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Beyond-the-meter: Unaccounted sources of methane emissions in the natural gas distribution sector

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28 **ABSTRACT**

29

30 The United States Environmental Protection Agency maintains an inventory of greenhouse gas emissions
31 in accordance with the Intergovernmental Panel on Climate Change. Methane (CH₄), a potent gas with a
32 global warming potential 86-125× that of carbon dioxide (CO₂) over a twenty-year period, is the main
33 component of natural gas (NG). As NG becomes an increasingly larger percentage of the energy resources
34 used in the United States, it is becoming ever more important to evaluate the CH₄ emissions inventory.
35 However, the inventory also does not account for all possible sources of CH₄ leaks, contributing to
36 uncertainty in the national CH₄ inventory. Discrepancies between top-down and bottom-up inventories of
37 CH₄ emissions imply that there are significant unaccounted-for sources of CH₄ leaks, especially over cities.
38 Diffuse CH₄ plumes above cities that are not attributable to distribution pipelines or other NG infrastructure
39 suggest many small beyond-the-meter leaks together contribute to large emissions. Here, we evaluate the
40 distribution sector of the CH₄ emissions inventory and make suggestions to improve the inventory by
41 analyzing end-user emissions. Preliminary research into beyond-the-meter emissions suggests that while
42 individually small, the appliances and buildings that make up the residential sector could contribute
43 significantly to national scale emissions. Furnaces are the most leak-prone of appliances, contributing to
44 0.14% of total CH₄ emissions from the NG sector in the United States. Combining measurements from
45 whole house emissions and steady-state operation of appliances, we estimate that residential homes and
46 appliances could release 9.1 Gg CH₄ yearly in the United States, totaling over 2% of the CH₄ released from
47 the NG sector. While factors such as appliance age and usage, climate, and residential setting could
48 influence the emissions profile of individual appliances, these preliminary estimates justify further
49 exploration of beyond-the-meter emissions.

50

51 **KEY WORDS**

52

53 Greenhouse gas inventory, Methane emissions, Natural gas supply chain, Fugitive gas

54

55

56 **1. INTRODUCTION**

57 The Environmental
58 Protection Agency (EPA)
59 maintains the Greenhouse Gas
60 Inventory (GHGI), an extensive
61 database of the sources and sinks
62 of greenhouse gases (GHGs) and
63 the estimated annual output from
64 each source. The GHGI divides
65 anthropogenic GHG emissions

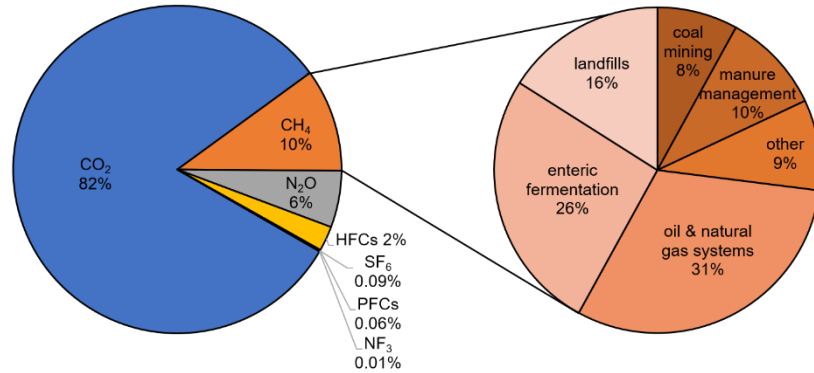


Figure 1. United States GHGI emissions by gas in 2017 based on CO₂ equivalents, and breakdown of anthropogenic CH₄ emissions in the GHGI. CO₂, carbon dioxide; CH₄, methane; N₂O, nitrogen dioxide; HFCs, hydrofluorocarbons; PFCs, perfluorocarbons; NF₃, nitrogen trifluoride. Source: United States EPA¹.

66 by source, economic sector, and type of gas emitted, including carbon dioxide (CO₂), methane (CH₄),
67 nitrous oxide, fluorinated hydrocarbons, sulfur hexafluoride, and nitrogen trifluoride (**Error! Reference**
68 **source not found.**). According to the EPA, an estimated 10% of all GHG emissions from the United States
69 is CH₄, the second-largest contributor to historical global warming after CO₂¹⁻². CH₄ is a powerful but
70 relatively short-lived GHG with 86-125× the global warming potential of CO₂ over a twenty-year period
71 and 25-36× over a one-hundred-year time span, although such equivalencies are under constant
72 readjustment based on new measurements and data analysis³⁻⁵. Though CH₄ is less prominent than CO₂ in
73 discussions about anthropogenic climate change policy and practice, reducing CH₄ emissions can have a
74 more dramatic effect on climate change over the short term than the equivalent reduction in CO₂^{2, 4}. Cutting
75 CH₄ emissions, however, depends on knowing the contributions of each source to determine effective
76 strategies for mitigating atmospheric losses. The purpose of this critical review is to describe a significant
77 gap in the GHGI and to propose methods for improving the CH₄ emissions inventory through surveying
78 unaccounted beyond-the-meter CH₄ emissions.

79

80 **2. ANTHROPOGENIC METHANE EMISSIONS**

81 CH₄ emissions come from natural as well as anthropogenic sources. Natural CH₄ seeps include wetlands

82 and the arctic, as well as aerobic CH₄ production from terrestrial and aquatic biota. Anthropogenic sources
83 of CH₄ emissions which are tabulated in the GHGI include biotic-related (landfills and sewage, enteric
84 fermentation, manure management, and rice agronomy) or energy-related sources (coal mining, oil and
85 natural gas [NG] systems, and other industrial processes) (**Error! Reference source not found.**). CH₄ is
86 the main component of NG, the second most common energy source behind petroleum in the United States⁶.
87 The NG industry is estimated to account for 10% of all CH₄ emissions in the United States, but is likely to
88 become an even greater percentage because of new extraction techniques and a shift away from coal⁷.
89 Fugitive CH₄ refers to gas unintentionally released to the ambient air; the term “emissions” will also be
90 used to refer to such fugitive leaks and not CH₄ released for the purpose of venting. Venting, a common
91 practice in NG production, may occur in the form of flares or periodic releases from components such as
92 pneumatic controllers or meters, which may also serve as conduits for unintentional CH₄ emissions. As NG
93 becomes a more prevalent source of energy in the United States, fugitive CH₄ emissions from the NG supply
94 chain will become much more important to consider in emissions mitigation strategies.

95 Some analysts suggest that NG only outcompetes coal and other energy sources in environmental
96 impact if unintentional emissions are less than 3-6% of the total usage^{3, 8}. A recent meta-analysis from
97 Álvarez *et al.* estimated 2.3% (\pm 0.4%) of NG produced is lost through fugitive emissions⁹. In close
98 agreement with the meta-analysis performed by Álvarez *et al.*, the National Petroleum Council estimates
99 that 2.2% of total gross NG production is lost as waste emissions¹⁰. These estimates are lower than previous
100 reports, reflecting new or updated data and analytics. In 2014, Brandt *et al.* proposed a much higher 5.4%
101 (\pm 1.8%) emissions loss for conventional NG and shale gas sources combined¹¹⁻¹². Low-level CH₄ emissions
102 become significant when extrapolated to the national scale, so even minor contributions (1% total
103 emissions) may have an impact on the GHGI and its ensuing application to energy and environmental policy
104 and practice. When considering the national energy outlook and environmental protection strategies, a very
105 accurate and precise inventory is necessary to ensure that all sources of CH₄ have been accounted so that
106 the environmental costs associated with NG usage are properly assessed.

107

108 **2.1 EMISSIONS FACTORS AND ACTIVITY FACTORS**

109 The United States GHGI is a
110 compilation of all sources and
111 sinks of GHGs. In order to
112 estimate the total amount of
113 each gas released from each
114 source, both the average
115 emissions rate and the number
116 of components of each source

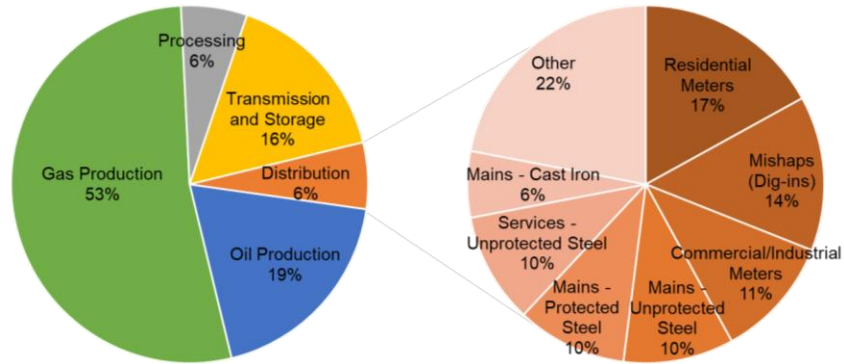


Figure 2. United States methane emissions from the NG supply chain in 2017, divided into sector, and the major components that comprise the distribution sector. Source: United States EPA¹.

117 type must be known. An emissions factor (EF), or the quantity of a pollutant released associated with an
118 activity and the rate of release from that activity, is assigned to each individual component within each
119 sector. The EF multiplied by the activity factor (AF), or the total number of each component in the country,
120 yields the total nationwide emission attributed to that specific component. The GHGI utilizes these
121 individual EFs and AFs to build the emissions inventory in what is known as a bottom-up strategy.

122 The NG supply chain is generally divided into four main sectors: production (wells and extraction
123 equipment), gathering and processing (pipelines, refineries, and processing facilities), transmission and
124 storage (pipelines, compressor stations, and storage facilities), and distribution. The distribution sector
125 begins with metering and regulating (M&R) stations and includes the pipelines and regulating stations that
126 carry gas to individual meters, ending with the appliances and other devices powered by NG (Figure). EFs
127 for each sector of the NG supply chain, as well as the individual components that make up each sector, have
128 been calculated for the GHGI and are regularly re-evaluated¹³.

129 Uncertainty levels are calculated for EFs and AFs to reflect the confidence in each reported value.
130 Known uncertainties include such sources as incomplete datasets or calculations that rely on outdated
131 measurement techniques, or activity rates that are based on old technologies or census data. Incomplete or
132 inadequate datasets and EFs that rely on measurements collected without considering temporal,
133 atmospheric, or other factors also contribute to uncertainty. The detection method used to determine leak

134 rates can contribute to increased
 135 uncertainty in emissions
 136 estimates¹⁴. Uncertainty may also
 137 be attributed to large variability of
 138 measured emissions, often
 139 reflected in fat-tailed
 140 distributions, which are datasets
 141 containing a few outliers with
 142 abnormally high emissions¹⁵⁻¹⁶.
 143 Across the NG supply chain,
 144 super-emitters result in non-
 145 normal distributions of leakage
 146 rates^{15, 17}. Typical inventory
 147 reporting may hide the presence of
 148 outliers, as well as the fact that by
 149 fixing a few abnormally

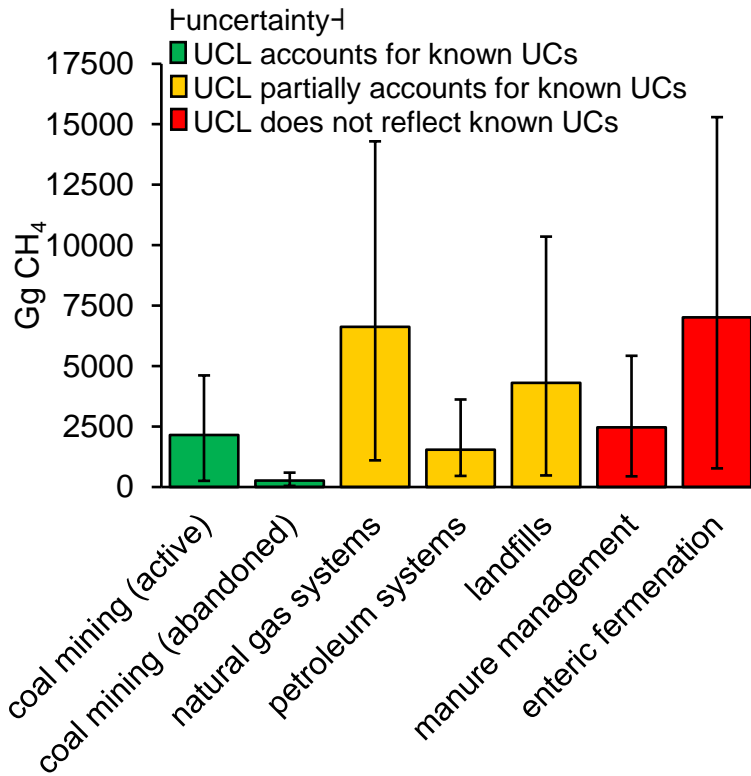


Figure 3. Uncertainty levels (UCLs) in the estimated annual CH₄ emissions (in Gg CH₄) of known sources. Error bars represent uncertainty ranges at the 95% confidence interval. Green: UCL accounts for current known uncertainties. Yellow: UCL partially reflects known uncertainties. Red: UCL does not reflect currently known uncertainties. Source: NAS Report²².

150 functioning components, an entire sector's CH₄ contribution could dramatically decrease. Unknown or
 151 unaccounted sources of emissions not included in the inventory also increase uncertainty in the GHGI.

152 The NG systems portion of the CH₄ emissions inventory has moderate coverage of known
 153 uncertainties and the gaps in data completeness are addressed annually as part of the annual EPA report
 154 (Figure 3). In order to reduce uncertainty, the EPA continually evaluates and incorporates new research
 155 findings; for example, the EPA adjusted the overall NG production sector emissions leak rate from 0.16%
 156 to 1.42% between its 2010 and 2011 reports, but by 2013 had lowered the rate to 0.88%, largely due to
 157 changes in accounting for emissions from liquid unloading and hydraulic fracturing practices in NG
 158 production¹⁸. Additionally, the global warming potential of CH₄ is under continual readjustment, having
 159 increased in CO₂ equivalents in recent years and increase the calculated relative impact of CH₄ emissions⁵.

160 While such alterations could reflect changing monitoring techniques and NG production technologies, the
 161 dramatic variability in CH₄ estimates reveals critical uncertainties in compiling the GHGI, including from
 162 the NG sector (Figure 3). Unknown contributions from unaccounted sources of emissions in the NG sector
 163 do not factor into calculated uncertainties, and yet are just as critical to understand and correct as known

164	uncertainties. Improved	Pressure	1992 EF	2015 EF	% change
165	emissions quantification and	category	(g/min)	(g/min)	
M&R					
166	identification of previously-	>300 psi	57.4	4.06	-93%
167	unaccounted emissions may	100-300	30.5	1.88	-94%
168	substantially alter the CH ₄	<100	1.4	N.D.	
Regulating					
169	emissions inventory.				
170	Adjustments to the	>300	51.6	1.64	-97%
171	GHGI occur through proposed	100-300	12.9	0.27	-98%
172	alterations of EFs and AFs.	40-100	0.32	0.31	-3%
173	There have been recent	<40	0	0	N.D.
174	changes to the NG distribution	vaults	0.03-0.41	0.1	-76 - 233%

175 sector accounting. Changes to **Table 1.** Methane emissions factors (EFs) from metering and regulating
 176 EF and AF values for (M&R) and regulating stations, delineated by input pressure, as
 177 regulating and M&R stations, calculated by the Gas Research Institute for the Environmental Protection
 178 sometimes referred to as city Agency in 1992¹³ and by Washington State University (WSU) in 2015¹⁹,
 and the change between EFs. Psi, pounds per square inch; N.D., not

179 gates, were under consideration and incorporated into the GHGI as recently as 2015¹⁹⁻²⁰. Updates to
 180 facilities and improved leak detection and repair (LDAR) techniques, in addition to stricter regulations and
 181 dedicated LDAR inspectors, have been invaluable improvements in decreasing the EF of M&R facilities,
 182 leading to these re-evaluations (Table 1)^{1,21}.

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

186 from sources downstream of the customer meter.

187

188 **2.3 REDUCING UNCERTAINTY IN THE NATURAL GAS EMISSIONS INVENTORY**

189 As previously mentioned, the EPA regularly reassesses EFs based on new technologies and measuring
190 techniques in an effort to reduce uncertainty in the GHGI. Each annual report documents updates to the
191 inventory since the last publication and calls attention to areas with concerning uncertainties or necessary
192 reassessment. While production, gathering and processing, and transmission and storage have relatively
193 well-defined segments, the distribution sector of the NG supply chain contains many more factors and
194 unknowns, which increases the uncertainties associated with NG distribution and usage. A recent report
195 from the National Academy of Sciences drew attention to this deficiency, calling for reductions in both
196 known and unknown uncertainties in the NG distribution sector²².

197 Nonetheless, there are current research efforts focused on improving the EFs and AFs of known
198 components in the distribution sector. For example, testing of industrial meters is underway to determine if
199 improvements should be made in EF values associated with the end user meter^{1, 23}. The focus of a
200 Department of Energy (DOE)-funded research endeavor, part of a collaboration with the Gas Technology
201 Institute (GTI) entitled “Classification of CH₄ emissions from industrial meters, vintage vs new plastic pipe,
202 and plastic-lined steel and cast iron pipe,” was to collect emissions measurements from these sources for
203 adjusting and bringing up-to-date the associated EFs. This project was expected to be completed in June
204 2019 but EF and AF calculation adjustments will not be incorporated into the GHGI until thoroughly
205 evaluated¹. Yet even as known uncertainty is being addressed in the distribution sector (Table 1), the
206 unknown and uninventoried sources of CH₄ emissions in the distribution sector must also be considered.

207 Not all of the NG that passes through an M&R station, the distribution pipelines, and customer
208 meters without escaping is actually fully combusted as the GHGI currently assumes²⁴. Thus, there is a need
209 to quantify how much of the fuel that is metered instead results in fugitive emissions. According to Jordaan
210 and Konschnik, measuring emissions from customer meters is plagued with difficulty as leakage rates
211 change with temperature, time, barometric pressure and gas pressure; many meters are broken, outdated, or

212 are in need of maintenance or replacement, all of which is not taken into account in the snapshot data used
 213 to calculate EFs²⁵. The EPA placed the AF at over 45,000,000 meters, including residential and
 214 commercial/industrial units, in 2013, and reported an EF three times higher for residential units than
 215 commercial/industrial units (Table 2)²⁶. Yet as new homes are built, old homes are remodeled, and energy
 216 practices change, these values quickly become outdated.

217 Residential meters, the last inventoried unit in the NG distribution sector, are known to have a
 218 noninsignificant leakage rate¹ and could indicate that beyond-the-meter components such as appliances
 219 may similarly produce noninsignificant fugitive emissions. Considering the residential use of NG was more
 220 than 5.43×10^6 TJ in 2018^{1, 27}, even a small percentage leaked to the atmosphere could impact the CH₄
 221 budget.

222

223 2.4 EVIDENCE FOR BEYOND-THE-METER EMISSIONS FROM TOP-DOWN ANALYSES

224 Recently, novel CH₄ detection strategies have enabled more extensive top-down studies through the use of
 225 aircraft bearing sensitive monitoring equipment such as thermal infrared imaging spectrometry and aerial
 226 mass balance²⁸⁻³⁰. In contrast to bottom-up inventories, which add together the products of EFs and AFs for
 227 each component in each sector of the NG supply chain, top-down inventories measure all emissions across
 228 a geographic region such as a city or oil field. Aerial-based monitoring methods typically estimate larger
 229 emissions than bottom-up surveys that rely on measurements from individual components, suggesting that
 230 unaccounted sources of CH₄ emissions are significant³¹⁻³². However, individual source attribution is not
 231 possible and the many assumptions about air mixing and plume characteristics increase uncertainty in top-
 232 down calculations.

233 Cities are well
 234 known to be a
 235 significant source of
 236 GHG emissions,
 237 especially CH₄,

Meter Type	AF (# 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

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. Source: United States EPA¹.

238 although the sources of the emissions are difficult to define and differentiate from top-down studies³³⁻³⁵. An
239 aerial survey across Indianapolis, Indiana determined that 67% of CH₄ emissions detected across multiple
240 flights came from anthropogenic non-landfill sources, not all of which could be attributed to the local
241 regulating station based on ground-based follow-up monitoring²⁹. In the same city, top-down measurements
242 and modeling yielded CH₄ emissions estimates 3.5-6.9× that of citywide bottom-up inventory methods³⁶.
243 Atmospheric measurements over Boston, Massachusetts suggested an emissions rate of $2.7 \pm 0.6\%$, 2.5×
244 higher than the bottom-up calculation of only 1.1%³⁷. These disagreements between top-down and bottom-
245 up estimates lead to the conclusion that there are unaccounted sources of CH₄ emissions³⁸. Reconciling
246 these divergent estimates is necessary for more accurately updating the CH₄ inventory.

247 Aerial and tower-based emissions studies can loosely attribute top-down fugitive emissions to large
248 sources like landfills and M&R stations but are not able to capture and differentiate small, high-density
249 leaks. Top-down detection of CH₄ from towers in Boston and Indianapolis revealed diffuse plumes of CH₄
250 that were not attributable to individual high-emitting sources such as the local landfills or M&R stations,
251 or even pipelines within city limits^{29, 36-37}. These diffuse CH₄ plumes, researchers concluded, most likely
252 arose from many small leaks across the city that were minor individually but combined to create a
253 significant CH₄ emissions source across the urban area. In Indianapolis, bottom-up estimates yielded a city-
254 wide inventory of 29 Gg CH₄ per year, while tower-based inverse modeling predicted 81 Gg CH₄ per year
255 and aircraft-based surveys with inverse modeling calculated 41 Gg CH₄ per year from the city³⁶.

256 Top-down methods cannot attribute CH₄ to single sources and are influenced by wind direction as
257 well as inherent biases in methods of modeling, time and season of flight, and restrictions to flight patterns²⁸.
258 ³⁰. Additionally, the large uncertainties associated with top-down estimates often diminish the differences
259 between the methodologies. Nonetheless, discrepancies between top-down and bottom-up surveys must be
260 reconciled. Many reports hypothesize that fugitive emissions beyond the customer meter, which are not
261 included in the GHGI, are responsible for the discrepancy seen in urban emissions surveys^{32, 37, 39}.

262

263

264 **3. KNOWN RESIDENTIAL METHANE EMISSIONS**

265 The NG supply chain distribution sector comprises M&R stations, distribution pipelines and regulating
266 stations, and individual meters. It also includes the homes, businesses, and appliances in those spaces that
267 are powered by NG. The United States GHGI accounts for CH₄ emissions from NG production through
268 distribution to the customer meter. Emissions from M&R stations have been discussed previously.
269 Distribution pipelines and customer meters contribute a nonsignificant amount of CH₄ to the inventory, and
270 other international inventories suggest that beyond-the-meter emissions do as well.

271

272 **3.1 DISTRIBUTION PIPELINES**

273 The main focus of bottom-up CH₄ emissions studies in urban areas has been leaks from distribution
274 pipelines, correlating leak severity and frequency to the age and composition of the pipeline⁴⁰⁻⁴². City-wide
275 ground-based CH₄ emissions studies have been conducted in multiple urban centers including Boston,
276 Massachusetts⁴⁰, Pittsburgh, Pennsylvania⁴³, and Washington, D.C.⁴⁴. The studies followed a similar
277 approach, placing CH₄ detection units on vehicles to track emissions from distribution pipeline leaks.
278 Identification of individual leak sources has confirmed that such studies detect pipeline leaks rather than
279 leaks from buildings, meters, or other aboveground CH₄ sources⁴¹. Pipeline leaks are dependent on pipeline
280 age and material. Older cast-iron pipes have the highest frequency of leaks and the highest leakage rates⁴².
281 Thus, different pipeline types are given different EFs in the GHGI.

282 Improvements such as the replacement of all cast-iron pipelines with more modern lined plastic
283 pipes would decrease the EFs associated with distribution pipelines. In turn, improvements in city
284 infrastructure such as NG distribution pipelines can greatly decrease leak frequency and severity,
285 decreasing harmful CH₄ emissions.

286

287 **3.2 COMMERCIAL AND RESIDENTIAL METERS**

288 The GHGI catalogues commercial, industrial, and residential meters EFs and AFs (Table 2). Indoor meters

289 are not included because an indoor meter leak
 290 should, theoretically, be quickly detected and
 291 repaired due to potential health effects and
 292 required indoor monitoring. Residential meters,
 293 which monitor gas provided to private dwellings
 294 for household use, contribute 116.42 Gg annually
 295 to national CH₄ emissions (Table 2)¹.
 296 Commercial and industrial meters, which are
 297 meters at nonmanufacturing establishments

housing type	# 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	

Table 3. Number of housing unit types in the United States according to the United States American Census Survey in 2017⁴⁶.

298 involved in the sale of goods or services and meters at facilities used for manufacture, mining, agriculture,
 299 or electricity generation, respectively, contributed a combined total of 4.43 Gg CH₄ yearly⁴⁵.

300 However, current reporting is outdated: the last research incorporated into EFs was concluded in
 301 2009 but was only incorporated into the GHGI in 2017, and current census housing data (Table 3) likely
 302 underestimates the number of residential and commercial/industrial meters as energy reliance shifts to
 303 NG⁴⁶. Additionally, meter leaks are likely dependent on many factors not currently evaluated, such as
 304 temperature, fluctuations in gas pressure and volume through pipelines, barometric pressure, age of the
 305 meter and pipelines, and time since the meter was last calibrated or received maintenance. All gas that
 306 reaches the customer meter is currently assumed to be completely combusted, with no fugitive emissions.
 307 Thus, the inventory does not account for NG that passes through a meter but is unintentionally released to
 308 the atmosphere prior to combustion through leaks in private customer pipelines, appliances, or other NG-
 309 fueled equipment. Yet there is evidence that chronic and typical leaks downstream of metering devices,
 310 called beyond-the-meter emissions, contribute a nontrivial amount of fugitive CH₄ emissions.

311
 312 **3.3 INTERNATIONAL REPORTING OF BEYOND-THE-METER EMISSIONS**

313 Like the United States, many nations that contribute emissions inventories to the IPCC do not include
 314 beyond-the-meter data. Current IPCC guidelines, set forth in 2006, do not require nations to report this

315 information. Although the IPCC regularly releases updates to emissions inventory lists and improves
316 reporting standards and guidelines, and NG inventory changes outlined in 2019 delineate many changes to
317 the production sector, the updates do not include requirements or recommendations for reporting beyond-
318 the-meter emissions¹.

319 Despite this lack of required reporting, a selection of countries does include end-user emissions
320 data in reports to the IPCC. For example, the United Kingdom inventories fugitive beyond-the-meter CH₄
321 emissions⁴⁷. AF statistics are collected and estimates are made for both residential and
322 commercial/industrial settings and is primarily comprised of emissions from heating units or furnaces (EF
323 of 4.3 kg/TJ CH₄ consumed)⁴⁷⁻⁴⁸. The United Kingdom estimates that NG heating units leak 4.25 Gg CH₄
324 per year⁴⁸. Overall, these beyond-the-meter emissions account for 1.5% total emissions in the United
325 Kingdom (Figure 4). While the United

326 States is less reliant on NG as a heating
327 fuel than the United Kingdom (48% of
328 homes vs. 85% of homes)^{46, 48}, the
329 United Kingdom estimates are
330 nontrivial and are further justification
331 for a thorough inventory of beyond-
332 the-meter emissions in all countries,
333 including the United States.

334 Other nations besides the

335 United Kingdom also report an EF for household NG-fueled furnaces, including Germany (2.3 kg CH₄/TJ
336 consumed)⁴⁹, Japan (4.5 kg CH₄/TJ consumed)⁵⁰, and Switzerland (1 kg CH₄/TJ consumed)⁵¹ (Table 4).
337 While these differing values likely reflect the type and efficiency of NG furnace common to each country,
338 the wide variability suggests that furnace technology and age may dramatically affect calculated EFs.
339 Additionally, the inventories only include residential furnace EFs but not EFs from other residential or
340 commercial appliances which are also powered by NG. So, while the United States lacks a thorough

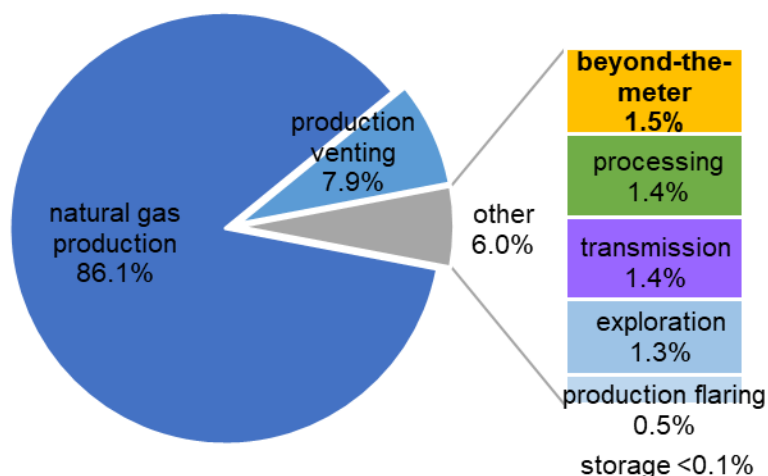


Figure 4. United Kingdom NG supply chain emissions in 2016⁴⁸. Blue, production sector; green, gathering and processing sector; purple, transmission and storage sector; yellow, distribution sector.

341 emissions inventory of beyond-the-meter EFs in commercial and residential settings, the country is not
342 alone in this regard. Even countries that report some beyond-the-meter emissions could improve inventory
343 estimates by considering other sources of beyond-the-meter fugitive emissions.

344

345 **3.4 BEYOND-THE-METER LEAKAGE SOURCES**

346 Residential usage of NG mainly occurs in space heating and water heating systems, and residences (vs.
347 commercial or industrial sites) are estimated to account for at least 65% of the total demand for heating.
348 Reliance on NG for heating – either directly or from NG-generated electricity – is typical in the United
349 States (Table 3)⁵². Importantly, while electric appliances are sometimes thought to have less of an impact
350 on the environment, they still rely on coal or NG generation of electricity. In fact, 33% of the NG consumed
351 annually in the United States is used to generate electricity^{8, 53}. While a full analysis of electric appliances
352 that use NG-generated power is beyond the scope of this review, it is important to note that residential
353 appliances are known to be a significant source of GHGs, contributing global warming potential through
354 inefficient use of electricity, fugitive emissions of carbon dioxide, or leaks of chlorofluorocarbons (CFCs)⁵⁴⁻
355 ⁵⁵. Life cycle assessments suggest that CFC refrigerant leaks account for 11-16% of the total global warming
356 potential of a hot water heater, so other GHGs such as CH₄ account for the majority of non-leak-associated
357 emissions from common household appliances^{52, 54}.

358 Hong and Howarth estimated the CH₄ EF for residential NG tankless and storage water heaters to
359 be 0.60 – 4.02 kg/GJ, or only about two times higher than the EF for electric heat pump systems⁵³. These
360 EFs constitute estimations of CH₄ life cycle losses based on both electricity and NG used, are not based on
361 actual measurements, and thus do not directly compare to measurements of component-based leaks from
362 appliances. Yet it is important to consider the emissions associated with an appliance over its lifetime in
363 order to compare the relative efficiencies of different energy sources, and to remember that even non-NG
364 utilizing elements may rely on NG-produced electricity and still contribute to CH₄ emissions.

365

366

367 **3.5 UNDETECTED LEAKS**

368 Complicating the issue of unknown beyond-the-meter emissions, steady and small NG leaks that remain
369 below levels that are hazardous to human health (<5,300 ppm) would not register as a leak on many
370 conventional detection devices or gas monitors⁵⁶. The Gas Piping and Technology Committee, a part of the
371 American Gas Association, has set forth standards for NG leaks based on concentration and location. Grade
372 1 leaks pose a threat due to potential for explosion or fire, are hazardous to human health, or have a reading
373 of greater than 80% the lower explosive limit (LEL), which is 50,000 ppm for CH₄. Grade 2 leaks, 20-80%
374 the LEL, are considered nonhazardous but could become so and are, like grade 1 leaks, prioritized for repair
375 when found in confined spaces such as homes. Common carbon monoxide and explosive gas monitoring
376 devices trigger an alarm at 25% the LEL, which for CH₄ is 12,500 ppm. Thus, while all grade 1 and most
377 grade 2 leaks trigger a gas alarm, all grade 3 leaks (a leak of less than 20% LEL in a confined space) and
378 some grade 2 leaks would be missed by standard-issue gas detectors. Leak detection methods vary widely
379 in accuracy, increasing uncertainty in measurements and sometimes leading to safety incidents when a
380 hazardous leak is missed^{14, 57}. A standard-issue gas detector only alerts the occupant to dangerous high-
381 emitting leaks but not chronic low-level leaks that would also not necessarily dramatically alter monthly
382 gas consumption.

383 Wennberg *et al.* estimated that if 5% of NG provided to homes were unintentionally released
384 uncombusted through such undetected leaks, this could account for 6 Tg CH₄ per year in the national
385 inventory, greatly reducing divergent estimates from top-down and bottom-up inventories while also
386 dramatically increasing national CH₄ emissions estimates³⁴. Thus, even nonhazardous indoor leaks could
387 be a significant contributor to national CH₄ emissions once scaled up to a national level. The assumption
388 that indoor meters are not a source of fugitive CH₄ should be re-evaluated. While beyond-the-meter CH₄
389 sources may individually contribute only trivial amounts of fugitive CH₄, these sources taken together
390 should not be ignored in the GHGI. In addition, appropriate methodologies for detecting minor, possibly
391 irregular leaks may need to be developed if current leak detection and repair protocols prove insufficient.

392

393 **4. INITIAL STUDIES IN RESIDENTIAL METHANE EMISSIONS**

394 Emissions from NG-powered appliances may include emissions during ignition, usage, extinguishment,
395 and leaks when the appliance is not actively operating. Leaks may come from the appliance itself, a pilot
396 light, pipes leading from the meter to the appliance, and connections between components. Inefficiency in
397 combustion or loss of NG prior to combustion both contribute to fugitive CH₄.

398 While beyond-the-meter emissions are not yet included in the United States GHGI, these
399 unaccounted emissions are gaining recognition and interest^{32, 58}. A recent study in California took advantage
400 of an energy auditing program available to California homeowners to quantify beyond-the-meter CH₄
401 emissions⁵⁹. The study, a first of its kind, used quiescent whole-house CH₄ emissions and measurements of
402 individual components within a house to determine the EFs for inactive whole-house leakage and appliance
403 pilot lights. A second study specifically focused on steady-state usage of NG-powered appliances⁶⁰.
404 Together, these studies can be used to make estimates for beyond-the-meter emissions at the national scale.

405

406 **4.1 COMBUSTION EFFICIENCY**

407 The first factor to consider in beyond-the-meter emissions is combustion efficiency (CE), or the measure
408 of the transformation of fuel into usable heat. The EPA estimates 1% CH₄ burned is emitted without
409 combustion from modern industrial furnaces⁶¹. This calculation is based on appliance efficiency under
410 optimal conditions, not field-verified, and does not consider additional sources of fugitive emissions from
411 the furnaces. Inefficiency in a furnace could result in incomplete combustion, releasing carbon monoxide,
412 or release of CH₄ through release without combustion of the fuel.

413 Similarly, the CE could be used as a baseline for appliance leakage rates for residential heating
414 units such as furnaces and water heaters. According to the Department of Energy, NG-powered water
415 heaters generally achieve CEs of 68-85%. Importantly, age is a significant determinant of CE: while hold
416 furnaces generally have a CE of 56-70%, modern furnaces regularly achieve over 95% conversion⁶²⁻⁶³.

417 In the United States, 46.5% of all households, of which there were a reported 128.8 million in the
418 2017 census, rely on NG-powered furnaces^{46, 64}. These 59.9 million furnaces run on a combined 2.8 TJ NG

419 per year, or on average 0.047 TJ per furnace annually⁶⁰. Assuming 80% efficiency (with a range of 50-
420 95%) and release of all non-combusted NG as CH₄ (called a fuel slip), up to 0.56 TJ NG could be released
421 annually from furnaces alone. Yet, in an inventory context, this amounts to only 0.0126 Gg CH₄ or
422 0.00048% of the national yearly CH₄ budget (0.000024 – 0.00012% for the range of possible efficiencies).
423 Assuming the 1% efficiency from industrial furnaces also applies to residential furnaces, this percentage
424 drops even lower (0.0000024%).

425 Even considering furnaces operating under nonoptimized conditions, combustion efficiency alone
426 does not explain observed methane plumes in cities or differences in top-down versus bottom-up
427 inventories. Additionally, fuel slip from furnaces alone would not be considered large enough to include in
428 the GHGI. Taken together with non-combusted CH₄ from other appliances in addition to other leakage
429 sources, however, beyond-the-meter emissions may become a significant factor.

430

431 **4.2 WHOLE HOUSE BEYOND-THE-METER EMISSIONS**

432 In the California study, researchers measured whole-house CH₄ emissions and additionally measured
433 emissions from specific components within the home (Figure 5)⁵⁹. The study reported that when all
434 appliances and pilot lights were inactivated, the average quiescent whole-house EF was <1 g CH₄ per day.
435 The investigators also included the contribution of a subset of individual appliances in calculating total
436 house emissions (Table 5). The study confirms that chronic, low-level typical leaks can be present in a
437 home without triggering a gas monitor and could, on an inventory scale, be significant.

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

445 Limitations to the study are that only a small number of single-family homes were analyzed, and
446 that few individual appliances were tested for leaks. The dataset was not large because of subject availability
447 and the time intensiveness of measurement techniques. Researchers could not draw conclusions about the
448 relationship between house age and incidence or severity of CH₄ leaks. Additionally, while pilot lights were
449 generally tested throughout the 75 homes that comprised the study set, the majority of appliances were not
450 assessed for incomplete combustion during use or component-specific leaks.

451 The study concluded that fugitive emissions from homes account for 2% of total CH₄ emissions in
452 California⁵⁹, which is close to the United Kingdom estimation of 1.5% of NG emissions coming from
453 beyond-the-meter leaks⁴⁸. This suggests the residential sector could be a significant unaccounted-for source
454 of fugitive emissions and requires further analysis to close gaps in data for beyond-the-meter emissions.
455 Closer inspection of the components within a residence or business may reduce uncertainty in EFs.

456

457 4.3 ESTIMATIONS FROM APPLIANCES

458 According to the initial study on steady-state CH₄ emissions from major home appliances, including
459 furnaces, boilers, stoves and ovens, and water heaters, space heaters have the greatest leakage rate, followed
460 closely by cooking appliances (**Error! Reference source not found.**)⁵⁹. CH₄ emissions from furnaces are
461 much higher than those estimated using energy efficiency ratings, suggesting furnaces operate under
462 nonoptimized conditions and have additional leakage
463 besides fuel slip.

464 Merrin and Francisco measured emissions
465 from furnaces, boilers, water heaters, and cooking
466 appliances⁶⁰. The initial ignition of the appliance
467 resulted in a sharp CH₄ spike, followed by low
468 emissions during steady-state and a second spike
469 upon extinguishment. Some appliances such as ovens
470 exhibited cycling behavior during steady-state usage

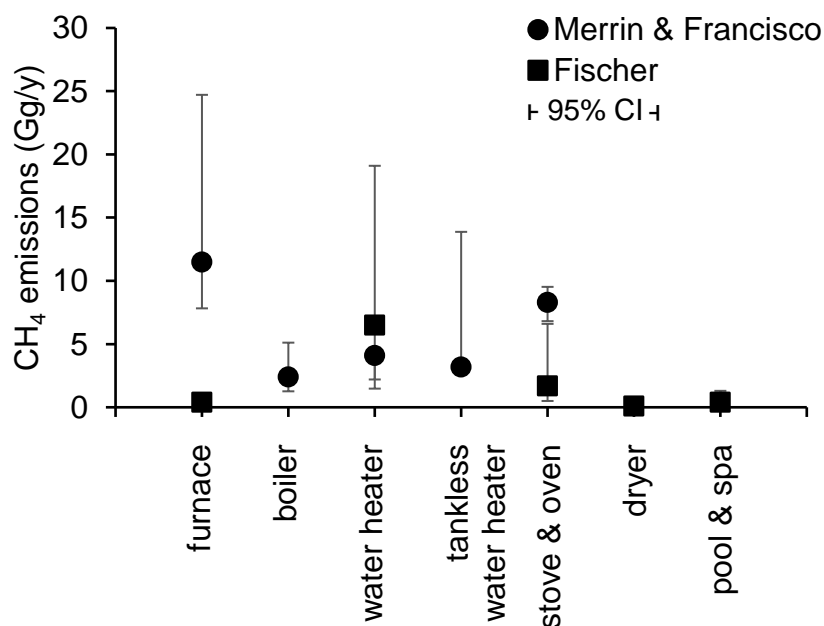


Figure 5. Schematic of appliances and devices within a residence that contribute to CH₄ emissions, which can be measured from individual components or as whole-house emissions^{1, 59}.

471 or additional release of CH₄ after extinguishment, resulting in additional emissions. Some CH₄ released in
472 the flue, however, could be burned during a subsequent ignition of the appliance, thereby decreasing
473 fugitive CH₄.

474 Using census data on average appliance usage, Merrin and Francisco calculated EFs for each
475 appliance (Figure 6) and determined that while furnaces have the largest EF, appliances have different
476 emission profiles depending on operation state⁶⁰. Interestingly, ovens emit the most of any appliance during
477 the ignition stage, while culprits for elevated steady-state emissions are stovetops and tankless water
478 heaters. Space heaters, boilers, and conventional water heaters had low ignition and steady-state operation
479 emissions on average. The dataset comprised appliances from 98 homes in multiple geographic regions but
480 was limited to colder climates.

481 Steady-state operation
482 of an appliance does not
483 necessarily indicate that
484 emissions remain consistent; in
485 addition to spikes during
486 ignition and extinguishment,
487 some appliances like ovens
488 cycle through low and high gas
489 usage, causing a fluctuation in
490 emissions. Thus, steady-state
491 usage and the off state should
492 not be ignored in emissions



491 **Figure 6.** Estimated CH₄ emissions from household appliance operation.
492 Error bars, 95% confidence interval (CI)^{59, 60}.

493 estimates. While Merrin and Francisco's EFs consider steady-state usage in addition to ignition⁶⁰, Fischer
494 *et al.* considered quiescent pilot-light emissions in addition to steady-state operation, but not ignition or
495 extinguishment⁵⁹. These different monitoring techniques, in addition to different instrumentation, may
496 account for the variability observed in CH₄ emissions (**Error! Reference source not found.**, Table 5),

497 although appliance age, regional location, and estimates of appliance usage may also contribute to variation.
 498 Additional data are required to decrease uncertainty in appliance contributions to the NG emissions
 499 inventory, but these preliminary studies in California, Boston, Illinois, and Indiana highlight that small
 500 contributions still impact overall inventory accounting. The whole-house emissions and individual
 501 component inventories suggest appliances, and thus other fugitive emissions beyond the meter, should be
 502 characterized and included in the GHGI.

503

504 4.4 NATIONAL SCALE ESTIMATIONS

505 From the initial appliance and whole-house monitoring studies, it is possible to estimate EFs for appliances
 506 and to consider CH₄ emitted to the atmosphere due to residential beyond-the-meter consumption on the

Source	Furnace EF (kg/TJ)	US total furnace emissions using EF (Gg CH ₄ /y)*	% Total US NG CH ₄ emissions**	% Total US CH ₄ emissions [‡]
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 ^{**}	3.2 (± 1.4)	9.1 (± 3.9)	0.14% (± 0.06%)	0.03% (± 0.01%)

* The national NG consumption in furnaces used in this calculation is 2.825 TJ⁶⁰.

** The total US CH₄ emissions from NG systems used in this calculation (6,624 Gg) is from the 2017 EPA GHGI¹.

‡ The total US CH₄ emissions used in this calculation (26,252 Gg) is from the 2017 EPA GHGI¹.

** 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.

Table 4. Reported emissions factors (EFs) for furnaces and estimates for national emissions from residential furnaces, with percentages of total natural gas (NG) systems CH₄ emissions and total anthropogenic CH₄ emissions.

507 national level (Table 4, Table 5).

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

511 Given 46.5% of the 128.8 million US households rely on NG for space heating, we calculated a
 512 national-scale EF using the preliminary results of beyond-the-meter emissions. We compared the furnace
 513 EFs reported in the GHGIs of Germany, Japan, Switzerland, and the United Kingdom to the EF found in
 514 the Merrin and Francisco study⁶⁰. The steady-state measurement from the Fischer *et al.* study was not
 515 included in the comparison because of the small sample size and because the estimation does not include
 516 the ignition or extinguishment of the appliance⁵⁹.

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

521

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%

Table 5. Sources of beyond-the-meter CH₄ emissions, estimates of contributions to the yearly CH₄ budget, and estimated percent of total CH₄ and NG emissions^{59, 60}.

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

524 Collection of appropriate data for calculating beyond-the-meter EFs is complicated and will involve
525 significant effort. However, beyond-the-meter emissions should be evaluated and, if deemed significant,
526 included in the United States CH₄ GHGI. Discrepancies between top-down and bottom-up CH₄ emissions
527 estimates may be reconciled through inclusion of beyond-the-meter emissions, better reflecting overall
528 fugitive emissions from the NG supply chain. Necessary objectives to address in beyond-the-meter field
529 campaigns include:

- 530 1. *Determining possible sources of fugitive emissions from residential and commercial/industrial*
531 *customers.* The California housing study focused on pilot lights on cooking appliances in single-
532 family homes⁵⁹. New tankless water heaters outside of residential settings were also analyzed. More
533 appliances and pipes within commercial, industrial, and residential settings may have small but
534 chronic leaks, including NG-powered fireplaces, clothes dryers, and gas barbecue grills. A
535 complete inventory of possible sources of leaks beyond the meter should be established, as well as
536 the factors that may influence the potential for and severity of leaks. AFs must also be tabulated
537 for the inventory at local, state, regional, and national scales.
- 538 2. *Determining the connection, if any, between housing type and CH₄ released per unit.* Future studies
539 should evaluate if the approach of the California study to calculate whole-house emissions is
540 appropriate and can be scaled to incorporate multi-family units. While residential houses
541 specifically in California have been the subject of study⁵⁹, the dataset was small and geographically
542 limited. The most common housing type in the United States is a detached single-family unit,
543 followed by apartments of 10 or more units (Table 3)⁴⁶, which have very different energy
544 requirements and therefore different potentials for leak frequency and volume. Housing geography,
545 type, and age are factors which may also heavily influence beyond-the-meter emissions due to type
546 and age of NG infrastructure. The impact of each of these variables may be determined by
547 collecting information about house age while measuring emissions and comparing age to incidence

548 and volume of leakage.

549 3. *Determining the connection, if any, between appliance and equipment age and CH₄ leakage.*

550 Whole-house or whole-building EFs may be less accurate than inventory values for each appliance
551 contained within the building, so individual appliance contributions should also be studied. The
552 National Petroleum Council predicted that while conversions of old appliances could decrease CH₄
553 leaks by 1%, new appliances in the residential sector could decrease residential CH₄ emissions by
554 up to 7% by 2030, or 33.6 TJ per year¹⁰. Older appliances and NG-utilizing equipment may be more
555 likely to have leaks due to older technology and equipment failure. To determine the effect of age
556 on CH₄ leak rates, a survey of residential units should include documentation of the age of each
557 appliance. Analysis of these metrics is necessary to determine a suitable sample size and
558 distribution to capture sufficient data for reliable beyond-the-meter EFs.

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

566 In the survey of appliances in 98 homes across Massachusetts, Indiana, Illinois, and New
567 York, there appeared to be little regional variation⁶⁰. However, it is imperative that the EF(s) take
568 into account such variation if it exists. Often, bottom-up studies obtain much more scattered,
569 clustered data than a top-down approach inventory collection, and such bias could increase the
570 uncertainty associated with any new EFs¹⁵. To increase robustness of the data, a national survey of
571 appliances across seasons and under multiple operating conditions is recommended. In colder
572 climates, appliances that rely on NG may be maintained and replaced more frequently due to
573 increased usage, leading to reduced leaks; conversely, increased usage could lead to more

574 component failures and increased leaks.

575 Statistical analysis in beyond-the-meter emissions must be carefully considered, as fat-
576 tailed distributions of emissions data may occur as they do across the NG supply chain. Whole-
577 house quiescent emissions and steady-state appliance operations do indicate super-emitters also
578 skew emissions estimates beyond the meter⁵⁹. In addition to considering non-Gaussian datasets
579 using probability distributions, the factor or factors contributing to the fat-tailed data distribution
580 should be determined⁶⁵.

581 5. *Determining appropriate measurement conditions and measurement devices.* Ignition and steady-
582 state usage of an appliance will differ in CH₄ production, as preliminary research has shown. The
583 EF for an appliance may need to incorporate emissions from all operation states. The
584 instrumentation used in these measurements may need to be designed to fit the particular situation,
585 as was the case for whole-house emissions⁵⁹. In the Merrin and Francisco study, the Picarro cavity
586 ring-down spectroscopy portable gas concentration analyzer was able to make accurate low-level
587 readings but could not be used above 800 ppm CH₄⁶⁰. Some appliance types could not be monitored
588 due to “lack of sampling apparatus” or a means to quantify emissions⁶⁰; researchers will need to
589 innovate to create appropriate chambers or sampling devices and may need to use a variety of
590 instruments in order to cover emissions rates across a spectrum.

591 6. *Partnering to create an appropriate study set.* Numerous gas and electric companies provide
592 energy audit services to clients within their zone of provision. In addition, various nonprofits
593 provide resources to low-income families in order to receive energy audits and improve energy
594 efficiency within the home. These nonprofits may provide connections to customers seeking better
595 energy efficiency who would be willing participants in a survey and CH₄ emissions analysis. Such
596 partnerships with nonprofits or energy audit companies could facilitate research projects aimed at
597 assessing beyond-the-meter emissions⁵⁹.

598

599

600 **6. PERSPECTIVES AND OUTLOOK**

601 NG consumption in the United States has increased 40% in the last twenty years even as emissions have
602 slowly dropped^{27, 36}. Yet while NG is widely considered less environmentally destructive than coal, NG
603 production, processing, transportation, and distribution releases CH₄, a potent GHG. A complete inventory
604 of sources of CH₄ emissions from the NG supply chain is essential to predict the impact of NG utilization
605 on the environment. The United States GHGI is missing emissions data from sources after the customer
606 meter, and these sources may significantly contribute to national CH₄ emissions. Initial studies reveal
607 diffuse CH₄ plumes from urban areas that are not attributable to pipelines or distribution stations, instead
608 coming from small but prevalent residential or commercial leaks. While preliminary analyses of single-
609 family residences reveal low-level and chronic CH₄ leaks, such emissions expanded out to the national scale
610 could alter the inventory of annual CH₄ emissions and reconcile bottom-up and top-down inventory
611 differences. By studying emissions from individual customer appliances and housing units, new CH₄
612 emissions data can be calculated for inclusion in the national GHGI.

613

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621 **Notes**

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