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Workshop on Quantifying Methane Emissions Across Natural Gas Infrastructure in Urban Environments

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Abstract

NIST, Stony Brook University, and the Environmental Defense Fund (EDF) organized and held a workshop at the EDF offices in Washington, DC, on June 15 and 16, 2022 to discuss the current state of knowledge and to define productive courses of action in better determination and source apportionment of methane emission rates and, specifically, natural gas emission rates, in urban environments. The workshop involved 56 attendees from universities, government agencies, non-governmental organizations (NGOs) and the private sector, including representatives from relevant utilities. This report covers discussion of the knowledge base to date about urban sources of natural gas methane emissions, their relative magnitudes, and areas of uncertainty. Specific suggestions and ideas for future experiments to be conducted that could improve our understanding are presented. Next steps, including the creation of working groups for field experiments and/or a research coordination network are discussed.

Keywords

Emissions; methane; natural gas; greenhouse gas; urban.

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Executive summary

NIST, Stony Brook University, and the Environmental Defense Fund (EDF) organized and held a workshop at the EDF offices in Washington, DC, on June 15 and 16, 2022 to discuss the current state of knowledge and to define productive courses of action in better determination and source apportionment of methane emission rates and, specifically, natural gas emission rates, in urban environments. The workshop involved 56 virtual and in-person attendees from universities, government agencies, non-governmental organizations (NGOs) and the private sector, including representatives from relevant utilities. This report covers discussion of the knowledge base to date about urban sources of methane, their relative magnitudes, and areas of uncertainty. The meeting discussion and presentations focused mostly on what seems to be the largest emission source of methane in cities, i.e. natural gas, and what studies have led to that conclusion. The attendees discussed the extent to which it is known what fraction of the total natural gas-related urban emissions derive from the NG distribution system, versus those that are derived from beyond the service meters, e.g. those related to appliance use and unburned combustion emissions at the user/building/community boiler, etc., level. This partitioning is not quantitatively understood at this time for most cities. The discussions on this matter focused significantly on approaches to better inform the community about where the largest emissions occur, and how to improve emission inventories (that in essentially all cases significantly underestimate urban methane emissions) to make them more useful in tracking progress in emission reduction efforts, and as supporting tools, e.g. for inversion analysis. Specific suggestions/ideas for experiments to be conducted, e.g., with respect to whole building measurements, and distribution system measurements are discussed and recommended. Future steps, including the creation of working groups for field experiments and/or a research coordination network are discussed.

Definitions

AHU	Air Handling Unit
EDF	Environmental Defense Fund
EIA	Energy Information Administration
GHGs	Greenhouse Gases
GHGI	Greenhouse Gas Inventory
GWP	Global Warming Potential
LDC	Local Distribution Company
M&R	Metering and Regulation
NG	Natural Gas
NGO	Non-Governmental Organization
PBL	Planetary Boundary Layer
RCN	Research Coordination Network

1. Introduction

In the past two decades there has been increasing interest in methane (CH_4) as a greenhouse gas (GHG). Methane's high warming potential and shorter atmospheric lifetime relative to carbon dioxide (CO_2) [1] means that the Earth's heat content will be more temporally responsive to anthropogenic CH_4 emission reductions than (CO_2) reductions. After levelling out during the mid-2000s, atmospheric CH_4 concentrations have been rapidly increasing by as much as 18 nmol/mol (also referred to as parts per billion, or ppb), per year (0.9%/yr) in more recent years. The 20-year timescale global warming potential for CH_4 is ~82; its radiative forcing is 0.54 W/m^2, which is 16 % of the total from all GHGs [1]. These factors have motivated policies designed to mitigate CH_4 emissions in urban areas. In addition, many countries have recently signed the Global Methane Pledge [2] committing to a 30 % reduction in global anthropogenic CH_4 emissions relative to 2020 levels by 2030.

While many cities have a GHG reduction plan in place and use their own inventories to set and track progress, it is widely known that these inventories are highly uncertain, and typically substantially underestimate CH_4 emissions determined from top-down observations. Indeed, observations from Los Angeles (LA), Washington DC (DC), New York City (NYC), and Boston all show CH_4 emissions much greater than those reported in respective inventories [3-10]. Such top-down studies have identified the dominant source of the discrepancy to be fugitive natural gas (NG) leakage (e.g. related to NG transmissions, distribution, and use), which is poorly defined at the individual leak level.

Researchers have demonstrated that accounting methods in urban domains largely miss fugitive emissions from the NG sector. Natural gas is largely comprised of CH_4 and other hydrocarbons, including ethane, allowing for the distinction of NG-derived CH_4 from that of other CH_4 sources which do not emit ethane by measuring both species. Ethane and CH_4 measurements from aircraft and buildings have shown that the majority of CH_4 emissions in urban environments in the eastern U.S. are from NG sources [7, 10-12]. Additionally, numerous mobile surveys in different cities have revealed large emissions from both NG leaks and wastewater (sewers) [13-19].

There are several potential sources of fugitive CH_4 emissions from the NG sector. Emissions of NG in urban areas could occur from the city gate, i.e., the custody transfer station (transmission-distribution transfer station) from which the local city distribution company receives NG from the transmission pipeline, or from any point within the urban NG distribution system, e.g., at metering and regulating (M&R) stations, leaks in mains and service pipes, at customer meters, etc. CH_4 emissions also occur from end uses that occur within industrial facilities or residential or commercial buildings, i.e., post-meter, e.g., valves and fittings within buildings, from pilot lights whether on or off, from partially combusted NG from furnaces, hot water heaters, stoves, and community boilers used for steam or hot-water heating, to name but a few [20-23]. Some recent studies have found correlations between urban NG emissions and NG consumption [9, 10, 24, 25], suggesting that at least some of these urban emissions depend on usage.

There is indeed a dearth of quantitative information about the absolute and relative magnitude of CH_4 emissions from pre-meter (e.g., distribution pipeline leaks, etc.) and post-meter sources. This is a challenging issue as typically co-emitted NG species (e.g., ethane) or

CH_4 isotopes ($^{13}CH_4$ or CDH_3) have not yet been of use in distinguishing between pre- and post-meter NG emissions. Post-meter NG emission is relevant not only for its implications for climate and GHG reduction targeting, but also for its impact on indoor air quality through the emission of non-CH_4 NG components such as benzene and other VOCs [26].

To help the community identify approaches that might be useful in this regard, the National Institute of Standards and Technology (NIST), Stony Brook University, and the Environmental Defense Fund (EDF), convened a 2-day workshop in Washington, DC, on June 15 and 16, 2022, with the workshop title "Quantifying methane emissions across natural gas infrastructure in urban environments." The major purpose of this workshop was to identify and define approaches and experiments for assessing the relative and absolute magnitude of pre- and post-meter NG CH_4 emissions in urban environments using atmospheric or other observations.

The workshop was attended by 56 people (28 remote, 28 in-person; see Appendix A), with attendees representing state agencies, federal government agencies, universities, foundations, and private sector entities. The final workshop agenda, with the speakers and their topics is shown below in Appendix B. The workshop objective was to develop a Workshop Report (this document) that outlines viable approaches for better quantifying and understanding the relative contribution of fugitive emissions from various NG components in cities. The Report will form the basis for targeted, tangible activities designed to estimate and quantify the relative proportion of pre- and post-meter leakage of NG. Additionally, these measurement activities could lead to updated emission factors for different system components and processes that could improve inventories. This document was written using meeting notes and was prepared and edited by the workshop attendees. The intent was to publish a workshop summary as a publicly available NIST technical report.

This report outlines what is known about urban CH_4 emissions from a variety of measurements in urban environments, from the scale of individual leaks to neighborhood and whole-city observations, using tracers and stable isotopes, and including biogenic (e.g., landfills and wastewater treatment plants) and thermogenic sources (natural gas). Emission rates by sector and source are not known as well for CH_4 as for CO_2, hence, the objective is to dramatically improve our ability to develop reasonably reliable high spatial and temporal resolution CH_4 emission inventories for cities. Here we discuss what has been done and how we can improve our quantitative knowledge of urban CH_4 sources. Section 2 below outlines top-down methodologies for quantifying total CH_4 emissions and attributing emissions between natural gas sources and biogenic sources in a metropolitan area. Section 3 focuses on emissions on the distribution side of the meter (before and at the customer meter), while Section 4 focuses on natural gas emissions beyond the customer meter, i.e., post-meter emissions. Section 5 discusses what would be needed to combine the information from the various components to fully understand CH_4 emissions from the different sources for an entire city (Fig. 1), and Section 6 outlines possible next steps. Appendix A lists the participants of the workshop and Appendix B is the workshop agenda.

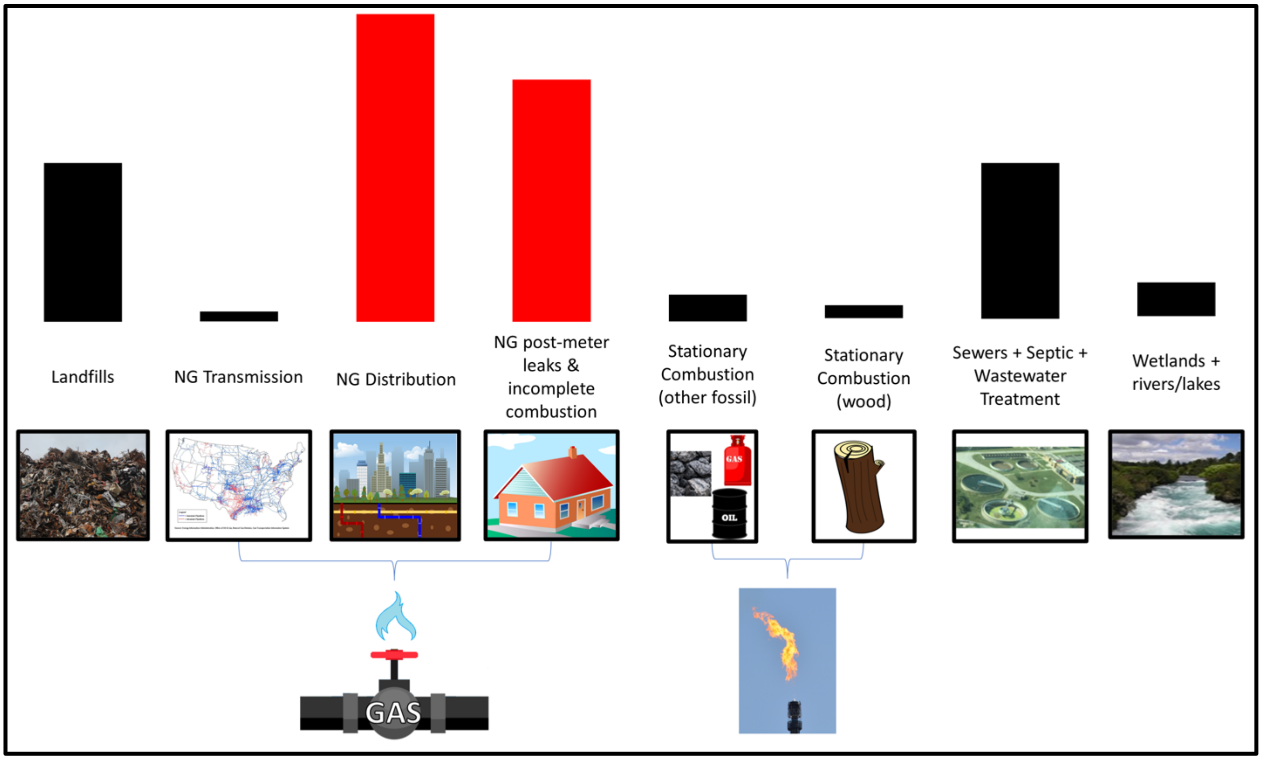

Figure 1. Schematic diagram of sources of methane (CH_4) to the atmosphere in urban areas. The height of the bars represents the relative importance of each source (data shown are for NYC from Pitt et al., [27]). This workshop focused on the two highlighted sectors: natural gas (NG) Distribution and NG post-meter leaks and incomplete NG combustion.

2. Top-down approaches: strengths and weaknesses

Researchers have used observations of atmospheric concentrations of CH_4 to estimate emissions at various spatial scales ranging from global and regional to whole-city and individual facilities. Here we summarize existing and prospective methods for estimating total and NG CH_4 emissions using atmospheric CH_4 concentrations in urban areas at different temporal or spatial scales, as well as methods used to separate NG from biogenic sources. We note that mobile street-level surveys are covered in Section 3 because they often focus specifically on NG pipeline leaks.

2.1. Flight surveys

Historically, flight surveys have often been used to quantify CH_4 emissions totals for an entire urban area [4-6, 28]. Aircraft-based in situ observations of CH_4 have been used to estimate whole-city emissions using various techniques: mass balance [6, 29, 30], tracer-ratio [7], and inverse modeling [4, 5, 28]. Facility-level emissions (landfills, powerplants, compressor stations, well-pads, etc.) have also been characterized in cities using aircraft observations [6, 31], although these studies are less common because there are not as many isolated large point sources in urban areas and flight restrictions often do not allow for flights close enough to individual facilities. Although aircraft observations have been used to detect and diagnose long-term emissions trends (e.g., Lopez-Coto*, et al.* [32] for carbon monoxide), their temporal resolution is limited by the frequency of flights.

In contrast to the high-precision, in situ observations described above, airborne imaging spectrometers may help provide more granular spatial information on urban CH_4 sources. It has not yet been shown whether these methods can be effective in an area of dense and distributed emissions such as occur in most cities, but these methods have been used to effectively quantify emissions from large, isolated point sources within broader urban regions [33]. Alternatively, drones with either remote or in situ measurements may also be able to achieve better spatial resolution for emissions estimates due to their ability to fly lower and closer to specific sources in populated areas (e.g., Burgués and Marco [34], Tuzson*, et al.* [35]), but they have not been used to date over cities. For all airborne platforms, flight restrictions over cities often present a challenge in achieving high spatial resolution and low altitude data over densely populated areas with tall buildings and other sensitive and spatially compact infrastructure.

Future research needs include improved coordination between air quality-focused and GHG-focused aircraft campaigns. Increased coordination could promote dual air quality and GHG objectives, as has been shown in a handful of campaigns (e.g., Brioude*, et al.* [28], Peischl*, et al.* [36]). Co-measurement of CH_4 with species such as ethane can assist with source attribution and flux quantification. Previous aircraft-based results have suggested that in the U.S. East Coast, most of the under-reported CH_4 in inventories is from the NG sector [7, 11].

2.2. Satellites

The number of existing and planned CH_4-observing satellites has expanded enormously in the past decade, as summarized in Jacob*, et al.* [37], with several existing or planned missions showing promise for detecting CH_4 emissions in urban areas at high resolution (e.g., MethaneSat and GHGSat), but few have a wide enough swath with which to image an entire large city. Recently, a study of CH_4 retrievals from TROPOMI leveraged simultaneous carbon monoxide (CO) observations to estimate whole-city CH_4 emissions using a scaling approach [38]. CH_4 products from a variety of satellites have also been used to identify large CH_4 super-emitters and quantify their emissions (e.g., Varon*, et al.* [39]; Maasakkers*, et al.* [40]). Current satellite observations (e.g., the TROPOMI sensor), while sometimes able to retrieve emissions over the ocean using glint observations [41], have difficulty retrieving CH_4 over areas close to water bodies (i.e., with pixels containing both water and land), limiting their use for coastal cities. Current observations are also not likely sufficiently selective to parse the relative contribution of different urban source types (e.g., NG emissions versus wastewater/sewer or landfill emissions).

Future research needs include the development of improved modeling tools for satellite observations and further evaluation and improvement of satellite datasets. For example, satellite datasets show enormous promise but require high-resolution atmospheric and inverse modeling frameworks that can effectively analyze the large amounts of data from current and forthcoming satellite sensors. We recommend urban-scale top-down observations and methods development, to improve the bases for comparisons with satellite retrievals. Satellite observations are subject to biases [42] and need to be rigorously evaluated and uncertainties quantified to maximize utility for top-down emission studies. This evaluation is typically done with airborne platforms and ground-based remote sensing networks (e.g.,Wunch*, et al.* [43]).

Future mission planning should also consider satellite-based CH_4 observations that better enable emissions estimation at urban spatial scales to complement ground-based networks (such as those in Los Angeles, Washington DC, Baltimore, New York City, and Boston) and extend emissions estimation to more cities. For example, NOAA is planning its next generation of Geostationary Extended Observations (GeoXO) and polar-orbiting satellite missions as follow-ons to its Geostationary Operational Environmental Satellite (GOES) – R mission and Joint Polar Satellite System (JPSS), respectively. Currently, a replacement for GeoCarb is not being planned for the GeoXO mission, although there is a partner payload slot available for a GeoCarb-like instrument capable of detecting GHGs within the boundary layer.

2.3. Stationary in situ observations

Several continuous in situ urban networks (e.g. based on towers or buildings) have been constructed in the last decade specifically designed to quantify urban GHG emissions, including CH_4, in Boston [12], Los Angeles [44], Indianapolis [45, 46], and in the Washington, DC and Baltimore metropolitan areas [47]. Typically, urban high-precision CH_4 observation networks are best-suited for quantifying emissions at ~1-10 km scales, depending on the network design [8, 9]. Recently, there has also been an interest in deploying lower-cost, lower precision CH_4

sensors in high-density networks (e.g., on buildings) throughout an urban area to enable higher-resolution spatial analyses. Although these sensors have lower precision and accuracy than the cavity ring-down spectrometers that are currently installed in many cities, deploying them at high densities may enable mapping of emissions at finer scales [48-50]. Deployment of such sensors must account for labor costs since maintaining these instruments and collecting data may be more costly than for a lower-density network using more established and stable measurement methods.

Continued public investment for installing and maintaining long-term tower networks over time will ensure that accurate trends can be assessed. Networks of stationary in situ observations are arguably one of the best means for tracking long-term changes in emissions from urban areas, as well as variability of whole-city emissions at sub-annual scales [9, 10, 51]. Cities often have regulatory monitors for determining compliance with ambient air quality regulations, and, in theory, GHG monitoring capabilities could be added to these existing monitoring stations (e.g., as they are presently being done in New York State (see: http://atmos.earth.rochester.edu/research/methane-inversions/)). However, these air quality monitors are usually sited near the ground – heights that are typical of human air quality exposures. By contrast, in situ GHG observations are often sited from ~30 m to several hundred meters above the ground to capture variations in GHG levels representative of a much larger region, mainly in order to be interpreted using mesoscale meteorological models, and to avoid sensitivity to local scale large sources and hyper-local flows such as in urban canyons or building wakes. However, the air quality measurement sites near the ground are useful for characterizing co-emitted species as they are often closer to the sources than the GHG observations, possibly allowing for a linkage between spatial scales. A formal evaluation of the ability of elevated tower-based observations versus near-ground measurements to capture urban-scale variations in CH_4, and the ability of transport models to model them, would be useful for the design of future observational networks. Co-located (i.e., at the same height) measurements of CH_4 and other pollutants could be complementary and help attribute CH_4 enhancements to specific sectors, as discussed in the next section.

2.4. Sectoral attribution of methane emissions

In urban areas, various economic sectors contribute to CH_4 emissions, including NG distribution and use, sewage and wastewater treatment, landfills, and agricultural activities. Urban emissions also include natural sources such as freshwater reservoirs, lakes, streams, wetlands, etc. All CH_4 sources need to be accounted for in order to reconcile more granular or bottom-up inventories with top-down methods that often estimate CH_4 emissions from all sectors combined. Inclusion of additional measurements of co-emitted trace gases (e.g., ethane, which is co-emitted from fossil sources but not from wastewater treatment or landfills) within top-down approaches can provide crucial additional information [10, 11, 52]. These measurements may be especially effective when an analysis includes measurements of additional tracers (e.g., CH_4 isotopes, because different emissions processes fractionate isotopically so that the isotopic composition of emitted CH_4 can yield information about the emissions source; [18, 53]).

To use measured methane/ethane ratios for source determination, it is critical to have current NG composition data. The gas composition is often measured by the local distribution company (LDC) at each city gate on a routine basis, (daily, weekly, or monthly, depending on the location) and can be available on request. The methane/ethane ratio from a given station is often quite variable in time, necessitating the use of currently measured NG composition for comparison to ambient ratio data. Composition also varies between different stations or city gates so information as to which facility serves specific areas (even within a city) would also be required.

In addition to available gas composition data, more frequent and area-specific composition information as well as characterization of the isotopic signature in the NG delivered and used in a study area is needed to reduce uncertainties in such methods and make them more effective (e.g., ability to distinguish between more source types). If the gas composition is known, measurements of tracer ratios (e.g. methane/ethane ratio) representing the entire city or other areas of interest can be used to calculate the fraction of CH_4 from NG sources. In some cases, particularly for tower locations, sufficiently precise (better than 100 ppb) measurements of carbon monoxide along with CO_2 and CH_4 can yield an understanding of combustion efficiency and, together with ethane measurements, point to CH_4 emissions that occur due to incomplete combustion from buildings, appliances, vehicles, power plants or other combustion sources (i.e., post-meter), which likely have different methane/ethane ratios from those of un-combusted NG. This data would probably be most useful to examine individual plume events passing the measurement location along with knowledge of the plume origin.

Using top-down methods to achieve CH_4 emissions estimates at higher spatial resolution can also enable distinction between different sectors, when NG sources are spatially distinct from other sources and their spatial distribution is known (e.g., large landfill vs. distributed along road network). A study in review for New York City [27] provides one such example, in which an atmospheric inversion is used to assign emissions to sectors based on spatial differences among different source types. However, we note that in some cases sources are co-located with NG emissions; for example, sewer CH_4 emissions are also distributed spatially along the road network, often parallel to NG lines [54]. In cases like this, a multi-tracer inversion scheme holds the potential of disentangling these confounding sources.

3. Local distribution company side of the meter

3.1. Background

Emissions from the local distribution company (LDC) side of the meter, i.e., NG infrastructure before or at the customer meter, arise from above or below ground metering and regulating (M&R) stations, from customer meters, and from underground pipeline leaks. The pipeline leaks can be especially challenging to detect because the surface emissions can be highly variable depending on soil and atmospheric conditions. LDCs are required by federal regulations to survey their systems periodically. Surveys are designed to locate leaks and prioritize them for repair; leaks are prioritized using a combination of gas concentration (typically at percent gas levels) and proximity to structures. The focus of this approach is safety and results in large leaks not near structures that can remain unrepaired for years. In contrast, leak measurements for the purpose of quantifying CH_4 emission rates for GHG inventories require more sensitive CH_4 instruments and techniques designed to measure gas flow rates.

For many urban area studies, there continues to be discrepancy between top-down satellite, tower, or aircraft-based emission estimates and corresponding bottom-up emission inventories (from the cities, the EPA's GHGI, or constructed by researchers) for CH_4 emissions from the NG distribution system. The bottom-up emission inventory generally takes the form of activity factors (i.e., pipeline length and leaks per pipeline km, or number of meters or facilities) multiplied by emission factors (emission rate per leak, meter, or facility) and includes M&R facilities, underground pipelines, both mains and services, and customer meters along with emissions from dig-ins and maintenance. Often the differences between top-down and bottom-up estimates are attributed to error in the bottom-up estimates, because generally there is a lack of confidence in both the activity data and emission factors used. For example, in a national sampling study [55], calculation of leak frequency assumed that routine utility surveys captured 85 % of all leaks, while recent results from mobile sampling suggest that such sampling might only detect 35 % of all leaks [56]. The relatively low rate reported by Weller*, et al.* [56] may be due to the less-sensitive sensors routinely used by LDC survey crews as well as other factors. In addition, there have been many more emission rate measurements collected (e.g., Weller*, et al.* [57]), but much of this data has not been incorporated into available emission factors for inventory purposes. Clearly more work is needed to improve the overall confidence in urban distribution system emission inventories and achieve consistency between top-down and bottom-up emission estimates.

In this section, we outline issues and approaches for improving bottom-up emission inventories for urban NG distribution systems. Some of the steps will require assistance and possible collaboration from LDCs, and a strong effort will be needed to establish a working relationship with the LDC for any particular urban study.

3.2. Infrastructure details

An important step to improve a bottom-up distribution system emission inventory for a particular urban area is to develop an accurate picture of the local NG distribution system. This includes the location and type of each M&R station, the kilometers and type/material of underground pipelines and the number and type of services and meters. This information is generally available, but the data is not in a central easy-to-use archive that is the same across locations, cities, distribution companies, etc. LDCs report this information annually to the EIA [58], but not with spatial or temporal granularity. Ideally, maps showing the locations of facilities, pipelines and services should be obtained and/or developed. Mobile surveys could be used to help locate and document M&R facilities since these often have distinct and measurable CH_4 plumes. Detailed data on the NG consumption should be collected and the gas composition should be documented, as noted previously. Gas composition data is available from the distribution company public informational postings but needs to be collected regularly as this data is not archived. Also, the specific station that serves different parts of the area is not available on the postings (i.e., there is no spatial information about the gas composition beyond the transmission station), and the location of the data varies by supplier. It is also very useful to obtain LDC leak detection survey results in terms of number and location of current leaks to the extent this data is available.

3.3. Metering and regulation stations

City gates and other M&R facilities can be large sources of CH_4 within an urban area, but the relative contribution of emissions from M&R stations is likely lower than fugitive emissions from other components in the NG distribution system. For example, emissions from M&R stations in Indianapolis were estimated to be less than 1% of the total distribution system CH_4 emissions for the city [3]. Similarly, Weller*, et al.* [56] reported that from mobile leak surveys, only 7% of detected leaks were attributed to M&R stations and 93% were attributed to underground pipeline leaks. These levels of contribution are low but could be quite different in different cities. Emission factors for these facilities, as a function of operating pressure, are available and used in current EPA emission inventories.

Often, CH_4 emissions from M&R stations and other large sources are quantified using mobile surveys and inverse plume modeling, including an EPA method based on sampling from a parked location [59]. More direct measurements can be collected by doing component surveys and hi-flow sampling within the facility, but this requires access from the LDC. Tracer ratio measurements are likely the most accurate method that does not necessarily require access to the facility [55]. However, this approach requires release of a tracer and a mobile sampling vehicle fitted with the appropriate CH_4 and tracer instrumentation.

3.4. Pipeline leak activity factors

CH_4 emissions from underground pipeline leaks continue to be a source of significant uncertainty in urban emission inventories. Various approaches are used to quantify individual distribution system leaks, e.g., as described in Lamb*, et al.* [3], Ars*, et al.* [15], von Fischer*, et al.* [16], Weller*, et al.* [56], and elsewhere. These include direct surface enclosure measurements [3] as well as mobile survey methods using empirical algorithms to quantify detected leaks [16]. Both approaches estimate emissions as the product of an activity factor (leak frequency, or number of leaks per km by pipe type) multiplied by an emission factor (EF) (g/min/leak). There are generally large uncertainties in both activity and emission factors for such leaks. We discuss each below.

Leak frequency has been calculated from routine LDC leak detection and leak repair data using a concept called equivalent leaks. These are conceptual leaks that occur for a year and are based on the fraction of leaks detected in routine surveys, initially estimated at 85 %, and the average time from leak detection to leak repair. Leak frequencies with this approach vary from more than 2 leaks/km for older cast iron or unprotected steel pipelines to less than 1 leak/km for new types of pipes. Lamb*, et al.* [55] estimated the overall leak frequency at 0.5 leaks/km using this approach. However, Weller*, et al.* [56], using a mobile leak detection approach compared to LDC survey results, estimated the fraction of leaks detected might be as low as 35 %. Using this detection estimate would increase the leak frequency by several times. Clearly more work is needed to assess overall leak detection and frequency.

Mobile survey approaches have also been used to estimate the leak frequency, with recent examples illustrating the value and limitation of these methods. Using relatively sensitive CH_4 sensors, these mobile surveys [13-15, 56, 60] return leak frequencies in the range of 0.1 leaks/km to 2.5 leaks/km, similar to the range of leak frequencies by pipe type reported by Lamb*, et al.* [55]. Mobile surveys may miss low-level leaks due to instrument detection limits in combination with vehicle speed, a limitation that could explain the differences between the results. Using walking or bicycle surveys with a sensitive portable analyzer may increase the detectability of low-level leaks. Another factor mentioned in these studies is that effective surveys require multiple passes along the survey route to confirm leaks. Ideally, measurements should include both CH_4 and C_2H_6, possibly along with CO_2 and CO sensors, and/or isotopic analyzers to help identify NG sources. Matching the mobile survey results using ethane/methane ratios to available NG composition data would improve the confidence in the survey results. The survey data should also be analyzed in terms of pipeline type along sections of the survey route to yield leaks per km by pipe type. Because of the large difference in leaks/km for older pipe types, including plastic installed before 1986, survey routes should be designed to includes areas where older pipe types are prevalent. Survey data should also be compared and analyzed with respect to available LDC routine leak survey and repair data to improve our understanding of the value and limitations of LDC routine survey data.

Previous inventories have separated mains and services, but mobile surveys generally cannot make this separation. In addition, some service leaks are at the T-junction with the main and it is often difficult to classify such a leak as a main or service leak. While the centerpiece of leak detection is a careful and complete mobile survey, all data sources available should be integrated to develop final leak frequency estimates. These include the routine LDC walking and mobile survey data, any available instrumented tower data, particularly smaller neighborhood scale towers, and any available drone data.

3.5. Pipeline emission factors

The other half of developing bottom-up estimates of urban distribution system emissions is to improve the accuracy in leak emission factors (EFs). Generally, two approaches have been used to develop EFs from underground pipeline leaks: dynamic enclosure methods and mobile surveys. Dynamic surface enclosure methods have been used to directly measure CH_4 emissions from identified leaks. While this is a time consuming and labor intensive method, the 1-sigma uncertainty in a single measurement is approximately ± 20 % or better [55]. In that study, three measured leaks accounted for 50% of total measured emissions. It should be noted that the type or age of plastic pipelines was not recorded for these measurements. There are indications that leak rates from vintage plastic may be much larger than from newer plastic pipelines. Efforts should be made to access and compile additional surface enclosure data that has been collected by LDCs, industrial groups, and academic researchers, in order to improve the accuracy of EFs.

Data from mobile surveys of the type described previously has also been used to quantify leak rates from detected leaks. Generally, these studies have all followed the approach developed by Weller*, et al.* [56] and von Fischer*, et al.* [16] where an empirical algorithm derived from controlled CH_4 releases is used to estimate leak rate as a function of the plume extent and/or peak plume concentrations. Because this approach is based on atmospheric measurements subject to the random nature of turbulence and wind speeds, and without a defined downwind distance, individual estimated emission rates have uncertainties greater than a factor of two or three [56]. This large uncertainty is offset by the much larger number of leaks that can be measured using the mobile approach. Several urban mobile studies [15, 53, 61] estimated emission factors (1 g/min/leak to 5 g/min/leak), generally larger than those obtained from surface enclosure measurements (0.3 g/min/leak to 1.2 g/min/leak)[55]. In fact, the mean city emission factor (1.8 g/min) is more than twice as large as from the surface enclosure method (0.8 g/min), possibly reflecting the likely higher detection limit for the mobile methods. The difference highlights the continued uncertainty in compiling accurate emission factors for specific urban areas. Nonetheless, developing new urban field programs that combine dense mobile surveys with a subset of dynamic enclosure measurements is recommended to improve our confidence in both activity levels and emission factors for underground pipeline leaks.

3.6. Customer meter emissions

There have been several studies of customer meters, including residential, commercial, and industrial meters. These studies are generally based on leak detection with portable sensors followed by hi-flow sampling for detectable leaks, and yield EFs that can be combined with data on the number of customers to estimate total emissions from customer meters. For the US, emissions from meters were estimated to be about half of pipeline leaks but accounted for 28 % of total distribution system emissions. In Indianapolis, emissions from meters were estimated to be about 10 % of total distribution system emissions [3]. As a result, it will be important to include estimates for meter emissions, and additional meter measurements in other cities will help determine the representativeness of the Indianapolis results.

3.7. Emissions variability

One remaining difficulty in the quantification of emissions from urban distribution systems is the general lack of information regarding short and longer/seasonal temporal variability of leak rates. It can be expected for underground pipeline leaks that measured leak rates will depend on soil properties and conditions including saturation from rainfall or freezing conditions in winter. For facilities and pipelines, the operating pressures and overall throughput could also affect facility and pipeline leak rates. Some information is available from tower based inverse estimates based on year-round measurements, indicating higher NG emission rates in winter [9, 10]. Further work using direct emission measurement methods (surface enclosure and mobile surveys) is needed to help clarify time varying emissions.

3.8. Gaps and needs

To improve the quality and accuracy of activity data and emission factors, additional data and measurements are needed. As described above, additional activity and NG composition data from LDCs would be useful to complement any additional atmospheric measurements, e.g., detailed composition data (at least daily) for a specific study area, maps of facilities and pipelines, line pressures, etc.

Standardized methods should be developed and applied using a combination of mobile surveys and dynamic surface enclosure measurements. Mobile surveys with multiple passes of detected leaks should be combined with a subset of surface enclosure measurements at the largest leaks detected. The mobile surveys will provide indicators of number of leaks (leaks per km) and a ranking of large to small leaks, while the direct surface measurements would provide accurate emission rates of the largest leaks. Since the large leaks dominate total emissions, this combination would provide a robust way to quantify urban pipeline leak totals. Given the time required to do both mobile surveys and surface measurements, the field study design might require concentrating on representative portions of an urban area. These portions should be selected on the basis of an analysis of pipeline types and km along with LDC routine leak survey data. Gao*, et al.* [62] and Cho*, et al.* [63] studied the impact of the effect of soil texture and soil moisture on CH_4 diffusion through soils under pipeline leak conditions and found that these variables have a significant impact on CH_4 concentrations above leaks. Given the lack of robust measurements of the same leak over different weeks, months and seasons, and soil conditions, an urban field program should include an effort to measure (large) leaks repeatedly over extended periods and to also document soil moisture and other environmental conditions for the measurement period.

Further, for selected areas, fixed small towers might be deployed for neighborhood scale inverse modeling or eddy-flux measurements and selected large buildings in these areas could be screened for post-meter emissions. The location of any observations needs to be tailored to capture all the emission points. Given complex flow dynamics in urban areas (e.g. urban canyons, building wakes), it may be necessary to measure at different heights and locations to fully capture both stack emissions and ground-level leaks. Both types of emissions will need to be quantified in order to close the gap between top-down and bottom-up emissions estimates.

4. Beyond the meter (post-meter)

Work on measurements of NG emissions beyond the meter, i.e., originating within commercial and residential buildings, has received significant focus in the last few years, and has suggested that these post-meter emissions could contribute a significant amount to national totals [20]. Sources for such CH_4 emissions include three broad categories: leakage inside a building (between the meter and appliances) or between apartments in a multi-unit building (e.g., service spaces); partially combusted gas and/or inefficient combustion from appliances or boilers; and leakage from appliances themselves (steady-state on, steady-state off, transient emissions during start-up or shut-off, and pilot lights). Here we address quantification of single-family residential home and large multi-family/commercial building emissions and what could or should be done to improve our understanding.

4.1. Single family residential

4.1.1. Previous work

Several studies have published emission rates or emission factors for CH_4 emitted from single-family residential homes and appliances. However, more research in this area would help corroborate existing measurements and methods as well as give a more representative picture from different building and appliance types and ages. For example, Fischer*, et al.* [64] measured quiescent emissions from 75 entire single-family homes in California. The EPA included post-meter emissions for the first time in the 2022 Greenhouse Gas Inventory (GHGI) [65, 66], using emission factors (per housing unit) derived from the Fischer*, et al.* [64] study. While Fischer et al. found significant leakage from quiescent sources (steady-state off, pilot lights, and leaks), they suggest that transient emissions (start-up/shut-down) may also play a large role as has been suggested in other appliance-level measurements [22]. More such studies at the household level and with specific appliance types are required to reduce the uncertainty and make these emission factors more representative throughout the US and for multi-unit residential buildings. Whole-house studies are challenging and time-consuming to conduct, however.

Various studies have found significant emissions from appliances (e.g., stoves, furnaces, water heaters) during transient periods (start-up/shut-down), steady-state on, and steady-state off periods. Merrin and Francisco [21] and Lebel*, et al.* [23] estimated total combined steady-state on and on-off CH_4 emissions from all gas stoves in the United States to be 2.7 Gg CH_4 yr^{-1} and 3.8 Gg CH_4 yr^{-1}, respectively. However, only Lebel*, et al.* [23] measured steady-state off emissions, which were almost five- to ten-fold larger: 21.2 Gg CH_4 yr^{-1} (while steady-state on emissions are larger per unit time, stoves are off a larger fraction of the time). Previous research for water heaters estimated CH_4 leakage to be 82 Gg CH_4 yr^{-1} from leaks and incomplete combustion, including relatively large emissions from tankless (on-demand) water heaters transient phases [22]. Emissions from unburned gas have been found to be small with a long-tailed distribution [64], indicating that their impact on total US emissions is still uncertain, and could be quite significant. These emission sources may be difficult to address due to small individual emission from a very large number of sources and their non-Gaussian distribution.

CH_4 emission from residential heating has been found to be significant in other countries, as is likely the case in the US as well [20], but gas furnaces have not been well-studied or characterized. Although space heating (e.g., furnaces, boilers) consumes most of the gas burned in residential buildings (~68 % according to the 2020 US Energy Information Administration's Residential Energy Consumption Survey [67]), we have limited measurements of unburned CH_4 in the exhaust gas from furnaces and almost no measurements of steady-state off leaks (i.e., leakage when the furnace is off) associated with furnaces. Due to the more controlled conditions and intentional combustion air in a modern furnace's combustion chamber, we expect more complete combustion and a lower proportion of unburned CH_4 compared to the open flame on a gas stove or water heater, however there is no a priori reason to expect steady-state off leakage to be lower for furnaces than for stoves or water heaters. Furnace leaks may be less likely to be smelled or otherwise detected since they are commonly located outside of the primary living space in basements, garages, attics, or on rooftops. We recommend research campaigns that target furnace emissions while off, on, and turning on and off.

Additional studies on residential post-meter emissions sources are needed to properly represent appliance emissions from steady-state on (including un-combusted fuel), off (including pilot lights), and transient periods. If emissions from furnaces, for example, are higher during periods of higher usage (from un-combusted gas, steady-state on, or transient leakage), this could account for recent findings of higher whole-city CH_4 emissions in winter, when gas usage for residential heating peaks [9, 10, 24]. On the other hand, steady-state off, or quiescent leakage, may not contribute to this seasonality. Whole-house studies are also critical for capturing additional leaks that are difficult to access or may not be associated with specific activities or appliances.

4.1.2. Methodology for single-family home measurements

Measurements of CH_4 emissions from single-family homes downstream of the meter are challenging, requiring significant resources as well as home-owner participation/assistance and permission. Fischer*, et al.* [64] describe their methodology for measuring whole-house quiescent emissions using a mass balance technique in detail, which involved building mechanical depressurization. A large exhaust fan is used to ventilate the house at a controlled flow rate, while measuring CH_4 concentrations in the fan exhaust stream and in the ambient outdoor air. These measurements and the known fan flow rate are used to calculate whole-house quiescent emissions. Generally with this method, a blower door is used to capture all pipe leaks, unvented and weakly drafting pilot lights, and steady-state off appliance leaks, but this method may underrepresent leaks in disjointed isolated spaces such as crawlspaces. This method may also be problematic when attempted with moderately complex architecture. A possible modified method could be utilized in restaurants or small commercial spaces with large mechanical ventilation (e.g., kitchen hoods), to determine emissions including from operation of a stove or grill.

A potentially simpler method to quantify quiescent whole-house emissions would replace the blower door method by measuring the air change rate within the home using a tracer decay approach [68]. Essentially, a trace gas (SF_6 or CO_2, for example) would be injected in a pulse into the home and the concentration decay rate (measured with a gas analyzer) used to determine the air change rate. Whole-house fans would be needed to ensure fully mixed conditions within the space, and in the case of CO_2, all CO_2 sources must be removed from the home during the measurement period. Then measurements of CH_4 concentrations inside and outside the house (similar to the Fischer et al. mass-balance approach) can be used to determine whole-house emissions.

Another whole building sampling approach that was discussed but ultimately not recommended is an encapsulation technique where the whole building would be enclosed with something comparable to a fumigation tent and quiescent emissions could be measured from a mechanical exhaust stream similar to the Fischer*, et al.* [64] blower door technique. This method is not recommended due to the explosion risk from gas buildup. When buildings are fumigated for pests with these tents it is typically required to turn off the gas supply at the meter to avoid leaks accumulating to dangerous levels within the tent.

Individual appliance emissions can be captured using in-flue sampling. One drawback to this method is that it captures undiluted emissions and thus may exceed concentration ranges for typical instrumentation; purposely diluting the emissions may be one method to alleviate this problem. It is also difficult to calculate flow with small flames, such as pilot lights. There is some uncertainty in stovetop measurements due to capture efficiencies and interactions with the burner, and thus this method is most relevant for furnaces and water heaters. Additionally, this method requires homeowner permission to drill a small hole in the flue pipe for sampler access.

Exhaust fan channeling and sampling is another option for measuring post-combustion emissions from individual appliances. This sampling method requires exterior access to the appliance flue termination with a substantial quantity of powered equipment. Monitoring of the combustion efficiency of appliances on a regular basis at the exhaust can be done to determine the combustion efficiency of the fuel. This method would require measuring CH_4, CO and CO_2 to calculate the combustion efficiency, but would not require knowledge of the flow rate of the exhaust, which can sometimes be difficult to quantify. When exhausts (flues) are located in elevated locations or on the roof, sampling at the rooftop location is logistically challenging, especially in inclement weather or on steep roofs.

4.2. Commercial and large residential buildings: measuring emissions by mass balance

Commercial buildings use air distribution systems to provide heating, cooling, and fresh air and to remove odors and air impurities (e.g., for cooking operations). The combination of air distribution systems installed in a specific building depends very strongly on building size, mix of uses within the building, structure, and general level of efficiency applied in the design.

An Air Handling Unit (AHU) is a common hardware component used in commercial buildings and one basic AHU design is shown schematically in Fig. 2. Key components include an air intake opening, coils for heating (e.g., hydronic or steam), coils for cooling (direct refrigerant expansion or chilled water), a supply air fan, a return air fan, and an exhaust. As shown in this figure, there is a bypass duct and damper arrangement on this AHU to recover some of the heat in the exhaust flow. There are many other designs available including some that recover heat with exchangers rather than direct duct flow. AHUs can be installed in rooftops, basements, or between floors. For the purpose of measuring CH_4 emissions from buildings, cases where all supply and exhaust flows are captured using AHUs or space-specific ducted exhaust provide an opportunity for direct emission determinations. Not all commercial buildings will meet this criterion including, for example, buildings with warehouse and/or vehicle service operations. Older multi-family residential or mixed-use multistory buildings with steam or hydronic heat and unit-specific air conditioning would also not meet this criterion.

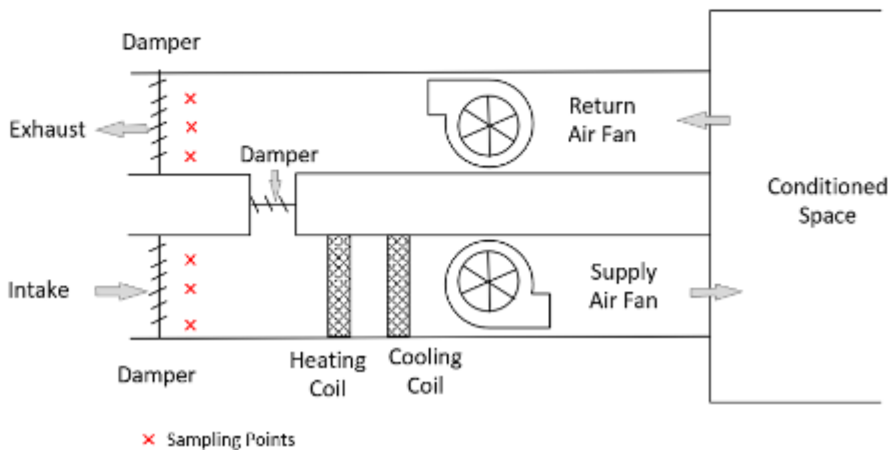

Figure 2. Schematic illustration of a typical Air Handling Unit (AHU)

To implement a complete CH_4 mass balance around a suitable commercial building it is necessary to measure volumetric air flow, temperature, and CH_4 concentration at all exhaust flow points and at least CH_4 concentration at intake points. The air velocity in the exhaust duct can present some measurement challenges if it is stratified or swirling. Flow straightener vanes may be installed in larger ducts which can improve this situation. Generally, with rectangular ducts, multipoint velocity measurements should be made to most accurately measure the total volume flow rate. While traverse-type velocity profiles can be made, these are most likely to be of value in initial measurements to evaluate the degree of stratification that might exist at a measurement point. For monitoring over extended periods, multipoint, averaging velocity measurements can be made and there are commercial products available that could be used for this.

Exhaust CH_4 measurements can be single point, multipoint sampling systems, or traverses. At the start of a measurement campaign of this type, traverses to evaluate the degree of stratification of CH_4 concentrations are recommended. With smaller, round local exhaust ducts single measurements at the center of the duct are expected to be acceptable. On the intake ducts, continuous measurement of CH_4 is recommended as local outdoor conditions can change rapidly. This could depend on wind and boundary layer conditions, and local scale emission impacts. We note that this method would not account for passive infiltration into and out of the building, as only the mechanical flows in and out of the building will be measured. Efforts should be taken to minimize passive flows. Also, as mentioned for the single-family residential measurements, this method would not address CH_4 leakage into low-exchange wall spaces, exterior walls or crawlspaces of the building.

In considering a measurement project for a specific building the following steps are offered as ideas for planning:

1. Document the uses of NG within the building.
2. Document all points of air exhaust and intake. As available, obtain information on nominal flow rates for each exhaust point.
3. Obtain information on control systems and routine operations that can impact in-use exhaust flows.
4. Through a review of drawings and site visits develop a plan for sampling locations, airflow locations, access ports, instrument siting options, and measurement points available through the building energy management system that can help with the planned project.
5. Develop a test plan based on the specifics of the building.
6. Procure/install needed sensors. One or a few high precision instruments could be installed sampling from multiple rapidly-flushed sample lines with a switching valve.
7. Make velocity profile measurements as needed in exhaust ducts.
8. Run planned tests – expect one week of monitoring. May be repeated in different seasons.
9. Conduct standard emission tests within the building to evaluate whole building methods.
10. Analyze results to complete CH_4 mass balance over all exhaust pathways and for the total building, and as a function of the internal use.

Because of the almost complete lack of data for large commercial or residential buildings, it is important to realize that making these types of measurements in even a small number of buildings will be extremely valuable. Initial building tests will provide very preliminary estimates of the range of CH_4 emissions that might occur and at the same time, the initial tests will provide valuable information on how to develop accurate screening methods for application to a larger number of buildings in a cost-effective manner. Developing a database of building scale emissions will require a phased approach, e.g., with an initial developmental test/learning phase.

5. Synthesizing different data types to determine whole-city emissions sources

Given the approaches outlined in the earlier report sections, here we outline a plan for quantifying how much CH_4 is emitted in a city and what portion of that total is emitted before and/or after the meter. The goal is to reach a point at which the top-down larger-scale measurements (perhaps of the entire city or metropolitan area) can be reconciled with distribution system, landfill, wastewater treatment and sewer emissions, and with smaller-scale building-level or local area studies of NG losses. Such studies can provide updated emission factors and activity data to enable development of reliable high resolution urban-scale CH_4 emission models. We note that we can only reconcile with Scope 1 (direct) emissions, as top-down measurements necessarily measure at the point of emissions and cannot account for Scope 2 or Scope 3 emissions (emissions occurring outside the domain, such as from imported electricity or goods, or exported waste, etc.).

5.1. Separating natural gas emissions into source sectors (pre- or post-meter)

High-resolution spatial mapping of NG emissions from top-down methods could enable better understanding of where those emissions originate. Given the spatial proximity of street-level leaks and homes, any approach relying on a mesoscale meteorological model and observations that integrate the signals from larger areas would not succeed in separating different sources of NG emissions at high spatial resolution. Thus, observations of CH_4 would need to be made at sufficiently high spatial resolution (possibly from both mobile surveys and simultaneous roof-top or stack sensors), coupled with highly-resolved flow models that can account for hyper-local circulation around buildings, to tie those concentrations to local emissions and correlate them with activity data that is also spatially resolved. For example, emissions may correlate with pipeline pressure or age of pipeline infrastructure vs. age or type of appliances in homes. Correlating temporal variability of emissions with activity data may also yield insight as to the source of the emission. For example, one could determine if emissions correlate with gas usage, combustion, time of day, and/or with a time series of pressure in the distribution network. Simultaneous measurements of $CO/CO_2/CH_4/C_2H_6$ will also be helpful in assessment of the contribution from incomplete combustion. For example, CH_4 enhancements correlating with CO enhancements could signal post-meter emissions from partially incomplete combustion of NG emanating from flues and stacks.

5.2. Pathways for scaling up distribution network studies

To date, mobile surveys of CH_4 (and sometimes ethane) concentrations in urban areas have been used to both qualitatively and quantitatively investigate emissions from NG distribution pipeline networks in the US and abroad. However, these surveys often take place in a specific neighborhood or core urban area, and in order to compare with top-down studies that quantify emissions on larger scales (e.g., of an entire metropolitan region, including suburban areas), some spatial scaling up is required. Temporal up-scaling (extrapolation) is also required if the goal is to quantify annual emissions based on studies that take place over only several days. A better understanding of the underlying emissions distribution and what activities or attributes correlate (rate of NG use, ambient temperature, time of day) with emissions magnitude may allow for the determination of emission factors (e.g., leak indicators per km, emission per leak) that can be applied outside the specific area of the measurement. For example, the spatial and temporal characteristics of the measured emissions can be used to determine or update an emission factor (e.g., if emissions correlate with pipeline pressure or type or age of pipeline infrastructure etc.). Ideally, more mobile surveys could be completed in additional cities (with different infrastructure characteristics), and over different seasons, to better characterize the dependence of emissions on different factors and achieve better statistical understanding, following methods introduced in Weller*, et al.* [57].

5.3. Pathways for scaling up building-level post-meter emissions studies

Far fewer studies on emissions from buildings exist than from mobile (street-level) surveys, and more of them are needed to determine more representative emission factors. The recent EPA greenhouse gas inventory for the entire US utilizes emission factors for residential quiescent (i.e., while appliances were turned off) post-meter emissions from the study by Fischer*, et al.* [64] on California single-family homes. There is a pressing need for additional similar studies in different regions with different types of infrastructure and climate to determine emission factors that likely better represent different areas and different types of buildings, especially commercial and multi-family residential buildings. Additional studies on appliance emissions when they are on or cycling on and off are also required, with their emissions quantified as a function of activity (such as gas usage). These would be required to reconcile the seasonally-dependent emissions found in whole-city studies with processes that lead to higher emissions in winter. More representative emission factors can be combined with activity data for an entire city or metropolitan area to provide meaningful post-meter emissions estimates. Emission factors could be tied to certain building properties (e.g., (heated) square footage, building use type, age, etc.) so that emissions from an appliance or building study can be scaled up using activity data that is specific to the type of building. At the time of this report, there have been no large commercial/residential building studies, so this needs to be prioritized by the community. It seems highly unlikely that the residential emission factor from Fisher et al. will apply to large multi-use or multi-family residential buildings. In addition, better data on the point of emission (surface vs. building top) could be obtained using drones or tethered drones, which can operate for much longer periods, and that could produce vertical profiles of CH_4 and ethane, which would likely be quite useful. Temporal characteristics of the emissions measurements could possibly be used to determine/improve emission factors (e.g. if emissions correlate with usage volume of gas, or time of day, or number of occupants).

5.4. Additional needs

To determine the sources of NG emissions in urban areas and their relative magnitudes, advanced and robust statistical approaches will be required to synthesize information from a small set of individual studies (e.g., Weller*, et al.* [57]). These might be specific to the metropolitan area in question and may require understanding of the underlying distribution of emissions which are generally non-Gaussian.

Additionally, better and more highly-resolved activity data (both spatially and temporally) will be needed to scale up and understand the results from studies. For example, currently in the US Northeast, gas composition and heat content data is provided along the Transco pipeline at main hubs at daily intervals. However, the data is removed every 90 days so must be downloaded periodically to obtain a full time series. Additionally, it is not possible to determine the composition of the gas that is delivered on a specific day to a given city, and the composition at the different stations varies widely, with significant day to day variability. Pipeline pressure data is unavailable as far as we know. NG usage data is available (separated by sector) at state-level, monthly, from the EIA and annually for the entire LDC domain, but more granular usage data would help interpret CH_4 emissions correlations with gas usage without relying on downscaling state-level consumption data to city scales. Gas composition data, pipeline pressure data, or anonymized usage/meter data at high temporal and spatial resolution (i.e., matching the top-down information – could be daily and by census tract or block) would improve our estimates of NG emissions because they could be analyzed against top-down measurements of ethane/methane ratio or total emissions from local areas. This could be enabled by ensuring that LDC representatives for cities of study are, in this case, encouraged to join the Urban Methane Working Group (see section 5.5 below). It would be useful if a laboratory were set up for rapid determination of NG composition for light hydrocarbons, or at least CH_4 and ethane for urban NG samples. This could be done with currently available commercial gas analyzers. It is also a very simple gas chromatography experiment that could be established in a Working Group laboratory, for hydrocarbons larger than ethane.

5.5. Establishment of productive collaborations

Future urban CH_4 studies will benefit from collaborations with universities, government laboratories/entities, and LDCs, who:

a) Have access to large buildings (e.g. the Mayor's Office of Sustainability in NYC has offered to help).
b) Have laboratories that could do supporting analysis of daily NG composition.
c) Study air quality indoors and ambient, who would be making useful measurements, e.g. VOCs, CO, CO_2, SO_2. In most big cities there are state environmental monitoring labs who might collaborate on a coordinated study.
d) In the LDC case, could provide supporting data on things like gas composition, usage, pipeline pressure, etc.

6. Next steps

A. Write a literature review paper for publication in the peer-reviewed scientific literature about known unknowns in urban CH_4 emissions. It should do its best to reconcile top-down vs. bottom-up estimates of CH_4 emission from existing data sets/publications. Note that top-down methods are necessarily Scope 1. Therefore it is important to reconcile bottom-up and top-down estimates in time, space, and scope; e.g. for many cities there are Scope 3 emissions in the inventory that are obviously not captured from top-down observations. Organization of this review paper is in progress.

B. Develop a common repository for data, with a common data format, from studies of urban CH_4 emissions. Invite researchers to pull all the data together – this could be more powerful than any one study. This may be a substantial effort, in terms of formatting, and producing directly comparable information. We are considering who might host this.

C. Formally develop a Research Coordination Network (RCN) for Urban Methane. There is interest, but this activity will need a proposal/organizing committee.

D. There is a consensus for a need to create an urban methane working group, but this could be the RCN. We will need to reach out to additional researchers with interest in this topic, including air quality researchers whose interests overlap given the indoor air quality impacts of NG leakage in homes. Along with CO_2 reduction, some CH_4 reduction efforts (e.g. NG leakage reduction) would have co-benefits for air quality, including indoor air quality. A working group/RCN would include logical stakeholders, i.e. researchers, industry experts, agency program managers, NASA/satellite data users/developers, city government, state government representatives who are developing inventories. NSF has funding opportunities for RCNs.

F. We propose the creation of a smaller/more focused working group that would develop a proposal(s) to fund whole building studies, in either the greater Washington DC/Northern Virginia area, or in the greater New York City area, or both. An initial project could start with studies of two different building types, e.g. one commercial use, the other multi-family residential, take stock of what was learned, and then expand the data set with revised approaches and many more buildings, in different cities DC, Baltimore NYC, Boston. The authors will assemble a working group to pursue this.

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* This list contains registration information, however all of the names above may not have participated any or part of the meeting.

Appendix B. Workshop Final Agenda

Workshop Agenda: Quantifying methane emissions across
natural gas infrastructure in urban environments.
June 15 -16, 2022
EDF offices, 1875 Connecticut Ave NW, Ste 600, Washington, DC

Objective:

Based on published literature, leaks from natural gas (NG) distribution systems are responsible for a significant portion of urban methane emissions. However, there is debate as to whether emissions stem from leaking NG distribution system components or from incomplete combustion and/or fugitive emissions associated with end-use systems components, e.g., appliances, boilers, furnaces, meters, etc. The purpose of this workshop is to develop a white paper that outlines viable approaches for better quantifying and understanding the relative contribution of fugitive emissions from various natural gas components in cities. This white paper will form the basis for targeted, tangible activities designed to estimate and quantify the relative proportion of pre- and post-meter leakage of NG. To date, there are limited studies that have quantified emissions along the full natural gas distribution system.

Agenda/Itinerary:
Day 1

8:30 - 9:00	**Check in at EDF lobby front desk, vaccination card check**
9:00 - 9:05	**Welcoming remarks (Joe Rudek, EDF; Anna Karion, NIST)**
9:05 - 9:20	**Introduction of workshop goals (Paul Shepson, Stony Brook University)**

Workshop purpose and goals, including a summary of the full workshop organization, how discussions aim to identify viable field observation approaches, and the expected white paper outcome. This is a working meeting where participants are expected to contribute to developing material during the workshop. We will begin with background presentations on the state of the knowledge of methane emissions for cities, and definition of the knowledge gaps, and possible approaches for addressing gaps.

National & city-scale studies

9:20 – 9:35	US GHGI NG distribution emissions	Melissa Weitz (EPA)
9:35 – 9:50	Lessons from Indianapolis	Brian Lamb (WSU)
9:50 – 10:05	Boston & follow-on implications	Steve Wofsy (Harvard)
10:05 – 10:20	Ethane/methane observations	Paul Shepson (SBU)
10:20 – 10:45	NYC inventory & inversion results	Joe Pitt; Israel Lopez-Coto (U. Bristol; NIST)
10:45 – 11:00	**Coffee Break**	

Local studies on natural gas distribution system and post-meter emissions

11:00 – 11:15	Pre- and post-meter natural gas leaks	Rob Jackson (Stanford)
11:15 – 11:30	Post-meter emissions	Natalie Pekney (DOE/NETL)
11:30 – 11:45	The Boston SEI leak program	Zeyneb Magavi (HEET)
11:45 – 12:00	VCPs and solvent emissions	Brian McDonald (NOAA)
12:00 - 1:15	**Lunch (served on-site)**	

Engineering systems - Leak infrastructure, building infrastructure & measurement techniques

1:15 – 1:35	Pre-meter	
	▪ NYC systems	Bill Slade and Rick Trieste (ConEd)
1:35 – 1:55	Post-meter	
	▪ Building systems	Jim Miller, Dylan Desimone and Tom Ferrara (GHD)
1:55 - 2:15	Overview of what we know on both sides of the meter	Joe von Fischer (CSU)
2:15 – 2:30	Needs of emission modelers	Jonathan Dorn (Abt)

Ongoing and Upcoming monitoring and field campaigns to leverage

2:30 - 2:45	NY State activities	Lee Murray (U. Rochester)
2:45 – 3:00	NY State, NYCity & related activities	Roisin Commane (Columbia)
3:00 – 3:15	Air quality monitoring & campaigns	Luke Valin (EPA)
3:15 – 3:30	**Break**	
3:30 – 4:30	Breakout Session to define potential approaches	
4:30 – 5:00	Groups report back - Making an agenda for the next day's discussion topics	
6:30	Group dinner for those interested (contact: Anna.Karion@nist.gov)	

Day 2:	**Discussion and planning**
8:30 - 9:00	**Check in at EDF Lobby**
9:00 – 10:30	Summary of breakout groups, and discussion
10:30 – 10:45	Break
10:45 – 11:45	Sharing slides, Open discussion, outline white paper / report; publish it?
11:45 – 12:30	Development of plans and action items, including plans for engaging stakeholders.
12:30 – 1:30	Open/informal Discussions led by stakeholder agency employees EPA, NOAA. EDF, DOE, NIST, NYSERDA, DEC

END Day 2

Discussion topic examples:

- Sketch what a specific project might look like, e.g., GSA/DC/NIS/NYC/Balt. building study
- Should we focus on one city for pilot study?
- Enumerate measurement needs, observational approaches
- Enumerate data or information needs (e.g., information about target city infrastructure and buildings)
- Pre-meter emissions: How to best sample mains vs. service lines vs. meters? How much does age and/or material matter? Are city gates/distribution points part of this effort?
- Post-meter emissions: How best to sample emissions from commercial or residential buildings, including large multi-family buildings? Can we use tracers for indoor air?
- How would any findings scale up (in space & time)?