Natural Gas Leakage in Brandt et al

Abstract

In their recent 2014 *Science* paper, "Methane Leaks from North American Natural Gas Systems", Brandt et al review 12 top-down and 6 bottom-up estimates of natural gas leakage. They find that observed leakage rates are in most cases higher than reported inventory values, with overall US-wide leakage likely between 1.25 and 1.75 greater than EPA Greenhouse Gas Inventory estimates. This implies a mean leakage rate of between 1.9 percent and 2.6 percent, with a potential upper bound of 6 percent if the implausible assumption is made that all detected excess atmospheric methane results from natural gas system leakages. A large fraction of leakage is identified as originating from a small number of "superemitters", raising important implications about the need for improved leak detection. Finally, Brandt et al conclude that system-wide leakage rates are unlikely to be large enough to negate the climate benefits of coal-to-natural gas substitution for electricity generation, but may be high enough to call into question the net climate benefit of using natural gas in vehicles, particularly heavy duty diesel trucks/busses.

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Introduction

The Brandt et al paper was published in *Science* in February 2014. It provided a meta-analysis of studies of methane emissions from natural gas systems, including both top-down monitoring studies (which use flyovers, drive-bys, and fixed monitoring stations to measure ambient air concentrations of methane over wide areas) and bottom-up studies which catalogue leakage rates from individual components, activities, and sites. The main innovation in Brandt et al was to make these diverse estimates intercomparable by expressing their findings as a ratio of observed leakage to the expected leakage based on reported official inventory values (via EDGER, Global Reporting Initiative, Greenhouse Gas Inventory, Canadian Association of Petroleum Producers, WRAP, and CARB).

Not all of the top-down studies included are able to effectively differentiate between emissions from natural gas systems and other sources, with potentially confounding sources including petroleum systems, coal mine methane, enteric fermentation, landfills, manure management, and others. Significant uncertainty remains regarding the extent to which excess measured atmospheric methane is attributable to natural gas systems.

The studies assessed by Brandt et al generally found higher emissions rates than reported by official inventories. Overall emissions of methane from large-scale top-down studies are estimated as somewhere between 1.25 and 1.75 times greater than reported EPA inventory values across all sources. Brandt et al do not explicitly provide the leakage rates (as a percent of production) implied by these leakage estimates, though they do provide a theoretical upper bound on natural gas system leakage rates for what they describe as the improbable case where all additional detected concentrations come from natural gas systems.

If all excess measured methane is attributable to natural gas systems, the system-wide leakage rate would be somewhere between 3% and 6%. However, they remark that these values require "an implausible set of assumptions" and that other studies have found that sources like enteric fermentation (livestock emissions) are significantly under-predicted, and a number of significant sources such as abandoned wells and geologic seeps are unaccounted for in existing inventories and likely contribute to observed excess CH_4. Actual leakage rates are likely lower, with a best estimate of between 1.9% to 2.6% based on the studies surveyed.

Brandt et al updated the earlier analysis of Alvarez et al (2012) to examine the implication of their results on the viability of natural gas both as a substitute for coal for electricity generation and as a replacement for gasoline in vehicles. They found that it would require a leakage rate of 7.37% or higher to make gas worse than coal over a 100-year time horizon, concluding that gas would be preferable to coal from a climate perspective "except in cases where extreme assumptions are made about the US gas industry". For light duty gasoline vehicles, however, they concluded that

it would only take a leakage rate of 3.84% to make natural gas worse than gasoline from a climate perspective, a value on the high end but within the possible range of leakage rates assessed by the Brandt et al study. For heavy-duty diesel vehicles, it would only take a leakage rate of 1.72% to make climate forcing from natural gas worse than that of diesel fuel for a 100-year time horizon.

Top-Down Studies

Brandt et al examined 16 different estimates from 12 top-down studies of methane emissions. These top-down studies utilize flyovers, drive-bys, fixed monitoring stations, and other methods to measure ambient air concentrations of methane over wide areas. They often utilize wind field data to try and predict the source areas of detected perturbations, and compare the results to natural gas production in those areas. These studies are reported both as published and normalized on a common baseline, expressed as the ratio of their emission estimates to those of the EPA's GHG Inventory for the same region, allowing all the studies to be effectively compared.

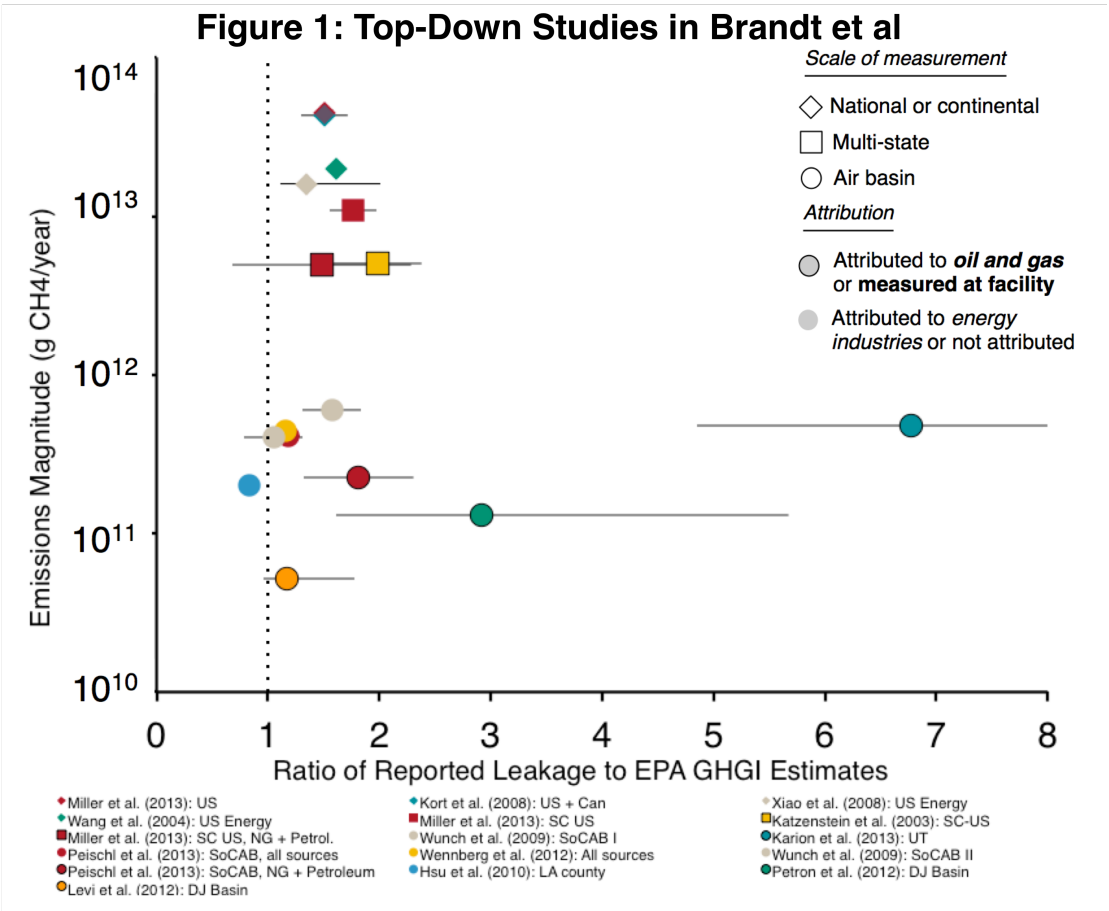


Figure 1, above, is adapted from Figure 1 of the Brandt et al paper. It shows the top-down studies assessed by Brandt as a ratio of reported EPA GHG Inventory (GHGI) estimates, with a value of one indicating estimates the same as those from GHGI. Values are shown for minimum, mean, and maximum estimates (when available), and the shape represents the scope of the study (national or continental, multi-state, or specific basin). Finally, shapes with a solid outline are studies where measured methane concentrations are directly attributable to oil and gas systems, while shapes without solid outlines are not easily attributable to any specific sectors.

Different top-down studies cover different geographical areas of the U.S. and differ in their ability to determine the source of detected methane. Table 1, below, shows all of the top down studies considered in Brandt et al, along with their scope (region of analysis), year in which the data was gathered, and the potential sectors from which the observed atmospheric methane concentrations could potentially originate. Most of the wider-region studies and all of the full US studies are not able to differentiate between methane from natural gas systems and methane from other sources such as landfills and enteric fermentation. Smaller-scale studies are often undertaken over areas with few landfills or livestock and are better able to identify atmospheric methane perturbations directly attributable to natural gas and petroleum systems.

Table 1: Top Down Study Characteristics

Study	Scope	Case Year	NGS	PS	CM	EF	LF	MM	OT
Miller et al. 2013 (1)	US	2008	X	X	X	X	X	X	X
Miller et al. 2013 (2)	TX, OK, KS	2008	X	X	X				
Miller et al. 2013 (3)	TX, OK, KS	2008	X	X	X	X	X	X	X
Kort et al. 2008	US and Canada	2003	X	X	X	X	X	X	X
Katzenstein et al. 2003	TX, OK, KS	2002	X						
Wang (via Xiao)	US	1998	X	X	X				
Xiao et al. 2008	US	2004	X	X	X				
Petron et al. 2012	Weld County, CO	2008	X	X					
Levi et al. 2012	Weld County, CO	2008	X	X					
Wunch et al. 2009 (1)	LA Region, CA	2008	X	X		X	X	X	X
Wunch et al. 2009 (2)	LA Region, CA	2008	X	X		X	X	X	X
Hsu et al. 2010	LA County, CA	2007	X	X			X		X
Wennberg et al. 2012	LA Region, CA	2008	X	X		X	X	X	X
Peischl et al. 2013 (1)	LA Region, CA	2010	X	X		X	X	X	X
Peischl et al. 2013 (2)	LA Region, CA	2010	X	X					
Karion et al. 2013	Uintah County, UT	2012	X	X					

Abbreviations: Natural gas systems (NGS), petroleum systems (PS), coalmines (CM), enteric fermentation (EM), landfills (LF), manure management (MM), and other (OT).

The most comprehensive top-down study surveyed by Brandt et al was Miller et al (2013). Miller et al estimated anthropogenic CH4 emissions over the United States

for 2007 and 2008 using comprehensive CH4 observations at the surface, on telecommunications towers, and from aircraft, combined with an atmospheric transport model and a geostatistical inverse modeling (GIM) framework. They used auxiliary spatial data (e.g., on population density and economic activity) and concurrent measurements of alkanes to help attribute emissions to specific economic sectors. They found overall methane emissions that were 1.45 to 1.57 times greater than the EPA GHG Inventory for the whole country, and 1.56 to 1.97 times greater in the South Central U.S. (e.g. TX, OK, and KS). Miller et al also included an estimate of emissions from the oil and gas sector in the South Central U.S., estimating them at 0.68 to 2.28 times greater than the EPA GHG Inventory for that region.

Table 2: Top Down Study Results

Study	Low	Mean	High
Miller et al. 2013 (1)	1.45	1.51	1.57
Miller et al. 2013 (2)	0.68	1.48	2.28
Miller et al. 2013 (3)	1.56	1.77	1.97
Kort et al. 2008	1.3	1.51	1.72
Katzenstein et al. 2003	1.59	1.98	2.38
Wang (via Xiao)		1.61	
Xiao et al. 2008	1.12	1.34	2.01
Petron et al. 2012	1.61	2.92	5.67
Levi et al. 2012	0.96	1.17	1.78
Wunch et al. 2009 (1)	1.31	1.58	1.84
Wunch et al. 2009 (2)	0.79	1.05	1.31
Hsu et al. 2010	0.81	0.84	0.86
Wennberg et al. 2012	1.05	1.16	1.26
Peischl et al. 2013 (1)	1.07	1.18	1.29
Peischl et al. 2013 (2)	1.33	1.82	2.31
Karion et al. 2013	4.85	6.77	8.7
Brandt et al estimate	1.25	1.5	1.75
Mean leakage estimate	1.88%	2.25%	2.63%
Worst case all gas leakage	3.02%	4.55%	6.07%

The Karion et al study represents a significant outlier for estimated leakage rates, reporting leakage between 4.8 and 8.7 times higher than official inventories. The study was comprised of twelve flights over a natural gas and oil production field in Uintah County, Utah. The authors note that emissions in this particular basin are likely not representative of other basins, pointing out:

> "An inventory analysis by the US Government Accountability Office (GAO) suggests, however, that the emissions from Uintah may be significantly higher than in other Western US basins. Using the Western Regional Air Partnership (WRAP) phase III inventory and

> production numbers for 2006 from federal leases, the GAO estimates that the proportion of Uintah natural gas that is flared or vented is much higher (5% of production) than in surrounding regions, including the Denver-Julesburg (2.1%), Piceance (2.5%), N. San Juan (0.34%) and S. San Juan (1.13%) Basins."

In the paper, Brandt et al point this out, and argue that "recent regional atmospheric studies with very high emissions rates are unlikely to be representative of typical NG system leakage rates".

Brandt et al estimate overall methane emissions at somewhere between 1.25 and 1.75 times greater than EPA GHG Inventory estimates. This number is difficult to directly translate into natural gas leakage rates, as most of the top-down studies surveyed are not able to limit the analysis only to natural gas sources, and natural gas systems do not represent the majority of U.S. CH_4 emissions. Other sources, like livestock, have a similar magnitude contribution in official inventories. If we assume that this excess methane is evenly distributed across inventory sources, we end up with implied natural gas leakage rates ranging from 1.88% to 2.63%. If we assume that all excess methane is attributable to natural gas systems, we find leakage rates ranging from 3.02% to 6.07%.

This latter number has received some attention, but Brandt et al caution that these numbers require "an implausible set of assumptions". They point out that evidence exists that other sources are also underestimated in official inventories. For example, the Miller et al (2013) paper found that emissions from livestock was "nearly twice" that of official EDGAR and EPA GHG Inventory estimates.

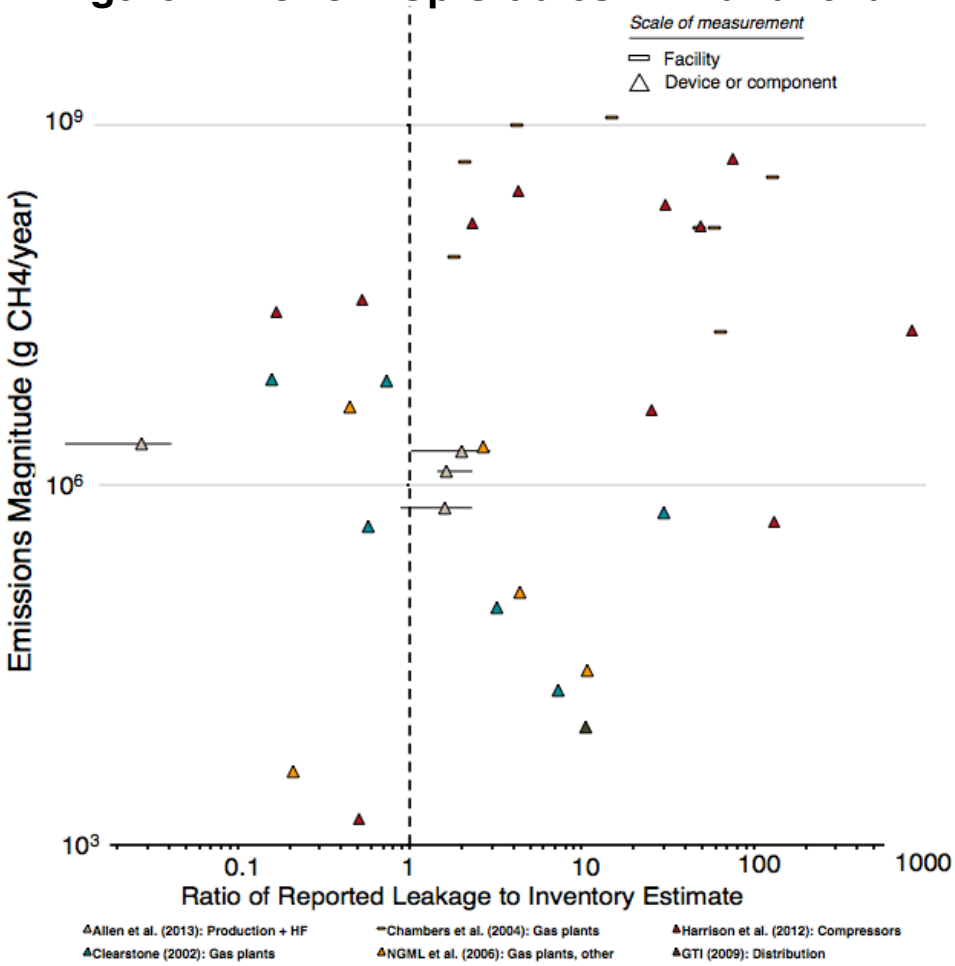
Brandt et al suggest that the leakage rates estimated based on top-down studies would only make gas worse than coal for electricity generation over 100-year climate forcing timeframes if "EPA inventory needs to be multiplied by highest scaling factor considered", "all excess observed CH4 comes from the NG industry, and no other inventory sources or unaccounted-for sources are contributing to excess", and "power generation suffers from the same distribution losses as all other end uses (unlikely, as power stations are generally connected to higher pressure mains)." They conclude that "fuel switching to [natural gas] from coal is favored... except in cases where extreme assumptions are made about the US gas industry."

Bottom-Up Studies

In contrast to diffuse regional top-down studies, bottom up studies of leakage in natural gas systems tend to focus on individual components, measure hundreds, thousands, or even tens of thousands of individual connectors, valves, compressors, and pieces of equipment. Brandt et al examined six major bottom-up analyses in his review. Four of the studies examined components at processing plants and well sites, one focused on leakage from meters, and the final one looked at shale gas well completions and overall well-site leakage rates.

Figure 2, below, shows the full range of bottom-up component and well leakage rates from studies surveyed. Unlike top-down estimates, EPA GHG Inventory estimates are generally not available for individual components; rather, studies are expressed as a ratio of measured leakage to the inventory estimates referenced in the original studies (from a range of sources including CAPP, EPA/GRI, and EPA GHGI). While there is a wide range of estimates across different components, the majority show emissions rates higher than previously published inventory estimates. Uncertainty are only available for the Allen et al (2013) study.

Figure 2: Bottom-Up Studies in Brandt et al



The table below shows the scope of each study, including the number of individual components for each type measured when available. It also shows the number of case studies that were included in Brandt et al's bottom-up study figure. Brandt generally included one case study for each component type measured in each study. The exception was for components for which no corresponding official inventory or emission factor could be found, as this precluded common baseline comparisons.

Table 3: Bottom-up Study Characteristics

Study	Scope	Cases in Brandt
Chambers et al 2004	Tanks, Flares, Fugitive, and Glycol Dehydrator	8
Harrison et al 2012	Valves (1634), Flanges (1244), Centrifugal Compressors (14), Reciprocating Transmission Compressors (38), Reciprocating Boosting Compressors (57)	15
Clearstone 2002	Connectors (82146), Block Valves (15136), Control Valves (1240), Pressure Relief Valves (385), Pressure Regulators (169), Meters (174), Crank Case Vents (36), Open Ended Lines (1610), Pump Seals (83), Compressor Seals (206), Blowdowns (6)	12
NGML 2006	Connectors (64369), Block Valves (7692), Control Valves (495), Pressure Relief Valves (124), Pressure Regulators (320), Orifice Meters (57), Crank Case Vents (27), Open Ended Lines (1055), Compressor Seals (299)	9
GTI 2009	Commercial Meters (836), Industrial Meters (46), Residential Meters (2400)	3
Allen et al 2013	Well Completions (27), Gas Well Unloading Events (9), Well Workovers (4), Normal Well Operation (489)	4

Chambers et al 2004

The Chambers et al study focused on emissions from natural gas processing plants in Canada, looking at a small set of sweet and sour gas processing plants in detail. They visualized leaks using a Hawk gas leak-imaging camera and estimated leak volumes through a downwind transect with differential adsorption lidar (DIAL) technology.

Chambers 2004	
Components	**Ratio**
Tanks - Plant E	64.30
Flare - Plant E	4.60
Glycol Dehydrator - Plant E	15.10
Tanks - Plant C, 2003	48.30
Flare - Plant C, 2003	58.80
Fugitives - Plant C, 2003	4.20
Tanks - Plant C, 2004	128.60
Fugitives - Plant C, 2004	2.10

Chambers et al. found that emissions from gas plants were considerably higher than the emission estimates from CAPP (Canadian Association of Petroleum Producers).

Harrison et al 2012

The Harrison et al study arose out of an EPA initiative to improve emission factors for compressors, with a specific focus on reciprocating and centrifugal compressors, including transmission, boosting/gathering and gas processing compressors. The team used infrared cameras to detect leaks, and measured leaks using a Hi-Flow sampler.

Harrison et al 2012 (1)	
Components	**Ratio**
Valves	0.51
Flanges	0.28
Centrifugal compressor - Average BD vent for run	0.01
Centrifugal compressor - Average BD vent for idle + run	0.17
Centrifugal compressor - Wet seal (run)	49.32
Reciprocating transmission compressor - Average BD vent for idle + pressurized	0.53
Reciprocating transmission compressor - Average BD vent for run	2.31
Reciprocating transmission compressor - Average BD vent for idle + depressurized	4.29
Reciprocating transmission compressor - Average rod packing for idle + pressurized	30.90
Reciprocating transmission compressor - Average rod packing for run	74.76
Reciprocating boosting compressors - Average BD vent for run	130.23
Reciprocating boosting compressors - Average BD vent for idle + depressurized	0.00
Reciprocating boosting compressors - Average PRV vent for run	823.57
Reciprocating boosting compressors - Average rod packing - Run	25.42

The results from the analysis were mixed, with some components having lower emission rates than existing emission factors, and others having multiple orders of magnitude more leakage. Centrifugal compressors (with the exception of the wet seal case) tended to have lower emissions than emission factors, while reciprocating transmission and boosting compressors tended to have higher emissions.

Clearstone 2002

The Clearstone 2002 survey was prepared for the Gas Technology Institute and the EPA. They surveyed over 100,000 components at gas plants and wells. Connectors, block valves, and pressure relief valves all showed significantly higher leakage rates than found in EPA/GRI emission factors. Open ended lines, compressor seals, and blowdowns all resulted in lower emissions than emission factor estimates.

Clearstone 2002	
Components	**Ratio**
Connector	7.28
Block Valves	3.24
Pressure Relief Valves	30.07
Open Ended Lines	0.57
Compressor Seals	0.73
Blowdowns	0.16

The Clearstone methodology surveyed all individual sources using bubble tests, portable hydrocarbon gas detectors, or ultrasonic leak detectors (Brandt et al.

2014). Of all components surveyed, roughly 2.6% were found to be leaking. Components found to be leaking were tested with either a Hi-Flow sampler or through bagging and direct measurement. The study found that overall leaks measured were generally higher than EPA/GRI emission factors, and that the a large portion of the leaks found would be cost-effective to repair.

National Gas Machinery Laboratory 2006

The National Gas Machinery Laboratory study was performed as a follow-up to the Clearstone 2002 study, looking as a similar set of material (sans blowdowns). Of the approximately 75,000 components surveyed, 2.2% of the components were found to be leaking. The ratios of observed leakage to EPA/GRI values is similar to that found in Clearstone for connectors, block valves, and compressor seals. Leak rates from pressure relief valves were much lower, however, and open-ended line leakage was somewhat higher. Overall emissions were higher than EPA/GRI emission factors, though the study found that the vast majority of leaks were able to be repaired at no net cost to the operator.

National Gas Machinery Laboratory (NGML) 2006	
Components	**Ratio**
Connector	10.82
Block valves	4.32
Pressure relief valves	0.21
Open ended lines	2.65
Compressor seals	0.44

Gas Technology Institute 2009

The Gas Technology Institute study in 2009 focused on distribution system emissions, specifically examining meters and metering/regulation stations. They found that leakage at residential meters was only a third of the estimated emission factors in the EPA's Global Reporting Initiative, but leakage from commercial and industrial meters were significantly higher (10x to 4000x of emission factors).

Gas Technology Institute (GTI) 2009	
Components	**Ratio**
Residential Meters	0.36
Commercial Meters	10.61
Industrial Meters	4254.20

Allen et al 2013

The Allen et al study was led by David Allen at the University of Texas with funding provided by the Environmental Defense Fund (EDF) and a number of major oil and gas producers. It found that emissions associated with completion flowback from hydraulic fracturing were only a small fraction (less than 3 percent)

Allen et al 2013			
Components	**Low**	**Mean**	**High**
HF Completion Flowback	0.01	0.03	0.04
Chemical Pumps	1.03	2.00	2.94
Pneumatic Controllers	1.44	1.63	2.33
Equipment Leaks	0.88	1.59	2.30

of those estimated in the 2011 EPA Greenhouse Gas Inventory (GHGI). However, measurements of leakage from other components (chemical pumps, pneumatic controllers, and equipment leaks) were between 1.6 and two times greater than GHGI estimates. The table below shows low, mean, and high estimates based on measurement uncertainties for the four components for which comparisons to GHGI estimates were available.

Allen et al. devised novel containment strategies to directly measure emissions from hydraulic fracturing flowback (both with and without reduced emissions completions technologies in place), allowing much improved understanding of both potential and net (after mitigation) emissions from completions operations. For smaller sources Allen et al. used initial scans with infrared cameras, followed by Hi-Flow sampling to quantify flux (Brandt et al 2014).

Allen et al strongly suggests that shale-gas-specific emissions associated with flowback are much lower in magnitude than those in official inventories, and no where near as high as postulated in Howarth et al 2011. It doesn't necessarily contradict the contention of Brandt that overall system-wide natural gas inventories may be underestimated, however, as Brandt suggests that much of the leakage is coming from a small fraction of poor performing conventional equipment rather than anything specific to hydraulic fracturing.

Evidence of Super-Emitters

The Brandt et al paper argues that while emissions may be higher on average than inventory estimates, there is considerable evidence across multiple studies that emissions are dominated by a long-tail of "super-emitters" that are responsible for the bulk of emissions. The table below, adopted from the Brandt et al supplementary materials, provides evidence over super-emitters from different studies surveyed. It includes the industry stage, the measurement techniques used, and a description of the distribution of the found leakage.

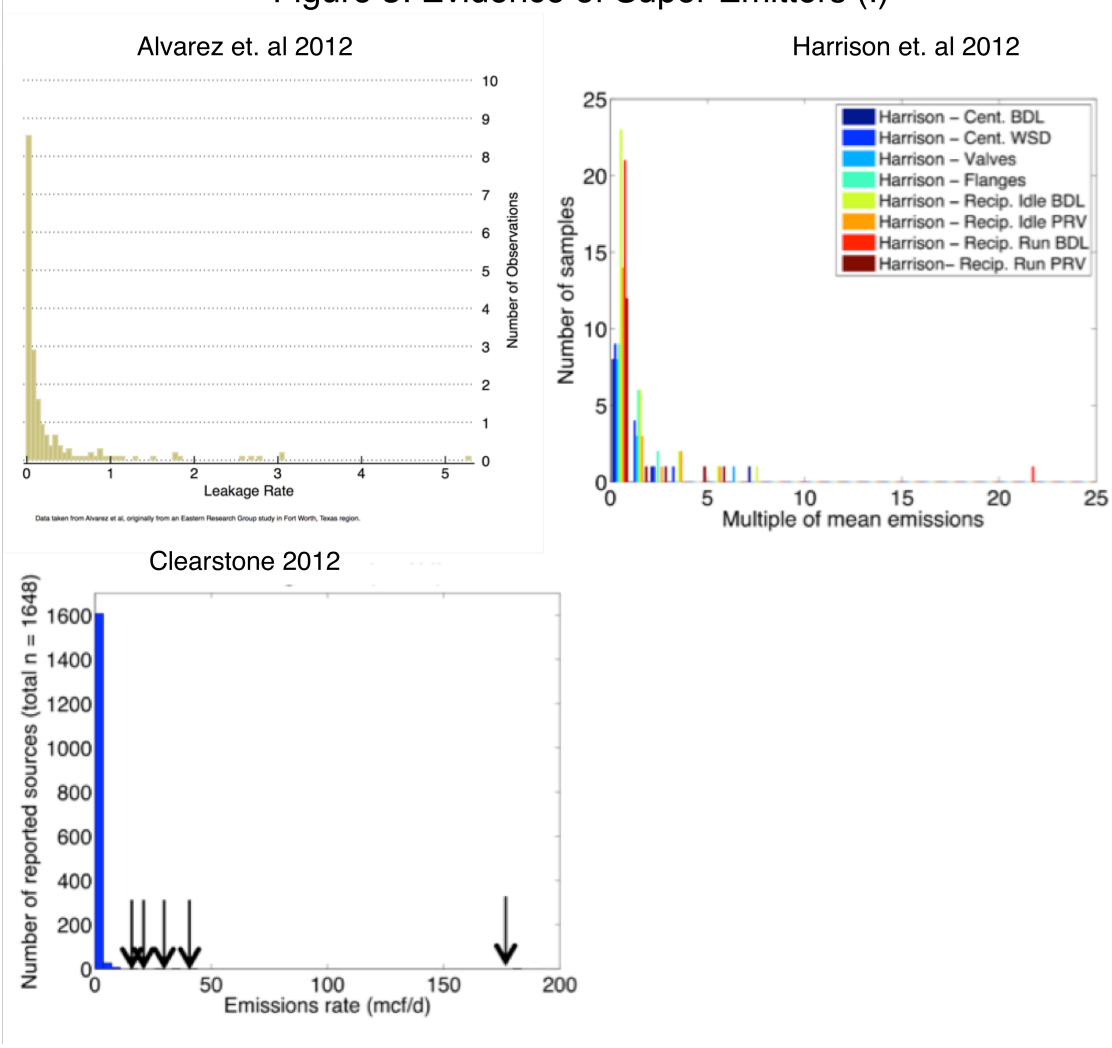
Evidence for Super-Emitters			
Study Name	**Industry Stage**	**Measurement Technique**	**Degree of Heterogeneity Noted**
Allen et al. 2013	Production	Direct measurement of unloading events	"Four of nine events contribute more than 95% of total emissions"
Alvarez 2012	Production	Analysis of reported emissions	"10% of well sites accounted for 70% of emissions"
Chambers 2006	Processing	Down-wind differential absorption LIDAR	At plant B a single intermittent leak from a pressure relief valve was located that increased site emissions from 104 kg/hr to 450 kg/h.
Clearstone 2002	Processing	Direct measurement using Hi-Flow sampler	>100,000 devices sampled across 4 facilities. between 35.7% and 64.6% of leakage from each facility was found leaking from top 10 leaks in each facility.
Cormack, 2007	Transmission compressors	Direct measurement with Hi-Flow sampler	Top leak accounted 40% of leakage. Top 20% of leaking components accounted for 80% of leakage.
Harrison et al. 2011	Compressor stations	IR camera, Hi-Flow sampler	Reported data in appendix B show outliers. For example, ~2,800 valves and flanges were screened with IR camera and 29 leaks were found. The single largest of these leaks (>1000 mscf/y) is >100,000 times larger than valve and flange EF estimated (0.05 or 0.09 mscf/y). Similar results seen elsewhere. See, e.g., blowdown line leaks from centrifugal compressors (Table B2) where largest leak represents 70% of the total leakage.
NGML 2006	Processing, well sites, gathering compressor stations	Direct measurement using Hi-Flow sampler and optical methods	> 74,000 components sampled. Approx. 1600 were found to be leaking (~2%). From executive summary: "Repairs to 10 largest emitting cost-effective-to-repair components at each site…would reduce natural gas losses by approximately…58%"
Picard 2005	All stages	Direct sampling via various methods across many studies	"Top 10 leaks typically contribute more than 80% of emissions from leaks."
Trefiak 2006	Compressor stations and gas plants	Optical measurement followed by Hi-Flow sampler	"23% of the 144 fugitive emissions sources were responsible for 77% of leakage."

The presence of super-emitters is by-and-large a positive finding; if leakage was evenly distributed across a large number of sites and equipment, it would be much less cost-effective to mitigate, and leakage detection efforts would be of limited usefulness. Super-emitters will likely be quite cost effective to mitigate given their

high losses, and their presence suggests that robust leakage detection efforts would be greatly beneficial.

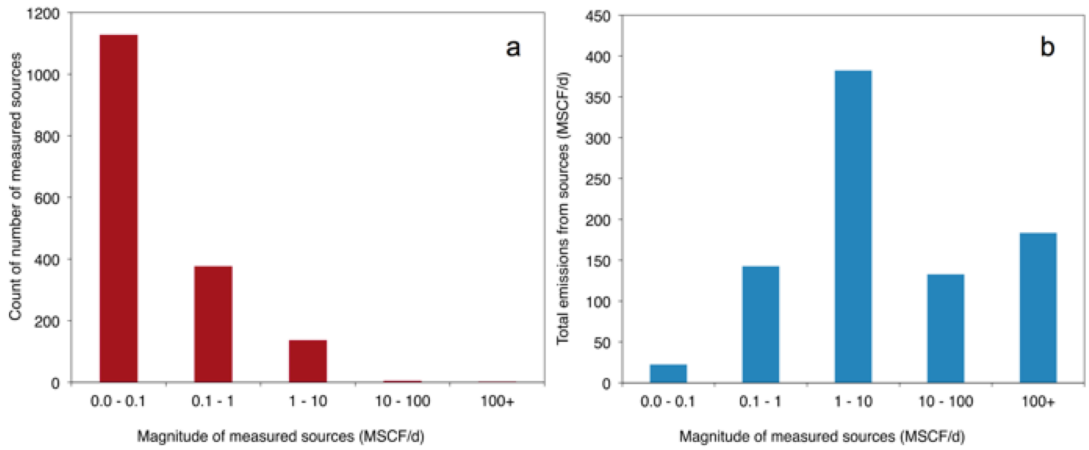
Figure 3, below, shows a distribution of leakage from well sites in Alvarez et al, and specific equipment in Harrison et al and Clearstone et al. In all cases, there is a distinctive "long tail" of sites or components that have much higher leakage, while the majority of sites have low leakage. This long tail is in many cases responsible for a significant majority of emissions.

Figure 3: Evidence of Super Emitters (I)



This is even more pronounced in Figure 4, taken from NGML (2006), which shows the distribution of leakage rates (in thousand standard cubic feet per day – MSCF/d) in panel a, and the magnitude of measured leakage rates in panel b. Here less than 10% of components are responsible for more than 80% of measured emissions.

Figure 4: Evidence of Super Emitters (II)



Conclusions

The studies reviewed in Brandt et al present a strong argument that existing inventories systemically underestimate methane emissions. These underestimates are fairly consistent across a variety of top-down and bottom-up studies surveyed. Larger regional and national top-down studies suggest that overall methane inventories are likely somewhere between 1.25 and 1.75 times larger than the EPA Greenhouse Gas Inventory.

Overall system-wide leakage rates (as a percent of production) remain highly uncertain. If this reported excess methane is divided evenly among reported inventory sources, it implies natural gas system-wide leakage rates of between 1.9 and 2.6 percent. If all excess methane is from natural gas system leaks, overall leakage rates could be as high as 6 percent. However, Brandt et al describe this case is "implausible", as there is strong evidence that a number of other sources (among them emissions from livestock, abandoned wells, geologic seeps) are also significantly underestimated in existing inventories. While a few studies of specific basins posit leakage rates of 6% or higher (e.g. Petron et al 2012; Karion et al 2013), Brandt et al conclude that "recent regional atmospheric studies with very high emissions rates are unlikely to be representative of typical [natural gas] system leakage rates.

Brandt et al assemble evidence from a number of studies of the existence of "superemitters", a long tail of individual components or well sites with high leakage rates that tend to dominate overall emissions. This finding helps chart a way forward, by pointing out the need for better inspections to determine which components are responsible for the bulk of observed leakage. If the bulk of leakage

is from a small number of components, this suggests that these will likely be quite cost effective to remediate when detected.

Finally, Brandt et al re-applied the analysis from Alvarez et al (2012) to see how their findings impact the climate viability of natural gas as a "bridge fuel" away from coal, as well as the relative viability of substituting gasoline of diesel fuel for natural gas in vehicles. Using 100-year time horizons, they found that it would require a leakage rate of 7.37% or higher to make gas worse than coal over a 100-year time horizon, concluding that gas would be preferable to coal from a climate perspective "except in cases where extreme assumptions are made about the US gas industry". For light duty gasoline vehicles, however, they concluded that it would only take a leakage rate of 3.84% to make natural gas worse than gasoline from a climate perspective, a value on the high end but within the possible range of leakage rates assessed by the Brandt et al study. For heavy-duty diesel vehicles, it would only take a leakage rate of 1.72% to make climate forcing from natural gas worse than that of diesel fuel for a 100-year time horizon.

Natural gas system leakage rates are still characterized by a high degree of uncertainty, and much more analysis will be needed to more precisely bound the likely values. Brandt et al provides a good starting point, an assessment of existing literature that makes a strong case for existing inventory underestimates but also tries to exclude some of the more surprisingly large basin-specific estimates as being characteristic of the system as a whole.

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