycle, but all the other stages of the lifecycle as well.

Estimate: EPA overestimates emissions
Method: BU
JIF: 3.582

Citations: 19

**Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation[19]**

Published in the journal *Environmental Science and Technology* in July 2007 by researchers from Carnegie Mellon University. This study quantifies the lifecycle emissions from natural gas liquefied natural gas (LNG) and synthetic natural gas (SNG) and compares these emissions to the lifecycle emissions from coal use. The study used data from the EPA STAR program and EPA emission reports to develop methane emission factors. The study assumed a leakage rate for methane from convention natural gas development of 1.07% of production relying on the 1996 emissions factors published by EPA. The results suggest that while natural gas generally has lower emissions than coal over the full lifecycles of the fuel, LNG and SNG have comparable or greater emissions over the lifecycles of the fuel. The study also analyzed the impact of "advanced technologies" such as CCS (carbon capture). Using CCS technology, LNG becomes the largest producer of GHG emissions compared to natural gas and coal. LNG has greater variability than SNG, but the range of SNG emissions is contained with the range of LNG emissions. The authors also point out that "upstream GHG emissions of NG/LNG/SNG have a higher impact in the total life-cycle emissions than upstream coal emissions".

Estimate: 1.07% EUR
Estimate: EPA estimates emissions accurately
Method: BU
JIF: 5.257
Citations: 127

**Greater focus needed on methane leakage from natural gas infrastructure[20]**

Published in the journal *Proceedings of the National Academy of Science* in February 2012 by researchers from The Environmental Defense Fund, Princeton University, Rochester Institute of Technology, and Duke University. This paper relies on EPA emissions data for leaked emissions to calculate the radiative forcing implications of fuel switching from gasoline, diesel or coal to natural gas. The paper proposes a new way of measuring global warming potential call a Technology Warming Potential (TWP) that takes into account the varying residence times of different gases in the atmosphere and the varying GWPs of those gases over time. The TWP is plotted against time and helps with decision making by showing at what point in the future a change will start having net climate benefits (the point at which the curve passes below a TWP of 1.0). The results for switching to natural gas from coal are displayed graphically and show the amount of time it would take to achieve a net climate benefit given a certain percentage leakage rate. For a 4% leakage rate, it would take about 25 years to achieve a net climate benefit. In addition, the authors find that "3.2% [is the] threshold beyond which gas becomes worse for the climate than coal for at least some period of time".

Estimate: EPA estimates emissions accurately
Method: BU
JIF: 9.737
Citations: 60

**Process Based Life-Cycle Assessment of Natural Gas from the Marcellus Shale[21]**
Published in the journal *Environmental Science and Technology* in April 2013 by researchers from the University of Pittsburg. Data obtained from two operators in the Marcellus play who control 28% of the production and processing of shale gas in Pennsylvania. In addition, "fugitive methane emissions data were … collected from midstream (gas gathering and processing) companies, who process raw gas and move it to main pipelines for distribution to end users." Additional data were obtained from PA DEP, which requires self reported, semi-annual production and waste management data from operators. The PA DEP "database remains the only large-scale source of per-well information". The report only uses IPCC 100-year GWP factors. The authors develop a model and use monte carlo simulation to predict emissions. The results were about 420 g $CO_2$e/kWh (approximately 2.2%) of emissions produced in the median Marcellus Shale well with the variability at the 90% confidence interval ranging from just over 400 g $CO_2$e/kWh (approximately 2.1%) to over 600 g $CO_2$e/kWh (approximately 3.2%). The authors compare there results to other major studies and find close agreement, but they chose not to compare these results to major studies that found high levels of leakage such as studies by Howarth, et al. They also find that natural gas has roughly 40% to 60 % the emissions of coal over the lifecycle of the fuels. However, the authors do not consider CCS technology when comparing natural gas emissions to coal emissions.

Estimate: EPA estimates emissions accurately
Method: BU
JIF: 5.257
Citations: 4

**Uncertainty in life cycle greenhouse gas emissions from United States natural gas end-uses and its effects on policy[22]**
Published in the journal *Environmental Science and Technology* in August 2011 by researchers from Carnegie Mellon University. This paper tries to determine the level of uncertainty that is part of all of the concurrent papers attempting to estimate GHG LCA emissions from natural gas and coal. The authors develop a model with parameters with distributions derived from the various estimates available then use a monte carlo simulation to estimate the range of emissions. The paper mostly relies on data from 2008. The paper concludes by showing the relationship between certainty as a function of emissions reductions. The higher the level of emissions reductions in question, the lower the certainty that this can be achieved. The authors estimate that for natural gas to replace coal there is a 100% certainty of emission reductions of 60 g $CO_2$e/MJ. The 100% certainty quickly drops to 0% certainty when considering emissions reductions of 80 g $CO_2$e/MJ or greater. This corresponds to a leakage rate of the total natural gas that a conventional well will produce of 0.4% for downstream (transmissions, storage and distribution) and 1.8% for midstream and upstream (well site and processing plant) (Howarth et al. 2012). The authors perform a sensitivity analysis where they concede that "the choice of GWP value could have serious impacts on the actual and relative results of this study" and "the assumption that all natural gas reported by EIA to be flared and vented … is flared". Other studies note that some states require flaring but most do not and that many producers choose to vent emissions rather than capture of flare them. This is a prime source of uncertainty in the literature. In addition, the paper estimates that using the high end of the IPCC 100-

year equivalency range for methane (this number has been disputed and many papers use higher equivalency rates) and assuming all emissions are vented reduces the certainty of emissions reduction for natural gas as a replacement to coal from 100% to 50% for a reduction of 60 g $CO_2$e/MJ. The paper does not consider shorter time spans for methane GWP. Finally, the authors point out that "uncertainty ranges derived in this study are likely to be underestimates, since literature and databases … usually report only average data without reporting variances".

Estimate: EPA estimates emissions accurately
Method: BU
JIF: 5.257
Citations: 34

**Assessing the greenhouse impact of natural gas[23]**
Published in the journal *Geochemistry Geophysics Geosystems* in June 2012 by a researcher from Cornell University. This paper attempts a simplified comparison of the benefits of switching from coal to natural gas versus the benefits of switching from coal to renewables (wind, solar, nuclear). The author analyzes three scenarios including a baseline consisting of the current mix of energy sources, an alternative consisting of a switch to natural gas from coal and a low carbon scenario envisioning a switch to renewables in the near future. The paper assumes that there is an inevitable switch to renewables by the year 2100 and looks at the "transition" period before then. The paper also examines 50, 100 and 200-year transitions and calculates the level of carbon dioxide and methane in the atmosphere as a function of time and the radiative forcing and temperature change as a function of time. The author assumes that methane leakage is 1% of consumption, but examines the effect of large methane leaks and considers the impact to global temperatures of a 10% leakage rate. The paper concludes that "when methane leakage is so large [10% of consumption] that substituting gas for coal and oil increases global warming in the short term, the benefit of gas substitution returns in the long-term". It is important to note that this scenario would have a higher maximum temperature change and other researchers have noted that a large temperature increase in the near-term could trigger more sweeping global warming effects. The paper concludes that switching to natural gas would produce 40% of the benefits of switching to renewables compared to not making any changes. One important point the authors make is that their paper demonstrates that "… the benefit of substituting natural gas depends only on its leakage rate." The author suggests that [one of] the policy implications of this paper is to reduce methane emissions to less than 1% of consumption.

Estimate: EPA estimates emissions accurately
Method: BU
JIF: 2.939
Citations: 14

**Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas[24]**
Published in the *Journal of Industrial Ecology* in January 2014 by researchers from Yale University. The study examines over 250 life cycle analyses for natural gas in the literature and selects 42 that pass screens for technological relevance and quality. The selected studies are then "harmonized" by

using the portions of the study that can be compared and then using emission factors, global warming potentials, emissions associated with construction and decommissioning, preproduction, liquids unloading that are consistent across the studies. In addition, the authors remove emissions associated with transmission and distribution of electricity. "Technical harmonization" included making the capacity factor, thermal efficiency and heating value consistent across studies. The study found that "harmoniz[ing] thermal efficiency had the largest effect in reducing variability" and that the same would be true for methane leakage; however, the study also concludes that "[methane leakage] was unharmonized in this assessment as a result of the significant current uncertainties in its estimation". The authors also conclude by stating that "the main element of uncertainty in life cycle GHG emissions from natural gas-fired electricity generation (both conventionally and unconventionally produced gas) is the rate of $CH_4$ leakage during the fuel cycle."

Estimate: NA
Method: NA
JIF: 2.276
Citations: 0

**Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study[25]**
Published in the *Journal of Geophysical Research* in February 2012 by researchers from the University of Colorado, the National Oceanic and Atmospheric Association, the National Renewable Energy Laboratory, Science and Technology Corporation, ENVIRON International Corporation, Western Regional Air Partnership, and Clemson University. The authors pioneered an approach to methane leak detection of sampling the atmosphere (from automobiles and from a 300-meter sampling tower) for methane and other gases and relating the results to methane fugitive emissions from natural gas facilities. The approach is able to use this data to estimate total emissions by relating alkane mixing ratios found in the atmosphere to ratios found in natural gas emissions. The researchers tested out their approach in an area north of the Denver/Boulder metropolitan area along the Colorado Rocky Mountain Front Range. The results were then compared to the bottom up calculated emissions. The authors calculated methane emissions by using VOC and $NO_x$ emission data required by the state through the Western Regional Air Pollution (WRAP) Phase III system and then applying EPA emission factors. WRAP is a coalition of state and tribal governments formed to meet the EPAs regional haze regulations.

The team reported that the "emission estimates [were] always larger than the inventory-based mean estimate … derived based on the WRAP Phase III inventory data". Using the data they developed, the determined that "methane [emissions] from natural gas systems in Colorado [are] most likely underestimated by at least a factor of two". They calculated downstream (well site and processing plant) emissions of 2.3% to 7.7%, with a "best guess," of 4% of production. In an article[26] in the journal *Nature*, the lead author Gabrielle Pétron is quoted explaining that "some of the emissions come from the storage tanks but a big part of it is just raw gas that is leaking from the infrastructure".

Estimate: 2.3 – 7.7% (production and processing)
Estimate: EPA underestimates emissions
Method: TD
JIF: 3.174

Citations: 92

**Comment on "Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study" by Gabrielle Pétron et al.[27]**

Published in the *Journal of Geophysical Research* in November 2012 by a fellow from the Council on Foreign Relations. The author disagrees with the original paper on the composition of vented natural gas. The comment modifies the assumptions used in the original paper, which has the effect of both increasing the uncertainty and bringing the emissions in line with current inventories. The author also suggests that the emission calculations were biased toward dry gas wells.

Estimate: EPA estimates emissions accurately
Method: NA
JIF: 3.174
Citations: 12

**Reply to comment on "Hydrocarbon emissions characterization in the Colorado Front Range—A pilot study" by Michael A. Levi[28]**

Published in the *Journal of Geophysical Research* in January 2013 by researchers from the University of Colorado, and the National Oceanic and Atmospheric Association. The authors acknowledge the additional uncertainty brought up in the previous comment, but address the uncertainty without revising their estimates. They also disagree with the comment's implication that the emissions they calculated were derived from dry gas wells. They agree with the comment's position that "there is an urgent need to statistically document the composition profiles and magnitudes of significant sources in oil- and gas-producing fields."

Estimate: EPA underestimates emissions
Method: NA
JIF: 3.174
Citations: 8

**Reply to "Reply to 'Comment on "Hydrocarbon emissions characterization in the Colorado Front Range – A Pilot Study"' by Michael A. Levi" by Gabrielle Pétron et al.[29]**

Published in the *Journal of Geophysical Research* in April 2013 by a fellow from the Council on Foreign Relations. This continues the debate first raised in the above paper about the certainty inherent in the data sets used to calculate emissions and the accuracy and interpretation of the calculations made in response to the paper. This comment makes the claim that: "Only one of two conclusions is possible: the results in Levi (2012) [the original comment to the paper] are correct, or the conclusions in both Levi (2012a) and Pétron et al. (2012a) [the original paper] are unjustified." There are very few citations to this comment.

Estimate: EPA estimates emissions correctly
Method: NA
JIF: 3.174

Citations: 3

**Toward a better understanding and quantification of methane emissions from shale gas development[30]**
Published in *Proceedings of the National Academies of Science* in April 2014 by researchers from National Oceanic and Atmospheric Administration, Cornell University, Pennsylvania State University, and University of Colorado, Boulder. The study directly measured methane emission from fracked wells in the Southwestern Pennsylvania Marcellus shale region. Measured emissions from several well pads were 2 to 3 orders of magnitude (100 - 1,000 times) greater than EPA estimates. Furthermore, the well pads were measured during the drilling process, prior to gas flow stimulation, which is a preproduction stage not previously associated with high methane emissions. The authors conclude that "high fugitive emission rates are likely to be a national-scale issue, although the mechanisms of these fugitive leaks may be different at each site." They also said that recent regional and national findings "indicate that overall sites leak rates can be higher than current inventory estimates," and that "high leak rates illustrate the urgent need to identify and mitigate these leaks as shale gas production continues to increase nationally."

Estimate: EPA underestimates emissions
Method: TD
JIF: 9.737
Citations: 0

**Anthropogenic emissions of methane in the United States[31]**
Published in the *Proceedings of the National Academy of Sciences* in October 2013 by academics from Harvard University, Carnegie Institute for Science, University of Michigan, National Oceanic and Atmospheric Association, Lawrence Berkeley National Laboratory, American and Environmental Research, European Commission Joint Research Centre and the University of Colorado, Boulder. Unpublished complimentary paper also submitted to PNAS at the same time by the nearly the same group from the same institutions has supporting analysis: *"Evidence for a large fossil fuel methane source over the south-central US[32]"*. Estimates total methane emissions across the US using directly measured atmospheric data along with transport models and emissions datasets. The paper relies on observations taken from "tall towers" and aircraft operated by the National Oceanic and Atmospheric Association and the Department of Energy. The researchers were able to relate methane concentrations back to oil and gas production, in part, by examining associated propane concentrations, as propane is "not produced by biogenic processes like livestock and landfills." The authors found that the total anthropogenic sources of methane in the US are 1.5 times greater than reported by EPA. Methane emissions in Texas, Oklahoma and Kansas account for 24% of US methane emissions. 45% (± 13%) of atmospheric methane concentrations in the South-central US are from fossil fuel extraction and refining. The paper finds that the fossil-fuel based emissions from Texas, Oklahoma and Kansas are 3.7±2.0 TgC/y, around 5 time greater than the EDGAR emissions inventory values. This corresponds to emissions of 3.6% or more of total production. The authors conclude by noting that the EPA reduced emissions factors for fossil fuel extraction and processing and that "$CH_4$ data from across North America instead indicate the need for a larger adjustment [by the EPA]."

Estimate: 3.6% of EUR
Estimate: EPA underestimates emissions
Method: TD
JIF: 9.737
Citations: 25

**Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California**[33]

Published in the journal Environmental Science and Technology in April 2014 by researchers from Lawrence Berkeley National Laboratory. The authors apply the EPA derived emissions factors to industry data for natural gas production, processing, transmissions and distribution. The authors estimate that emissions were 3 to 7 times higher for production than reported by industry. The emissions from the other stages of the natural gas lifecycle, transmission and distribution, were equivalent to the public inventories. The authors then compared their results and the emissions in the public inventories to top down atmospheric measurements taken by aircraft over the state of California. Based on the top down models, the inventories for production are accurate, but the inventories for transmission and distribution are low by a factor of 2. The authors also estimate the total methane emissions from California and determine that EPA underestimates emissions by about a factor of 2. Finally the authors note that "uncertainties relative to the mean for a given region are likely larger than that for the State total, emphasizing the need for additional measurements in under sampled regions."

Estimate: EPA underestimates emissions
Method: TD
JIF: 5.257
Citations: 0

**Methane emissions estimates from airborne measurements over a western United States natural gas field**[34]

Published in the journal *Geophysical Research Letters* in August 2013 by researchers from the National Oceanic and Atmospheric Administration and the University of Colorado, Boulder. Measured natural gas production in Uintah County, Utah and found downstream emissions of 6% and 12% of production. This emissions estimate is 1.8 to 38 times inventory-based estimates from this region and five times the US EPA nationwide average estimate of leakage from the production and processing of natural gas. The authors conclude by saying:"[Our study is] the first atmospheric measurement-based estimate of methane emissions from a producing gas and oil field to date that does not rely on atmospheric transport models or bottom-up inventory information. Such independent verification of inventory-based estimates is essential for evaluating inventory methodologies, quantifying the effectiveness of future regulatory efforts, and accurately determining the climate impact of natural gas over other fossil fuels."

Estimate: 6-12% EUR (production and processing)
Estimate: EPA underestimates emissions
Method: TD
JIF: 3.982
Citations: 26

**Quantifying the relative contribution of natural gas fugitive emissions to total methane emissions in Colorado, Utah, and Texas using mobile delta13CH4 analysis[35]**
Abstract published in *Abstracts of the American Geophysical Union* in December 2013 (conference in December 2013) and otherwise unpublished by researchers from Picarro Inc, the University of Colorado at Boulder and the National Oceanic and Atmospheric Administration. There is no indication in the abstract that the authors submitted the paper for publication. The research involved a method to directly measure methane in the atmosphere and correlate the methane with natural gas fugitive and vented emissions by comparing emissions that include a stable isotope of methane only found in natural gas to emissions that do not include that isotope of methane. The study considered methane emissions at three different production sites, the Denver-Julesburg basin in Colorado, the Uintah basin in Utah, and the Barnett Shale in Texas. The study looked only at atmospheric concentrations above areas with known natural gas production and processing facilities. The study found that "the fraction of total methane emissions in the Denver-Julesburg basin attributed to natural gas emissions is 78 +/- 13%. In the Uinta basin, which has no other significant sources of methane, the fraction is 96% +/- 15%." The results from the third area are preliminary.

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|---|---|
| Estimate: | NA |
| Method: | TD |
| JIF: | NA |
| Citations: | 2 |

**Quantifying sources of methane using light alkanes in the Los Angeles basin, California[36]**
Published in *Journal of Geophysical Research: Atmospheres* in May 2013 by researchers from the University of Colorado, National Oceanic and Atmospheric Administration, University of Miami, University of California, Irvine, Harvard University, and the University of California, Berkeley. Researchers attempted to reconcile discrepancies in previous top down and bottom up estimates of methane emissions in the Los Angeles basin by determining the source of the un-inventoried methane emissions. This study focused mostly on the transportation and distribution phases of the natural gas lifecycle. The researchers used aircraft to ambient measurements of methane and other alkanes. The researchers use the data from previous studies to determine the correct ratios of methane to other alkanes to apportion the observed methane to appropriate sources. Sources examined include landfills, dairy farms, wastewater treatment facilities and oil fields. The analysis shows that the inventoried emissions from each of these sources agree with the observed methane levels attributed to each source; however, there were still uncounted methane emissions. These un-inventoried emissions were traced back to leakage in the municipal natural gas distribution system and possible migration of methane from natural gas and oil extraction and processing facilities near the Los Angeles basin. The results suggest that about 8% of the methane emissions in the Los Angeles basin are from oil and gas production and processing, 45% from known sources such as landfills and dairy farms and 47% from leakage from urban natural gas distribution systems and natural geologic seeps. The authors note that they were not able to distinguish between leakage from distribution systems and geologic seeps. The total potential leakage from natural gas distribution systems is 192 ± 54 Gg methane/yr. The authors recommend that "basin-wide mobile studies targeting methane and ethane alkane emissions from natural gas pipelines and urban distribution

systems, geologic seeps, and local oil and gas industry production sites would be useful to further distinguish the sources of methane in the L.A. basin."

| | |
|---|---|
| Estimate: | EPA underestimates emissions |
| Method: | TD |
| JIF: | 3.174 |
| Citations: | 16 |

For more information contact James McGarry at james@chesapeakeclimate.org/240-396-1983

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