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Extended Report on a Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York City, New York

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by

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[This report is subject to revision.]

EXECUTIVE SUMMARY

DCS requested that GSI extend the work effort described in our initial Report on a Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York City, New York (16 December 2012) to assess the practicality of developing an estimate of methane emissions in Manhattan. Specifically the effort was to focus on providing an estimate of methane emissions that could be used in evaluating the role of natural gas leakage in Manhattan with respect to fossil fuel dependence, climate impacts and other environmental and economic concerns.

Currently the greenhouse gas equivalence of methane is widely accepted as at least 20 times the effect of carbon dioxide over a 100-year time frame. In

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other words, leakage of 1/20th, or 5%, of the methane moving through a natural gas production-transport-distribution system will effectively double the greenhouse gas impact of the use of that natural gas. That is, leakage of only 5% of natural gas from point of production to point of use would eliminate any greenhouse gas advantage of natural gas compared to other fossil fuels. More complex efforts by others have looked into the greenhouse gas emissions advantages of using natural gas instead of other fossil fuels. It appears that those more elaborate efforts are settling in at ≤3.2% gas loss to leakage as the maximum leakage rate at which use of natural gas retains an advantage. Hence, the loss of even a few percent of gas during production, transport, distribution and utilization is critically important to management and planning of present and future national and international energy supply and utilization systems. Therefore, it was concluded the extended GSI work effort should be focused on the need to assess total methane emissions. The available data was from Manhattan. Among the production, transport, local distribution and utilization systems, this work addressed the collective effect of only local gas distribution and utilization systems, along with any other methane sources that might be present in Manhattan .

GSI efforts for this extended report focused on three objectives: (1) find existing estimates from industry, government or other sources, of the amount of methane being released in Manhattan, (2) develop such an estimate from the ground-level methane data collected during our preliminary investigation of methane levels in Manhattan, and (3) compare those estimates and consider their implications with regard to broader environmental and economic concerns. Since this investigation was limited to Manhattan (augmented with comparative data from the Bronx, and other areas across New York and Connecticut), ConEd is the relevant gas distribution company.

An examination of existing estimates, or methods for estimating, methane emissions led to the conclusion that such estimates have little basis in actual data. Natural gas companies are required to file yearly reports of Lost- and-Unaccounted-for (LAUF) gas. Presumably these reports would approximate the amount of gas leaked from the pipelines and other infrastructure of the reporting companies. However, the meters in those gas systems are only required to be accurate to ±2%. Each such system may contain hundreds of thousands of meters. Each meter is subject to normal wear and tear. Another problematic issue is the reported LAUF gas volume may incorporate other gas volumes by rule, contract, regulation, or for other administrative reasons. Consequently, the annual reported LAUF gas volumes should not be regarded as reliable estimates of the amounts of gas actually lost or emitted to the atmosphere. However, since the LAUF gas volume is ultimately based mostly on measurements using meters that are accurate to ±2%, it follows that long-term average LAUF values should provide a reasonably meaningful mean with a ±2% variability. A ten-year average LAUF for ConEd was 2.2% with a range of 0.4 to 4.3%, i.e, ±2% variability. The 10-year-average-LAUF based estimate of annual methane emissions for the entire ConEd system was 2.2% or about 6.6 billion cubic feet per year.

The apparently most widely used method for estimating gas leakage and methane emissions from gas pipelines appears to be from a 1996 report by the U.S. Environmental Protection Agency and the Gas Research Institute (EPA/GRI). Estimates generated using the EPA/GRI 1996 method have such a wide confidence interval (±65%) that their general accuracy and usefulness is questionable. The report recognizes the likely importance of gas leaks that are undetectable by the standard industry leak detection practice, but the estimation method makes no attempt to account for such undetectable leaks. Finally, a related report of a more thorough study of cast iron pipelines in Brazil, suggested that the EPA/GRI method may provide estimates that are too low by almost half. Application of the EPA/GRI method to the pipeline statistics for the entire ConEd system generated an estimated methane emissions rate of 1 billion cubic feet per year, which can be meaningfully compared to the 10-year average ConEd LAUF gas estimate of 6.6 billion cubic feet per year. Since most leakage in gas delivery systems occurs from the pipes in the system, such a disparity between the EPA 1996-based estimate for ConEd pipeline leakage and the 10-year average ConEd LAUF gas volume would seem to indicate problems in one or both of those estimates.

During the research for this Report, we thoroughly reviewed the methane data collected by GSI during the previously reported Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan. We also reviewed the meteorological literature and meteorological data available for Manhattan. Based on that information we developed a simple model (patent pending) that could process our preliminary Manhattan methane data and meteorological data from local sources to generate a preliminary estimate of total methane emissions in Manhattan. The resulting estimate was the flow of methane to the atmosphere from all sources in Manhattan. Such an estimate can be used to assess the relative importance of those emissions in terms of methane as a greenhouse gas (GHG) and the relative impact of gas service/use in Manhattan in a broader climate/GHG context. Wherever reasonable in the application of the model, input values were selected conservatively, so that any errors in the result should be to the low side.

The resulting methane emissions estimate for Manhattan alone was 8.6 billion cubic feet per year, or about 2.86% of the 300 billion cubic feet of gas handled by the entire ConEd system each year, even though Manhattan comprises only about 5% of the land area and one-third of the customers in the ConEd service territory. There are also substantial losses that occur in the natural gas system before natural gas reaches the ConEd distribution system. It, therefore, appears inevitable that the loss of gas in the system serving NYC via ConEd is above the simple critical level of 5%, and well above the more elaborately derived critical levels of ≤3.2%. That is, the methane leakage in the system serving NYC through ConEd is likely already at a level where the methane leaked has as much or more climate impact as the remaining approximately 95% of the gas that is actually usefully burned by consumers in NYC. This necessarily raises doubts about the claimed value of natural gas as a "clean bridge fuel". Further work should be done to verify the findings we report here and to identify specific methane sources, as well as to improve natural gas leak prevention and management. Furthermore, the evidence suggests that leakage from natural gas systems has a more substantial role in climate change than was believed that has only recently begun to be appreciated.

Panoramic image looking south from the upper deck of the 'Top of the Rock' observation deck on Rockefeller Center. Image taken and assembled by Daniel Schwen on Dec 6th, 2004. {GFDL Wikipedia}

INTRODUCTION

In our initial report (dated 16 December 2012) on the preliminary investigation of ground-level ambient methane levels in Manhattan, New York City, New York we stated, “Further work is needed to determine whether an approximate estimate of the amount of methane being released to the atmosphere can be developed from the data generated by this preliminary methane survey.” To that end our efforts have focused on three objectives: (1) find existing estimates of the amount of methane being released in Manhattan from industry, government or other sources, (2) develop such an estimate from the ground-level methane data collected during our preliminary investigation, and (3) to compare those estimates and consider their implications with regard to broader environmental and economic concerns. Since this investigation was limited to Manhattan (augmented with comparative data from the Bronx, and other areas across New York and Connecticut), ConEd is the relevant gas distribution company.

Available Estimates of Methane Emissions in Manhattan

There are readily available documents that imply measurement-based estimates of methane (natural gas) releases in Manhattan have been developed.[3,4] However, review of those estimates leads to the conclusion that they are all largely based on other estimates, some periodically updated, but apparently never actual measurements of gas emissions in the field. This is presumably due in part to the historical lack of readily available, reliable approaches to actually measure methane concentrations and calculate methane emissions under field conditions.

LAUF Gas

Among the more prominent of such estimates-based-on-other-estimates would seem to be the Lost And Unaccounted For (LAUF) gas that companies are required to report to the New York State Department of Public Service (NYSDPS). Actually, the reported LAUF is a calculated number that includes volumes actually measured by meters in the gas distribution system along with various add-ins and deductions that are matters of contract, regulation, or used for operational accounting reasons. In addition to the arbitrariness of the add-ins and deductions, gas meters are only required to be accurate to ±2%. Malfunctions leading to metering errors of more than 2% can be expected to occur. It is important to realize that the estimation and reporting of LAUF gas was never intended to represent actual losses of gas from the gas distribution system, but to facilitate annual reconciliation of costs for gas purchased to revenues for gas sold while providing incentive to minimize actual loss of gas.[5] The reliability of LAUF numbers as estimates of actual gas losses is easily appreciated in the following statement (with original footnotes) found in a New

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[3] ConEdison Gas Long Range Plan 2010-2030, December 2010 [accessed at http://www.coned.com/PublicIssues/PDF/GLRP1210c.pdf], and various ConEd annual and other reports.

[4] Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 - 2009, USEPA, April, 2011., Annex 3 (PDF) (232 pp, 9.6 MB) - Methodological Descriptions for Additional Source or Sink Categories. [http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html].

[5] NYS DEPARTMENT OF PUBLIC SERVICE, STAFF WHITE PAPER ON LOST AND UNACCOUNTED FOR (LAUF) GAS, issued January 27, 2012. [White paper accessed at http://www.google.com/search?client=safari&rls=en&q=NYS+DEPARTMENT+OF+PUBLIC+SERVICE,+STAFF+WHITE+PAPER+ON+LOST+AND+UNACCOUNTED+FOR+(LAUF)+GAS,+Hearing+Exhibit+No.+76,+GRP-15&ie=UTF-8&oe=UTF-8]

York State Department of Public Service Staff White Paper on Lost and Unaccounted for (LAUF) Gas[3] (NYSEG is New York State Electric and Gas Corporation):

> "<u>Negative Losses</u>
> Staff must address negative losses because NYSEG[12] has experienced consistent negative losses for the past 3 years. Negative losses are physically impossible. However, consistent year to year calculated negative losses are possible when the offset[13] between the set of meters reading gas in and the set of meters reading gas out is negative and the natural variability is less than that offset. Additionally, natural variability in the LAUF can produce negative losses in some years for LDCs whose offset is positive.
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> [12] Case 09-G-0669
> [13] Two sets of meters will never provide the same measurement. The difference between those two measurements is defined as offset."
> Note: LDCs are Local Distribution Companies

NYSEG LAUF gas values over those "past three years" (2008-2010) averaged -0.359%, while the ConEd average LAUF for the same three years was +1.249%. NYSEG is not ConEd, but gas metering and related LAUF errors inevitably affect the reported LAUF gas amounts of every company and probably in different and unforeseeable ways that change from year to year. Unaccounted for gas estimates are also reported annually to PHMSA[6]. When ten years (2002-2011) of those reported values were examined for this report, they were not the same as those stated in the NYS DPS Staff White Paper[3], presumably due to different reporting requirements. Though consistently low, the NYSEG unaccounted for gas reported to PHMSA, were never negative, ranging from 0.1% to 0.3% for the eight years 2004-2011. Though not implausible, such consistent and low numbers are interesting given that meters used in gas systems are only required to be accurate to ±2%. For the ten years 2002-2011, ConEd reported annual unaccounted for gas percentages ranging from 0.4-4.3. In contrast to the consistently low numbers of NYSEG, the ConEd numbers appear to have a variation of very close to ±2% around a mean of 2.2%. Coincidentally, 2.2% also happens to be the mean of all unaccounted for gas percentages reported to PHMSA from 2002-2011, though among those numbers individual annual reports ranged from -28% to +109%. Such examples serve to illustrate that LAUF numbers provide little if any useful insight into the actual amounts of gas lost from companies' gas distribution systems at any given time, or over a given year. Still, it is helpful to consider a bit further the implications of the average

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[6] PHMSA - US Department of Transportation Pipeline and Hazardous Materials Safety Administration. Lost and Unaccounted for Gas reports accessed at http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.ebdc7a8a7e39f2e55cf2031050248a0c/?vgnextoid=a872dfa122a1d110VgnVCM1000009ed07898RCRD&vgnextchannel=3430fb649a2dc110VgnVCM1000009ed07898RCRD&vgnextfmt=print

unaccounted for gas percentage of 2.2%.

A Little Bit Matters

A loss of 2.2% might seem almost trivial. Each gas consumer, based on the required accuracy of the meter that measures gas consumption, can expect that they may be over or undercharged by as much as 2% anyway. Why, then, should anyone concern themselves with a loss of a few percent over the distribution system as a whole? A first answer would be a fair allocation of the monetary cost of the lost gas. In 2011 ConEd had total gas sales and transportation revenues of around 1.5 billion dollars, 2.2% of which amounts to 33 million dollars. That is a substantial amount of money and has to be accounted for and fairly allocated, a process that is regulated by the NYS Department of Public Services. Again, though, in the grand scheme of things, the consequences for each customer are relatively minor, only 0.2% more than the ±2% of metering accuracy. So, we are still left with the question, why does such a seemingly small amount matter?

There are two closely related reasons. One, it remains that, regardless of the reporting of the amounts of lost and unaccounted for gas, those reported amounts do not seem to provide a reliable indication of the actual losses of gas that are occurring. Two, when methane, which makes up over 90% of natural gas, escapes from the distribution system it can accumulate to pose direct risks of injury and property damage. A less obvious but greater global concern is the role of methane as a potent greenhouse gas. Any leakage of methane poses an effectively invisible, but potentially substantial threat to human health and the environment. These reasons provide a means of understanding why the actual amounts, and locations, of even seemingly small gas losses matter.

Even small natural gas leaks in confined spaces are dangerous, posing explosion and asphyxiation hazards. When a small underground gas leak finds a pathway to an enclosed space, such as a manhole, the gas can accumulate to explosive levels (5%-15% methane). Basements and other poorly ventilated spaces can also accumulate leaked gas to hazardous levels. Explosions related to such accumulations of leaked gas, though not common, are recurrent wherever natural gas is used. In addition, where even relatively small amounts of gas are leaked into the soil for extended periods, vegetation will be damaged, loss of urban trees being a common impact. Still, the ConEd record of gas safety with regard to direct hazards is relatively good.

ConEd, like other gas companies, has a routine program to detect, manage and repair leaks. However, the objective of such leak control programs is to detect leaks, not measure the amount of gas lost through them. Such measurements would be impractical, especially for the potentially very large numbers of very small leaks that can be expected to develop in pipe systems that contain substantial amounts of old pipe. Over 70% of the cast iron pipe in the ConEd system is over 100 years old, and almost all was installed before 1930, i.e., is more than 80 years old.[3]

EPA Leakage Estimates for Natural Gas Pipelines

In this scenario, we are left with potentially large numbers of small leaks, and smaller numbers of larger leaks in gas pipe systems. Measurement of the gas losses that occur through such leaks is in practical terms impossible. Most of the small leaks will never be identified, let alone measured. How, then, does anyone arrive at some reasonable estimate of how much gas is being lost? In 1996 the U.S. Environmental Protection Agency (EPA) released an approach for estimating such losses.[7] This approach is of considerable importance because it has become the basis for international estimates of methane/natural gas leakage as well.[8]

The EPA approach[7] is relatively simple, based on 4 types of pipe materials, cast iron, unprotected steel, protected steel, and plastic. The estimated leak rates for the 4 types of pipe were based on data collected in a 1992 study by the EPA and the Gas Research Institute (GRI). The length of pipe of a given type in a system is multiplied by an estimated leak rate for a given length of that type pipe. For cast iron pipes, the oldest and leakiest type, the estimated leak rate is in standard cubic feet per mile of pipe per year (scf/mile-yr). That study looked at a total of 21 samples of cast iron pipe. The estimated methane leak rate for cast iron pipe was 399,867 scf/mile-yr (with a 90% confidence interval of 227,256). This was reduced by another factor intended to account for the amount of methane that would be biologically oxidized in soil before escaping into the atmosphere to produce a "Methane Emission Factor" for each type of pipe. After that reduction the estimated emission factor for cast iron pipe became 238,736 scf/mile-year (with a 90% confidence interval of 152,059).

The 90% confidence intervals and numbers of samples are mentioned in this discussion because it is important to understand how imprecise these estimates

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[7] EPA/GRI. Methane Emissions from the Natural Gas Industry. Volume 9: Underground Pipelines. June 1996. http://www.epa.gov/gasstar/documents/emissions_report/9_underground.pdf.

[8] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>.

are. The numbers seem so imprecise that their usefulness seems questionable. The statistically strongest data set in EPA/GRI[7] was that for cast iron pipe. The data indicates that there is only 90% confidence that the true mean leak rate for cast iron pipe is somewhere in the range of 399,867±65%, that is, somewhere between 172,000 and 626,000 scf per mile of pipe per year.[9] The 90% confidence level seems low for an estimate that has implications as broad and important as this one. Accuracy is critical in estimating emissions of the second most important greenhouse gas, methane, when these estimates are being used in both national and international estimates for climate change modeling and planning of mitigation and response measures..[8] At least a 95% confidence interval would seem more traditional and appropriate to the purpose. However, back calculation from the 90% confidence levels and sample numbers in EPA/GRI[7] report indicate that the 95% confidence intervals would extend below zero for unprotected steel and plastic pipes, and would approach zero for protected steel. In fact, in the case of plastic pipe, with a high variability (range 0.008 to 61 std.cu.ft. per leak per hour) and the lowest number of samples (N=6), even at the liberal 90% confidence level, the lower limit of the confidence interval was -60,000 std.cu.ft. per leak per year, implying the impossible situation that relatively large amounts of gas could be taken in instead of emitted by leaks in plastic gas lines. One might reasonably set aside the issue of implied negative leak rates, and allow that leak rates below zero cannot occur. Even from this perspective, one is left with the predicament that the EPA/GRI[7] data for plastic pipe do not distinguish at a 90% confidence level between 260,000 scf per leak per year and no leak at all.

A Leakage Estimate from Comgas in Brazil

The EPA estimate approach is still the international norm, but more recent work reported out of Brazil provides a different picture.[10] That study by the Brazilian natural gas distribution company Comgas used a different approach to selecting samples, and a very conservative approach to disregard all suspiciously or inexplicably high leak rates. The Comgas study was apparently continuous from 2005 through at least 2009 as part of a pipe system upgrade program. Consequently, pipe sections selected for testing were each almost

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[9] EPA/GRI[7] is not clear regarding whether a one-sided or two-sided confidence interval was used. The statement, "an overall accuracy of ±65% based on a 90% level of confidence" suggests a two-sided confidence interval was used, but repeatedly in footnotes to tables "upper bound minus the mean" may indicate a one-sided confidence interval was used. We assumed that all confidence intervals referred to in EPA/GRI[7] were two-sided.

[10] Carey Bylin et al. 2009. New measurement data has implications for quantifying natural gas losses from cast iron distribution mains. Pipeline and Gas Journal. (www.pgjonline.com).

certainly considerably larger than the minimum 20-foot sections in the EPA/GRI 1992 study[11] and were effectively more randomly selected. Random selection based on work scheduling without regard to prior detection of leaks combined with measurements of longer pipeline segments means the Comgas study would more likely measure total leakage, where the EPA/GRI approach was based on detection of leakage before testing. In the course of the Comgas work in Brazil, 912 pipe sections were tested, compared to only 21 in the EPA/GRI 1992 study. The Brazilian cast iron pipe system was reported to be otherwise comparable to the U.S. cast iron system studied by EPA/GRI in 1992. The Brazilian cast iron pipe, however, would likely be considerably younger than that in the ConEd system in which 70% of the cast iron pipe is over 100 years old. Instead of a methane leak rate of 399,867 scf/mile-yr the Brazilian study found a leak rate of 750,513 scf/mile-yr. It is interesting that though the Brazilian study may be regarded as contrasting with the EPA/GRI, in fact, it actually is statistically compatible. We back calculated the standard deviation of the EPA/GRI[7] cast iron pipe results and concluded the 750,000 scf/mile-yr appears to be within 99% confidence bound of the EPA/GRI[7] study. That is, the findings of the two studies do not seem to conflict. The Brazilian is simply a more robust, larger study that should provide a more accurate estimate and is statistically compatible with the EPA/GRI estimate.

Yet, even the higher Brazilian numbers may be too low because data from pipe sections with suspiciously or inexplicably high leak rates (>1,991,444 scf per mile per year) were excluded. The excluded data was 15.4% of the total data. The concern behind that elimination of high leak data was that such data could be caused by measurement procedural problems in the field or unmapped service lines connected to the cast iron mains. It would seem likely that leaks of this size would result in noticeable mercaptan odors and consequent leak reports. Nevertheless, it also seems reasonable that such large leaks may develop slowly and exist for some time before odor motivates reports of suspected leaks, though 15.4% of pipeline test sections seems implausibly high. The concern that such high data are due to procedural difficulties or unmapped services seems reasonable, but one avoided at the risk of entirely missing some actual large leaks. For example, if the tested sections are relatively long, there could be several moderate sized leaks that collectively cause leak rates above

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[11] The actual lengths of cast iron pipe sections were apparently variable and not clearly specified in the 1996 EPA/GRI[7] report of the results of the 1992 EPA/GRI study of pipe leak rates: (on page 20 of that report) “The segment to be tested was either: 1) a service which was isolated … at the service-to-main connection and the customer’s meter, 2) a short segment of main (at least 20 feet long) containing the detectable leak which was isolated by capping both ends, or 3) a long segment of main containing multiple leaks…isolated by capping off each end. … For cast iron pipes, a segment test approach was used since many undetected leaks are known to exist in cast iron.”

the Comgas sample rejection level. Without knowing the lengths of the Comgas test sections, it is not possible to resolve this doubt. For present purposes, it is sufficient to let the Comgas test results stand as reported.

Estimates of Methane Leakage for ConEd based on EPA/GRI and Comgas Reports

Most of the oldest and leakiest pipe in many natural gas systems is cast iron. About 30% of the mains in the ConEd pipe system are cast iron, with another 30% unprotected steel, the next leakiest type. Now, using the EPA Methane Emission Factor extrapolation approach would seem reasonable enough, in fact, a practical necessity given the amount of underground pipe in natural gas distribution systems. For example, ConEd has about 1300 miles of cast iron mains, with similar amounts of unprotected steel, all of which feed eventually into hundreds of thousands of smaller service lines. Clearly the amount of gas leaking from each segment of such an extensive gas pipe system cannot be monitored continuously.[12] Given the soil conditions under the streets of Manhattan, biological oxidation of methane is probably limited. So, if one applies the (no soil methane oxidation) EPA Methane Leakage Factor of (rounded) 400,000 scf/mile-yr for cast iron mains to the 1300 miles of cast iron pipe in the ConEd system one arrives at estimated methane emissions of 520,000,000 scf/yr. If one uses the Brazilian Comgas cast iron pipe leak rate this becomes 975,000,000 scf/yr, which could also be too low.

Other Leak Sources and Other Estimates

One could similarly generate estimates for the other likely sources of gas leakage in the ConEd system in accordance with EPA estimating methods. In fact, beginning in 2010 ConEd, along with most other large emitters of greenhouse gases, has to file a report of estimated emissions of GHGs, including methane, with the EPA every year. However, during the preparation of this report only the 2010 GHG emissions report for ConEd had been filed and released by EPA. That 2010 ConEd report contained only volumes of natural

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[12] In fact, in general any given section of pipe is checked every 1-3 years. Type 3 leaks that are detected but do not present an explosion hazard at the time of detection, and are deemed not likely to subsequently present such a hazard, are not repaired but put on a somewhat more frequent inspection schedule to assure they do not increase to a hazardous level. That is, they are left to continue leaking until they increase to an explosion hazard level or are repaired under routine leak repair efforts. Such unrepaired Type 3 leaks effectively release methane emissions without a control effort because they do not present an immediate or foreseeable explosion hazard.

gas delivered, which totaled 286,962,094,000 scf. The number of potential sources of leaked methane, besides cast iron pipe, in the ConEd system is large, perhaps explaining why the 2010 ConEd GHG emissions report to EPA is empty. For the purposes of this report, a simpler approach may serve the immediate purpose of showing that presently reported numbers are not reliable and approaches to actual measurement are needed.

Consider in this regard that through the EPA Natural Gas STAR program ConEd has been credited with reducing methane emissions by 4,393,613,000 scf cumulatively since 1993. That 18-year (or so) cumulative reduction barely makes up for somewhere between 4 and 8 years of the estimated ongoing leakage from cast iron pipes alone, depending on the leak rate factor used. ConEd reported to the EPA GasSTAR program that in its best single year, 2008, it reduced methane emissions by 158,795,000 scf. That is, in its best year, ConEd eliminated the equivalent of barely 30% of just one year of losses from the cast iron pipe alone. So, given there are still 1300 miles of cast iron pipe in the ConEd system, and there are many other potential leaks in the ConEd system, ConEd may well be losing ground with respect to overall net methane emissions. Further, if one considers that the total gas handled annually by ConEd amounts to about 300,000,000,000 scf[1], then the estimated cast iron pipe leakage alone amounts to in the range of 0.17-0.33%, and this estimate could still be low.

When Is a Leak a Leak?

When It Is Detectable.

Another matter worth considering is the functional definition of a leak. In the ConEd Long Range Gas Plan (2010)[1] there is the following statement (including associated original footnotes).

> "Con Edison also performs extensive leak repairs annually and has managed to reduce the backlog of leaks … . In 1988, the gas leak backlog was just over 15,000 leaks and year-end 2009 leaks were under 1,400. Most of the leaks in the leak backlog are Type 3[23] leaks which are not hazardous. We enter each winter with less than 100 hazardous leaks. Gas leak repairs are a major commitment of our O&M expenses. Con Edison has the highest amount of leak reports issued annually of all NYS utilities. Con Edison has committed to the NYS Public Service Commission that ConEd will maintain a leak backlog of less than 1,600[24] leaks at the end of the year.
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> [23] A Type 3 leak is not immediately hazardous at the time of detection and can be reasonably expected to remain that way. However, Type 3 leaks shall be reevaluated during the next required leakage survey or annually whichever is less.
> [24] NYS PSC mandates a leak backlog less than 1600 leaks at the end of the year."

The contention of ConEd regarding the total number of leaks may be reasonable given industry leak detection practices, but not at all accurate in terms of actual total pipe leakage. A similar statement has to be made with respect to the previously discussed 1996 EPA/GRI report[7] providing the now widely used methane emission factors for gas pipelines.

Cast iron gas distribution (pipe) mains have been in the ground longest among all the predominant pipe types in the commercial natural gas system. EPA/GRI[7] reported that cast iron pipelines were found to be much leakier than the pipelines of the other pipe materials. The high leakage from cast iron pipes is due to large number of small leaks, "For cast iron pipes, a segment test approach was used since many undetected leaks are known to exist in cast iron." EPA/GRI[7] also reported experiments indicated 40.3% of the methane leaked from cast iron pipes was oxidized during its rise to the soil surface, but only 1.8-3.0% for the other pipe types. Soil methane oxidation rates measured around cast iron pipes were much higher than for other types because the methane leakage is spread more widely around and along cast iron pipes. For the other pipe types, detected leaks tended to be larger but fewer in number resulting in more concentrated methane and less oxidation in the soil.

So, when, then, is a leak a leak? When gas escapes from a pipeline is it like the proverbial tree falling in the forest? When gas escapes from a pipeline is it a leak, or is it not a leak until the gas company detects it? The following quote from the EPA/GRI report[7] explains the typical industry approach to detecting gas leaks.

> "Gas distribution operators use leak detection procedures to locate and classify leaks for repair. To identify a leak in a section of pipe, a portable hydrocarbon analyzer or flame ionization detector (FID) was used to screen immediately above the ground level while walking the pipeline. Any excursions above the background level (typically 2-3 ppm) may indicate a nearby leak."

However, the EPA/GRI[7] report also states that "many undetected leaks are known to exist" in cast iron gas mains. That is, there are undetectable leaks, and potentially a lot of them. Again quoting the EPA/GRI[7] report (page 20),

> "This technique was based on testing leaks which are detected using leak survey procedures (i.e., detected leaks), and may exclude smaller or more diffuse leaks that are not detected at the soil surface."

Now, having established there are undetectable leaks, and since undetectable leaks are undetectable, they are not included in the leak counts of ConEd, or any other gas company using a similar leak detection method. Similarly, since this method was used in the EPA/GRI[7] pipeline leakage study to select pipe sections for leak testing, whether or not it accounts for any undetected leaks is unclear. That report states,

> "The leak flow rate measurement used should have accounted for all leaks in a pipe segment. … The segment of pipe tested was also surveyed to determine the number of detected leaks and the corresponding concentration of methane detected for each leak in the segment."

However, it is not clear whether or how this survey "to determine the number of detected leaks" might have included "undetectable leaks".

So, we are left with data in industry records and the widely used EPA/GRI[7] study results that by default do not seem to address "undetectable" leaks even though those records and that report clearly indicate substantial amounts of such leaks do occur. At least we do know that a leak is a leak no matter how small.

A Consideration of Undetectable Leaks

In Cast Iron Pipe

At this point one may wonder what then might an undetectable leak be like and what difference, if any, might such leaks make? The question would seem to resolve to how many undetectable leaks might there be that would escape detection by the typical industry leak detection method. Leaks are usually detected by surveying at the ground surface above a pipe with an FID instrument set to alarm if methane (actually combustible gas) levels rise above background levels. EPA/GRI[7] accepted and included in their emission factors an estimate by Southern Cross Corporation that 15% of detectable leaks are simply missed using the standard leak survey. It would seem to make sense that those 15% might be predominantly smaller, hence, harder to detect leaks.

Actual individual leak data were not provided in the EPA/GRI[7] report except for the 6 data points for plastic pipe. The lowest leak measured, hence, presumably detected, was 0.008 scf per leak per hour. It is not clear, however, that this was a leak that actually allowed detection as the next nearest leak rate, 0.700 scf per leak hour, was approaching 100 times larger. EPA/GRI[7] reported that this 0.008 scf per hour leak value was a potential statistical outlier. Coincidentally, it also happens to be the smallest of 6 data points, and, therefore, comprises roughly the bottom 15% of the leaks, i.e., the percentage estimated to be routinely missed in leak surveys. So, if the 0.008 scf/leak-hour value is disregarded, among the remaining five data points, the next highest 3 fall in the range of 0.7-1.62 (average 1.15) scf/leak-hour. Since these are the only data immediately available, we will assume for this discussion that the smallest leak that can be reliably detected using the industry leak detection method will have a leak rate of 1 scf/leak-hour.[13] As discussed below, it matters little whether the actual undetectable leak is 1 scf per hour or considerably lower.

It would seem to follow that if two 1-scf-per-hour leaks were next to each other, then at the soil surface they would present the same methane concentration as one 2-scf-per-hour leak. That is, they would be detectable. So, then, at what distance of separation would they cease to be detectable? Gas Safety, Inc. experience with gas leak detection indicates that under a paved surface small leaks are detectable over a surrounding, roughly circular area in the range of 20-25 feet in diameter, and about half that if the soil surface is not paved over. Recall the test sections in the EPA/GRI[7] study were around 20 feet which would, therefore, imply that small (≤1 scf -per-hour) leaks separated by more than 20 feet would not likely have been detected or measured in that study. To provide some notion of what such leaks might mean, one could assume there ought to be a range of such small undetectable leaks that should vary from just more than zero to just less than 1 scf per hour, which would generate an average undetectable leak size of 0.5 scf per hour.

Because undetectable leaks are undetectable, there is at present no data that provide direct indications how many there might be per length of pipe, regardless of the material the pipe is made of.[14] Nevertheless, a rough indication can be extracted from the data in the EPA/GRI[7] report. For ten reporting gas distribution companies, there was an average of 1.38 leak repairs per mile of cast iron pipe. It follows that if a repair were undertaken, then it was because a detectable leak had been found. This is actually a conservative approach because a repair implies a detected leak, but not all detected leaks are repaired (within a year of detection). EPA/GRI[7] estimated the average

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[13] Based on decades of experience in gas pipeline leak detection, Gas Safety, Inc, considers such small leaks unlikely to be detectable by conventional gas leak surveys in open field, unpaved soil surface conditions. In urban settings, i.e., where gas lines are under paved surfaces that can cause methane to accumulate in the soil or in underground channels or spaces, a larger proportion of such leaks might be detected. The urban/rural setting of the EPA/GRI[7] sampling sites was not specified.

[14] Except for the Comgas study[7] in Brazil regarding leaks from cast iron pipes, implications of which are discussed later in this report.

number of active detectable leaks per repair was 2.14. Converting 1.38 repairs per mile to the distance between detected leaks (repairs) yields one detected leak for every 0.725 miles of pipe. Applying the EPA/GRI[7] estimate of 2.14 actual detectable leaks per repair reduces the distance between detectable leaks to 0.725/2.14=0.339 miles. Since the (presumably) total leak rate for cast iron pipe was 399,867 scf per mile per year, the total leak rate for the average length of pipe between two adjacent detectable leaks, i.e., 0.339 mile, would be (0.339 X 399,867) = 135,469 scf per year.

We are trying to develop some understanding of the potential importance of undetectable leaks. The EPA/GRI[7] cast iron leakage rate supposedly includes both detectable and undetectable leaks. So, if we deduct the rate for detectable leaks in cast iron pipe from the total leakage, we should have the rate for undetectable leaks. Unfortunately, there was no reported leak rate per leak in cast iron pipe because, as previously discussed, cast iron pipe typically has a large number of small leaks. As an alternative, we used the leak rate of 52,748 scf per leak per year for the most similar pipe, unprotected steel. Each detectable leak is on average 0.339 miles from the next, and each 0.339 miles of pipe has a total leakage of 135,469 scf per year. The undetectable leakage should be the difference between the total leakage (135,469 scf/yr) and leakage from the detectable leak (52,748 scf/yr), which is 82,721 scf per year. This then is an estimated average leakage from undetectable leaks for the pipe between each two detectable leaks, which occur on average every 0.339 miles. Converting this undetectable leakage rate to leakage per mile per year yields 244,000 scf per mile per year.

This volume of leakage would be accounted for by one undetectable 0.5-scf-per-hour leak every 95 feet along the cast iron pipeline. Perhaps, though, the actual undetectable leak size is smaller. Even if the average undetectable leak were smaller, say, 0.2 scf per hour, then the interval between undetectable leaks that would account for 82,271 scf/0.339 mile per year would be 39 feet, still farther apart than the likely 20-foot interval that might make 1-scf-per-hour leaks detectable and well beyond the ends of the 20-foot test segments used in the EPA/GRI[7] study. So, it matters little whether the threshold for leak detection is 1, 0.5 or 0.2 scf/hour, the implications of undetectable leaks remain large, at least for cast iron pipe. With regard to the plausibility of this estimate of leakage from undetectable leaks in cast iron pipe, one may consider that adding this 244,000 scf per mile per year to the EPA/GRI[7] estimated 400,000 scf per mile per year (presumably based on pipe sections with detectable leaks) generates a total estimated leakage of 644,000 scf per mile per year, still well below the 750,000 scf per mile per year total leakage actually measured in the Comgas study in Brazil.

Undetectable Leaks In Pipelines Made of Other Materials

This potential importance of undetectable leaks cannot be simply ruled inapplicable to pipes made of other materials. There seems no reason to rule out occasional minor manufacturing defects, damage during installation and due to natural underground processes and animal and human activities after installation. Indeed, unprotected steel is subject to corrosion problems, as is protected steel, though to a lesser degree. The question becomes, then, how to generate an estimate of the potential importance of undetectable leaks in steel and plastic gas lines. One approach would seem to be to again exploit the logical association of repairs to detected leaks. It was estimated above that leaks as large as 1 scf/hour and as close together as every 20-25 feet would likely be undetectable using the typical industry leak detection method. Once again referring to EPA/GRI[7], the reported repair interval for unprotected steel pipeline was 1.09 repairs per mile per year, and 0.08 for both protected steel and plastic. These can be converted, as above, to miles between adjacent repairs, which are 0.917 miles for unprotected steel and 12.5 miles for both protected steel and plastic. Now, it would seem reasonable to conclude if pipe injury/defects/etc. were causing detectable leaks in cast iron, then undetectable leaks in other pipe materials will ultimately be due to the same causes. So, if leaks have the same causes in all pipe materials, then the ratio of detectable leaks to undetectable leaks should be reasonably similar for all pipe materials.

Applying this same-ultimate-causes-for-leaks reasoning and extrapolating the estimated undetectable leakage rate for cast iron pipelines to unprotected steel pipelines yields an effective distance between detectable leaks of 0.429 miles, and an estimated leakage from undetectable leaks of 47,543 scf per year for each 0.429 miles of pipe, or 111,000 scf per year per mile of unprotected steel pipeline. Extrapolating the above approach indicates flows from undetectable leaks are likely to be <10% of those for detectable leaks in plastic and protected steel pipes. It should be borne in mind, however, that these pipe materials have not yet progressed far into their expected service lives, whereas cast iron pipes still in service are old, 70% over 100 years for ConEd. It would seem that monitoring for leaks previously regarded as undetectable would be advisable to assure environmentally safe management of natural gas leaks in a future where so much more gas and presumably so many more gas lines are expected to be in use, regardless of the pipe material.

Why Are More Accurate Measures of Natural Gas Leakage Needed?

Whether one considers the ConEd LAUF as reported to NYSDPS, or to PHMSA or to EPA based on factors given in EPA/GRI[7], the reality is we have little reason to believe any of these estimates provide a reliable indication of how much natural gas is leaking from natural gas distribution systems, or of how much methane that leakage is releasing to the atmosphere. Hopefully it is at this point obvious to the reader that actual identification and measurement of every gas leak, or even leakage of gas from every segment of gas pipeline in service, is an impossible, and perhaps meaningless task. In the end there remain three objectives:

1. Fair and reasonable allocation of unaccounted for costs in the natural gas public service system.
2. Prevention of hazardous situations related to accumulation of leaked gas to levels that are explosive or asphyxiating (to humans, animals or plants).
3. Mitigation of the expected climate affecting impacts of methane emissions to the atmosphere.

At present there are, as already discussed, procedures in place that achieve the first two of these objectives to a reasonably satisfactory level. The third, however, is not effectively addressed at all by those approaches, and apparently inadequately by currently used estimation methods based on EPA/GRI[7].

RESULTS

An Estimate Based on Ground-Level Ambient Methane Levels

We developed a method (patent pending) to generate a preliminary estimate of total methane emissions in Manhattan from the data collected by GSI during the previously reported Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan. The method appears to be broadly applicable to other trace gases, sites and situations. In the present case of Manhattan, such emissions estimates can be used to assess the relative importance of those emissions in terms of methane as a greenhouse gas (GHG) and the relative impact of gas service/use in Manhattan in a broader climate/GHG context. More precisely, the estimate that can be generated from the GSI Manhattan preliminary ground-level methane data is the rate of flow of methane from Manhattan to the atmosphere beyond.

The approach used is relatively simple. Only four pieces of information are needed to calculate a flow rate, in this case for methane from Manhattan into the atmosphere. What are the boundaries of the source area for the flow; in this case what are the effective boundaries for air flow to/from Manhattan? What is the concentration of methane in the air when the air enters the source area, i.e., Manhattan? What is the methane concentration when the air exits Manhattan? How fast is the air entering/exiting Manhattan?

The GSI preliminary Manhattan methane data provide a large set of (over 700,000) measurements of the concentration of methane at various points around the island, and other areas in the vicinity and region, at various times over a period of five days. The challenge is to sort that data into subsets such that the methane concentration data can be associated with air moving into Manhattan, picking up methane in Manhattan, and then departing, and how to estimate how much air was moving during the relevant sampling times. Fortuitously, during certain parts of the GSI Manhattan preliminary methane survey winds and survey pathways occurred in such patterns that evaluation of the methane concentration in air entering and leaving Manhattan is practical. In order to enable use of that methane data, it was necessary to gather information and data from meteorological literature and monitoring and reporting programs. The times and conditions of one relevant data subset from the GSI Manhattan methane survey were as follows.

The 29 November 2012 Methane Survey Data

From roughly 4 PM to 5 PM on the afternoon of 29 November 2012 a survey run was made along the west, south, and eastern sides of Lower Manhattan near the shorelines. At that time the wind was consistent, from roughly the southwest (compass bearing 240 degrees) at 8 miles per hour. These wind conditions and that survey path provided data for distinct upwind and downwind areas along the near-shoreline areas around Lower Manhattan. The upwind data provided methane concentration of air arriving on the island, while downwind data provided methane concentration of air departing the island on the same wind direction path. The City College of New York has a robust weather monitoring program. By accessing the NYCMetNet website an estimated height for the mixing layer of the atmosphere over Manhattan for the same time period was obtained.[15] The length of the travel paths in the upwind

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[15] The mixing layer is the lowermost layer of air in the atmosphere where air flows over and is influenced by the land or water surface below (see image on page 22). Above the mixing layer, winds tend to have a smoother, laminar flow, but within the mixing layer winds tend to have turbulent flows that cause most gases or aerosols released near the land or water surface to disperse rapidly laterally and vertically throughout the air to the upward limit of turbulent flow. The height of the mixing layer changes over time, but is consistent for time periods longer than necessary for the purposes of the current data interpretation effort. Height of the mixing layer and other meteorological data are accessible through the NYCMetNet, provided by the Optical Remote Sensing Laboratory of The City College of New York (ORSL), http://nycmetnet.ccny.cuny.edu.

and downwind portions of that survey run were estimated using Google Earth. These data were as follows:

Methane Concentrations in Ground-Level Air
Upwind 1.92 ppm ±0.003ppm (99.9999% Confidence Interval)
Downwind 2.165 ppm ±0.021ppm (99.9999% Confidence Interval)

Wind speed (speed of air entering/exiting Manhattan) 8 mph (11.7 feet per second)
Wind direction (from) WSW (compass bearing 240 degrees)
Manhattan wind cross-sectional length: 7 miles (36960 feet)
Mixing layer height: 2600 ft.[14]

These data can be applied in the following sequence of calculations:

To get the volume of air entering/leaving Manhattan per second:
Wind speed X wind cross-sectional length of Manhattan X mixing layer height =
11.7 ft/sec X 36960 ft X 2600 feet = 1.1 billion cubic feet per second

To get the amount of methane added while the air passed over Manhattan, take the difference between the upwind and downwind methane concentrations and apply it to the amount of air leaving Manhattan per second:
(Downwind methane concentration - Upwind concentration) X Volume of air leaving Manhattan per second =
(2.16 ppm - 1.92 ppm) X 1,100,000,000 cu.ft./sec. = 270 cubic feet per second

To get cubic feet per second of methane added by Manhattan to cubic feet of methane added per year:
Cubic feet per second added by Manhattan X 60 seconds per minute X 60 minutes per hour X 24 hours per day X 365 days per year =
270 cu.ft./sec X 60 sec/min X 60 min/hr X 24 hr/day X 365 days/ yr = 8,600,000,000 or 8.6 billion cubic feet per year.

This estimated annual methane flow rate from Manhattan is approximate. Each of the measured data values used could be a source of error. The methane data for a given time frame is highly reliable, 99.9999% confidence intervals ± <1% (0.021 ppm). However, methane concentrations in the air vary with location, time, wind, temperature, barometric pressure, humidity/precipitation, and the complex collective interactions of all these and possibly other factors. To examine the likely accuracy of the 29 November methane data used in the above Manhattan flux estimate other data subsets from the full data set were examined. Each of these data subsets was collected at different times, covered different locations on and off Manhattan island, and occurred under different weather conditions. Nevertheless each data set is still relatively large, the smallest containing over 2000 methane data points. The following subsets were identified and examined:

Manhattan mean methane levels relative to reference area for given date					
Date (2012)	11-27	11-29	11-30	12-09	
Wind (from)	NE	WSW	NE	NNE	
Mean Methane Concentration (ppm)					
					Means over all 4 dates
Manhattan	2.079	2.165	2.345	2.261	2.213
Reference Area	1.866	1.92	2.008	2.002	1.949
Increase while over Manhattan Island	0.213	0.245	0.337	0.259	0.264
99.9999% Confidence interval for all Manhattan and Reference Area Mean Methane Concentrations was ≤ 1 % relative (0.002 to .022 ppm)					

On 27 November data were collected on Manhattan island that generated a mean methane level of 2.079 ppm, while the average methane level traveling to NYC was 1.866 ppm. The wind that day was out of the NE (compass bearing 50 degrees) at an average speed of 5.8 mph. On this day the wind was blowing from the area travelled to arrive in Manhattan. Hence, deducting the average methane level before arrival in Manhattan, 1.866 ppm, from that measured in Manhattan, 2.079 ppm, indicates the increase due to methane sources on Manhattan island, 0.213 ppm. This compares reasonably well with the 0.245 ppm increase due to methane sources on Manhattan island on 29 November.

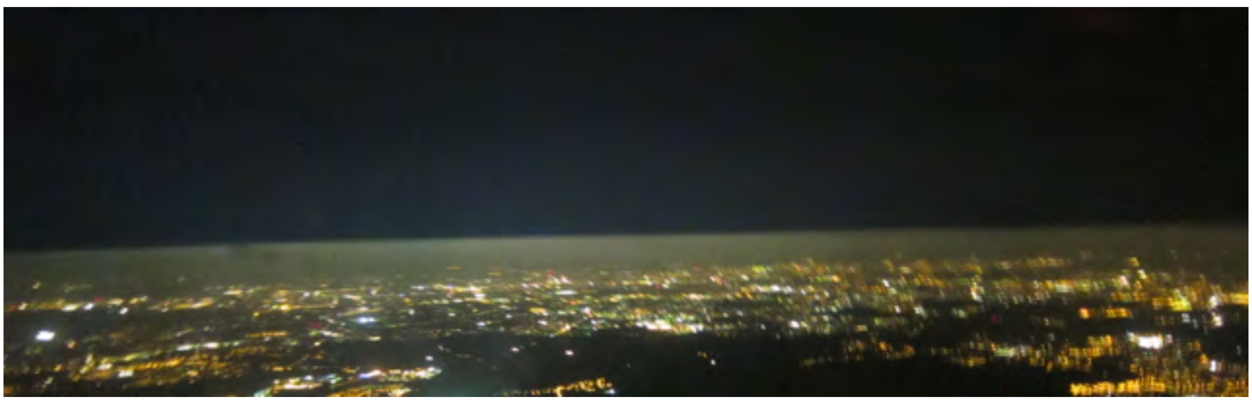
Similar data subsets were available in the 30 November and 09 December data sets, each day with different wind conditions and, consequently, different upwind areas used as sources of reference methane levels. On 30 November the indicated methane concentration increase due to methane sources on Manhattan island was 0.337 ppm. On 09 December the increase was 0.259 ppm. The table above summarizes the indicated increases in methane concentration due to sources on Manhattan island.

Given that these data subsets were for different survey paths on Manhattan, different reference zones off the island, and on different days, times of day and weather conditions, all effectively random, unplanned occurrences within the body of general methane survey data, the consistency of the indicated increase in methane concentration over Manhattan is actually impressive. In fact, the 99% confidence interval for the mean of the four days mean methane levels was ±0.068 ppm, or ±25%. Recall that the EPA/GRI[7] 90% confidence interval for cast iron pipelines was ±65%. For the purposes of evaluating the likely accuracy of the estimate of methane emissions on Manhattan Island, we will use ±25% as the likely accuracy of the data for increases in methane concentration in the air while passing over Manhattan Island. For data quality and field observational reasons, and to maintain a conservative approach, the 29 November data was regarded as most reliable and was used in the above calculation of annual methane flux to the atmosphere from Manhattan.

Weather data were obtained from online sources based on National Weather Service data or CCNY observations.[15] Wind speed is likely accurate to within 0.1 mph or 0.15 feet per second. Winds were moderate averaging 5.5 to 6.8 mph on the 4 survey days in the table above. The actual winds during the survey times in the table above tended to be above the average wind speed for the day. Since the data for 29 November was to be used in the calculation of the Manhattan methane flux rate, the wind speed for 4PM to 5PM on that day was estimated to be 8 mph and was the wind speed used. Potential error should not have been greater than 10% for the wind speed used in the calculation.

Wind direction was used for two purposes. One was identification of appropriate upwind methane reference areas and selection of an appropriate reference data subset within the full set of methane data. The other was to determine the length of the extent of Manhattan Island perpendicular to the direction of the wind. This length was used because the actual volume of air flowing over Manhattan should be related to the direction of the wind with respect to the greater N-S length and shorter E-W width of the island. If wind were blowing along the N-S length of the island, then, near the land surface, the band of air blowing onto and off the island would be about 2.5 miles wide. If the wind were blowing across the N-S length of the island, then the band of air would be closer 10 miles wide. So, at the land surface less air would be flowing onto and off the island for roughly N-S winds than for roughly E-W. It might seem this would cause some difficulty in that days with N or S winds would seem to have less air flowing over the island than days with E or W winds of the same speed. However, the height of the mixing layer increases with time over land compared to over water. So, this effect is probably in part compensated by related changes in the mixing layer height. In fact, on only one (09 December) of the four days did the wind run directly along the length of the island, and on that day the mixing layer height did increase substantially to a height of approximately 7200 feet.[15]

The width of the band of air blowing over the island was the length of the projection of the profile of Manhattan onto a line perpendicular to the wind direction, which we call the cross-wind length. On three of the four days the winds were nearly opposite in direction, from either the southwest or the northeast, so the cross-wind lengths of Manhattan were very similar except on 9 December when there was a compensating increase in mixing layer height. The cross-wind length of the island for any given wind direction can be relatively easily estimated to within a few percent using Google Earth.



A nighttime image showing the mixing layer over Berlin, Germany. Aerosol particles dispersed in the mixing layer cause light from below to be diffracted/reflected revealing the mixing layer as brighter and distinct from the clear (dark), uncontaminated air in the overlying layers of the atmosphere. Ralf Steikert http://userpage.fu-erlin.de/~kyba/images/night_boundary_layer.html

Another potential error source that might affect the calculation was the thickness or height of the mixing layer (see image above). Equipment capable of measuring the height of the top of the mixing layer is not common, but such equipment is in place in Manhattan.[15] Initially, the data was obtained in a graphic format and a 5% error was assumed due to graph reading inaccuracies. The graphs were read conservatively to assure the height of the mixing layer was not overestimated. The mixing layer occasionally has a somewhat diffuse upper boundary. This occurred at 4PM-5PM on 29 November. Only the mixing height that appeared to have the same or stronger composition (backscatter) as near the land surface was used. This predisposes the height of the mixing layer to underestimation as well as the resulting estimate of the actual methane flux, but, again, a conservative approach was preferred.[16]

Another potential source of error is the thoroughness of upward mixing of methane in the mixing layer at the time measurements were taken in the downwind sampling area, i.e., where air was leaving the island. Less than thorough mixing vertically throughout the mixing layer would seem likely if certain conditions were present. The land surface was relatively smooth, with few tall obstructions. The gas of concern was relatively dense and diffused slowly in the air. Winds were weak or inconsistent. The conditions during the relevant periods of the preliminary Manhattan methane survey were the opposite of these. Methane is lighter than air and diffuses rapidly through it, with a tendency to move upward. Winds were appreciable and consistent. With over 90 buildings more than 600 feet tall among many others of considerable height (see the image of the view from the "Top of the Rock" at the beginning of this report) the land surface of Manhattan is nearly the opposite of smooth. Further, the graphic representations of the ceilometer data for the relevant time periods indicated diffuse layers of air between the mixing layer and the overlying free atmosphere. Those diffuse layers were not included in the height of the mixing layer used in our calculations. At the time of this report, there did not appear to be reason to assume less than thorough vertical mixing of methane in the mixing layer. We anticipate opportunities to collect data that more directly address this possible source of error soon, and to revise our Manhattan methane emissions estimate in the near future.

Counter to a potential overestimate of methane emissions due to incomplete vertical mixing of methane in the mixing layer over Manhattan, there is also an unaccounted for potential loss of methane through the upper boundary of the mixing layer. Methane is only about half as dense as air, and is, therefore, strongly disposed to migrate upward in the atmosphere regardless of other conditions. It is, therefore, likely that at any given time a portion of the methane in the mixing layer is moving through the top of the mixing layer and on up into the atmosphere. Such "excessive vertical mixing" would not be accounted for in our calculations and would cause our emissions estimate to be low. We had no data on the thoroughness of vertical mixing of methane before the air in the mixing layer departs the island on the downwind side. We also have no data on what proportion of methane escapes out through the top of the mixing layer, but it seems unreasonable to expect that vertical methane loss

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[16] In the final stages of preparation of this report, the results of the application of two different mixing layer algorithms to the raw ceilometer data were provided courtesy of Mark Arend and Yonghau Wu of the City College of New York Optical Remote Sensing Lab and made available through the NOAA CREST NYCMetNet (http://nycmetnet.ccny.cuny.edu/). The average of the twelve results (6 time intervals X 2 algorithms) for 4PM-5PM 29 November time period was 0.815 kilometers, just 0.015 kilometers over our graphic estimate of 0.8 kilometers.

would be zero. It also seems likely that either incomplete or excessive mixing may be dominant in different areas within the downwind sampling area. Ultimately we assumed both processes were in effect, the effects of both countering each other in the overall data set. That is, we assumed that on average the vertical mixing was neither incomplete nor excessive. Again, we anticipate opportunities to collect data that will help us address this possible source of error, and hope to release those findings, and update our emissions estimate at the earliest practical date.

The potential error due to inadequate or excessive vertical excessive mixing in the mixing layer could not be estimated. At the time of preparation of this report, we had found only two publications on comparable measurement-based methane emissions from another large metropolitan area.[17,18] Both were for Krakow, Poland. The first of these, Kuc et al. (2003), estimated methane emissions were around 760 million cubic feet per year (2.15 X 10^{-7} m^3 yr^{-1}) over the period 1996-1997. The later, Zimnoch et al. (2010), reported around 220 million cubic feet per year (6.2 X 10^{-6} m^3 yr^{-1}) over the period 2005-2009, an apparent 3.5-fold decrease from the 1996-1997 estimate. In the intervening years the gas service operator in Krakow had undertaken a substantial gas infrastructure improvement program, presumably substantially reducing gas leakage. The population of Krakow is about 800,000[19], while Manhattan is very close to twice that, at 1.6 million[20]. The per capita gas consumption in Poland is around 16,000 cubic feet per year[21] and for New York is around 200,000 cubic feet per year[22]. Adjusting the 1996-1997 Krakow emissions for the higher population of Manhattan and New York per capita gas consumption rate, one obtains an emissions level of 19 billion cubic feet per year. The 2005-2009 Krakow emissions adjusted to Manhattan population and NY consumption rates becomes 5.5 billion cubic feet per year. We concluded

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[17] T. Kuc et al. 2003. Anthropogenic emissions of CO_2 and CH_4 in an urban environment. Appl. Energ. 75(3-4), 193-203.

[18] M. Zimnoch et al. 2010. Assessing surface fluxes of CO_2 and CH_4 in urban environment: a reconnaissance study in Krakow, Southern Poland. Tellus (2010), 62B, 573-580.

[19] http://www.krakow-info.com/people.htm

[20] http://www.nyc.gov/html/dcp/html/census/popcur.shtml

[21] http://www.indexmundi.com/map/?t=0&v=137000&r=eu&l=en (in cubic meters per year per capita, converted to cubic feet per year per capita)

[22] http://www.usnews.com/news/slideshows/the-10-states-that-use-the-least-energy-per-capita/11 (in BTU per capita in 2008, converted to cubic feet per capita per year)

our estimate of 8.6 billion cubic feet per year for Manhattan is reasonable in light of the estimates of Kuc (2003) and Zimnoch (2010) for Krakow.

In summary, among the measured data that were potential sources of error the 99% confidence interval of 25% relative for the methane concentration increase over Manhattan was the largest likely error. Each of the other potential sources of error were considered subject to errors of <10% relative. Further, when interpretation of data was required, those interpretations were conservative. It would seem reasonable at this point to hold that the estimated annual methane flux for Manhattan may contain an error of as much as ±25%.

Comparisons of the Estimated Emissions from Manhattan

An EPA/GRI[7]-Factors-Based Estimate

Applying the EPA/GRI[7] factors for pipe lengths and materials in the entire ConEd system[1], we arrived at an estimate of 915 million cubic feet as total gas leakage from the entire ConEd system of gas mains and service connection lines (services). Allowing an additional arbitrary 85,000,000 cubic feet for potential leakage from other ConEd gas infrastructure, we arrived at an estimated total methane leakage of around 1 billion cubic feet per year. Also, because soil conditions under Manhattan probably do not support optimal conditions for methane oxidation, we used the EPA/GRI[7] methane leakage factors instead of the methane emission factors. Use of the methane emission factors would have generated an even lower estimate of natural gas losses/ methane emissions.

An Average Long-Term LAUF Estimate

The ConEd ten-year average of LAUF gas (reported to PHMSA) was 2.2%. Even though the LAUF does not represent actual measured gas losses from the ConEd system, its preparation does involve metered gas flows albeit through many meters. Consequently, the LAUF might provide some indication of gas losses if inherent variability can be overcome, which can be accomplished by taking a long-term average. It should be kept in mind that 2.2% was the average ConEd LAUF over 10 years. As the average of 10 years this value is more reliable than the annual LAUF estimates used to calculate the average, but this greater reliability comes with costs. The average provides a more reliable estimate for leakage over times greater than one year, but may not be reliable for an individual year, say, a year impacted by a major storm. Also, leak detection and repair efforts are continuous. Use of a ten-year reporting period in order to have a reliable leakage rate would be useless with respect to annual or more frequent efforts to identify and control leakage. For present purposes of estimating total leakage, however, the 10-year average is the best value we can extract from the reported ConEd LAUF estimates. At 2.2% the ConEd LAUF for the entire ConEd gas system that handles about 300 billion scf/yr[1] would be 6.6 billion cubic feet of lost gas, or around 6.1 billion cubic feet of methane.

The GSI Estimate Based on Preliminary Ground-Level Methane Survey Data
The actual measured levels of methane in Manhattan and adjacent areas were used to develop an estimate of the likely rate of methane emissions from the natural gas system in Manhattan. The estimate did not include any ConEd gas distribution or service beyond the shorelines of Manhattan Island. The estimate used conservative criteria in selection of which data from outside (meteorological) sources would be used to generate the estimate. The resulting estimate of total emissions of methane (functionally losses of natural gas) was 8.6 billion cubic feet per year (≈9.2 billion cubic feet of natural gas).

This estimate is 1/3 larger than the 10-year average LAUF losses and nearly 10 times greater than the methane leakage estimates using the EPA/GRI[7] factors applied to the entire ConEd system of mains and services. Given that the primary function of reported values for LAUF gas is accounting reconciliation and equitable cost allocation, the error of 33% over the long term might be acceptable. However, given that the 33% higher estimate was based on methane-in-air measurements only in Manhattan, which accounts for only about one-third of the customers and 5% of the land area in the ConEd gas service territory, the question of how much more gas may be leaking in the remainder of the ConEd gas system service area stands unaddressed. Similarly, we leave for others to discuss the implications of the difference between our estimated methane emission rate for Manhattan and the reported LAUF gas from the entire ConEd system.

The difference between the annual Manhattan methane emission rate developed from GSI methane survey data and that generated by application of the EPA/GRI[7] pipelines leakage factors is more striking. If one were to assume that the EPA/GRI[7] data did account for distribution and service gas lines leakage within the accuracy given in that report (90% confidence interval was ±65% relative), then one would would expect that the entire ConEd system might have an emission rate up to 65% greater than the above mentioned estimate of 1 billion cubic feet per year based on the EPA/GRI[7] factors. That is, at the extreme upper limit proposed by EPA/GRI[7], the methane emissions for the entire ConEd system should be something around 1.65 billion cubic feet per year. Even if one uses this upper limit of an EPA/GRI[7]-based estimate, our estimate based on actual methane measurements in Manhattan alone is still almost 6 times greater.

Again, a Little Bit Matters

Returning to the issue of how much methane leakage is of practical concern, we need to put some perspective on the 8.6 billion cubic feet per year of methane emissions that we derived from our preliminary methane data for Manhattan. To do that we will need to make some assumptions. Our first assumption is pipeline natural gas is 93% methane (EPA/GRI[7]). Our second is that natural gas pipelines are the only sources of methane emissions on Manhattan. Our third assumption is there are no natural gas leaks from the ConEd system outside of Manhattan. This third assumption is obviously not true, but allows us to put 8.6 billion cubic feet into some perspective, while assuring that our conclusion is certainly conservative. Again, for clarification, Manhattan comprises about only 5% of the land area and accounts for only about 1/3 of the customers in the ConEd service territory.

Our measurements do not distinguish between methane sources. There could be methane sources in Manhattan other than the ConEd natural gas system. Given no data on this question at present, and based on GSI experience with methane surveys over fairly broad areas of the Northeast, our opinion is that it is unlikely methane from other sources would approach 10% of the emissions level indicated by our methane survey data in Manhattan. So, for purposes of this discussion the effects of the first two assumptions counter each other, plus ≈10% due to 93% methane content of pipeline natural gas, and minus ≈10% due to other potential methane sources in Manhattan.

Putting a number on the perspective for the estimated 8.6 billion cubic feet per year methane emissions from Manhattan now requires only comparison of that volume of gas to that handled by the ConEd system as a whole, i.e., ≈300 billion cubic feet per year. So our estimated annual methane emissions for Manhattan amount to only (100 X 8.6 billion / 300 billion =) 2.86%. Once again, why does this matter?

As mentioned back in the discussion of LAUF gas, this gas loss is actually 0.66% greater than the long-term average ConEd LAUF of 2.2%. With respect to hazards of explosive concentrations of methane in susceptible locations, this amount is probably not particularly important or informative. Though it seems reasonable to conclude such risks could increase proportionately with gas leakage (methane emissions), that would seem to matter little as the ConEd leak detection and management program has been running relatively effectively for decades with no real knowledge of what actual methane emissions have been. With respect to cost reconciliation and fair allocation, using the annual ConEd gas sales and services revenue of 1.5 billion dollars, 0.66% is 9.9 million dollars, consideration of which we will leave for ConEd, its customers, and

NYSDPS. With respect to the impacts of methane as a greenhouse gas, however, there is more to be said.

Methane is a potent greenhouse gas. A widely accepted minimum relative greenhouse gas strength of methane is 21 times greater than that of carbon dioxide over a 100-year time frame.[23] There have been complex and ongoing discussions about what the greenhouse equivalence of methane actually is, which the reader may want to consult.[24] Those discussions generally are resulting in incremental increases in the accepted value for methane greenhouse gas equivalence, but for this presentation we will use the simpler approach of using the lowest widely used greenhouse equivalence for methane. For convenience, we will further lower this by rounding it to 20 times greater than that of carbon dioxide. So, if methane is approximately 20 times stronger than carbon dioxide as a greenhouse gas, and if the natural gas upon reaching its destination is entirely burned to carbon dioxide (and water), then how important are gas (methane) leaks from the natural gas production and delivery system that delivered it?

We can restate that methane as a greenhouse gas is 20 times stronger than carbon dioxide by stating that it only takes 1/20 or 5% as much methane to cause as much atmospheric warming as a given quantity of carbon dioxide. If the natural gas arrives at its intended destination and is burned, it will form carbon dioxide (and water), so its original form (as methane) does not matter since it is now carbon dioxide. However, if only 5% of natural gas escapes as it moves from within the earth through the production, transport and delivery systems, that 5% will have as much GHG impact as the other 95% burned as fuel.

FINDINGS

The findings suggest the role of leakage from natural gas systems has a more substantial role in climate change than has been appreciated.[24] Apparently present provisions in state utility regulations allow gas companies to charge their customers for up to 2% (varies by state) of their handled gas volume as lost and unaccounted for gas (discussed earlier in this report). Depending on

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[23] http://epa.gov/climatechange/ghgemissions/gases/ch4.html, or, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html, among others.

[24] Alvarez, R. A., Pacala, S. W. Winebrake, J. J., Chameides, W. L. & Hamburg, S. P. Greater focus needed on methane leakage from natural gas infrastructure. Proc. Natl Acad. Sci. USA **109**, 6435-6440 (2012).

the state, presumably such allowances apply to each sector of the gas system separately, i.e., production (gas wells), transportation (long distance pipelines), and distribution (gas utilities). In the end the methane emissions that affect the greenhouse gas impact of natural gas as fuel are the total methane emissions along the whole path the gas travels through the entire production-transport-distribution network. The infrastructure in each sector in that network can and does leak natural gas.

A 2.86% leakage of all the natural gas handled by ConEd in Manhattan alone leaves only 2.14% for the rest of the ConEd system, and the production and transport system feeding it, to leak collectively before total losses exceed the 5% level at which the greenhouse gas cost of using natural gas is effectively at least doubled. So far GSI efforts to gather data on volumes of gas lost by leakage or other processes in the natural gas system have indicated all such data are based on methods that are not founded in well-documented data on actual leaks, let alone actual measurements of leaks or field emissions. Some actual field data have recently been reported for production and early stage transport of shale gas. In the Denver-Julesberg Fossil Fuel Formation, largely in Weld County in northeast Colorado, emissions of methane were estimated at 2.3% to 7.7% of production.[25] Preliminary results from the Uinta Basin in Utah discussed at recent meetings of the American Geophysical Union indicated methane leakage in the field reached 9% of total production.[26] Even if the Marcellus shale gas fields planned to serve New York City release methane emissions at the lowest rate indicated by field data from northeast Colorado, and if that were added to just the GSI estimated methane emission for Manhattan alone, that would already put the total methane emission leak rate for Marcellus Shale gas delivered through the ConEd system at 5.16%. This leakage rate, which does not account for leakage from gas transmission lines to ConEd or from the rest of the ConEd system outside Manhattan, is already in excess of our simple calculation for the total leakage rate (5%) at which the leaked gas has as much potential climate impact as the burned gas. In fact, this leakage is well in excess of the total leakage rate of 3.2% at which other authors using more elaborate approaches have concluded that natural gas ceases to have a "clean fuel" advantage over coal for power production.[18]

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[25] Gabriel Petron et al. Hydrocarbon Emissions Characterization in the Colorado Front Range - A Pilot Study. National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Boulder, Colorado, USA. (Nature 482, 139–140; 2012)

[26] http://www.nature.com/news/methane-leaks-erode-green-credentials-of-natural-gas-1.12123#/ref-link-4

Caveats and Cautions Regarding the GSI Preliminary Estimate of the Manhattan Methane Emissions Rate

The GSI method (patent pending) used to estimate the Manhattan methane emissions rate from preliminary mobile methane survey data does not provide an estimate that is relative to natural background levels for natural areas in the region. It is difficult to imagine that there might even be an area anywhere in the vicinity of New York City where natural background methane emissions rates might be evaluated. The GSI approach was instead based on an alternate approach that could be evaluated because Manhattan is an island making physical boundaries of the Manhattan land surface emissions area relatively easy to define. Further, because of observations during the methane survey and analyses of the survey data, it became apparent that air arriving on the upwind and departing the downwind sides of the island at any given time necessarily provide a functional methane baseline and impacted air concentration level for the island. Hence, it is not necessary to know the natural methane baseline for the area or region, or even the surrounding waters, in order to calculate an emission rate for the island. Also, this approach eliminates any need to understand or attempt to correct off-island incoming air methane concentrations for methane sources within the geographical methane reference area since the only needed data is methane concentration in the incoming air.

The height of the mixing layer is important to the accuracy of the GSI approach to estimating area methane emissions based on ground level methane concentrations. Fortunately mixing height data is measured in Manhattan. However, the measurement used was collected at a single location not in the area where the departing air methane concentration data were collected. Nevertheless due to the mixing layer measurement location being relatively upwind from the air departure area it is more likely the mixing layer height used was too low rather than too high. Also, the measurement used was chosen to exclude diffuse zones at the upper edge of the mixing layer. Actual above ground and airborne measurements would be useful to assess variations of concentration of methane throughout the mixing layer.

There are potential and actual sources of methane in Manhattan other than the ConEd natural gas system. The GSI approach to estimating methane emissions cannot distinguish the contributions of various potential sources of methane to the overall methane emissions rate. One clearly distinguishable localized release of possible "sewer gas" was observed in the GSI Manhattan methane survey data collected at the outlet of a storm drain on the east side of the island. The elevated methane level was apparent, but not particularly high. How many other methane elevations might have been due to sewer gas or other potential, non-ConEd, methane sources, e.g., old fill areas, is not known. However, based on GSI experience in other urban and rural areas, the effects of using conservative allowances and assumptions wherever reasonable likely exceed the influence of landfill, sewer or other biologically generated methane in the GSI Manhattan preliminary methane emissions estimate. The relative importance of biogenic methane sources in Manhattan probably could be assessed using methane isotopic composition analysis. It is also worthwhile to note that just because gas is being released from a sewer or storm drain does not necessarily confirm that the gas is actually generated in the sewage or storm water and residues. Sewers and storm drains can also receive and transport gas leaked from gas pipes.

There is also potential for losses due to pirated or illegal gas taps, and post-metering losses at the consumer level. Again, such losses cannot be distinguished within the GSI Manhattan methane emissions estimate, but seem likely to be small in comparison to leakage from ConEd gas infrastructure and operations.

RECOMMENDATIONS

The estimated Manhattan methane emission rate presented in this report indicates the need for actual measurements of methane flux for urban, petroleum and gas field areas, etc. instead of estimates based on extrapolations of typically very limited and generally indirect data.

In Manhattan, additional ground level methane survey work seems needed to support more effective and rapid detection and identification of gas leaks, to determine areas where gas pipe is in need of general replacement or lining rather than stop-gap repairs. Additional ground level work is needed that is specifically designed to develop and refine the approach developed and presented in this report for rapid actual-measurement-based estimation of methane emissions. Additional supplementary work is needed to explore and refine the level of knowledge regarding the height of the mixing layer and methane distribution within it for Manhattan and other urban and non-urban settings.

The findings from this data analysis effort indicate there is need to re-evaluate:
- Methane emissions estimates and assumptions being used as the basis for global climate modeling and projections regarding the path and speed of climate change
- Plans and projections regarding short-term high-impact opportunities to reduce greenhouse gas emissions by focusing initially on methane emissions

associated with fossil fuel development, production, and utilization
- Regulation of the fossil fuel industry
- The actual economic and environmental costs of fossil fuel compared to alternative energy technologies over all time frames.

Our findings, based on actual measurements, necessarily raise doubts about the claimed value of natural gas as a "clean, bridge fuel" and call for further work to verify the reported findings and to begin to identify specific methane sources and improve natural gas leak prevention and management.

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