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Beyond-the-Meter: Unaccounted Sources of Methane Emissions in the Natural Gas Distribution Sector

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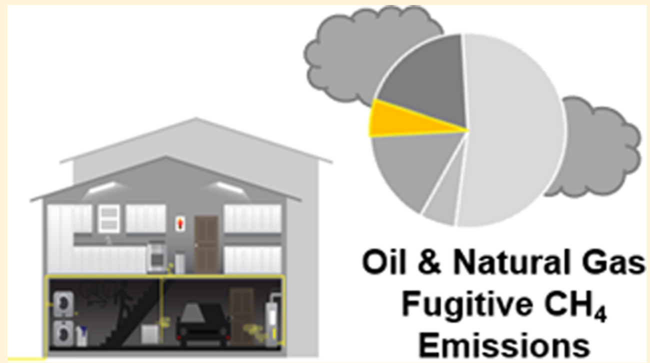
ABSTRACT: The United States Environmental Protection Agency maintains an inventory of greenhouse gas emissions in accordance with the Intergovernmental Panel on Climate Change. Methane (CH_4), a potent gas with a global warming potential 86−125× that of carbon dioxide (CO_2) over a twenty-year period, is the main component of natural gas (NG). As NG becomes an increasingly larger percentage of the energy resources used in the United States, it is ever more important to evaluate the CH_4 emissions inventory. However, the inventory also does not account for all possible sources of CH_4 leaks, contributing to uncertainty in the national CH_4 inventory. Discrepancies between top-down and bottom-up inventories of CH_4 emissions imply that there are significant unaccounted-for sources of CH_4 leaks, especially over cities. Diffuse CH_4 plumes above cities that are not attributable to distribution pipelines or other NG infrastructure suggest many small beyond-the-meter leaks together contribute to large emissions. Here, we evaluate the distribution sector of the CH_4 emissions inventory and make suggestions to improve the inventory by analyzing end-user emissions. Preliminary research into beyond-the-meter emissions suggests that while individually small, the appliances and buildings that make up the residential sector could contribute significantly to national scale emissions. Furnaces are the most leak-prone of appliances, contributing to 0.14% of total CH_4 emissions from the NG sector in the United States. Combining measurements from whole house emissions and steady-state operation of appliances, we estimate that residential homes and appliances could release 9.1 Gg CH_4 yearly in the United States, totaling over 2% of the CH_4 released from the NG sector. While factors such as appliance age and usage, climate, and residential setting could influence the emissions profile of individual appliances, these preliminary estimates justify further exploration of beyond-the-meter emissions.



1. INTRODUCTION

The Environmental Protection Agency (EPA) maintains the Greenhouse Gas Inventory (GHGI), an extensive database of the sources and sinks of greenhouse gases (GHGs) and the estimated annual output from each source. The GHGI divides anthropogenic GHG emissions by source, economic sector, and type of gas emitted, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide, fluorinated hydrocarbons, sulfur hexafluoride, and nitrogen trifluoride (Figure 1). According to the EPA, an estimated 10% of all GHG emissions from the United States is CH_4, the second-largest contributor to historical global warming after CO_2.[1,2] CH_4 is a powerful but relatively short-lived GHG with 86−125× the global warming potential of CO_2 over a twenty-year period and 25−36× over a one-hundred-year time span, although such equivalencies are under constant readjustment based on new measurements and data analysis.[3−5] Though CH_4 is less prominent than CO_2 in discussions about anthropogenic climate change policy and practice, reducing CH_4 emissions can have a more dramatic effect on climate change over the short term than the equivalent reduction in CO_2.[2,4] Cutting CH_4 emissions, however, depends on knowing the contributions of each source to determine effective strategies for mitigating atmospheric losses. The purpose of this Critical Review is to describe a significant gap in the GHGI and to propose methods for improving the CH_4 emissions inventory through surveying unaccounted beyond-the-meter CH_4 emissions.

2. ANTHROPOGENIC METHANE EMISSIONS

CH_4 emissions come from natural as well as anthropogenic sources. Natural CH_4 seeps include wetlands and the arctic, as well as aerobic CH_4 production from terrestrial and aquatic biota. Anthropogenic sources of CH_4 emissions which are tabulated in the GHGI include biotic-related (landfills and sewage, enteric fermentation, manure management, and rice agronomy) or energy-related sources (coal mining, oil and natural gas [NG] systems, and other industrial processes) (Figure 1). CH_4 is the main component of NG, the second most common energy source behind petroleum in the United States.[6] The NG industry is estimated to account for 10% of all

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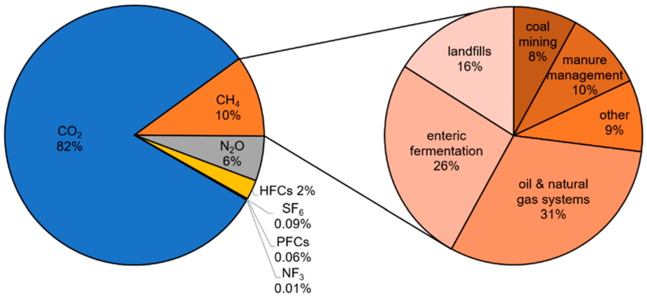

Figure 1. United States GHGI emissions by gas in 2017 based on CO_2 equivalents and breakdown of anthropogenic CH_4 emissions in the GHGI. CO_2, carbon dioxide; CH_4, methane; N_2O, nitrogen dioxide; HFCs, hydrofluorocarbons; PFCs, perfluorocarbons; NF_3, nitrogen trifluoride. Source: United States EPA.[1]

CH_4 emissions in the United States but is likely to become an even greater percentage because of new extraction techniques and a shift away from coal.[7] Fugitive CH_4 refers to gas unintentionally released to the ambient air; the term "emissions" will also be used to refer to such fugitive leaks and not CH_4 released for the purpose of venting. Venting, a common practice in NG production, may occur in the form of flares or periodic releases from components, such as pneumatic controllers or meters, which may also serve as conduits for unintentional CH_4 emissions. As NG becomes a more prevalent source of energy in the United States, fugitive CH_4 emissions from the NG supply chain will become much more important to consider in emissions mitigation strategies.

Some analysts suggest that NG only outcompetes coal and other energy sources in environmental impact if unintentional emissions are less than 3−6% of the total usage.[3,8] A recent meta-analysis from Álvarez et al. estimated 2.3% (±0.4%) of NG produced is lost through fugitive emissions.[9] In close agreement with the meta-analysis performed by Álvarez et al., the National Petroleum Council estimates that 2.2% of total gross NG production is lost as waste emissions.[10] These estimates are lower than previous reports, reflecting new or updated data and analytics. In 2014, Brandt et al. proposed a much higher 5.4% (± 1.8%) emissions loss for conventional NG and shale gas sources combined.[11,12] Low-level CH_4 emissions become significant when extrapolated to the national scale, so even minor contributions (1% total emissions) may have an impact on the GHGI and its ensuing application to energy and environmental policy and practice. When considering the national energy outlook and environmental protection strategies, a very accurate and precise inventory is necessary to ensure that all sources of CH_4 have been accounted so that the environmental costs associated with NG usage are properly assessed.

2.1. Emissions Factors and Activity Factors. The United States GHGI is a compilation of all sources and sinks of GHGs. To estimate the total amount of each gas released from each source, both the average emissions rate and the number of components of each source type must be known. An emissions factor (EF), or the quantity of a pollutant released associated with an activity and the rate of release from that activity, is assigned to each individual component within each sector. The EF multiplied by the activity factor (AF), or the total number of each component in the country, yields the total nationwide emissions attributed to that specific component. The GHGI utilizes these individual EFs and AFs to build the emissions inventory in what is known as a bottom-up strategy.

The NG supply chain is generally divided into four main sectors: production (wells and extraction equipment), gathering and processing (pipelines, refineries, and processing facilities), transmission and storage (pipelines, compressor stations, and storage facilities), and distribution. The distribution sector begins with metering and regulating (M&R) stations and includes the pipelines and regulating stations that carry gas to individual meters, ending with the appliances and other devices powered by NG (Figure 2). EFs for each sector of the NG supply chain, as well as the individual components that make up each sector, have been calculated for the GHGI and are regularly re-evaluated.[13]

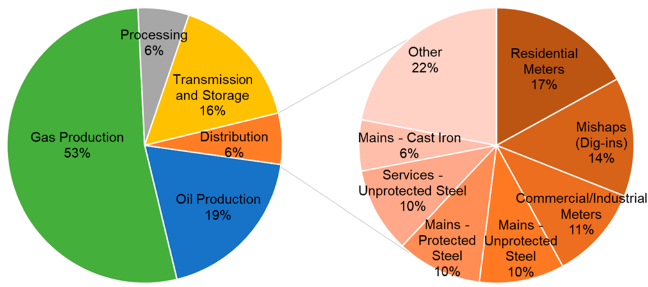

Figure 2. United States CH_4 emissions from the NG supply chain in 2017, divided into sector, and the major components that comprise the distribution sector. Source: United States EPA.[1]

Uncertainty levels are calculated for EFs and AFs to reflect the confidence in each reported value. Known uncertainties include such sources as incomplete datasets or calculations that rely on outdated measurement techniques or activity rates that are based on old technologies or census data. Incomplete or inadequate datasets and EFs that rely on measurements collected without considering temporal, atmospheric, or other factors also contribute to uncertainty. The detection method used to determine leak rates can contribute to increased uncertainty in emissions estimates.[14] Uncertainty may also be attributed to large variability of the measured emissions, often reflected in fat-tailed distributions, which are datasets containing a few outliers with abnormally high emissions.[15,16] Across the NG supply chain, super-emitters result in non-normal distributions of leakage rates.[15,17] Typical inventory reporting may obscure the presence of outliers, as well as the fact that by fixing a few abnormally functioning components, an entire sector's CH_4 contribution could dramatically decrease. Unknown or unaccounted sources of emissions not included in the inventory also increase uncertainty in the GHGI.

The NG systems portion of the CH_4 emissions inventory has moderate coverage of known uncertainties and the gaps in data completeness are addressed annually as part of the annual EPA report (Figure 3). To reduce uncertainty, the EPA continually evaluates and incorporates new research findings; for example, the EPA adjusted the overall NG production sector emissions leak rate from 0.16% to 1.42% between its 2010 and 2011 reports, but by 2013 had lowered the rate to 0.88%, largely because of changes in accounting for emissions from liquid unloading and hydraulic fracturing practices in NG production.[18] Additionally, the global warming potential of CH_4 is under continual readjustment, having increased in CO_2 equivalents in recent years leading to an increase in the

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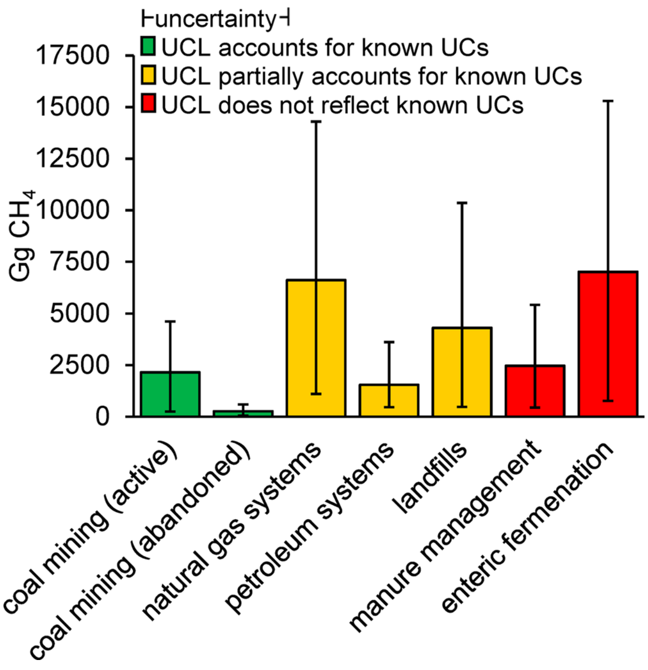

Figure 3. Uncertainty levels (UCLs) in the estimated annual CH_4 emissions (in Gg CH_4) of known sources. Error bars represent uncertainty ranges at the 95% confidence interval. Green: UCL accounts for current known uncertainties. Yellow: UCL partially reflects known uncertainties. Red: UCL does not reflect currently known uncertainties. Source: NAS Report.[22]

calculated relative impact of CH_4 emissions.[5] While such alterations could reflect changing monitoring techniques and NG production technologies, the dramatic variability in CH_4 estimates reveals critical uncertainties in compiling the GHGI, including from the NG sector (Figure 3). Unknown contributions from unaccounted sources of emissions in the NG sector do not factor into calculated uncertainties and yet are just as critical to understand and correct as known uncertainties. Improved emissions quantification and identification of previously unaccounted emissions may substantially alter the CH_4 emissions inventory.

Adjustments to the GHGI occur through proposed alterations of EFs and AFs. There have been recent changes to the NG distribution sector accounting. Changes to EF and AF values for regulating and M&R stations, sometimes referred to as city gates, were under consideration and incorporated into the GHGI as recently as 2015.[19,20] Updates to facilities and improved leak detection and repair (LDAR) techniques, in addition to stricter regulations and dedicated LDAR inspectors, have been invaluable improvements in decreasing the EF of M&R facilities, leading to these re-evaluations (Table 1).[1,21]

Yet even as known uncertainties in the distribution sector are reduced, unaccounted sources related to distribution and usage remain. Currently, the GHGI only includes pipelines, M&R stations, and customer meters in building up the distribution sector emissions estimates but does not include fugitive emissions from sources downstream of the customer meter.

2.3. Reducing Uncertainty in the Natural Gas Emissions Inventory. As previously mentioned, the EPA regularly reassesses EFs based on new technologies and measuring techniques in an effort to reduce uncertainty in the GHGI. Each annual report documents updates to the inventory since the last publication and calls attention to areas with concerning uncertainties or otherwise in need of reassessment. While production, gathering and processing, and transmission and storage have relatively well-defined segments, the distribution sector of the NG supply chain contains many more factors and unknowns, which increases the uncertainties associated with NG distribution and usage. A recent report from the National Academy of Sciences drew attention to this deficiency, calling for reductions in both known and unknown uncertainties in the NG distribution sector.[22]

Table 1. Methane (CH_4) Emissions Factors (EFs) from Metering and Regulating (M&R) and Regulating Stations, Delineated by Input Pressure, As Calculated by the Gas Research Institute for the Environmental Protection Agency in 1992[13] and by Washington State University (WSU) in 2015,[19] and the Change between EFs[a]

pressure category (psi)	1992 EF(g/min)	2015 EF(g/min)	% change
	M&R		
>300	57.4	4.06	−93
100−300	30.5	1.88	−94
<100	1.4	N.D.	
	regulating		
>300	51.6	1.64	−97
100−300	12.9	0.27	−98
40-100	0.32	0.31	−3
<40	0	0	N.D.
vaults	0.03−0.41	0.1	−76−233

[a]Psi, pounds per square inch; N.D., not determined.

Nonetheless, there are current research efforts focused on improving the EFs and AFs of known components in the distribution sector. For example, testing of industrial meters is underway to determine if improvements should be made in EF values associated with the end user meter.[1,23] The focus of a Department of Energy (DOE)-funded research endeavor, part of a collaboration with the Gas Technology Institute (GTI) entitled "Classification of CH_4 emissions from industrial meters, vintage vs new plastic pipe, and plastic-lined steel and cast iron pipe", was to collect emissions measurements from these sources for adjusting and bringing up-to-date the associated EFs. This project was expected to be completed in June 2019 but EF and AF calculation adjustments will not be incorporated into the GHGI until thoroughly evaluated.[1] Yet even as known uncertainty is being addressed in the distribution sector (Table 1), the unknown and uninventoried sources of CH_4 emissions in the distribution sector must also be considered.

Not all of the NG that passes through an M&R station, the distribution pipelines, and customer meters without escaping is actually fully combusted, as the GHGI currently assumes.[24] Thus, there is a need to quantify how much of the fuel that is metered instead results in fugitive emissions. According to Jordaan and Konschnik, measuring emissions from customer meters is plagued with difficulty as leakage rates change with temperature, time, barometric pressure and gas pressure; many meters are broken, outdated, or are in need of maintenance or replacement, all of which is not taken into account in the snapshot data used to calculate EFs.[25] The EPA placed the AF at over 45 000 000 meters, including residential and commercial/industrial units, in 2013, and reported an EF three times higher for residential units than commercial/industrial units (Table 2).[26] Yet as new homes are built, old homes are

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remodeled, and energy practices change, these values quickly become outdated.

Table 2. Activity Factors (AFs) and Emission Factors (EFs) for Residential and Commercial/Industrial Customer Meters Currently Used to Calculate Total Emissions in the GHGI[a]

meter type	AF (no. meters)	EF (kJ/y/meter)	total emissions (Gg CH_4)
residential	42 192 085	148 109	116.42
commercial/industrial	4 797 283	49 518	4.43

[a]Source: United States EPA.[1]

Residential meters, the last inventoried unit in the NG distribution sector, are known to have a noninsignificant leakage rate[1] and could indicate that beyond-the-meter components such as appliances may similarly produce non-insignificant fugitive emissions. Considering the residential use of NG was more than 5.43 × 10^6 TJ in 2018,[1,27] even a small percentage leaked to the atmosphere could impact the CH_4 budget.

2.4. Evidence for Beyond-the-Meter Emissions from Top-down Analyses. Recently, novel CH_4 detection strategies have enabled more extensive top-down studies through the use of aircraft bearing sensitive monitoring equipment such as thermal infrared imaging spectrometry and aerial mass balance.[28−30] In contrast to bottom-up inventories, which add together the products of EFs and AFs for each component in each sector of the NG supply chain, top-down inventories measure all emissions across a geographic region such as a city or oil field. Aerial-based monitoring methods typically estimate larger emissions than bottom-up surveys that rely on measurements from individual components, suggesting that unaccounted sources of CH_4 emissions are significant.[31,32] However, individual source attribution is not possible and the many assumptions about air mixing and plume characteristics increase uncertainty in top-down calculations.

Cities are well known to be a significant source of GHG emissions, especially CH_4, although the sources of the emissions are difficult to define and differentiate from top-down studies.[33−35] An aerial survey across Indianapolis, Indiana, determined that 67% of CH_4 emissions detected across multiple flights came from anthropogenic non-landfill sources, not all of which could be attributed to the local regulating station based on ground-based follow-up monitoring.[29] In the same city, top-down measurements and modeling yielded CH_4 emissions estimates 3.5−6.9× that of citywide bottom-up inventory methods.[36] Atmospheric measurements over Boston, Massachusetts, suggested an emissions rate of 2.7 ± 0.6%, 2.5× higher than the bottom-up calculation of only 1.1%.[37] These disagreements between top-down and bottom-up estimates lead to the conclusion that there are unaccounted sources of CH_4 emissions.[38] Reconciling these divergent estimates is necessary for more accurately updating the CH_4 inventory.

Aerial and tower-based emissions studies can loosely attribute top-down fugitive emissions to large sources like landfills and M&R stations but are not able to capture and differentiate small, high-density leaks. Top-down detection of CH_4 from towers in Boston and Indianapolis revealed diffuse plumes of CH_4 that were not attributable to individual high-emitting sources, such as the local landfills, M&R stations, or even pipelines within city limits.[29,36,37] These diffuse CH_4 plumes, researchers concluded, most likely arose from many small leaks across the city that were minor individually but combined to create a significant CH_4 emissions source across the urban area. In Indianapolis, bottom-up estimates yielded a city-wide inventory of 29 Gg CH_4 per year, while tower-based inverse modeling predicted 81 Gg CH_4 per year and aircraft-based surveys with inverse modeling calculated 41 Gg CH_4 per year from the city.[36]

Top-down methods cannot attribute CH_4 to single sources and are influenced by wind direction, as well as inherent biases in methods of modeling, time and season of flight, and restrictions to flight patterns.[28,30] Additionally, the large uncertainties associated with top-down estimates often diminish the differences between the methodologies. Nonetheless, discrepancies between top-down and bottom-up surveys must be reconciled. Many reports hypothesize that fugitive emissions beyond the customer meter, which are not included in the GHGI, are responsible for the discrepancy seen in urban emissions surveys.[32,37,39]

3. KNOWN RESIDENTIAL METHANE EMISSIONS

The NG supply chain distribution sector comprises M&R stations, distribution pipelines and regulating stations, and individual meters. It also includes the homes, businesses, and appliances in those spaces that are powered by NG. The United States GHGI accounts for CH_4 emissions from NG production through distribution to the customer meter. Emissions from M&R stations have been discussed previously. Distribution pipelines and customer meters contribute a nonsignificant amount of CH_4 to the inventory, and other international inventories suggest that beyond-the-meter emissions do as well.

3.1. Distribution Pipelines. The main focus of bottom-up CH_4 emissions studies in urban areas has been leaks from distribution pipelines, correlating leak severity and frequency to the age and composition of the pipeline.[40−42] City-wide ground-based CH_4 emissions studies have been conducted in multiple urban centers including Boston, Massachusetts,[40] Pittsburgh, Pennsylvania,[43] and Washington, D.C.[44] The studies followed a similar approach, placing CH_4 detection units on vehicles to track emissions from distribution pipeline leaks. Identification of individual leak sources has confirmed that such studies detect pipeline leaks rather than leaks from buildings, meters, or other aboveground CH_4 sources.[41] Pipeline leaks are dependent on pipeline age and material. Older cast-iron pipes have the highest frequency of leaks and the highest leakage rates.[42] Thus, different pipeline types are given different EFs in the GHGI.

Improvements to NG infrastructure, such as the replacement of all cast-iron pipelines with more modern lined plastic pipes, would decrease the EFs associated with distribution pipelines. In turn, these improvements can greatly decrease leak frequency and severity, decreasing harmful CH_4 emissions.

3.2. Commercial and Residential Meters. The GHGI catalogues commercial, industrial, and residential meter EFs and AFs (Table 2). Indoor meters are not included because an indoor meter leak should, theoretically, be quickly detected and repaired due to potential health effects and required indoor monitoring. Residential meters, which monitor gas provided to private dwellings for household use, contribute 116.42 Gg annually to national CH_4 emissions (Table 2).[1] Commercial and industrial meters, which are meters at nonmanufacturing establishments involved in the sale of goods or services and meters at facilities used for manufacture, mining, agriculture, or electricity generation, respectively, contribute a combined total of 4.43 Gg CH_4 yearly.[45]

However, current reporting is outdated: the last research incorporated into EFs was concluded in 2009 but was only incorporated into the GHGI in 2017, and current census housing data (Table 3) likely underestimates the number of residential and commercial/industrial meters as energy reliance shifts to NG.[46] Additionally, meter leaks are likely dependent on many factors not currently evaluated, such as temperature, fluctuations in gas pressure and volume through pipelines, barometric pressure, age of the meter and pipelines, and time since the meter was last calibrated or received maintenance. All gas that reaches the customer meter is currently assumed to be completely combusted, with no fugitive emissions. Thus, the inventory does not account for NG that passes through a meter but is unintentionally released to the atmosphere prior to combustion through leaks in private customer pipelines, appliances, or other NG-fueled equipment. Yet there is evidence that chronic and typical leaks downstream of metering devices, called beyond-the-meter emissions, contribute a nontrivial amount of fugitive CH_4 emissions.

Table 3. Number of Housing Unit Types in the United States According to the United States American Census Survey in 2017[46]

housing type	no. units	%
single family, detached	84 733 118	61.67
single family, attached	8 056 664	5.86
2−9 units	17 330 008	12.61
10+ units	18 659 373	13.58
mobile home	8 500 432	6.19
other (boat, RV, van, etc.)	127 713	0.09
total	137 407 308	

3.3. International Reporting of Beyond-the-Meter Emissions. Like the United States, many nations that contribute emissions inventories to the IPCC do not include beyond-the-meter data. Current IPCC guidelines, set forth in 2006, do not require nations to report this information. Although the IPCC regularly releases updates to emissions inventory lists and improves reporting standards and guidelines, and NG inventory changes outlined in 2019 delineate many changes to the production sector, the updates do not include requirements or recommendations for reporting beyond-the-meter emissions.[4]

Despite this lack of required reporting, a selection of countries does include end-user emissions data in reports to the IPCC. For example, the United Kingdom inventories fugitive beyond-the-meter CH_4 emissions.[47] AF statistics are collected and estimates are made for both residential and commercial/industrial settings and is primarily comprised of emissions from heating units or furnaces (EF of 4.3 kg/TJ CH_4 consumed).[47,48] The United Kingdom estimates that NG heating units leak 4.25 Gg CH_4 per year.[48] Overall, these beyond-the-meter emissions account for 1.5% total emissions in the United Kingdom (Figure 4). While the United States is less reliant on NG as a heating fuel than the United Kingdom (48% of homes vs 85% of homes),[46,48] the United Kingdom estimates are nontrivial and are further justification for a thorough inventory of beyond-the-meter emissions in all countries, including the United States.

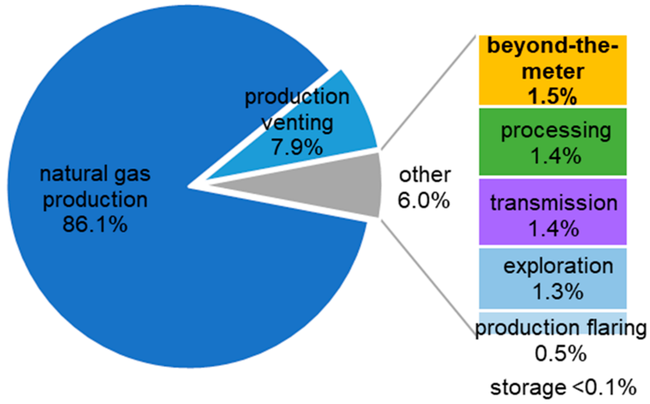

Figure 4. United Kingdom NG supply chain emissions in 2016.[48] Blue, production sector; green, gathering and processing sector; purple, transmission and storage sector; yellow, distribution sector.

Other nations besides the United Kingdom also report an EF for household NG-fueled furnaces, including Germany (2.3 kg CH_4/TJ consumed),[49] Japan (4.5 kg CH_4/TJ consumed),[50] and Switzerland (1 kg CH_4/TJ consumed)[51] (Table 4). While these differing values likely reflect the type and efficiency of NG furnace common to each country, the wide variability suggests that furnace technology and age may dramatically affect calculated EFs. Additionally, the inventories only include residential furnace EFs but not EFs from other residential or commercial appliances, which are also powered by NG. So, while the United States lacks a thorough emissions inventory of beyond-the-meter EFs in commercial and residential settings, the country is not alone in this regard. Even countries that report some beyond-the-meter emissions could improve inventory estimates by considering other sources of beyond-the-meter fugitive emissions.

3.4. Beyond-the-Meter Leakage Sources. Residential usage of NG mainly occurs in space heating and water heating systems, and residences (vs commercial or industrial sites) are estimated to account for at least 65% of the total demand for heating. Reliance on NG for heating—either directly or from NG-generated electricity—is typical in the United States (Table 3).[52] Importantly, while electric appliances are sometimes thought to have less of an impact on the environment, they still rely on coal or NG generation of electricity. In fact, 33% of the NG consumed annually in the United States is used to generate electricity.[8,53] While full analyses of all GHG emissions from appliances and emissions from NG-powered electric appliances are beyond the scope of this Critical Review, it is important to note that residential appliances are known to be a significant source of GHGs, contributing global warming potential through inefficient use of electricity, fugitive emissions of CO_2, or leaks of chlorofluorocarbons (CFCs).[54,55] Life cycle assessments suggest that CFC refrigerant leaks account for 11−16% of the total global warming potential of a hot water heater, so other GHGs, such as CH_4, account for the majority of non-leak-associated emissions from common household appliances.[52,54]

Hong and Howarth estimated the CH_4 EF for residential NG tankless and storage water heaters to be 0.60−4.02 kg/GJ, or only about two times higher than the EF for electric heat pump systems.[53] These EFs constitute estimations of CH_4 life cycle losses based on both electricity and NG used, and are not based

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Table 4. Reported Emissions Factors (EFs) for Furnaces and Estimates for National Emissions from Residential Furnaces, with Percentages of Total Natural Gas (NG) Systems CH_4 Emissions and Total Anthropogenic CH_4 Emissions

source	furnace EF (kg/TJ)	US total furnace emissions using EF (Gg CH_4/y)[a]	% total US NG CH_4 emissions[b]	% total US CH_4 emissions[c]
Merrin & Francisco (United States)[60]	4.1	11.5	0.17	0.04
Germany[49]	2.3	6.5	0.10	0.02
Japan[50]	4.5	12.7	0.19	0.05
Switzerland[51]	1.0	2.8	0.04	0.01
United Kingdom[48]	4.3	12.1	0.18	0.05
average[d]	3.2 (±1.4)	9.1 (±3.9)	0.14 (±0.06)	0.03 (±0.01)

[a]The national NG consumption in furnaces used in this calculation is 2.825 TJ.[60] [b]The total US CH_4 emissions from NG systems used in this calculation (6624 Gg) is from the 2017 EPA GHGI.[1] [c]The total US CH_4 emissions used in this calculation (26 252 Gg) is from the 2017 EPA GHGI.[1] [d]Average (mean) and standard deviation of the mean are based on values presented in the table and do not reflect uncertainties within the reported values.

on actual measurements; thus, they do not directly compare to measurements of component-based leaks from appliances. Yet it is important to consider the emissions associated with an appliance over its lifetime to compare the relative efficiencies of different energy sources and to remember that even non-NG utilizing elements may rely on NG-produced electricity and still contribute to CH_4 emissions.

3.5. Undetected Leaks. Complicating the issue of unknown beyond-the-meter emissions, steady and small NG leaks that remain below levels that are hazardous to human health (<5300 ppm) would not register as a leak on many conventional detection devices or gas monitors.[56] The Gas Piping and Technology Committee, a part of the American Gas Association, has set forth standards for NG leaks based on concentration and location. Grade 1 leaks pose a threat due to potential for explosion or fire, are hazardous to human health, or have a reading of greater than 80% the lower explosive limit (LEL), which is 50 000 ppm for CH_4. Grade 2 leaks, 20−80% the LEL, are considered nonhazardous but could become so and are, like grade 1 leaks, prioritized for repair when found in confined spaces such as homes. Common carbon monoxide (CO) and explosive gas monitoring devices trigger an alarm at 25% the LEL, which for CH_4 is 12 500 ppm. Thus, while all grade 1 and most grade 2 leaks trigger a gas alarm, all grade 3 leaks (a leak of less than 20% LEL in a confined space) and some grade 2 leaks would be missed by standard-issue gas detectors. Leak detection methods vary widely in accuracy, increasing uncertainty in measurements and sometimes leading to safety incidents when a hazardous leak is missed.[14,57] A standard-issue gas detector only alerts the occupant to dangerous high-emitting leaks but not chronic low-level leaks that would also not necessarily dramatically alter monthly gas consumption.

Wennberg et al. estimated that if 5% of NG provided to homes were unintentionally released uncombusted through such undetected leaks, this could account for 6 Tg CH_4 per year in the national inventory, greatly reducing divergent estimates from top-down and bottom-up inventories while also dramatically increasing national CH_4 emissions estimates.[34] Thus, even nonhazardous indoor leaks could be a significant contributor to national CH_4 emissions once scaled up to a national level. The assumption that indoor meters are not a source of fugitive CH_4 should be re-evaluated. While beyond-the-meter CH_4 sources may individually contribute only trivial amounts of fugitive CH_4, these sources taken together should not be ignored in the GHGI. In addition, appropriate methodologies for detecting minor, possibly irregular leaks may need to be developed if current LDAR protocols prove insufficient.

4. INITIAL STUDIES IN RESIDENTIAL METHANE EMISSIONS

Emissions from NG-powered appliances may include emissions during ignition, usage, extinguishment, and leaks when the appliance is not actively operating. Leaks may come from the appliance itself, a pilot light, pipes leading from the meter to the appliance, and connections between components. Inefficiency in combustion or loss of NG prior to combustion both contribute to fugitive CH_4.

While beyond-the-meter emissions are not yet included in the United States GHGI, these unaccounted emissions are gaining recognition and interest.[32,58] A recent study in California took advantage of an energy auditing program available to California homeowners to quantify beyond-the-meter CH_4 emissions.[59] The study, a first of its kind, used quiescent whole-house CH_4 emissions and measurements of individual components within a house to determine the EFs for inactive whole-house leakage and appliance pilot lights. A second study specifically focused on steady-state usage of NG-powered appliances.[60] Together, these studies can be used to make estimates for beyond-the-meter CH_4 emissions at the national scale.

4.1. Combustion Efficiency. The first factor to consider in beyond-the-meter emissions is combustion efficiency (CE), or the measure of the transformation of fuel into usable heat. The EPA estimates 1% CH_4 burned is emitted without combustion from modern industrial furnaces.[61] This calculation is based on appliance efficiency under optimal conditions, not field-verified, and does not consider additional sources of fugitive emissions from the furnaces. Inefficiency in a furnace could result in incomplete combustion, releasing CO, or release of CH_4 through release without combustion of the fuel.

Similarly, the CE could be used as a baseline for appliance leakage rates for residential heating units such as furnaces and water heaters. According to the Department of Energy, NG-powered water heaters generally achieve CEs of 68−85%. Importantly, age is a significant determinant of CE: while older furnaces generally have a CE of 56−70%, modern furnaces regularly achieve over 95% conversion.[62,63]

In the United States, 46.5% of all households, of which there were a reported 128.8 million in the 2017 census, rely on NG-powered furnaces.[46,64] These 59.9 million furnaces run on a combined 2.8 TJ NG per year, or on average 0.047 TJ per furnace annually.[60] Assuming 80% efficiency (with a range of

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50–95%) and release of all non-combusted NG as CH_4 (called a fuel slip), up to 0.56 TJ NG could be released annually from furnaces alone. Yet, in an inventory context, this amounts to only 0.0126 Gg CH_4 or 0.00048% of the national yearly CH_4 budget (0.000024–0.00012% for the range of possible efficiencies). Assuming the 1% efficiency from industrial furnaces also applies to residential furnaces, this percentage drops even lower (0.0000024%).

Even considering furnaces operating under nonoptimal conditions, combustion efficiency alone does not explain observed methane plumes in cities or differences in top-down versus bottom-up inventories. Additionally, fuel slip from furnaces alone would not be considered large enough to include in the GHGI. Taken together with non-combusted CH_4 from other appliances in addition to other leakage sources, however, beyond-the-meter emissions may become a significant factor.

4.2. Whole House Beyond-the-Meter Emissions. In the California study, researchers measured whole-house CH_4 emissions and additionally measured emissions from specific components within the home (Figure 5).[59] The study reported that when all appliances and pilot lights were inactivated, the average quiescent whole-house EF was <1 g CH_4 per day. The investigators also included the contribution of a subset of individual appliances in calculating total house emissions (Table 5). The study confirms that chronic, low-level typical leaks can be present in a home without triggering a gas monitor and could, on an inventory scale, be significant.

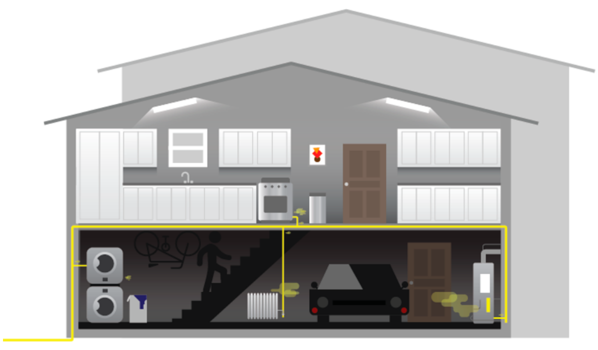

Figure 5. Schematic of appliances and devices within a residence that contribute to CH_4 emissions, which can be measured from individual components or as whole-house emissions.[1,59]

Surprisingly, pilot light emissions accounted for nearly 25% of quiescent emissions. This estimate for the relative contribution of pilot lights to the whole-house leakage was based on a rough approximation of pilot light NG use and a limited number of individual measurements. Although the methodological approach was not comprehensive and data were limited, this result suggests that further studies on pilot light emissions may be important, given the relatively large contribution of pilot lights to the whole-house leakage. Pilot lights can be found on many NG appliances, including water heaters, heating units, fireplaces, and stoves.

Limitations to the study are that only a small number of single-family homes were analyzed and that few individual appliances were tested for leaks. The dataset was not large because of subject availability and the time intensiveness of measurement techniques. Researchers could not draw conclusions about the relationship between house age and incidence or severity of CH_4 leaks. Additionally, while pilot lights were generally tested throughout the 75 homes that comprised the study set, the majority of appliances were not assessed for incomplete combustion during use or component-specific leaks.

Table 5. Sources of Beyond-the-Meter CH_4 Emissions, Estimates of Contributions to the Yearly CH_4 Budget, and Estimated Percent of Total CH_4 and NG Emissions[59,60]

citation	source	Gg CH_4/y	% total NG CH_4 emissions	% total CH_4 emissions
Merrin & Francisco[60]	major appliances (ignition, steady state, extinguishment)	29.50	0.45	0.11
Fischer[59]	major appliances (steady state)	44.67	0.67	0.17
Fischer	minor appliances (steady state)	5.40	0.08	0.02
Fischer	whole house quiescent emissions (incl. pilot lights)	114.86	1.73	0.44
Fischer	total house (quiescent, major and minor appliances)	164.92	2.49	0.63
	total house (Fischer house, Merrin & Francisco major appliances)	144.36	2.18	0.55

The study concluded that fugitive emissions from homes account for 2% of total CH_4 emissions in California,[59] which is close to the United Kingdom estimation of 1.5% of NG emissions coming from beyond-the-meter leaks.[48] This suggests the residential sector could be a significant unaccounted-for source of fugitive emissions and requires further analysis to close gaps in data for beyond-the-meter emissions. Closer inspection of the components within a residence or business may reduce uncertainty in EFs.

4.3. Estimations from Appliances. According to the initial study on steady-state CH_4 emissions from major home appliances (including furnaces, boilers, stoves and ovens, and water heaters), space heaters have the greatest leakage rate, followed closely by cooking appliances.[59] CH_4 emissions from furnaces are much higher than those estimated using energy efficiency ratings, suggesting furnaces operate under non-optimal conditions and have additional leakage besides fuel slip.

Merrin and Francisco measured emissions from furnaces, boilers, water heaters, and cooking appliances.[60] The initial ignition of the appliance resulted in a sharp CH_4 spike, followed by low emissions during steady-state and a second spike upon extinguishment. Some appliances such as ovens exhibited cycling behavior during steady-state usage or additional release of CH_4 after extinguishment, resulting in additional emissions. Some CH_4 released in the flue, however, could be burned during a subsequent ignition of the appliance, thereby decreasing fugitive CH_4.

Using census data on average appliance usage, Merrin and Francisco calculated EFs for each appliance (Figure 6) and determined that while furnaces have the largest EF, appliances have different emission profiles depending on operation state.[60] Interestingly, ovens emit the most of any appliance during the ignition stage, while culprits for elevated steady-state emissions are stovetops and tankless water heaters. Space heaters, boilers, and conventional water heaters had low ignition and steady-state operation emissions on average. The dataset comprised appliances from 98 homes in multiple geographic regions but was limited to colder climates.

Steady-state operation of an appliance does not necessarily indicate that emissions remain consistent; in addition to spikes

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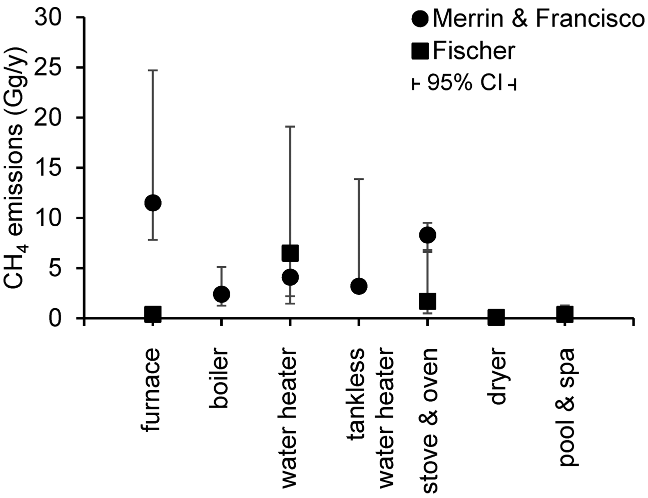

Figure 6. Estimated CH_4 emissions from household appliance operation. Error bars: 95% confidence interval (CI).[59,60]

during ignition and extinguishment, some appliances, like ovens, cycle through low and high gas usage, causing a fluctuation in emissions. Thus, steady-state usage and the off state should not be ignored in emissions estimates. While Merrin and Francisco's EFs consider steady-state usage in addition to ignition,[60] Fischer et al. considered quiescent pilot-light emissions in addition to steady-state operation, but not ignition or extinguishment.[59] These different monitoring techniques, in addition to different instrumentation, may account for the variability observed in CH_4 emissions (Table 5, Figure 6), although appliance age, regional location, and estimates of appliance usage may also contribute to variation. Additional data are required to decrease uncertainty in appliance contributions to the NG emissions inventory, but these preliminary studies highlight that small contributions still impact overall inventory accounting. The whole-house emissions and individual component inventories suggest appliances, and thus other fugitive emissions beyond the meter, should be characterized and included in the GHGI.

4.4. National Scale Estimations. From the initial appliance and whole-house monitoring studies, it is possible to estimate EFs for appliances and to consider CH_4 emitted to the atmosphere due to residential beyond-the-meter consumption on the national level (Tables 4 and 5).

Furnaces were the highest emitters in regions of the United States with seasonality and are found in some national inventories (Figure 6, Table 4). Differences in furnace efficiencies, measuring methodologies, and statistical analyses may all contribute to the variations in reported EFs.

Given 46.5% of the 128.8 million US households rely on NG for space heating, we calculated a national-scale EF using the preliminary results of beyond-the-meter emissions. We compared the furnace EFs reported in the GHGIs of Germany, Japan, Switzerland, and the United Kingdom to the EF found in the Merrin and Francisco study.[60] The steady-state measurement from the Fischer et al. study was not included in the comparison because of the small sample size and because the estimation does not include the ignition or extinguishment of the appliance.[59]

Given the assumptions required for in making these estimations, from the number of NG furnaces to the average usage, as well as the unknown but possibly significant variation in individual appliance leakage, the emissions estimates here should be interpreted as approximations which merit further data collection and analysis.

5. RECOMMENDATIONS FOR REDUCING DATA GAPS IN BEYOND-THE-METER EMISSIONS

Collection of appropriate data for calculating beyond-the-meter EFs is complicated and will involve significant effort. However, beyond-the-meter emissions should be evaluated and, if deemed significant, included in the United States CH_4 GHGI. Discrepancies between top-down and bottom-up CH_4 emissions estimates may be reconciled through inclusion of beyond-the-meter emissions, better reflecting overall fugitive emissions from the NG supply chain. Necessary objectives to address in beyond-the-meter field campaigns include:

1 *Determining possible sources of fugitive emissions from residential and commercial/industrial customers.* The California housing study focused on pilot lights on cooking appliances in single-family homes.[59] New tankless water heaters outside of residential settings were also analyzed. More appliances and pipes within commercial, industrial, and residential settings may have small but chronic leaks, including NG-powered fireplaces, clothes dryers, and gas barbecue grills. A complete inventory of possible sources of leaks beyond the meter should be established, as well as the factors that may influence the potential for and severity of leaks. AFs must also be tabulated for the inventory at local, state, regional, and national scales.

2 *Determining the connection, if any, between housing type and CH_4released per unit.* Future studies should evaluate if the approach of the California study to calculate whole-house emissions is appropriate and can be scaled to incorporate multi-family units. While residential houses specifically in California have been the subject of study,[59] the dataset was small and geographically limited. The most common housing type in the United States is a detached single-family unit, followed by apartments of 10 or more units (Table 3),[46] which have very different energy requirements and, therefore, different potentials for leak frequency and volume. Housing geography, type, and age are factors, which may also heavily influence beyond-the-meter emissions due to type and age of NG infrastructure. The impact of each of these variables may be determined by collecting information about house age, while measuring emissions and comparing age to incidence and volume of leakage.

3 *Determining the connection, if any, between appliance and equipment age and CH_4leakage.* Whole-house or whole-building EFs may be less accurate than inventory values for each appliance contained within the building, so individual appliance contributions should also be studied. The National Petroleum Council predicted that while conversions of old appliances could decrease CH_4 leaks by 1%, new appliances in the residential sector could decrease residential CH_4 emissions by up to 7% by 2030, or 33.6 TJ per year.[10] Older appliances and NG-utilizing equipment may be more likely to have leaks due to older technology and equipment failure. To determine the effect of age on CH_4 leak rates, a survey of residential units should include documentation of the age of each appliance. Analysis of these metrics is necessary to

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determine a suitable sample size and distribution to capture sufficient data for reliable beyond-the-meter EFs.

4 *Determining the sampling size and scope necessary to create a nationwide EF for individual beyond-the-meter components.* Some relevant questions to consider include the following: Will data need to be collected from houses across the country to account for climate? Does seasonality influence leakage from outdoor appliances and residential or commercial pipes? What is an appropriate sample size for reducing uncertainty in the EF calculations? What are the AFs for each individual component under consideration? What are the appropriate statistical methods to be implemented in data analysis?

In the survey of appliances in 98 homes across Massachusetts, Indiana, Illinois, and New York, there appeared to be little regional variation.[60] However, it is imperative that the EFs take into account such variation if it exists. Often, bottom-up studies obtain much more scattered, clustered data than a top-down approach inventory collection, and such bias could increase the uncertainty associated with any new EFs.[15] To increase robustness of the data, a national survey of appliances across seasons and under multiple operating conditions is recommended. In colder climates, appliances that rely on NG may be maintained and replaced more frequently due to increased usage, leading to reduced leaks; conversely, increased usage could lead to more component failures and increased leaks.

Statistical analysis in beyond-the-meter emissions must be carefully considered, as fat-tailed distributions of emissions data may occur as they do across the NG supply chain. Whole-house quiescent emissions and steady-state appliance operations do indicate super-emitters also skew emissions estimates beyond the meter.[59] In addition to considering non-Gaussian datasets using probability distributions, the factor or factors contributing to the fat-tailed data distribution should be determined.[65]

5 *Determining appropriate measurement conditions and measurement devices.* Ignition and steady-state usage of an appliance will differ in CH_4 production, as preliminary research has shown. The EF for an appliance may need to incorporate emissions from all operation states. The instrumentation used in these measurements may need to be designed to fit the particular situation, as was the case for whole-house emissions.[59] In the Merrin and Francisco study, the Picarro cavity ring-down spectroscopy portable gas concentration analyzer was able to make accurate low-level readings but could not be used above 800 ppm of CH_4.[60] Some appliance types could not be monitored due to "lack of sampling apparatus" or a means to quantify emissions;[60] researchers will need to innovate to create appropriate chambers or sampling devices and may need to use a variety of instruments to cover emissions rates across a spectrum.

6 *Partnering to create an appropriate study set.* Numerous gas and electric companies provide energy audit services to clients within their zone of provision. In addition, various nonprofits provide resources to low-income families in order to receive energy audits and improve energy efficiency within the home. These nonprofits may provide connections to customers seeking better energy efficiency who would be willing participants in a survey and CH_4 emissions analysis. Such partnerships with nonprofits or energy audit companies could facilitate research projects aimed at assessing beyond-the-meter emissions.

6. PERSPECTIVES AND OUTLOOK

NG consumption in the United States has increased 40% in the last 20 years even as emissions have slowly dropped.[27,36] Yet, while NG is widely considered less environmentally destructive than coal, NG production, processing, transportation, and distribution releases CH_4, a potent GHG. A complete inventory of sources of CH_4 emissions from the NG supply chain is essential to predict the impact of NG utilization on the environment. The United States GHGI is missing emissions data from sources after the customer meter, and these sources may significantly contribute to national CH_4 emissions. Initial studies reveal diffuse CH_4 plumes from urban areas that are not attributable to pipelines or distribution stations, instead coming from small but prevalent residential or commercial leaks. While preliminary analyses of single-family residences reveal low-level and chronic CH_4 leaks, such emissions expanded out to the national scale could alter the inventory of annual CH_4 emissions and reconcile bottom-up and top-down inventory differences. By studying emissions from individual customer appliances and housing units, new CH_4 emissions data can be calculated for inclusion in the national GHGI.

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Notes

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