U.S. Methane Leakage from Natural Gas Systems: Academic Literature from 2014 and 2015

Chesapeake Climate Action Network

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2015 Research

Methane Emissions from the Natural Gas Transmission and Storage System in the United States[1]

Published in *Environmental Science & Technology* in July 2015 by researchers from Colorado State University, Fort Lewis College, and Carnegie Mellon University, this study estimated methane emissions from the transmission and storage (T&S) sector of the United States natural gas industry using new data collected during 2012, including 2,292 onsite measurements, additional emissions data from 677 facilities and activity data from 922 facilities. The largest emission sources were found to be fugitive emissions from certain compressor-related equipment and "super-emitter" facilities. *The authors estimate total methane emissions from the T&S sector at 1,503 [1,220 to 1,950] Gg/yr (95% confidence interval) compared to the 2012 Environmental Protection Agency's Greenhouse Gas Inventory (GHGI) estimate of 2,071 [1,680 to 2,690] Gg/yr.*

For T&S stations that are required to report to the EPA's Greenhouse Gas Reporting Program (GHGRP), this study estimated total emissions to be 260% [215% to 330%] of the reportable emissions for these stations, primarily due to the inclusion of emission sources that are not reported under the GHGRP rules, updated emission factors, and super-emitter emissions.

Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol[2]

Published in *Environmental Science & Technology* in February 2015 by researchers from Carnegie Mellon University, Fort Lewis College, Colorado State University, and Aerodyne Research Inc. The authors examined the equipment- and site-level methane emissions from 45 compressor stations in the transmission and storage (T&S) sector of the U.S. natural gas system, including 25 sites required to report under the EPA greenhouse gas reporting program (GHGRP). Direct measurements of fugitive and vented sources were combined with AP-42-based exhaust emission factors to produce a study onsite estimate. Site-level methane emissions were also concurrently measured with downwind-tracer-flux techniques. At most sites, these two independent estimates agreed within experimental uncertainty. Site-level methane emissions varied from 2–880 standard cubic feet per minute.

Compressor vents, leaky isolation valves, reciprocating engine exhaust, and equipment leaks were major sources, and substantial emissions were observed at both operating and standby compressor stations. *The site-level methane emission rates were highly skewed; the highest emitting 10% of sites (including two superemitters) contributed 50% of the aggregate methane emissions, while the lowest emitting 50% of sites contributed less than 10% of the aggregate emissions.* The authors found that if the two superemitters were excluded, study-average methane emissions from compressor housings and noncompressor sources are comparable to or lower than the corresponding effective emission factors used in the EPA greenhouse gas inventory. If the two superemitters are included in the analysis, then the average emission factors based on this study could exceed the EPA greenhouse gas inventory emission factors, which highlights the *potentially important contribution of superemitters to national emissions*. However, quantification of their influence requires knowledge of the magnitude and frequency of superemitters across the entire T&S sector.

Only 38% of the methane emissions measured by the comprehensive onsite measurements were reportable under the new EPA GHGRP because of a combination of inaccurate emission factors for leakers and exhaust methane, and various exclusions. The authors found that the bias was even larger if one accounted for the superemitters, which were not captured by the onsite measurements. The magnitude of the bias varied from site to site by site type and operating state. Therefore, while the researchers deemed GHGRP to be a valuable new source of emissions information, they also noted that care must be taken when incorporating these data into emission inventories. The authors concluded that “the value of the GHGRP can be increased by requiring more direct measurements of emissions (as opposed to using counts and emission factors), eliminating exclusions such as rod-packing vents on pressurized reciprocating compressors in standby mode under Subpart-W, and using more appropriate emission factors for exhaust methane from reciprocating engines under Subpart-C.”

Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results[3]

Published in *Environmental Science & Technology* in February 2015 by researchers from Carnegie Mellon University, Colorado State University, Aerodyne Research Inc., and Fort Lewis College. The study measured facility-level methane emissions at 114 gathering facilities and 16 processing plants in the U.S. natural gas system. *At gathering facilities, normalized emissions (as a % of total methane throughput) were less than 1% for 85 gathering facilities and 19 had normalized emissions less than 0.1%. The range of normalized methane emissions rates for processing plants was <1% in all cases.* The distributions of methane emissions, particularly for gathering facilities, were skewed. For example, *30% of gathering facilities contribute 80% of the total emissions.* Normalized emissions rates are negatively correlated with facility throughput. The researchers thought that the variation in methane emissions also appeared to be driven by differences between inlet and outlet pressure, as well as venting and leaking equipment. *Substantial venting from liquids storage tanks was observed at 20% of gathering facilities, at which, on average, around four times the emissions rates were observed* compared to similar facilities without substantial venting.

Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region[4]

Published in *Environmental Science & Technology* in July 2015 by researchers from the Environmental Defense Fund, University of Arkansas – Fayetteville, University of Houston, Purdue University, Aerodyne Research, Inc. Colorado State University, and Carnegie Mellon University. The authors estimated methane emissions from the oil and gas industry (O&G) and other sources in the Barnett Shale region by constructing a spatially resolved emission inventory. Eighteen source categories were estimated using multiple data sets, including new empirical measurements at regional O&G sites and a national study of gathering and processing facilities. Spatially referenced activity data were compiled from federal and state databases and combined with O&G facility emission factors calculated using Monte Carlo simulations that account for high emission sites representing the very upper portion, or fat-tail, in the observed emissions distributions. Total methane emissions in the 25-county Barnett Shale region in October 2013 were estimated to be 72,300 (63,400–82,400) kg CH4 h–1. O&G emissions were estimated to be 46,200 (40,000–54,100) kg CH4 h–1 with 19% of emissions from fat-tail sites representing less than 2% of sites. The researchers concluded that the *"estimate of O&G emissions in the Barnett Shale region was higher than alternative inventories based on the United States Environmental Protection Agency (EPA) Greenhouse Gas Inventory, EPA Greenhouse Gas Reporting Program, and Emissions Database for Global Atmospheric Research by factors of 1.5, 2.7, and 4.3, respectively*." *Gathering compressor stations*, which accounted for 40% of O&G emissions in the study's inventory, *had the largest difference from emission estimates based on EPA data sources*, primarily due to the study's use of more comprehensive activity factors and inclusion of emissions from fat-tail sites.

Characterizing Fugitive Methane Emissions in the Barnett Shale Area Using a Mobile Laboratory[5]

Published in *Environmental Science & Technology* in July 2015 by researchers from the University of Houston. The authors measured atmospheric methane (CH4) using a mobile laboratory to quantify fugitive CH4 emissions from Oil and Natural Gas (ONG) operations in the Barnett Shale area. They sampled more than 152 facilities, including well pads, compressor stations, gas processing plants, and landfills. Emission rates from several ONG facilities and landfills were estimated using an Inverse Gaussian Dispersion Model and the Environmental Protection Agency (EPA) Model AERMOD. Model results show that well pads emissions rates had a fat-tailed distribution, with the emissions linearly correlated with gas production. Using this correlation, we estimated a total well pad emission rate of 1.5 ×105 kg/h in the Barnett Shale area. *The authors found that CH4 emissions from compressor stations and gas processing plants were substantially higher, with some "super emitters" having emission rates up to 3447 kg/h, more then 36,000-fold higher than reported by the Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (GHGRP).* Landfills were also determined to be a significant source of CH_4 in the Barnett Shale area, and the authors argue that they should be accounted for in the regional budget of CH_4.

Allocating Methane Emissions to Natural Gas and Oil Production from Shale Formations[6]

Published in *ACS Sustainable Chemistry & Engineering* in January 2015 by researchers from the University of Texas at Austin, URS Corporation, and Southwestern Energy Company, along with an independent consultant. The researchers used life cycle allocation methods to assign methane emissions from production wells operating in shale formations to oil, condensate, and gas products from the wells. The emissions allocated to the gases were then attributed to three main products: (1) salable natural gas, (2) natural gas liquids, and (3) hydrocarbon liquids (oil). Emissions for each product were allocated based on mass, energy and economic value, for each product gas product for each of the individual sampling sites that were reported by Allen et al. The emission allocations are based on a data set of 489 gas wells in routine operation and 19 well completion events. The methane emissions allocated to natural gas production are approximately 85% of total emissions (mass based allocation), but there is regional variability in the data and therefore this work demonstrates the need to track natural gas sources by both formation type and production region. *Methane emissions allocated to salable natural gas production from shale formations, based on this work, are a factor of 2 to 7 lower than those reported in commonly used life cycle data sets.*

Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions[7]

Published in the *Journal of Geophysical Sciences: Atmospheres* in March 2015 by researchers from the University of Colorado Boulder, NOAA Earth System Research Laboratory, Texas Commission on Environmental Quality, and Aerodyne Research, Inc. In this study, the authors presented measurements of methane (CH_4) taken aboard a NOAA research aircraft in 2013 over the Haynesville shale region in eastern Texas/northwestern Louisiana, the Fayetteville shale region in Arkansas, and the northeastern Pennsylvania portion of the Marcellus shale region, which accounted for the majority of Marcellus shale gas production that year. They calculated emission rates from the horizontal CH_4 flux in the planetary boundary layer downwind of each region after subtracting the CH_4 flux entering the region upwind. They found one-day CH_4 emissions of $(8.0 \pm 2.7) \times 107$ g/h from the Haynesville region, $(3.9 \pm 1.8) \times 107$ g/h from the Fayetteville region, and $(1.5 \pm 0.6) \times 107$ g/h from the Marcellus region in northeastern Pennsylvania. Finally, the authors compared the CH_4 emissions to the total volume of natural gas extracted from each region to derive a *loss rate from production operations of 1.0–2.1% from the Haynesville region, 1.0–2.8% from the Fayetteville region, and 0.18–0.41% from the Marcellus region in northeastern Pennsylvania. The researchers found generally lower loss rates than those reported in earlier studies of regions that made smaller contributions to total production.* This may mean that the national average CH_4 loss rate from shale gas production are lower than values extrapolated from the earlier studies.

Methane Emissions from United States Natural Gas Gathering and Processing[8] (EDF Cited Study)

Published in *Environmental Science & Technology* in July 2015 by researchers from Colorado State University, Fort Lewis College, Carnegie Mellon University, and Aerodyne Research Inc. In this study, new facility-level methane (CH4) emissions measurements were obtained from 114 natural gas gathering facilities and 16 processing plants in 13 U.S. states were combined with facility counts obtained from state and national databases in a Monte Carlo simulation to estimate CH4 emissions from U.S. natural gas gathering and processing operations. Total annual CH4 emissions of 2421 (+245/−237) Gg were estimated for all U.S. gathering and processing operations, *which represents a CH4 loss rate of 0.47%* (±0.05%) when normalized by 2012 CH4 production. *Over 90% of those emissions were attributed to normal operation* of gathering facilities (1697 +189/−185 Gg) and processing plants (506 +55/-52 Gg), with the balance attributed to gathering pipelines and processing plant routine maintenance and upsets.

The median CH4 emissions estimate for processing plants is a factor of 1.7 lower than the 2012 EPA Greenhouse Gas Inventory (GHGI) estimate, with the difference due largely to fewer reciprocating compressors, and a factor of 3.0 higher than that reported under the EPA Greenhouse Gas Reporting Program. Since gathering operations are currently embedded within the production segment of the EPA GHGI, direct comparison to our results is complicated. However, the study results suggest that *CH4 emissions from gathering are 87% higher than the current EPA GHGI estimate and are equivalent to 30% of the total net CH4 emissions in the natural gas systems GHGI.* Because CH4 emissions from most gathering facilities are not reported under the current rule and not all source categories are reported for processing plants, the *total CH4 emissions from gathering and processing reported under the EPA GHGRP (180 Gg) represents only 14% of that tabulated in the EPA GHGI and 7% of that predicted from this study.*

Onshore Petroleum and Natural Gas Operations on Federal and Tribal Lands in the United States[9]

The Environmental Defense Fund (EDF) commissioned an economic analysis of methane emission reduction opportunities from oil and natural gas operations on Federal and Tribal lands. The report, written by ICF International in June 2015, estimates that *fugitive and vented losses from oil and natural operations on Federal and Tribal lands amounted to over 65 billion cubic feet (Bcf) in 2013, which would be worth more than $360 million* at present and enough natural gas to meet the heating and cooking needs of 1.6 million homes. These losses led to over 1 million tons of methane emitted, *representing about 12% of the nation's methane emissions in 2013*, or approximately the equivalent to the greenhouse gas pollution from 5.6 million cars. Losses do not only accrue to oil and gas companies. Had there been zero leakage, *$32 million in taxpayer royalties* (based on gas at $4/Mcf and a 12.5% royalty rate) *would have been collected.* Finally, the report estimates that *companies can reduce these oil and gas methane emissions by nearly 40% using available methane mitigation opportunities at a net annual savings of $0.62* *per thousand cubic feet of gas (Mcf) reduced on federal lands, and a net annual cost of $0.25 per Mcf reduced on tribal lands (less than a penny per Mcf produced).*

2014 Research

Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations[10]

Published in *Earth's Future* in September 2014 by researchers from the Institute of Environmental Physics, University of Maryland, and the UK's NERC Centre for Ecology and Hydrology. The authors relied on data from the ENVISAT satellite, which measured atmospheric methane by measuring reflected solar radiation in the near-infrared/shortwave infrared spectral range. They specifically focused on atmospheric methane resulting from oil and natural gas production operations in the Bakken and Eagle Ford shale formations in North Dakota and Texas. The study found clear increases in atmospheric methane concentrations around production areas during the studied time period (2009-2011), which coincides with when shale production in those areas began, relative to earlier measurements from 2006-2008 before shale production began in those formations. The authors found "the following leakage-production ratios in terms of energy content result: 10.1± 7.3% for Bakken and 9.1± 6.2% for Eagle Ford." That means that *in the Bakken Shale formation, the average leakage rate was estimated to be 10.1%*, with upper bound estimate of 17.4% leakage and a lower bound estimate of 2.8% leakage. *For the Eagle Ford Shale formation, the average leakage rate was estimated to be 9.1%*, with upper bound estimate of 15.3% leakage and a lower bound estimate of 2.9% leakage. *The authors conclude by stating that "methane emissions from energy production of both target formations are likely underestimated (88% probability) in current bottom-up inventories," and that "at the current methane loss rates, a net climate benefit on all time frames owing to tapping unconventional resources in the analysed tight formations is unlikely."*

Toward a better understanding and quantification of methane emissions from shale gas development[11]

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."*

Methane Leaks from North American Natural Gas Systems[12]

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%. 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"*

Methane Leaks from North American Natural Gas Systems[13]

Published in the journal *Environmental Science & Technology* in June 2014 by researchers from Carnegie Mellon University and the National Oceanic and Atmospheric Administration. The study estimated natural industry representative fugitive emission rates using global atmospheric methane and ethane measurements over three decades, and literature ranges of (i) tracer gas atmospheric lifetimes, (ii) non-natural gas source estimates, and (iii) fossil fuel fugitive gas hydrocarbon compositions. *The authors found an upper bound global average fugitive emission rates of 5% during 2006–2011, and a most likely fugitive emission rates of 2–4% since 2000. The authors conclude that "further emissions reductions by the NG industry may be needed to ensure climate benefits over coal during the next few decades," and that "policies to further reduce fugitive emissions appear justified."*

A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas[14]

Published in the journal *Energy Science and Engineering* in June 2014 by Robert Howarth from Cornell University. This paper reviewed new data about natural gas methane emissions that has come out since the release of a 2011 research paper that he led, where he estimated that that lifecycle methane emissions are 3.6% to 7.9% of production for shale gas and 1.7% to 6% of production for conventional gas. This paper also updated the author's 2011 findings based on the fifth assessment report from the Intergovernmental Panel on Climate Change released in 2013. Dr. Howarth concludes by saying that "The best data available now indicate that our estimates of methane emission from both shale gas and conventional natural gas were relatively robust." He goes on to say that *"using these new, best available data and a 20-year time period for comparing the warming potential of methane to carbon dioxide, the conclusion stands that both shale gas and conventional natural gas have a larger GHG than do coal or oil, for any possible use of natural gas and particularly for the primary uses of residential and commercial heating. The 20-year time period is appropriate because of the urgent need to reduce methane emissions over the coming 15–35 years."*

Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania[15]

Published in *Proceedings of the National Academies of Science* in December 2014 by researchers from Princeton University. The authors took direct measurements of methane fluxes from abandoned oil and gas wells in Pennsylvania, using static flux chambers at locations near the wells in forested, wetland, grassland, and river areas in July, August, October 2013 and January 2014, respectively. The authors concluded that *"[m]ethane emissions from abandoned oil and gas wells appear to be a significant source of methane emissions to the atmosphere," and that "these emissions are not currently considered in any emissions inventory." Methane emissions from abandoned wells may account for "4–7% of estimated total anthropogenic methane emissions in Pennsylvania."* The authors recommend that "the research required to quantify these emissions nationally should be undertaken so they can be accurately described and included in greenhouse gas emissions inventories."

Air Impacts of Increased Natural Gas Acquisition, Processing, and Use: A Critical Review[16]

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.*

Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California[17]

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."

Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas[18]

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."*

Natural Gas Fugitive Emissions Rates Constrained by Global Atmospheric Methane and Ethane[19]

Published in the journal *Environmental Science and Technology* in June 2014 by researchers from the Carnegie Mellon University and the National Oceanic and Atmospheric Administration. The paper estimated global average fugitive emissions rates (FER) related to the natural gas life cycle in order to better understand whether recently reported high FER of 6-9% are representative of the larger natural gas industry. The study found that "the most likely FER was found to be 2-4% since 2000, and currently (2006-2011) having an upper bound FER of 5%." The authors go on to say that *"the most likely global FER range (2-4%) is slightly higher than many recent bottom-up estimates (1.1-3.2%; full life cycle) in the U.S. and elsewhere," but lower than recent high estimates of 6-9% in the U.S., which "may be possible at individual sites, but do not appear representative of the national average." The authors conclude by saying that "policies to further reduce fugitive emissions appear justified."*

U.S. Natural Gas System Methane Emissions: State of Knowledge from LCAs, Inventories, and Atmospheric Measurements[20]

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.

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