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Title
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Permalink
https://escholarship.org/uc/item/1zx0b9mz

Journal
ACS ES&T Air, 3(10)

ISSN
2837-1402

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Publication Date
2026-10-09

DOI
10.1021/acsestair.6c00131

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Methane Emissions from Post-Meter Residential Natural Gas Infrastructure: Integrating Existing Data to Inform California's Statewide Inventory

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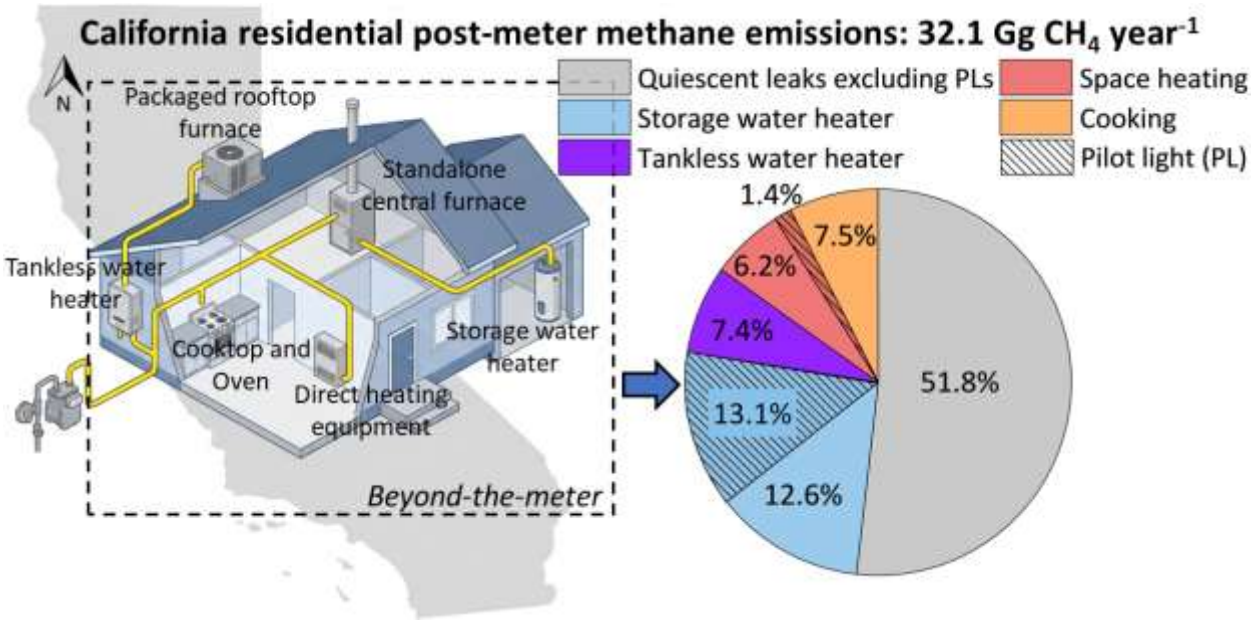
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The content of this document is the manuscript that was accepted for publication in ASC ES&T Air in August 2026. The citation for the paper is provided below.

Sharma B, Chan WR, Delp WW, Lebel ED, Kashtan YS, Finnegan CJ, Jackson RB, Merrin Z, Francisco PW, Blizman B, Fischer ML, Biraud SC, Blum H, Rapp VH, Singer BC. Methane Emissions from Post-Meter Residential Natural Gas Infrastructure: Integrating Existing Data to Inform California's Statewide Inventory. *ACS ES&T Air, Vol 3, Issue 10, 2578-2590. October 9, 2026.* https://doi.org/10.1021/acsestair.6c00131

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Abstract:
This study compiles, synthesizes and analyzes existing measurements of methane emissions from residential post-meter natural gas infrastructure including (1) all infrastructure within a home under quiescent conditions, (2) pilot lights as discrete sources, (3) sustained combustion of main appliance burners, and (4) transient emissions during ignition and extinguishment. Quiescent leak measurements in 64 houses and emissions from 39 pilots and 509 appliances, mostly for cooking, water heating and space heating are combined with usage estimates to calculate annual emissions by appliance, housing type, and statewide in California. Per appliance, tankless and storage water heaters have the highest annual emissions (mean estimates of 2456 and 395 g CH_4 yr^{-1}, respectively) and the average pilot emits 355 g CH_4 yr^{-1}. Statewide residential post-meter emissions are estimated at 32.1 (90% CI: 21.0–52.9) Gg CH_4 yr^{-1}, improving a prior estimate from the same quiescent data, 9 pilots and 129 appliances. This post-meter estimate is 2.2% of statewide methane emissions. This work also advances knowledge through improved estimates of pilot emissions, which account for 23% of quiescent and 15% of total residential, adding transients, estimated at 11% of total, and providing inventories by appliance category and process.

Keywords: gas appliance, pilot light, gas leak, water heater, furnace, incomplete combustion

1. Introduction

Natural gas (NG), composed predominantly of methane, is an important fuel for the residential sector. It directly provides 45% of on-site energy needs nationally[1,2] and larger fractions in many states, including California (56%), for which it provides 88.6%, 90.0%, and 16.1% of the direct energy for space heating, water heating and other end uses, respectively.[2] In the atmosphere, methane is an important driver of warming, with effects that are 80-83 and 27-30 times higher than CO_2 over 20 and 100 years.[3]

Methane that leaks or is otherwise uncombusted during distribution and use represent undesirable waste for this widely used fuel; identifying the sources and mechanisms of these losses can thus lead to a more efficient and economical NG infrastructure. The first top-down estimates of methane fluxes in urban areas, which were derived from atmospheric measurements, indicated much higher emissions than those estimated from bottom-up approaches that identified and quantified mechanisms and specific sources.[4] These results spurred research into methane leaks within the residential[5–8] and commercial sectors.[9]

In both residential and commercial buildings methane leaks can occur at meter set assemblies (MSAs) and beyond the meter. Post-meter, methane can be emitted through leaks in the distribution piping and shut-off valves, or at regulators and valves within appliances. Methane is also emitted from gas appliance use, via leaks or incomplete combustion during sustained burner

operation or from pilot lights, and from small fuel releases during the transient processes of ignition and flame extinguishment.

Two large field studies measured methane emissions from MSAs across the U.S.: 1600 in 1992 and 2400 in 2007-2009.[10,11] A statewide field study in California in 2017-2018 quantified emissions for 94 MSAs selected from 166 that had leaks detected with a gas sensor, and a study in Southern California during 2021-2023 reported emissions of 485 MSAs.[12,13] Outside the U.S., Williams et al.[14] and Vollrath et al.[11] reported measurements of 71 and 37 residential MSAs in Montreal and Calgary (Canada), respectively.

A series of studies starting with one in California that was published in 2018[5] and another in the Midwest and Northeast published in 2019,[6] have measured emissions from residential post-meter infrastructure and appliances in the U.S.[7,8,15] and China[16] and some have used the measurements to estimate aggregate emissions (inventories) for specific appliances or the residential post-meter infrastructure.[7,8,16] The measurement approaches and metrics used in these studies are described in the Methods section.

The overall goals of the work presented in this paper were to compile, critically review and analyze available measurements to generate improved estimates of aggregate, residential post-meter methane emissions in California and to identify data gaps. This effort was an early task in the ongoing California Residential Methane Emissions Characterization (CARMEC) study, which aims to improve the statewide CH_4 inventory and to inform cost-effective strategies to reduce CH_4 losses. Existing data relevant to California homes are analyzed to quantify CH_4 emissions from quiescent leaks at the house level and from gas appliances during sustained combustion and transient emissions of burner operations.

2. Methods

2.1. Overview

This section describes the research methods used to achieve the following specific objectives.

1. Compile existing data on residential methane emissions into a unified database with consistent metrics and house and equipment metadata to support analysis.

2. Calculate emission distributions by source and process (whole-house quiescent, pilots, transient and sustained combustion) and from furnaces, water heaters and cooking appliances.

3. Estimate annual emissions for the whole house, pilot, and appliances for which data are available.

4. Calculate an annual inventory of methane emissions from residential NG infrastructure in California, resolved by source.

5. Identify uncertainties and information gaps.

2.2. Compilation of existing emission data

We compiled methane emissions measurements from several studies that have been described in publications; previously unpublished, supplemental data from two published studies; and data collected in a study that has completed field work (Table 1). Fischer et al.5 measured fugitive emissions from post-meter infrastructure, including pilot lights, and emissions during sustained appliance burner operation in 75 Northern and Southern California homes. Lebel and colleagues reported emissions from 18 storage and 17 tankless water heaters (TWH) in Northern California and hundreds of individual cooking burners (cooktop, broilers and ovens) in 53 homes throughout California, including both sustained and transient burner operation.[7,8] Lebel et al.[8] also contributed unpublished data from 10 storage water heaters (SWH) measured during the study of cooking appliances. Similarly, we acquired cooking burner measurements made but not previously reported by Kashtan et al.[17] in 19 Colorado and California homes. Blum et al.[15] published data from 8 direct heating equipment (DHE; 6 wall furnaces and 2 room heaters) retrieved from California homes. Herein these are described as wall furnaces (WF) as they are 90% of the primary DHE in California.[18] Merrin and Francisco[6] reported measurements for water heaters, furnaces (36 CF; 1 WF), and cooking appliances in 101 homes in Boston, Indianapolis, New York and Illinois. The SUper-eMitters of Methane detection using Aircraft, Towers, and Intensive Observational Network (SUMMATION) study,[19] which deployed a suite of CH_4 emissions monitoring in California's Southern San Joaquin Valley, measured emissions from 21 SWH, 4 TWH, 30 furnaces, and almost 100 cooking burners in homes around Bakersfield, CA.

The leaders of each of these studies, all co-authors on this paper, provided primary and processed data which were compiled into a database of measured CH_4 and CO_2 concentrations and sampling airflows, calculated emission metrics, and metadata about the homes and appliances. This level of data resolution enabled us to calculate emissions for a common set of metrics described below.

The following paragraphs briefly describe the measurement approaches and metrics used in prior studies and the reasons why we excluded some data from our analysis. More detailed descriptions of the methods are described in their original publications.

Aggregate emissions from post-meter infrastructure (quiescent whole-house) have been quantified by depressurizing the house with a known airflow at a single point, and measuring the increase in methane concentration in the air exiting the structure compared to the nearby outdoor air. This method, thus far reported only by Fischer et al.,[5] uses a blower door with a calibrated fan that can be modulated to achieve a target depressurization or airflow. An important uncertainty of this approach is the degree to which leaks from gas appliances and distribution infrastructure in connected spaces, including attics, crawlspaces, attached garages and closets, are pulled through the living space in the home and thus measured at the blower door. The field teams for Fischer et al.[5] took steps to increase connectivity, such as opening doors

to attached garages and attics. A controlled release of 5.0 ± 0.6 g CH_4 day^{-1} of CH_4 at 5 m distance from the blower door of each home was performed for quality assurance (QA). In their paper, they reported that 64 homes met their QA criteria. We note that the authors did not use the tracer release to investigate or confirm if the attached garages, attics, etc. were coupled to the living space. The authors noted this was not practical within the time allocated to measure at each home. Several approaches have been used to measure emissions associated with burner operation. The options are first differentiated by the presence or absence of a flue that directs combustion products from the burner chamber out of the appliance and a vent that directs exhaust from the appliance to outside the house. For atmospherically vented appliances, the flue and vent are connected by a draft diverter that pulls in dilution air from the zone containing the appliance, which is also the space that supplies combustion air. Direct vent appliances use a fan to pull in outside air and push exhaust gases back outside in a loop that is not connected to the indoor space. Power vented appliances use a fan to drive flow from the appliance to the exterior while pulling combustion air from the zone with the appliance.

For water heating and space heating appliances, which all have a dedicated outlet for combustion products, methane emissions have been measured by the following two methods:

- Direct sampling measures CH_4 and CO_2 mixing ratios in the flue, draft diverter or vent at a location that is within the ranges of the gas analyzer(s) for both analytes. These mixing ratios can be compared to those in the air used for combustion and venting, which enters at the draft diverter. For atmospheric and power-vented appliances, the mixing ratios for combustion and venting air are measured in the appliance zone. This approach was used by Fischer et al.[5] and Merrin and Francisco[6] to measure emissions from both pilot lights and main burners. This method can yield fuel-normalized emission factors during sustained combustion (explained in Section 2.2); but not transient emission factors because total airflow during the transient event is not known.
- Total capture / dilution sampling pulls the entire flow of exhaust gas along with excess air through a duct whose opening is placed nearby to the vent outlet. The duct is connected to a calibrated fan and the CH_4 and CO_2 mixing ratios measured at the end of the duct are multiplied by the air flow rate to obtain a mass flow of each analyte.7 The mass flows of CH_4 and CO_2 introduced with combustion and dilution air are estimated from measurements of mixing ratios in the surrounding, ambient air. This method can be used to quantify both emission rates (sustained combustion; explained in Section 2.2) and emission factor (transient; explained in Section 2.2); but it can include some bias for natural draft or power draft appliances that draw combustion and dilution air from inside the structure. Bias results when the ratio of excess CH_4 to excess CO_2 in the inside air relative to outside air is different from the ratio added by the appliance. While the total capture method can be used for both pilot and main burners, the potential errors

associated with different CH_4 and CO_2 mixing ratios inside vs. outside are much larger for pilot burners as they add so much less CO_2 than the main burners. Quantifying pilot emissions using this method thus requires measurement of CH_4 and CO_2 mixing ratios near the combustion air intake zone and draft diverter of the appliance.

For cooking appliances, past studies used various methods to measure methane emissions. Fischer et al.[5] used direct sampling to measure CH_4 and CO_2 mixing ratios at a short distance (10-15 cm) above the flame during sustained burner operation. The absolute mixing ratios at this location vary with time based on plume mixing dynamics; however, the enhancement ratio of CH_4:CO_2 can be relatively consistent. Lebel et al.,[8] Kashtan et al.,[17] and the SUMMATION study used a static flux chamber method by setting up a temporary enclosure around the cooking appliance. Changes in methane concentrations in the enclosure were measured for the pilot light only, during sustained combustion, and for transient emissions during ignition and extinguishment. Merrin and Francisco[6] used a device to mimic the presence of a cooking vessel and to channel the exhaust plume to where CH_4 and CO_2 mixing ratios were measured.

Some existing emissions data were not included in our compilation and analysis. First, we excluded the transient emissions for water heaters, furnaces, and cooking appliances from Merrin and Francisco,[6] which they calculated based on directly measured mixing ratios and an assumed volumetric flow of exhaust gas based on the maximum rated firing rate of the burner. In actuality, the exhaust flow changes rapidly from zero with no pilot light, or very low with a pilot light, to the fully developed flow that occurs during sustained combustion over the same interval that the ignition spike occurs. And while the change in flow is likely less during extinguishment, it is nevertheless not reliable to assume it is the same. We also excluded 66%, 40%, and 23%, respectively, of the sustained combustion measurements of water heater, furnaces, and cooking appliances from Merrin and Francisco[6] that included imputed values for missing data when concentrations exceeded the quantitation limits of the measurement instruments. Second, we excluded standby or "steady-state Off" measurements of 49 storage water heaters measured using dilution sampling by Lebel et al.,[7] supplemental measurements made during Lebel et al.,[8] and SUMMATION. These measurements made at high flow rate (900-1100 cubic feet per minute) included both pilot light emissions and leaks from other sources within the home.

2.3. Emission measurement metrics

In prior work, methane emissions from residential sources have been expressed using metrics of the following forms:

- Enrichment ratio (R) is the ratio of ΔCH_4 to ΔCO_2, during burner operation, where each delta is the increase in mixing ratio from combustion air to exhaust, and the metric is expressed in parts per hundred or %.

- Emission rate (E) with units of mass emitted per unit time.
- Emission factor (F) in units of mass per transient event or per unit of fuel consumption, expressed as mass, volume or energy.

In this work, we use the following metrics to quantify CH_4 emissions. Whole house quiescent leaks are expressed as a mass emission rate on a daily basis (E_{QL}). Transient emissions are expressed as the mass emission factor for each burner event, including ignition and extinguishment (F_{TR}). Emissions from pilot lights (R_{PL}) or sustained combustion with main burners (R_{SC}) are expressed as enrichment ratios and also converted to fuel-normalized emission factors (F_{PL} and F_{SC}, Equation 1). Since each methane molecule is oxidized to one molecule of CO_2 during combustion and typically over 90% of the fuel carbon is in the form of methane, the enrichment ratio approximates the unburned fraction of fuel with roughly a 5-10% error. For ovens, the enrichment ratio is used to separately express the emissions during pre-heat (R_{PH}) and on-off cycles (R_{OC}) needed to maintain the setpoint temperature, respectively. To translate from enrichment ratio to a fuel-normalized emission factor (Equation 1), we assume natural gas composition of 93.5% methane, 4.8% ethane, and the remainder inert components (nitrogen and/or CO_2.[20] This conversion is imprecise and introduces small errors to individual measurements as the composition of NG varies spatially and temporally.[21]

$$F_i\ (ng\ CH_4\ J^{-1}) = \frac{R_i \times 1.048\ mol\ C\ per\ mol\ of\ fuel \times MW_{CH4} \times 10^9}{907030\ J\ per\ mol\ of\ fuel} \quad [1]$$

In Equation 1, R_i is the enrichment ratio of any source *i* ; MW_{CH4} is the molecular weight of CH_4 (16.04 g mol^{-1}); 907,030 is the weighted sum, higher heating value of methane and ethane expressed as J mol^{-1}.

For each post-meter emission process (whole house quiescent, pilot, transient or sustained combustion by appliance) we used bootstrapping to calculate the mean and 5^{th}–95^{th} percentile confidence interval (CI) without assuming a distribution function. To elucidate emission variability, we present the 10^{th} and 90^{th} percentiles of the actual measurement distribution for each emission metric. We applied the nonparametric Mann-Whitney Test with null hypothesis as difference between medians equal to zero for statistical tests of significance.

2.4. Annual emission estimates

We present annual emissions from post-meter sources within three frameworks. First, we look at emissions at the unit level, including quiescent leaks from a single house without pilot(s), a single pilot burner, and operating emissions by appliance, also excluding the pilot. Next, we present the statewide inventory of emissions from all units of each source. Finally, we combine all the sources within each housing type (single detached, townhouse/attached, 2-4 unit, 5+ unit, manufactured) and sum across housing types. The connection of metrics to annual emission estimates is shown in Figure S1. The presentation uses a combination of English and metric units

aiming to align with those used by different communities who may be interested in this work. Burner firing rates are expressed in BTU hr^{-1} as provided for U.S. appliances and annual energy use is therms yr^{-1} as provided in California's Residential Appliance Saturation Study (RASS).[22] Fuel-based emission factors (ng J^{-1}) and annual emission inventories (Gg yr^{-1}) are expressed in metric units as commonly used in the scientific literature.

2.4.1. Quiescent emissions from individual houses and pilot lights

Annual quiescent emissions for a single house (E_{QLY}), including pilot(s) were calculated from the bootstrap estimate of the mean daily emission factor by scaling to 365 days.

Annual emissions from a standing (continuously burning) pilot (E_{PLY}) were calculated by multiplying the bootstrap estimate of the mean emission factor (F_{PL}) by the annual fuel use of 47.4 therms yr^{-1}, based on the mean firing rate of 541 BTU hr^{-1}, from the compiled data (see Section S2 and Figure S2), using Equation 2, below. We note that the firing rate used in this estimate is substantially higher than the value of 300 BTU hr^{-1} assumed by Fischer et al.[5]

$$E_{PLY}\ (g\ CH_4\ yr^{-1}) = F_{PL}\ (ng\ J^{-1}) \times F_{burner}\ (BTU\ hr^{-1}) \times 1{,}055.06\ (J\ BTU^{-1}) \times 8760\ (hr\ yr^{-1}) \times 10^{-9}\ (g\ ng^{-1}) \quad [2]$$

To estimate quiescent emissions for a home excluding pilot(s) (E_{QLY*}), we subtract one pilot burner from the annual quiescent emissions for a home. This is based on the estimate by Fischer et al.[5] that there are 0.82–1.26 pilot lights per house in California and our own estimate of 0.93–1.03 pilot lights per residence, with the range reflecting variability across housing types, as described in the SI.

2.4.2. Emissions from individual appliances

To estimate emissions from individual appliances, we combine emission factors and activity for each process in each appliance category. The burners of water heaters, furnaces, and cooktops emit methane through sustained combustion and transient ignition and extinguishment. For appliances with a pilot, main burner emissions can be added to those from the pilot to obtain an appliance total. Presenting pilots separately illustrates the potential to reduce emissions by shifting from a continuous pilot to electronic ignition. For ovens, emissions are expressed during pre-heat and temperature maintenance modes, with the latter featuring burner cycling.

The annual methane emissions from sustained combustion (E_{SCY}) for an individual unit of each appliance type are estimated from the bootstrapped mean emission factor from our data compilation and the unit energy consumption (UEC, therms yr^{-1}) from the 2019 RASS,[22] adjusting for fuel use by a pilot, as appropriate.

$$E_{SCY}\ (g\ CH_4\ yr^{-1}) = F_{SC}\ (ng\ J^{-1}) \times UEC_{SC}\ (therm\ yr^{-1}) \times 1{,}055.06\ (J\ BTU^{-1}) \times 10^{5}\ (BTU\ therm^{-1}) \times 10^{-9}\ (g\ ng^{-1}) \quad [3]$$

RASS provides UECs for the following end uses in each housing type: conventional water heating, primary heating, and cooking. The energy used by the main burner of a typical storage water

heater (UEC_{SC}) is estimated by subtracting the annual fuel use by the pilot light (47.4 therms yr^{-1}; see above), assuming that all SWH have pilots. For tankless water heaters, we multiply the UEC for conventional water heaters by 0.71 based on Lebel et al.[7] reporting that they use 29% less fuel; and there is no adjustment for a pilot because they are all electronic ignition.

RASS only provides UEC for total cooking, including cooktop and oven combined. Based on the compiled characteristics of rated cooktop burner and oven burner size, and prior studies measuring the length and frequency of cooking events in California homes,[23–25] we estimate that 70% of the combined UEC is attributable to cooktop and 30% is attributable to oven use (see SI for more details). And since only a small fraction of existing cooking appliances still have pilots, we don't reduce the UEC by pilot burner fuel use.

The annual methane emissions for an average oven burner (E_{OTY}) are calculated by summing emissions during pre-heat (E_{PHY}) and oven cycling (E_{OCY}), each calculated using Equation 3. The annual energy used for pre-heat and cycling phases is estimated based on a mean pre-heat time of 12 min (from the compiled database) and a mean oven use duration of 45 min from prior studies in California homes.[23–25] As the burner does not stay lit continuously during the cycling phase, active burner operation is assumed to be 50% of the oven use time, after the pre-heat (see SI for more details).

Annual emissions for an average central furnace or wall furnace (as representative of DHE) in each housing type are calculated using Equation 3, which accounts for energy used in the pilot lights that are in many DHE and older central furnaces. We first assume that the UEC for primary heating is applicable to both central and wall furnaces used as primary heating. Our analysis does not estimate emissions for wall furnaces or other DHE that are used for supplemental heat. We then estimate the fraction of furnaces in each housing type that have a pilot light. Blum et al.[18] found that the majority (88.5%) of DHE used as primary heat in California homes have pilot lights. The most used primary DHE is wall furnace (69% upright and 21% console wall furnace), followed by room heater (6%) and floor furnace (4%). For central heating, we note that in the compiled database 41% of the 17 furnaces older than 2000 had pilots while only 7% of the 41 furnaces manufactured after 2000 had them. We also account for pilots that are not used year-round. Blum et al.[18] reported that 53% of households with primary DHE keep the pilot on year long, 40% turn it off outside the heating season, and the remaining (7%) have intermittent pilots. We thus assume that half of the primary DHE pilot lights operate throughout the year and the rest only during the heating season (~6 months), and apply a use factor of 0.75. For central heating, the compiled database does not have enough information about the location of furnaces with pilot light, which makes it difficult to estimate the fraction of households having easy access to their furnace (indoor closet or attached garage) to turn the pilot light off during non-heating season, as in the case of DHE. We thus assume that 100% of the pilot light in central furnaces stays lit throughout the year. Pilot lights are present in 14-34% of the primary heating appliances across

housing types based on data from the 2020 Residential Energy Consumption Survey (RECS; described in Section 2.4.3). The fractional presence of pilots and their operation in space heating appliances is used to estimate the contribution of pilots to primary heat UEC for each housing category. For example, the primary heat UEC of 189 therms yr^{-1} (Table S2) for detached houses is reduced by 7 therms yr^{-1}, averaged across the stock. The estimate of 7 therms yr^{-1} is based on the 18% of single family homes that have a furnace with a pilot, including 13% that have a central furnace and 5% that are heated primarily by a DHE. Overall, the primary heat UECs provided by RASS 2019 are reduced by 6-13 therms yr^{-1} across housing types.

The mean annual emissions from transient operation of water heater, furnace, and cooktop burners (E_{TRY}) are estimated using Equation 4.

$$E_{TRY}\ (g\ CH_4\ yr^{-1}) = \frac{E_{TR}\ (mg\ per\ firing) \times N_{BF}(\#\ firing\ day^{-1}) \times 365(day\ yr^{-1})}{1{,}000\ (mg\ g^{-1})} \quad [4]$$

where N_{BF} is the number of burner firings for each appliance type. Here, we briefly summarize how N_{BF} is determined (see SI for more detailed explanations).

The number of burner firings for water heaters was measured in California homes by Lebel et al.[7] and in the SUMMATION study. From their measured data of 41 SWH totaling 1,151 monitoring days, the estimated mean burner firings per day (N_{BF}) is 5 (CI: 4 to 6). Lebel et al. and the SUMMATION study measured burner firing of 33 TWH over a total of 1,200 monitoring days. The estimated mean number of burner firings from bootstrapping for TWH is 44 per day (CI: 35 to 59). The distributions of these data are provided in Figures S4-S5.

The number of burner firings for furnaces was estimated using data from the Ecobee Donate Your Data (DYD) program.[26] The dataset is compiled from Ecobee customers who agreed to have data from their thermostat shared for research purposes. We obtained 5-minute interval heating runtime data from 332 California homes in 2017 and used the data to identify the start and end of a heating cycle. A heating cycle was assumed to be continuous and ongoing if it lasted the entire 5 minutes during an interval, uninterrupted. Our analysis shows that the number of heating cycles peaked in January with substantial numbers in November to March (Figure S3). The estimated mean number of heating cycles from bootstrapping was 1759 yr^{-1} (CI: 1642-1894). It is possible that our assumption underestimates the number of firings by missing heating cycles that last less than 5 minutes. However, we expect short heating cycles to be uncommon and not a key source of error. We assume the number of heating cycles, which is mostly developed from central furnaces, also applies to wall furnaces.

The number of cooking events using cooktop burners and ovens was obtained from monitoring data in 57 single-family homes and 23 low-income apartments with gas cooking appliances in California (Figure S6).[23–25] The cooking events were determined for one week in each home based on measurements from temperature sensors installed next to each burner and at the oven vent

and occupant activity logs. The mean (90% CI) number of cooking events involving any cooktop burner was 12.3 (9.2–13.5) per week, and 1.7 (1.4–2.7) per week for the oven.

The sum of sustained combustion (E_{SCY}) and transient (E_{TRY}) provides the annual methane emissions for each individual water heater (storage and tankless), furnace (wall and central), and cooktop. For an oven, it is the sum of emissions during pre-heat (E_{PHY}) and cycling (E_{OCY}).

2.4.3. Statewide emissions for each source category

We calculate statewide emissions for each of the following sources: quiescent leaks without pilot, water heating, space heating, and cooking. The calculation uses data from the 2020 RECS, which provides the number of homes with NG connections and the number of NG appliances in single-family, townhouse, 2-4 unit, 5+ unit, and manufactured housing in California (Table S1).

To estimate quiescent leaks excluding pilots, we assume that all other housing types have the same per-unit emissions (E_{QLY*}) as those measured in houses.

To estimate emissions from SWH pilots and central furnaces, we multiply annual emissions from a pilot light (E_{PLY}) by the total number of SWHs and the fraction of central furnaces with pilots (see Section 2.4.2). For DHE, we reduce E_{PLY} by 25% to account for the half that are turned off during the non-heating season and multiply by the estimated number of pilots in DHE primary heating (Section 2.4.2). Statewide, 79% of pilot lights are in SWH.

To estimate emissions from water heating appliances, emissions from SWH pilots are summed with the annual operational emissions for SWH and TWH multiplied by their prevalence.

Similarly, for space heating appliances, the emissions from central and wall furnace pilot lights are summed with the annual operational emissions for wall and central furnaces multiplied by their prevalence in the state. We use wall furnace emissions to represent all DHE in California because those are the most measured DHE appliances. As explained in Section 2.2, since wall furnaces are 90% of the primary DHE in California, this assumption should not introduce large uncertainty to the space heating category.

For cooking appliances, the annual emissions estimated for individual cooktops and ovens are multiplied with their respective prevalence in the state. The RECS numbers for homes with NG cooking do not distinguish cooktops and ovens and thus do not provide an estimate for the fraction that have a gas cooktop and an electric oven, either combined or as separate appliances. In the compiled database, 68% of homes with gas cooktops were recorded as also having gas ovens. For each housing type, we assume that all homes with a NG cooking have a gas cooktop but only 68% have a gas oven.

2.4.4. Statewide emissions from housing categories

The statewide emissions inventory is also expressed based on housing type. Equation 5 shows the calculation of statewide emissions for single-family homes (M_{SFY}).

$$M_{SFY} = (E_{QLY*} \times H_{SF} + \text{Sum}\ [\ (E_{SCY,i} + E_{TRY,i}) \times N_{SF,i}\ ] + \text{Sum}\ [\ E_{OTY,j} \times N_{SF,j}\ ] + E_{PLY} \times N_{SF,k}) \times 10^{-9} \quad [5]$$

M_{SFY} is the total Gg CH_4 yr^{-1} emitted from detached homes; E_{QLY*}, E_{SCY}, E_{TRY}, E_{OTY}, and E_{PLY} are the annual emissions from whole house excluding pilot light(s), sustained combustion, transient ignition and extinguishment, summed oven pre-heat and cycling, and standing pilot, respectively; H_{SF} is the number of detached homes with NG connections; $N_{SF,i}$ is the number of each appliance type i in detached homes including: storage water heater, tankless water heater, central furnace, primary DHE, and cooktop; $N_{SF,j}$ is the number of ovens in detached homes; $N_{SF,k}$ is the number of pilot burners in detached homes.

Equation 5 is also applied to calculate statewide methane emissions for other housing types. As stated in Section 2.4.3, we make the simplifying assumption that the whole house quiescent leak emissions estimated for single detached houses (E_{QLY*}) and appliance emissions measured mostly in detached homes (83% of data) apply to other housing types. We also applied the burner firing frequencies derived from measurements that occurred mostly in single houses to the other housing types.

Table 1. Number of methane emission measurements compiled from existing data.

Service	Unit	Process	Fischer et al.[5,a]	Merrin and Francisco[6,a]	Lebel et al.[7,8,a]	Blum et al.[15,a]	Supplemental data[b]	SUMMATION[c]	Total
Post-meter infrastructure	Whole-house	Leaks from distribution, & resting appliances	64						64
Water heating	Storage Water Heater	Pilot light	5	23					28
		Sustained combustion	60	27	18		10	21	136
		Transient			17		10	21	48
	Tankless Water Heater	Sustained combustion	6		17			4	27
		Transient			17			4	21
Space heating	Central Furnace	Pilot light	3						3
		Sustained combustion	5	36				17	58
		Transient						17	17
	Rooftop Packaged Unit	Sustained combustion	1					11	12
		Transient						11	11
	Wall Furnace	Pilot light				8			8
		Sustained combustion		1		6		2	9
		Transient						2	2
Cooking	Cooktop Burner	Sustained combustion	54	200	349		49	67	719
		Transient			224		48	64	336
	Oven	Pre-heat			40		19	25	84
		Burner cycling			38		16	25	79

[a]Published sources.

[b]Supplemental data collected for 10 storage water heaters and 19 ranges / ovens during Lebel et al.[8] and Kashtan et al.[17] study campaigns.

[c]Data collected during SUper-eMitters of Methane detection using Aircraft, Towers, and Intensive Observational Network (SUMMATION) study in Bakersfield, California, California Energy Commission Agreement PIR-17-015.

3. Results

3.1. Measurements of methane emissions

3.1.1. Characteristics of sampled homes and appliances

Table 1 summarizes the emission measurements included in our analysis. Approximately 70% of the total measurements are from California homes and more than 40% of the California homes sampled are in disadvantaged communities per CalEnviroScreen 4.0 (as checked in February 2025; Figure S8). While multiple studies have measured methane emissions from NG appliances, only one study quantified whole house quiescent leaks. There are more data on emissions during sustained combustion compared to transient events. The most measured burners are cooktops, followed by water heaters, pilot lights, ovens, and furnaces. Among water heating appliances, there are fewer measurements of tankless (TWH) compared to storage water heaters. Most pilot lights sampled were from storage water heaters (N=28), followed by wall furnaces (8), and central furnaces (3).

As shown in Figure S9, the majority of homes with measurements were site-built, detached houses (83%). There were fewer apartments (13%), townhouses (3%) and manufactured homes (1%). Compared to 2023 American Housing Survey (AHS) statistics for California,[27] the homes in which methane emissions have been measured include more single-detached relative to other housing types, similar percentages of homes built since 1990 and similar percentages of homes larger than 2500 ft^2. The sample includes more homes older than 1950 and smaller than 1500 ft^2. Most of the measured gas appliances were manufactured after 2000. Only about 20% of the furnaces, 8% of the cooking appliances and 6% of water heaters in the compiled data were manufactured before 2000. Most water heating (83%) and space heating (58%) appliances were atmospherically vented.

3.1.2. Whole house quiescent leaks

Using the bootstrapping method, we estimate the mean quiescent leaks (E_{QL}) to be 5.0 g CH_4 day^{-1} (90% CI: 3.6-7.2) from measurements of 64 California homes. In their analysis, Fischer et al.[5] noted that the measured values are highly skewed with a long tail distribution. Our analysis suggests some potential associations. Figure 1 shows that higher E_{QL} was measured in older homes (pre-1978) compared to newer homes (Mann Whitney, p = 0.002) and homes with a crawlspace, 86% of which were pre-1978, versus slab foundation, 77% of which were 1978 and newer (p=0.02). These results are consistent with degradation of gas distribution pipes and valves over time in older homes with more impacts to infrastructure in the crawlspace, which can be more exposed to weather and moisture. The size of the home, divided into small (<1500 sq ft), medium (1500-2500), and large (>2500) dwelling units,[28] was not predictive of the quiescent emission rate. Interestingly, the quiescent emission rate decreased with an increasing number of gas appliances associated with the property (not specifically inside the structure) and emissions

in homes with 2-3 appliances at the site were marginally significantly higher (p=0.08) than homes with 5-7 appliances. This result may be related to a confounding correlation between number of appliances and year of construction, as the median construction year was 1979 for homes with 2-3 gas appliances and 1989 for those with 5-7 appliances. Fischer et al.[5] observed that E_{QL} variations could not be explained by the small amount of pipe leaks detected by the field team, but noted that leak testing may have underestimated the actual number of pipe leaks in homes due to inaccessibility.

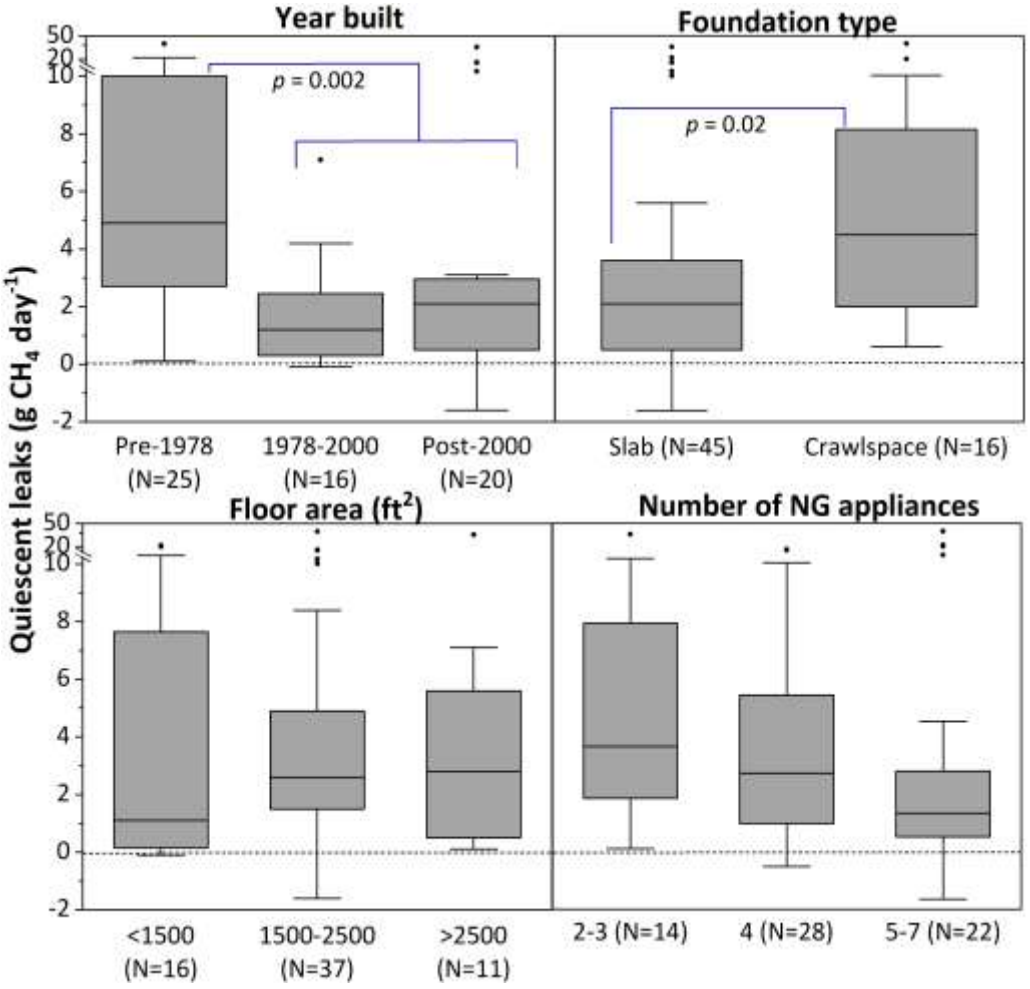


Figure 1. Whole house quiescent leaks in California homes based on year built, foundation type, floor area, and presence of natural gas (NG) appliances. These are as-measured and include emissions from any pilot burners in the mixing volume. Boxes show the interquartile range (IQR) and median and whiskers extend to 1.5x IQR. *P*-values based on Mann-Whitney test, are shown only for those comparisons that have p <0.05.

Figure 1 shows that the distribution of measured quiescent leaks extends to negative values. Two possible explanations are (1) near zero leaks with measurement uncertainties leading to negative values and (2) fluctuations in outdoor methane concentrations over the time scale of a whole

house measurement, particularly when leaks within the home are low. Measurement resolution can be improved by limiting the airflow through the blower door to the minimum needed to establish depressurization; this increases the indoor methane concentrations relative to the outdoor level while lengthening the time required to reach steady state and reducing the robustness of air connection to buffer zones. In the data collected by Fischer et al.[5] (N=75), the attic and attached garage were the buffer zones that most commonly had gas appliances. One home had a furnace in its crawlspace. Furnaces were the only appliances located in the attic while the attached garage mostly housed water heaters (59% of the total water heaters), followed by clothes dryers (28%) and furnaces (16%).

The Fischer et al.[5] field team connected attached garages and attics to the living space by opening the garage access door and partially opening the attic hatch. We expect that the large opening of the garage access door robustly connected that space to the space where the blower door was installed. Owing to the smaller opening, the pressure connection to the attic was not as robust, and vented attics with large openings to the outside may have had some two-way airflow with the outdoors, even during depressurization of the living space. Any direct airflow connection between the attic and outdoors would bias the whole-house quiescent leakage measurement because some of the emissions in the attic would not be transported to the blower door.

3.1.3. Emissions from pilot lights

The distribution of direct measurement of 28 SWH pilot lights, which are the appliances that most commonly have pilot burners in California homes, and 11 furnace (3 CF and 8 WF) pilot lights were investigated. The inter-quartile range (IQR) of enrichment ratios were 0.13-0.47% and 0.23-0.95% for water heater and furnace pilot lights. The emissions from pilot light of both water heating and space heating did not exhibit significant difference (p=0.13).

We therefore use the direct sampling measurements for 28 SWH, 3 CF, and 8 WF to calculate annual pilot burner emissions and their mean contributions to quiescent emissions and the statewide inventory. Bootstrapping analysis of these 39 pilot lights yields a mean enrichment ratio of 0.41% (90% CI: 0.31–0.55%) and emission factor of 75 ng J^{-1} (CI: 56–100 ng J^{-1}). The annual emissions for a single pilot burner and comparison to those from individual appliance operations and whole-house quiescent are presented in Figure 4 and the contributions to the statewide inventory are shown in Figure 5.

The mean enrichment ratio of SWH pilots from direct measurements was 0.34% (90% CI: 0.25-0.48%) and our analysis of “steady-state Off” emissions from 18 SWH reported by Lebel et al.,[7] found a mean enrichment ratio of 1.34% (90% CI: 0.71-2.34%). The medians were 0.22% and 0.37% (p=0.07), suggesting that other sources inside the home may have commonly added to the pilot burner emissions when the dilution sampling method was used, as noted by Lebel et al.[7]

3.1.4. Emissions from sustained combustion

Figure 2 summarizes the available data on methane emissions from sustained combustion (R_{SC}). Gas furnaces within rooftop units (RTU), standalone central furnaces (CF), and wall furnaces (WFs) had the lowest emissions during sustained combustion, followed in order of increasing emissions by SWH, TWH and cooking burners.

Substantial fractions of RTU (75%), CF (24%), and SWH (50%) had zero or negative enrichment ratios (Figure 2a). While negative values may result from methodological imprecision when emissions are very low, we assess that these results accurately capture the many cases in which methane emissions are truly net zero or even negative, reflecting some methane in the combustion air being burned in the appliance.[5–7] We therefore retain them in the distribution for an accurate determination of the mean emission rate for inventory purposes. Methodological imprecision can result from heterogeneity in the flue or vent flow during direct measurements and/or variations in CH_4 and CO_2 concentrations in the combustion and/or dilution air with direct or dilution sampling. Figure 2b shows that TWH had a much higher mean enrichment ratio (0.18%; CI: 0.13-0.25%) and emission factor (33 ng J^{-1}; CI: 24-46 ng J^{-1}) compared to SWH (0.09%; CI: 0.05-0.19%) / (16 ng J^{-1}; CI: 9-35 ng J^{-1}), with only 7% of measurements indicating zero or negative emissions. This may be explained by the difference in their burner designs and operating patterns. SWH have relatively spacious combustion chambers and single stage burners optimized for their firing rate. They operate for many minutes at a time in a steady state. By contrast, TWH have very small combustion chambers and burners that are optimized to modulate over a wide range of firing rates as water flow varies. They can have turndown ratios (highest to lowest firing rates) of >10. TWHs also have larger capacity burners (mean rated maximum firing rate from database: 176,000 BTU hr^{-1}) compared to SWH (mean rated firing rate from database: 40,000 BTU hr^{-1}).

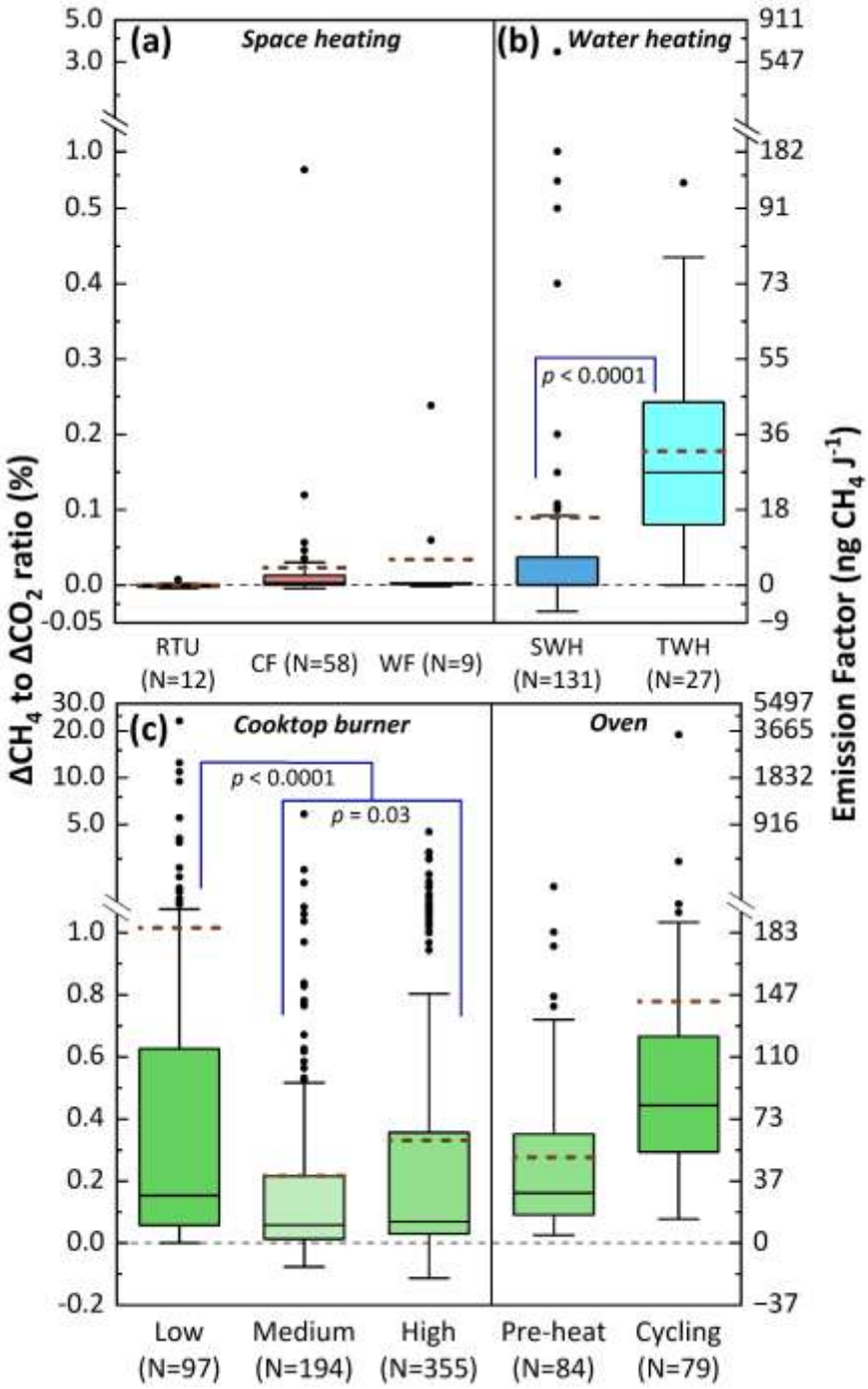


Figure 2. Methane emissions from appliances during sustained combustion (firing) of main burner, expressed as enrichment ratio (left axis) and emission factor (right axis). The abbreviations are defined as follows: RTU = furnace in packaged rooftop unit, CF = central furnace, WF = wall furnace, SWH = storage water heater, TWH = tankless water heater. Refer to Figure 1 for box and whisker parameters.

Figure 2c shows that cooking appliances tend to have higher enrichment ratios compared to space and water heating appliances. Cooktop burners had higher normalized emissions when the burner was operated at a low flame setting (1.1%; CI: 0.65-2.0%), compared to medium (0.22%; CI: 0.16-0.33%) or high flame setting (0.33%; CI: 0.28-0.41%). Both pairwise comparisons were statistically discernible based on Mann-Whitney ($p < 0.0001$ for medium vs low and $p = 0.03$ for medium vs. high). The lower emission factors, and also lower variability, observed when cooktops were operated on a medium setting than a low or high setting was noted by Lebel et al.,[8] who provided the majority of emissions data from cooktops at settings other than high. The enrichment ratios of ovens during pre-heating (0.28%; CI: 0.23-0.36%) and cycling for sustained operation (0.78%; CI: 0.52-1.94%) are similar to the values measured for cooktop burners. However, since the pre-heating and cycling emissions include transients, this suggests higher sustained combustion emissions for cooktop burners. Translating oven pre-heat and cycling enrichment ratios to emission factors leads to E_{PH} = 51 ng J^{-1} (CI: 42-67 ng J^{-1}) and E_{OC} = 142 ng J^{-1} (CI: 95-356 ng J^{-1}). Oven pre-heat emissions are lower than cycling because pre-heating involves one long, steady burn (mean pre-heat duration: 12 mins) with only two transient peaks (ignition and extinguishment). In contrast, cycling undergoes multiple short bursts (mean cycle of 3-4 mins) and include two transient peaks for each cycle, leading to higher overall emissions.

In the absence of user operability data on cooktop burners (low, medium, and high mode), we equal weight the emission factors observed in different flame settings, leading to sustained combustion emission factor of 95 ng J^{-1} (CI: 80-118 ng J^{-1}). We estimate that this roughly translates to operating the burners at high, medium, and low flame settings for 14%, 29%, and 57% of the cooking duration, respectively. This breakdown would result from using a 12,000 Btu hr^{-1} burner at medium and low flame settings of 6000 Btu hr^{-1} and 3000 Btu hr^{-1}, respectively. We combined RTU and CF and estimated their mean emission factor of 4 ng J^{-1} (CI: 2-13 ng J^{-1}). Table S3 summarizes the mean (with 90% CI) emission factors of pilot light, water heaters, furnaces, cooktop, and oven used for calculating the statewide methane emissions.

3.1.5. Transient emissions

Figure 3 shows the transient emissions from ignition and extinguishment separately, which are later summed to obtain the mass emitted per burner event (E_{TR}). For each type of appliance, emissions during ignition were responsible for 66-79% of transient emissions. TWH had much higher transient emissions (mean 114 mg CH_4 $event^{-1}$; CI: 90-142) than SWH (mean 20 mg CH_4 $event^{-1}$; CI: 14-27). Mean transients were higher for RTUs and CFs (69 mg CH_4 $event^{-1}$; CI: 52-107) than for WFs (15 mg CH_4 $event^{-1}$; CI: 14–16). These differences among appliances could be related to their different burner and ignition configurations. TWH, RTU, and CF have larger burners with higher flow rates of NG compared to SWH and WF, leading to relatively more unburned gas being emitted during their ignition and extinguishment. All TWH and many central furnaces have multistage burners with different sections or numbers of burners firing to meet varied heating

demands. And almost all TWH and RTU/CF sold over the past several decades have electronic ignition. By contrast, most SWH and WF have pilots and single stage (firing rate) burners.

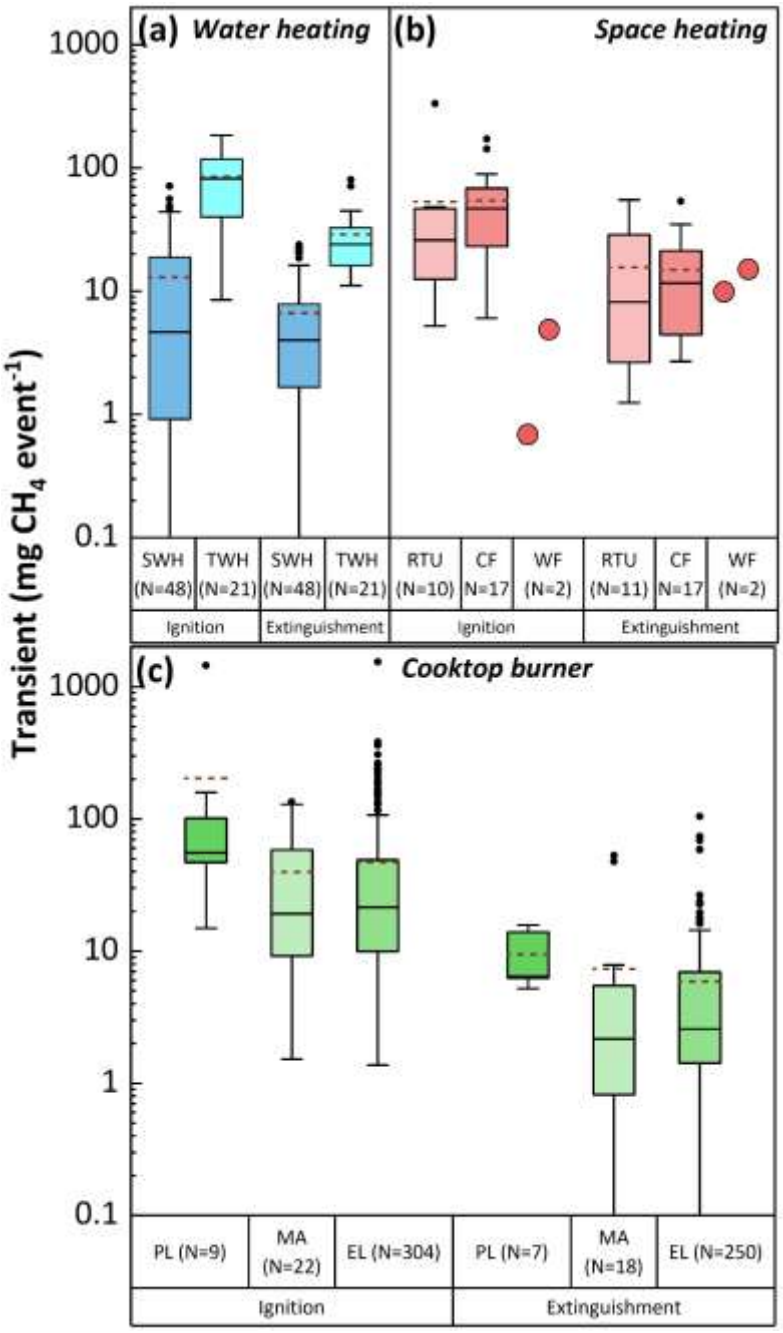


Figure 3. Methane emissions during the transient events of appliance main burner ignition and extinguishment. Abbreviations for panels (a)-(b) in Figure 2 caption. In panel (c), PL = pilot light, MA = match light and EL = electric spark ignition. Refer to Figure 1 for box and whisker parameters.

For cooking appliances, Figure 3c shows that transient emissions, especially during ignition, are higher for appliances with pilot ignition compared to match (p=0.02) or electronic ignition (p=0.006). In contrast to space and water heating appliances, Lebel et al.[8] posited that delay in ignition time may drive the higher transients for cooktop burners with pilot lights. Since the data for pilot ignition is only from three cooktops (or 9 individual burners), this warrants additional investigation. For inventory analysis, transient emissions from cooktop burners with electronic ignition (mean 52 mg CH_4 $event^{-1}$; CI: 44-71) is used as the most representative for the current stock.

Table S4 shows the mean (90% CI) emission factors for space heating, water heating, and cooking appliances that were used for calculating the statewide methane emissions.

3.2. Annual emission per appliance and quiescent leaks per home

Figure 4 shows the estimated annual CH_4 emitted from a single unit of each appliance or housing unit. It also shows the variability based on the emission metrics (10^{th} and 90^{th} percentiles), while keeping the usage parameters the same (UEC and N_{BF}, mean values only). For WFs, which had only nine and two measurements for sustained combustion and transient emissions, respectively, the minimum and maximum values are presented instead of the 10^{th} and 90^{th}. This analysis shows that, when present, a TWH often will be the largest source within a home, largely due to high transients, and subject to large variability. We estimate mean TWH emissions of 2456 g CH_4 yr^{-1} with a 10^{th}–90^{th} range of 584-5491 g CH_4 yr^{-1}. Since TWH are not very prevalent, the largest source in most homes is the aggregate of whole house quiescent leaks, even without pilot light(s) included (mean = 1470, 10^{th}–90^{th}: 38-5039 g CH_4 yr^{-1}). A single pilot burner is typically the next largest distinct source in a home. Among the most common appliances, SWH are estimated to emit about 395 g CH_4 yr^{-1} (mean) from transients and sustained combustion, in addition to most having standing pilot lights that emit 355 g CH_4 yr^{-1} on average. The pilot emissions estimate is 32% higher than Fischer et al.,[5] resulting from a lower enrichment ratio (0.41%, determined from 39 measurements vs. 0.56% from 9 measurements) and a higher firing rate (541 BTU hr^{-1} from measurements vs. 300 BTU hr^{-1} assumed). Annual emissions associated with space heating and cooking are smaller. We estimate that wall furnaces emit somewhat more (mean 233 g CH_4 yr^{-1}) than central furnaces (mean 180 g CH_4 yr^{-1}). As in the case of SWH, a WF or CF with continuous pilot will have additional emissions of 355 g CH_4 yr^{-1} on average. The combined emissions from cooktop (mean 206 g CH_4 yr^{-1}) and oven (mean 81 g CH_4 yr^{-1}) is similar to the estimate for a space heating appliance.

Methane emissions from TWHs and CFs are dominated by transients. This can be explained by their frequent burner cycles when the appliance is in use and higher E_{TR}. Methane emissions for the other appliances are largely associated with sustained combustion and pilots.

Appliance-wise, TWH has the highest mean methane loss rate (0.8%), followed closely by cooktop (0.7%), oven (0.6%), and pilot light (0.5%), while SWH (0.1%) and furnace (0.06%) show the lowest

losses. Weighting these based on their estimated stock in California and annual fuel use per appliance (RASS 2019), we calculate 0.38% mean methane loss from major residential appliance usage in homes, translating to an overall fuel combustion efficiency of 99.6%.

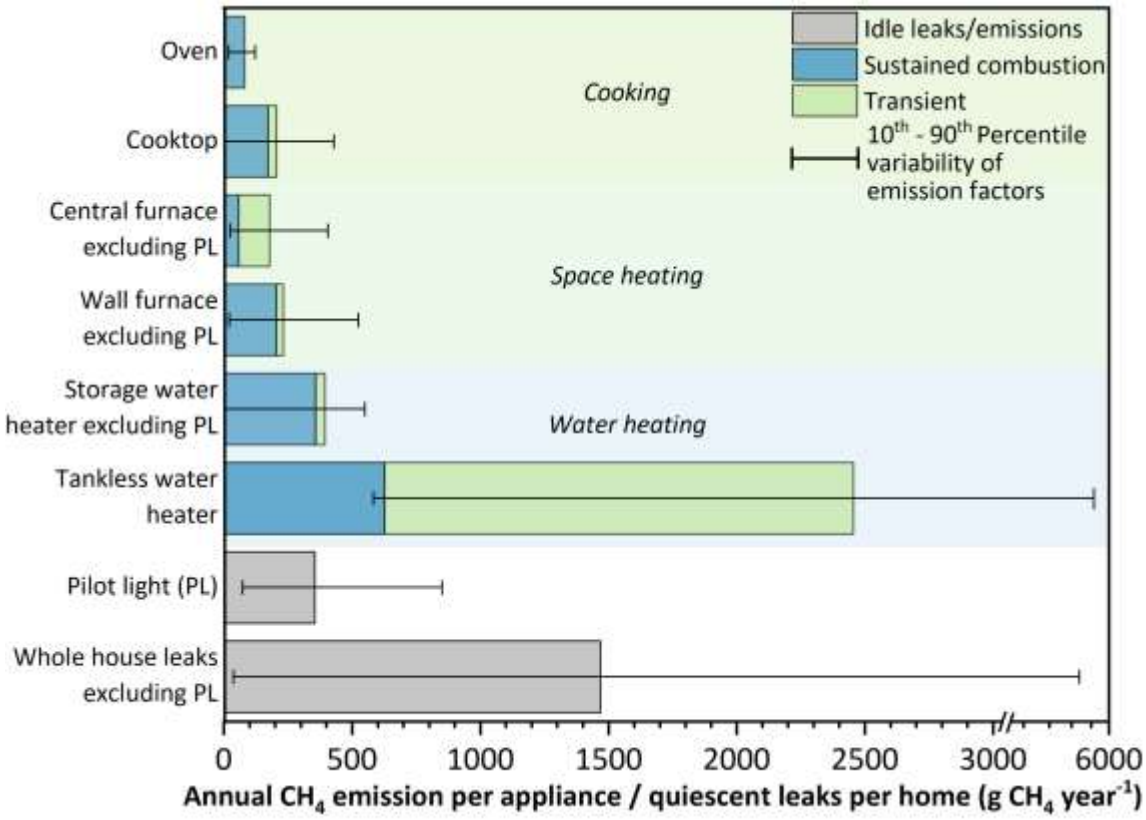


Figure 4. Estimated annual methane emissions per appliance (excluding pilot light), pilot light, and quiescent leaks excluding pilot in California homes, averaged across housing types. Whiskers show the 10th–90th percentile variability of measured emission factors for each source except the wall furnace, which shows the minimum and maximum of nine sustained combustion emissions and two transient emissions measurements. All estimates use fixed estimates of activity factors described in the Supplement.

3.3. Annual emissions from appliances and quiescent leaks in California

From the estimated annual CH_4 emitted from quiescent leaks per home and distinct equipment, we estimated the aggregate statewide emissions from each source (Figure 5 and Table S5) and housing type (Table S6). The whiskers in Figure 5 and bracketed values in Tables S5 and S6 represent the 5th and 95th percentile confidence intervals (CI). These include the uncertainties in emission factors, burner firing frequencies, and the numbers of appliances and homes with NG connections. Consequently, the 5th percentile, mean, and 95th percentile of these distributions define the low, best, and high estimates, respectively. We did not consider uncertainty in the UECs by end use and housing type.

For single detached houses, we estimate total emissions of 20.2 Gg CH_4 yr^{-1}, of which 49% is associated with quiescent leaks excluding pilot light. We estimate that water heating (including pilot light) is the next leading contributor, accounting for 34% of the total of sources that we considered in the residential sector. Space heating (including pilot light) and cooking contribute 9% and 8%, respectively.

As mentioned earlier, we made several simplifying assumptions when extending Equation 5 to estimate emissions for housing types other than single detached, where most methane measurements were made. For this reason, our estimates for the other housing types are more uncertain. Compared to single family homes, the estimates for other housing types indicate slightly lower contributions from water heating and space heating, and slightly higher contributions from quiescent leaks.

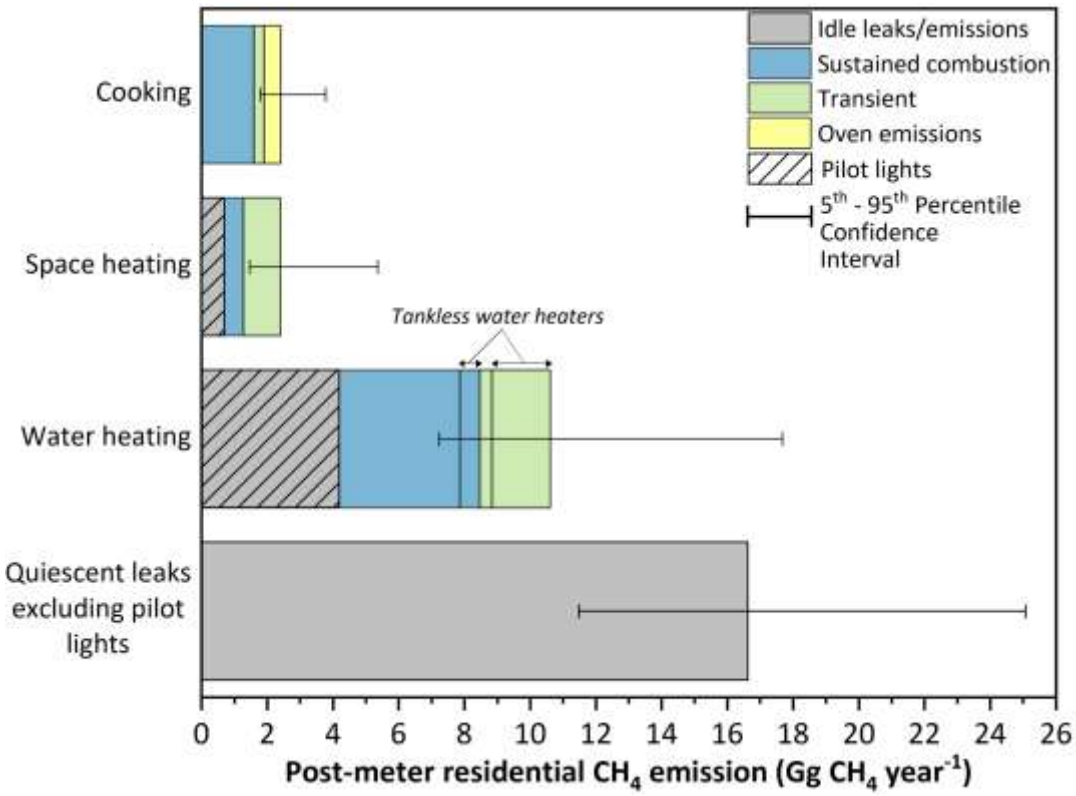


Figure 5. Estimated annual methane emissions from residential post-meter infrastructure and natural gas appliances in California. Diagonal solid patterns indicate the estimated contribution of standing pilot lights. Operational and transient emissions for cooking refers to the cooktop burners. Whiskers refer to the 5^{th}–95^{th} percentile confidence intervals of the total emissions for each category. All estimates use activity factors described in the Supplement.

For all California homes, we estimate post-meter emissions of 32.1 (21.0–52.9) Gg CH_4 yr^{-1}, which is similar to the estimate of 35.7 Gg CH_4 yr^{-1} (21.7–64.0) by Fischer et al.[5] Quiescent leaks (excluding pilot light) are the largest contributor (51.8%), followed by water heating (including

pilot light: 33.1%), space heating (including pilot light: 7.6%), and cooking (7.5%). The similarity of our estimate to that of Fischer et al.[5] is expected because quiescent leaks comprise the largest source and we used the Fischer et al.[5] data for this portion of the inventory. Quiescent leaks (excluding pilot light) are estimated to emit 16.6 (11.5-25.1) Gg CH_4 yr^{-1}. The second largest contributor is water heating, totaling 10.6 (6.3–19.3) Gg CH_4 yr^{-1}. Within the water heating category, we estimate that TWH contributes 22% of emissions despite comprising less than 10% of the appliances. Space heating (2.4 Gg CH_4 yr^{-1}; 1.5-5.4) and cooking appliances (2.4 Gg CH_4 yr^{-1}; 1.8–3.8) contribute equally. All standing pilot lights are estimated to emit 4.9 (3.1-7.5) Gg CH_4 yr^{-1}, of which 86% is attributable to pilot lights in storage water heaters. Pilot emissions are 15% of the total residential post-meter inventory.

4. Discussion

4.1 Potential associations that warrant further investigation

Beyond the associations of emissions with home and appliance characteristics noted in the Results, we note below additional factors that may impact methane emissions.

SWH manufactured before 2003 (N=13) had lower sustained combustion enrichment (mean R_{SC} = 0.009%) compared to those manufactured after 2003 (N=72; mean = 0.08%), as shown in Figure S10; but the two distributions were not statistically distinguishable (p = 0.68). A change in emissions around this time is plausible because SWH air intakes were modified to incorporate flammable vapor ignition resistant (FVIR) technology to prevent accidental fire.[29] All of the SWH identified as outliers with R_{SC} >0.09% were manufactured after 2003.

For space heating (Figure S11), the 13 central furnaces in the database that were manufactured before 2000 had notably higher emissions than 32 newer units (R_{SC} of 0.08% vs. 0.01%; p = 0.07). The older CFs were more likely to have pilots (8 out of 13) than the newer ones (4 out of 32); however, the presence of a pilot does not relate to sustained combustion emission (p = 0.63). R_{SC} was also observed to be higher (p = 0.03) for single-stage CFs (mean = 0.03%; N=35) compared to multi-stage CFs (mean = 0.01%; N=13), which could be more related to age, as a larger fraction of pre-2000 CFs (87%) were single-stage compared to newer ones (71%).

Cooktop burners with pilots had higher transient emissions than those with electric ignition (p = 0.009). Lebel et al.[8] suggested that ignition delay in cooktop burners with pilots might explain their higher transient emissions. As more data are being gathered for the CARMEC study, these associations can be examined again for their statistical significance and implications.

4.2 Limitations of the existing data

The analysis was conducted with the best available data; but the samples from which those data were obtained are still relatively limited. Whole-house leaks (excluding pilots) are solely based on Fischer et al.,[5] and most of the appliance transient emissions are from Lebel et al.[7,8] and SUMMATION studies (Table S7).

The data on whole-house quiescent leaks were obtained exclusively from measurements of single detached houses and may not accurately represent all residential units, especially multifamily. While data on whole-house quiescent leaks were available for only 64 houses from a sample of 75 selected to span the ranges of building age, floor area, and number of stories in the 2011 American Housing Survey,[5] their representativeness for statewide methane emissions is nevertheless uncertain. Within that limitation, we note and agree with the assertion by Fischer et al.[5] that data from single houses can be used to estimate emissions from other housing types which have similar numbers of gas appliances and distribution infrastructure of similar scale, including townhouses, 2-4 unit homes, and manufactured homes. Their relevance is much lower for larger and taller multifamily buildings, that tend to have fewer appliances within the units, more commonly have central hot water, and have different internal distribution infrastructure. Recently, other methods have been used to measure quiescent leaks in other housing types.[30,31] Using a room chamber method, Nicholas et al.[31] measured quiescent leaks in 20 buildings in Boston, reporting emissions that correspond to 1.8 (90% CI: 1.3–2.5) g CH_4 day^{-1} in 11 basements in single-family homes and 2.9 (90% CI: 1.4–5.7) in the basements of 7 buildings with 2-3 units each. While these are a bit lower than the 5.0 (90% CI: 3.6-7.2) g CH_4 day^{-1} for houses in Fischer et al.,[5] the difference could result from the Nicholas et al.[31] approach not including all gas infrastructure and appliances in the home, notably excluding cooking appliances, or from real differences in the two samples. Karion et al.[30] reported whole house leakage of 0.3 g CH_4 day^{-1} in a single manufactured home with stove and furnace and no pilots. More measurements of quiescent emissions from other housing types, especially apartments and equipment rooms in large multifamily buildings are needed to bolster inventory estimates.

While we compiled large numbers of emissions measurements from storage water heaters, central furnaces, cooktops and ovens, there were fewer measurements of tankless water heaters, furnaces in packaged units, and wall furnaces. And the existing data includes no measurements of other types of gas appliances including, indoor fireplaces, clothes dryers, outdoor grills, firepits, and pool and spa heaters. Measurements of these appliances are needed to assess their contributions to the inventory.

As with many emission inventories, there is the potential bias that the measured homes and appliances do not proportionally include super-emitters that can drive population emissions when they exist. It is plausible that there are appliances in very poor working condition and homes that are very poorly maintained that were not represented in the existing data. The

recruitment approaches of the studies that contributed data varied, and the SUMMATION study intentionally sought to sample in lower-resourced homes; but the teams conducting the studies encountered very few appliances or homes that were in severe states of disrepair. Unfortunately, we have no basis to estimate this potential bias.

4.3 Limitations of the present analysis

The estimated emissions for an average unit of each source (whole-house quiescent, pilot, various appliances) considered only the observed variability of emission rates and not variability in appliance use across homes.

As a simplification, we assumed that all natural gas SWH in California have standing pilots; but this is not correct, as models with electronic ignition are available and sold in the state. We were not able to identify a robust estimate of the fraction of such models in the stock or in current sales. And their small prevalence is supported by the fact that all of the gas SWH measured in the contributing studies and also in the measurements conducted for the CARMEC study had standing pilots.

The current study did not compile and analyze emissions data for meter set assemblies (MSAs). Studies have reported highly variable estimates of methane emissions from MSAs. Measured mean MSAs emissions in California homes were 0.8 g CH_4 day^{-1} (N=94; statewide estimate) and 312 g CH_4 day^{-1} (N=485) for homes in Southern California.[12,13] The more than two orders of magnitude larger mean estimate of MSAs leaks for Southern California is strongly driven by 8% of the dataset being classified as "hazardous" (mean = 4,550 g CH_4 day^{-1}; 90% CI: 2,320-7,140). In the case of statewide measurement, the maximum observed MSAs leak was 44 g CH_4 day^{-1}. At 0.8 g CH_4 day^{-1}, MSAs in California would contribute about 10% additional emissions to the statewide total residential methane emissions, leading to 35.0 Gg CH_4 yr^{-1}. Studies in Canada estimated 5.5 g CH_4 day^{-1} for Montreal (N=71) and 29 g CH_4 day^{-1} in Calgary and Alberta (N=37).[11,14] It is clear that emissions from MSAs are an important contributor associated with residential NG usage and more data are needed. In some cases, depending on the location of the MSA, its contributions could also impact whole-house quiescent leak measurements. While Fischer et al.[5] observed it in only a couple of homes, the authors have heard from contractors and building energy raters that it is common to have MSAs in crawlspaces in older homes in Southern California. And several of the co-authors have observed MSAs located adjacent to crawlspace vents.

4.4 New insights on the residential post-meter methane inventory

This study advances over previous California post-meter residential methane inventory estimates by compiling and synthesizing emissions measurements from 509 appliances and 39 pilot lights, together with quiescent emissions from 64 homes, and providing data-supported insights about contributions of specific equipment and processes. While our estimate of total emissions from

the sector and the prominence of quiescent leaks are similar to those of Fischer et al.,[5] they are now supported by robust estimates of emissions during appliance operation, including transient processes. Our analysis of pilot burner emissions, which is based on substantially more direct measurements than Fischer et al.[5] conducted, and measured rather than estimated firing rates, reveals that roughly 23% of quiescent emissions are attributable to pilot burners. We also used the available appliance emissions data to provide more granularity to the inventory, with estimates by appliance type and process, considering pilots, transients, and sustained combustion. This analysis indicates that among the three most prominent gas end uses, water heating appliances contribute 33% of total methane emissions with smaller contributions from space heating (7.6%) and cooking (7.5%). Within the water heating category 39% of methane emissions are from pilot burners on storage water heaters and 20% are from transients, with most of those from tankless water heaters. Additionally, we found through comparison to direct measurements of pilot burner enrichment ratios that dilution method measurements of storage water heaters during resting mode likely included substantial contributions from other sources in the house beyond the pilot burner.

4.5 Emission inventory context

The calculated inventory of 32.1 Gg CH_4 yr^{-1} from California's post-meter residential infrastructure translates to 0.80 metric tons of CO_2 equivalent ($MMTCO_2e$) based on a 100 year Global Warming Potential (GWP) of 25[32] used by the California Air Resources Board.[33] This is slightly lower than the CARB 2023 inventory estimate of 0.94 $MMTCO_2e$ yr^{-1}, with 0.93 $MMTCO_2e$ yr^{-1} attributed to fugitive emissions.[34] Compared to the CARB 2023 estimates of methane emissions from all anthropogenic sources (36.7 $MMTCO_2e$), emissions from residential fuel use, including CO_2 (28.4 $MMTCO_2e$) and the statewide total of 360 $MMTCO_2e$ from all sources in 2023,[35] our estimate for the post-meter residential sector accounts for 2.2% of total methane, 2.8% of residential GHG emissions from fuel use, and 0.2% of total GHG emissions in the state. Considering that the residential sector uses 23% of the natural gas in the state,[36] the attributable fraction of GHG emissions from Natural Gas transmission and distribution (T&D) to residences is 0.99 $MMTCO_2e$, or roughly 1.25 times the emissions we estimate from all post-meter processes.

4.6 Comparison with top-down estimates

Flux-based estimates of methane emissions in urban areas of Baltimore, Washington DC, Boston, Los Angeles, and New York in the United States suggest fugitive emissions (losses) comprise 1-3% of commercial and residential NG consumption.[37–40] These emissions may occur during transmission and distribution to buildings, losses at meter set assemblies, and from post-meter processes including quiescent leaks, pilot burners and equipment operation. The U.S. Energy Information Administration[41] estimated that in California the residential and commercial sectors used 408,468 and 305,089 million cubic feet (MCF) of gas, or a split of residential using 57% and commercial 43% of the combined total during 2025. The California methane inventory estimates

a total of 4.26 MMTCO$_2$e of losses during transmission and distribution (T&D),[34] which translates to 9798 MCF of gas. Since residential and commercial sectors account for 40% of the natural gas used in the state, the T&D emissions attributable to those sectors is 3919 MCF of gas annually and this loss is 0.55% of the total gas used for the two sectors. Our estimate of post-meter methane loss in the residential sector is 1840 MCF, or 0.45% of the total gas used in the residential sector.

Funding

The primary work on this manuscript was supported by California Energy Commission (CEC) Contract PIR-21-008 and associated subcontracts between LBNL and PSE for Healthy Energy. Additional support, including the subcontract to Stanford, was provided by the US Department of Energy prior to FY25 under Contract DE-AC02-05CH11231. Collection of the as-yet unpublished data from the SUMMATION project was supported by CEC Contract PIR-17-015.

Acknowledgements

The authors thank Sharon Chen for conducting the laboratory evaluations of DHE, and Jing Ke for post-processing and analyzing the data. We thank the members of the project's Technical Advisory Committee and the Energy Commission Agreement Manager for their helpful input. The ToC Art was created using Figure Labs Ai.

Supporting Information

The SI includes the following: a schematic overview of data compilation and analyses, estimation of pilot burner firing rate, estimation of pilot light prevalence in California homes, annual energy consumption by end use, calculation of burner firing frequency for space heating and water heating appliances, usage frequency and attribution of unit energy to cooktop and oven burners, exploration of buffer zone(s) connection in whole house leaks measurement, and additional supplemental figures (Figure S8, S9, S10, and S11) and tables (Table S3, S4, S5, S6, and S7) referenced in the article.

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Supplementary Information

Methane Emissions from Post-Meter Residential Natural Gas Infrastructure: Integrating Existing Data to Inform California's Statewide Inventory

8 Sections, 11 Figures, and 7 Tables

1. Schematic overview of the data compilation and analyses

Figure S1 below provides a schematic representation of the data compilation and analysis presented in the manuscript.

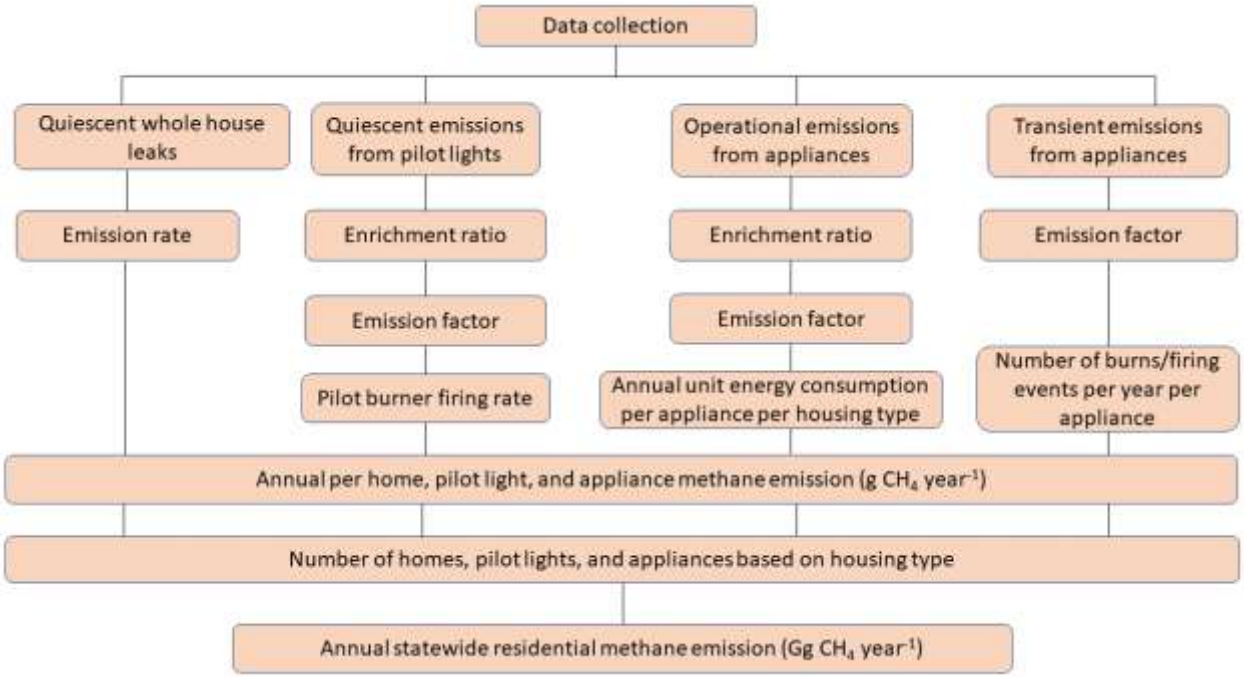


Figure S1. Schematic description of data collection, sorting, metrics calculation, and scaling factors involved in building annual statewide post-meter residential methane emission inventory for California.

2. Estimation of firing rate of pilot burner

Pilot burner firing rates (F_{burner}) were calculated from natural gas flows measured in two studies by Lebel and colleagues[1,2] The researchers obtained the gas flows by time-stamped video-recording of gas meters when no appliances in the home were being used and the only gas use was for the pilot of a single water heater. Equation S1 provides the calculation.

$$Firing\ rate\ (F_{burner}; BTU\ hr^{-1}) = Burner\ gas\ use\ (CFM) \times 1038 \times 60 \quad [S1]$$

In Equation S1, the gas use is in units of cubic feet per minute (CFM), 1038 BTU cf^{-1} is the assumed higher heating value of natural gas and 60 converts from minutes to 1 hour. Figure S2 shows the frequency distribution of SWH pilot light firing rate. The firing rate of 541 BTU hr^{-1} (90% CI: 482-600) is considered for both SWH and furnaces (old central furnace and wall furnace) for estimating pilot light emission rate.

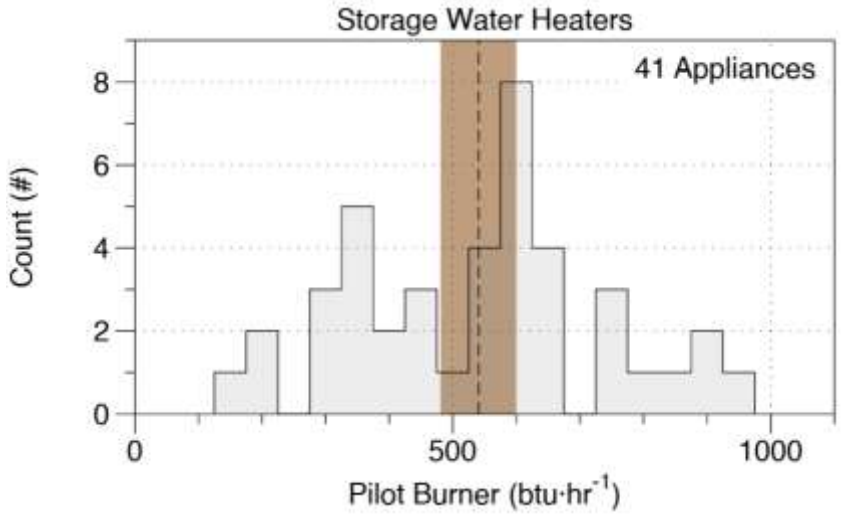


Figure S2. Frequency distribution of standing pilot light firing rate (BTU hr^{-1}) for pilot burners in storage water heaters.

3. Estimation of pilot light prevalence in California homes

To estimate the contribution of pilot lights to whole house leaks (as would be determined by our test method), we estimated the number of pilot lights per home for each housing category. For this, we used the 2020 Residential Energy Consumption Survey (RECS), which provides statistics on the number of homes with NG connections and the number of NG appliances in single-family, townhouse, 2-4 unit, 5+ unit, and manufactured housing in California (Table S1). We estimated the total number of pilot burners within the structures as the sum of 84% of the storage water heaters, 100% of the wall furnaces and 100% of central furnaces older than 2000. We then divided that number by the number of homes with natural gas connections within each housing category. We assume that all SWH have pilots and that 84% of those are inside the structures because 16% of the 142 storage water heaters in the compiled dataset were located in a detached garage, detached utility room or outdoor closet. We note that the assumption that all SWH, wall furnaces and older central furnaces have pilots is an overestimation. Also, the location of storage water heaters within or outside of the structure which were mostly based on single family homes and the proportion may differ in other housing types.

Table S1. Number of homes with natural gas connections and appliances, by housing type, in California as estimated in the 2020 Residential Energy Consumption Survey (RECS; revised March, 2023). All values

are reported in units of 100,000. The numbers within brackets are the 90% confidence intervals. ND = no data.

Appliance/Housing type	Single-family	Townhouse	2-4 unit apartment	5+ unit apartment	Manufactured homes	Total
Storage water heater	63.98 (62.88-65.08)	7.32 (4.83-9.81)	7.39 (7.20-7.57)	19.87 (19.02-20.71)	4.15 (4.06-4.23)	102.71 (98.01-107.40)
Tankless water heater	6.88 (6.75-7.00)	0.28 (0.10-0.46)	0.51 (0.49-0.53)	1.90 (1.77-2.03)	0.15 (0.14-0.15)	9.71 (9.25-10.17)
Central furnace (older than 2000)†	12.50 (12.31-12.69)	1.73 (1.23-2.22)	0.66 (0.65-0.67)	2.59 (2.51-1.67)	0.18 (0.18-0.19)	17.66 (16.88-18.45)
Central furnace (since 2000)†	54.87 (53.92-55.82)	4.63 (2.77-6.49)	3.76 (3.66-3.87)	6.77 (6.50-7.05)	2.96 (2.90-3.03)	73.00 (69.75-76.25)
Direct heating	4.27 (4.21-4.34)	1.31 (0.96-1.66)	1.58 (1.56-1.61)	2.96 (2.87-3.06)	0.22 (0.21-0.22)	10.35 (9.81-10.88)
Cooktop/range*	59.17 (58.16-60.17)	6.87 (4.18-9.56)	7.98 (7.76-8.20)	14.47 (13.90-15.04)	3.68 (3.60-3.75)	92.17 (87.61-96.73)
Total homes with NG connections	70.02 (68.99-71.05)	8.60 (8.21-9.00)	9.43 (8.88-9.98)	23.68 (22.45-24.92)	4.25 (3.85-4.64)	115.98 (112.38-119.58)

*68% of the total cooking appliances have a gas oven as per the current database with 266 cooktop/ranges.

†Number of old and new central furnaces are summed up during statewide inventory estimates.

4. Annual Energy Consumption by End Use

The California Residential Appliance Saturation Study (RASS, updated in 2019)[3] provides annual unit energy consumption by end use (UEC; therms per year) as a function of housing type (Table S2).

Table S2. Unit energy consumption (UEC; therms per gas appliance per year) by housing type based on the 2019 California Residential Appliance Saturation Study (RASS). N is the number of households that responded to the survey.

Category	Single-family (N=22,846)	Townhouse (N=2872)	2-4 unit apt (N=2124)	5+ unit apt (N=4189)	Manufactured homes (N=551)
Primary heat*	189	83	69	53	144
Conventional water heat†	258	257	246	248	253
Range/oven	25	33	24	21	19

* This UEC is applied to central furnaces or wall furnaces (direct heating equipment), when designated as the primary heating appliances in the Residential Energy Consumption Survey, shown in Table S1.

†Tankless water heater consumes 29% less energy than conventional/storage water heater.[1]

5. Calculation of burner firing frequency for space heating and water heating

The Donate Your Data (DYD) program (https://www.ecobee.com/en-us/donate-your-data) initiated by the Ecobee company in 2015 allows customers to voluntarily share the thermostat data. Some of the valuable operational information captured in this dataset includes heating or cooling runtime, setpoints, and indoor temperatures. We obtained and analyzed data from 332 California homes for the year 2017, which included a total of ~0.6 million furnace cycles.[4] The Ecobee database provides information about time (seconds) the furnace was on during each 5-minute interval. We considered a cycle of burner operation as occurring when there was an uninterrupted furnace-ON signal across a 5-minute interval. Mechanically, furnaces or HVAC systems are not designed to perform short-cycles (less than 5 minutes) to prevent damage; however, there is a possibility of few homes with furnaces undergoing short-cycles, for which the number of firings per year might be underestimated. The data reveals strong seasonality with the most cycles in November-March (Figure S3) and shows that short-term appliance monitoring may not capture the annual pattern. The estimated annual firings per space heating appliance is 1759 (90% CI: 1642-1894).

41 storage water heaters monitored using thermocouple loggers during Lebel et al.[1,2] and SUMMATION[5] studies (1151 measurement days) indicated firing frequency of 5 (90% CI: 4-6) per day (Figure S4). For tankless water heaters (TWHs), Lebel et al.[1] and SUMMATION[5] indicated 44 (90% CI: 35-59) activations per day of the combustion air fan, which operates whenever the burner is firing. The distributions of data from each study are shown in Figure S5.

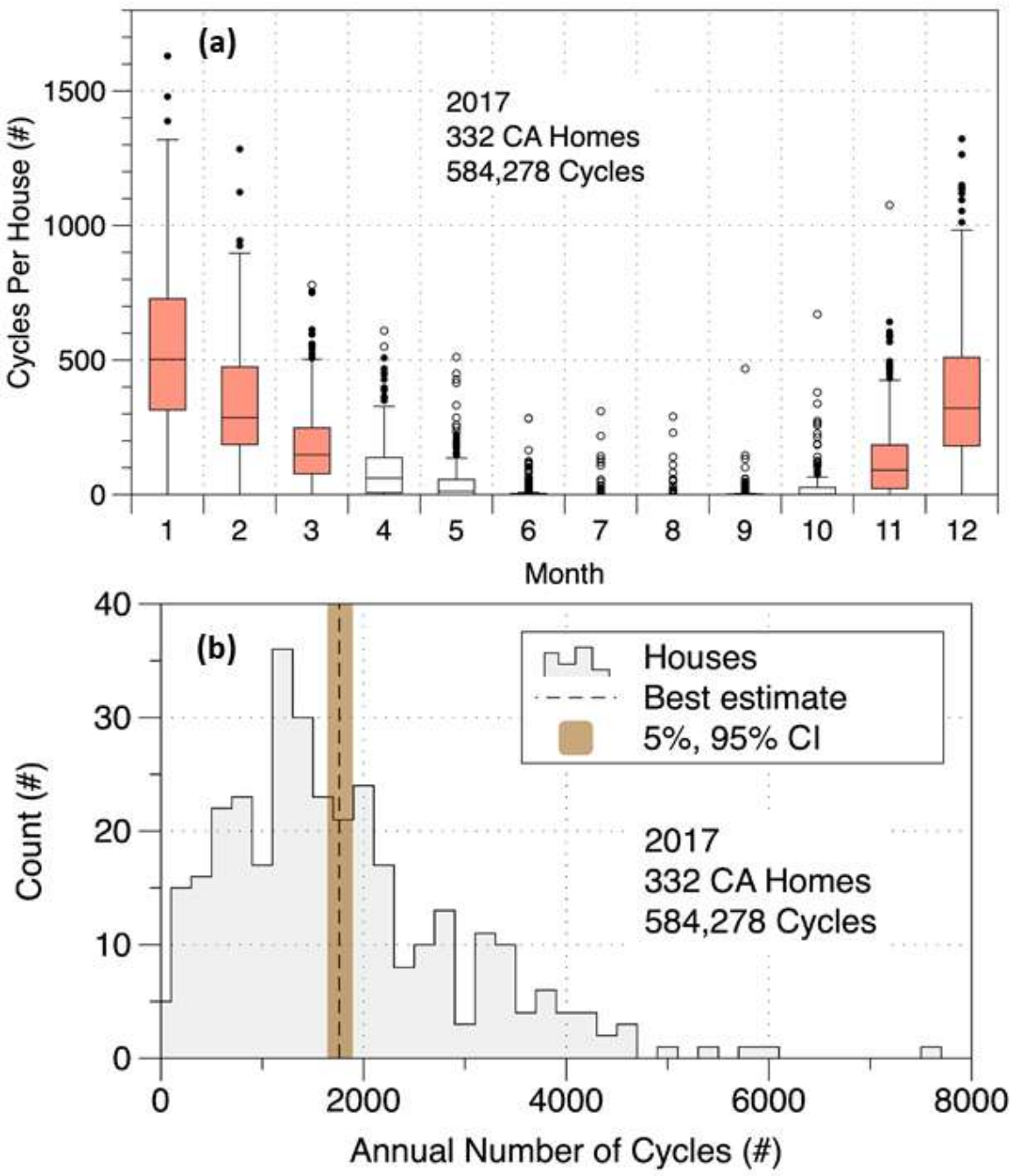


Figure S3. (a) Estimated distribution of furnace burner cycles by month and (b) frequency distribution with central estimate (bootstrapping method) for annual furnace firing event in California, obtained from Ecobee thermostat data.

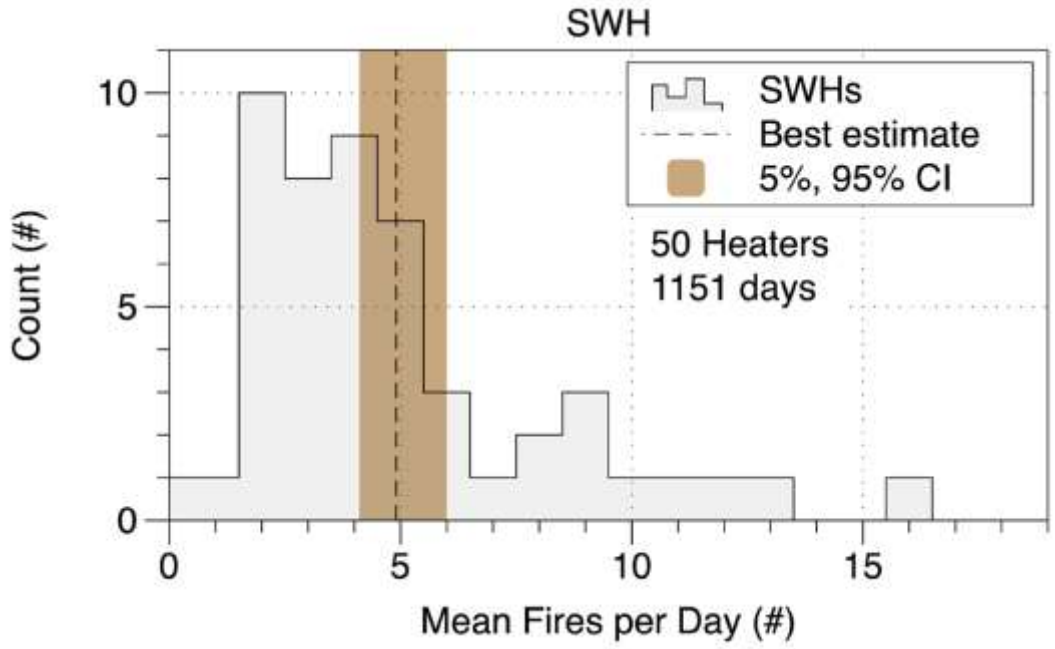


Figure S4. Frequency distribution with central estimate (bootstrapping method) for storage water heater (SWH) burner cycles (firings per day).

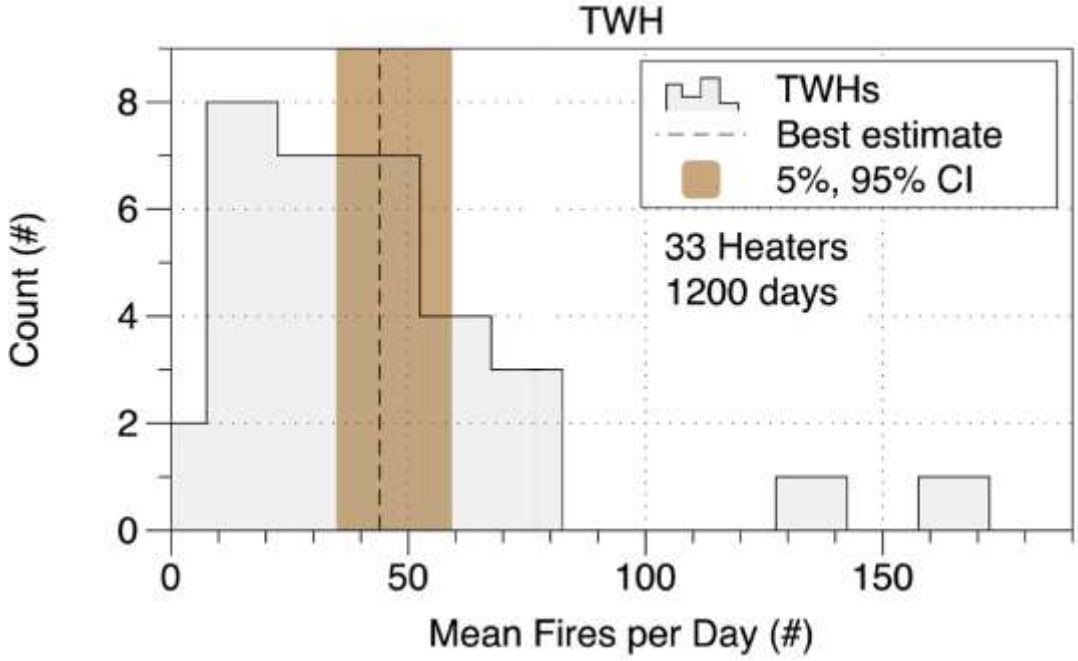


Figure S5. Frequency distribution with central estimate (black dashed line; bootstrapping method) for tankless water heater (TWH) burner cycles (firings per day) from Lebel et al.[1] and SUMMATION.[5]

6. Use frequency and attribution of unit energy to cooktop and oven burners

UEC provided for cooking appliances in RASS 2019 is the combined total for cooktop and oven use. For highlighting their individual contribution to CH_4 emissions, it was necessary to separate their share in energy consumption. In an ongoing methane emission characterization, and appliance information and usage data collection effort in California residential methane emission characterization (CARMEC) study, participants reported that they mostly used the front two cooktop burners, whose rated firing rates (BTU hr^{-1}) averaged to be ~12,000; and that of oven to be ~17,500 based on the compiled data.

The burner activation frequency is determined from measurements of cooking burner use in 57 single family homes and 23 apartments, which were compiled in Zhao et al.[6] from studies in California homes in 2016-2019.[7,8] Across all instances of cooking burner use over the approximately one-week of sampling in each home, the mean usage rate for any cooktop burner and the oven were 12.39 (90% CI: 9.20-13.50) and 1.69 (1.40-2.70) times per week, and the mean use durations were 19.72 and 45.3 minutes, respectively. The distributions are shown in Figure S6.

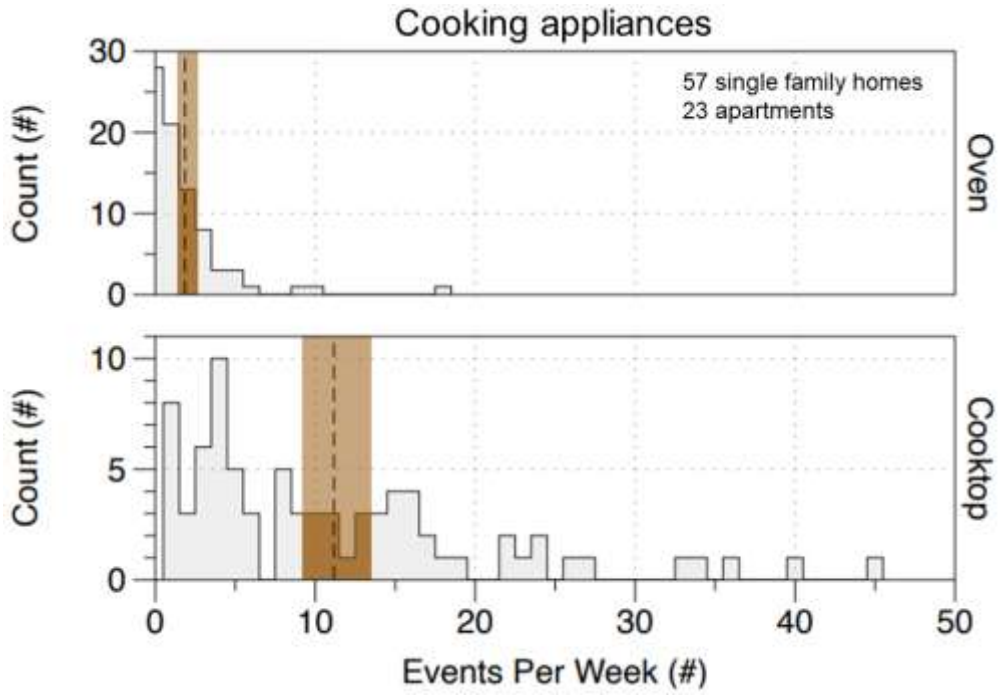


Figure S6. Frequency distributions with central estimates (bootstrapping method) for oven and cooktop burner usage obtained from Zhao et al.[6] analysis of data from single family detached homes and apartments of California.

The energy use of each type of burner is then determined by considering the mean firing rate of each and the total burn time on a weekly basis, using Equation S2, below. In this equation, T_{burner} is the burner operating time in hours, F_{burner} is the time-averaged firing rate (BTU hr^{-1}), and N_{uses} is the number of uses per week.

$$Weekly\ Energy\ (kBtu) = T_{burn} \times F_{burner} \times N_{uses} \quad [S2]$$

For cooktops, we assumed an average firing rate of 8,000 BTU hr^{-1} to account for burners being used at a range of settings, including sometimes for extended periods at lower and medium heat as occurs for simmering, pasta cooking, etc. We note the average rating (maximum setting) for front burners in the database is 12,000 Btu hr^{-1}. Combining the averages for firing rate, burner time per event and events per week yields an estimated 32.4 kBtu of weekly energy use by the cooktop. For the oven, it is necessary to divide the time between pre-heat and cycling phases. The mean pre-heat time based on compiled data (N=84) is taken as 12 minutes. Subtracting this from the average usage time of 45 minutes yields an average of 33 minutes of cycling per usage event. Considering that the burner operates for about 50% of the time during cycling translates to 16.5 minutes of oven burner operation during cycling and 28.5 minutes total per use, and a breakdown of 42% for pre-heat and 58% for cycling. The average burner time was combined with an average oven burner firing rate of 17,500 from the database to yield an estimate of 14.1 kBtu of weekly energy use by the oven. We note that these bottom-up weekly energy use estimates for cooktops and ovens translate to a UEC of 24 therms yr^{-1}, which align with the RASS estimates for single-family and apartments (Table S2).

The calculated weekly averages for cooktop (32.4 kBtu) and oven (14.1 kBtu) energy use indicate a breakdown of roughly 70% for the cooktop and 30% for the oven. These fractions are applied to the UEC for cooking in each housing type to obtain the annual energy used by each type of cooking burner.

7. Buffer zone (garage) connection in whole house leaks measurements

To explore whether the Fischer et al.[9] method was able to connect buffer zones (in this case, attached garage) with NG appliances and infrastructure, the homes were classified among these three categories: (I) pilot light (PL) in living space (N=11), (II) PL in attached garage (N=33), and (III) No PL / PL outside building envelope (N=14). There were four measurements that indicated the presence of two PL, which were excluded to maintain uniformity of one PL comparison. PL outside building envelope refers to homes with SWH located outside (N=10), generally in an outdoor closet. Non-parameteric Mann-Whitney Test among these categories indicated: a) significant difference between category I and II (p=0.002), and b) no difference between categories I and III (p=0.41), and II and III (p=0.21) (Figure S7). Broadly, looking at the data as homes with (N=44) and without (N=14) PL also indicated no difference (p=0.49). This suggests that presence of PL (which are non-zero emissions) is not a robust indicator of connection of buffer zones as the whole house leaks exhibit large variability with leaks from NG infrastructure and appliances masking the contribution from a PL. Hence, we cannot ascertain the coupling / de-coupling of buffer zones in Fischer et al.[9] whole house quiescent leaks test. For the analysis purpose, we use 64 data points that met their quality assurance out of 75 tested homes.

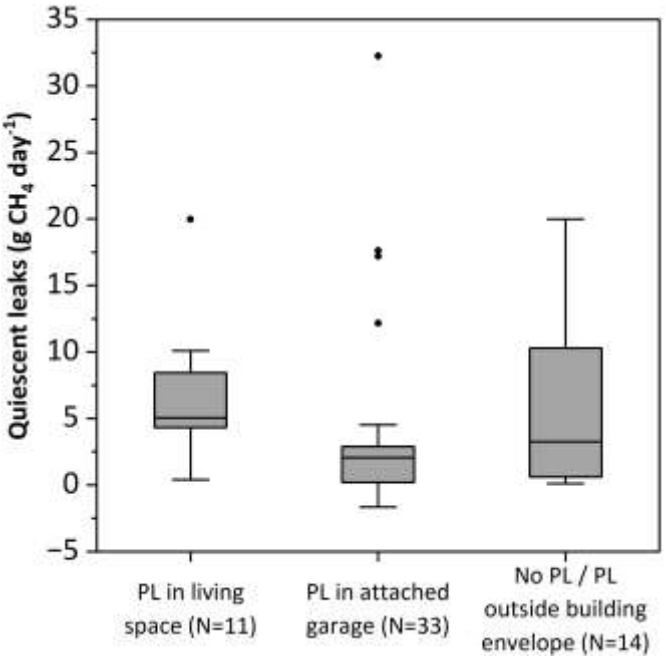


Figure S7. Quiescent leaks based on the presence / absence of a standing pilot light (PL).

8. Additional Supplemental Figures and Tables Referenced in the Main Text

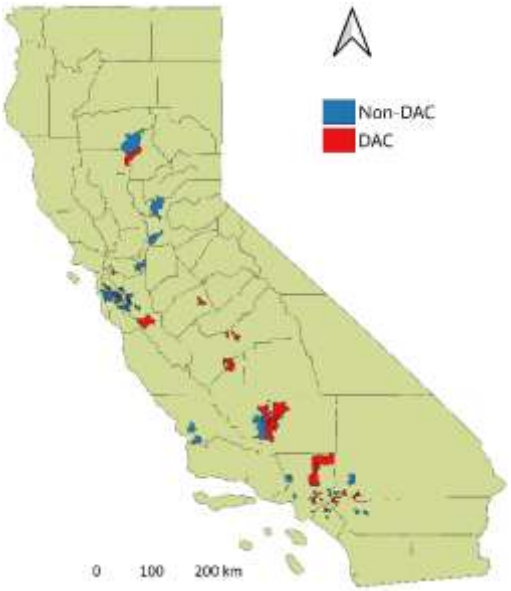


Figure S8. Spatial distribution of sampling location as color-coded zip codes for California. Red and blue represent disadvantaged communities (DAC) and non-DAC regions as per CalEnviroScreen 4.0, respectively.

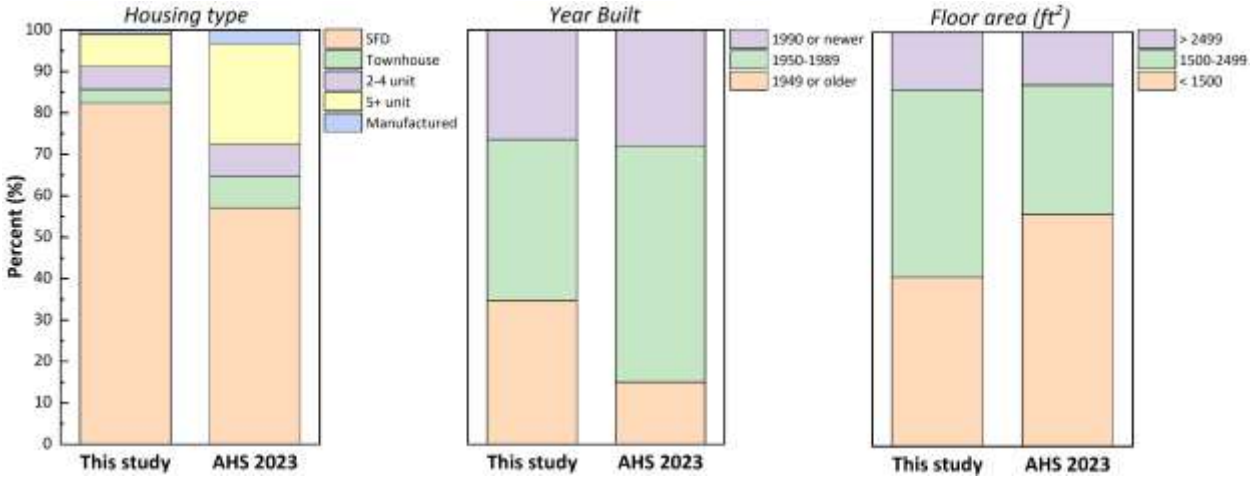


Figure S9. Comparison of sampled housing characteristics (housing type, year built, and floor area) with the American Housing Survey (AHS) 2023 data for the State of California.

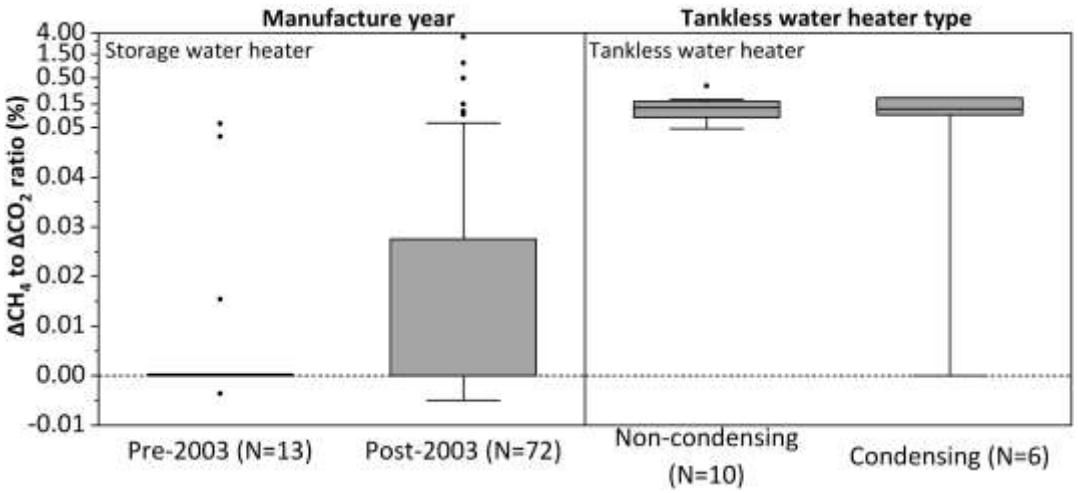


Figure S10. Operational ΔCH_4 to ΔCO_2 ratios (R_{SC}) for storage water heaters by year of manufacture and for tankless water heaters based on fuel utilization efficiency.

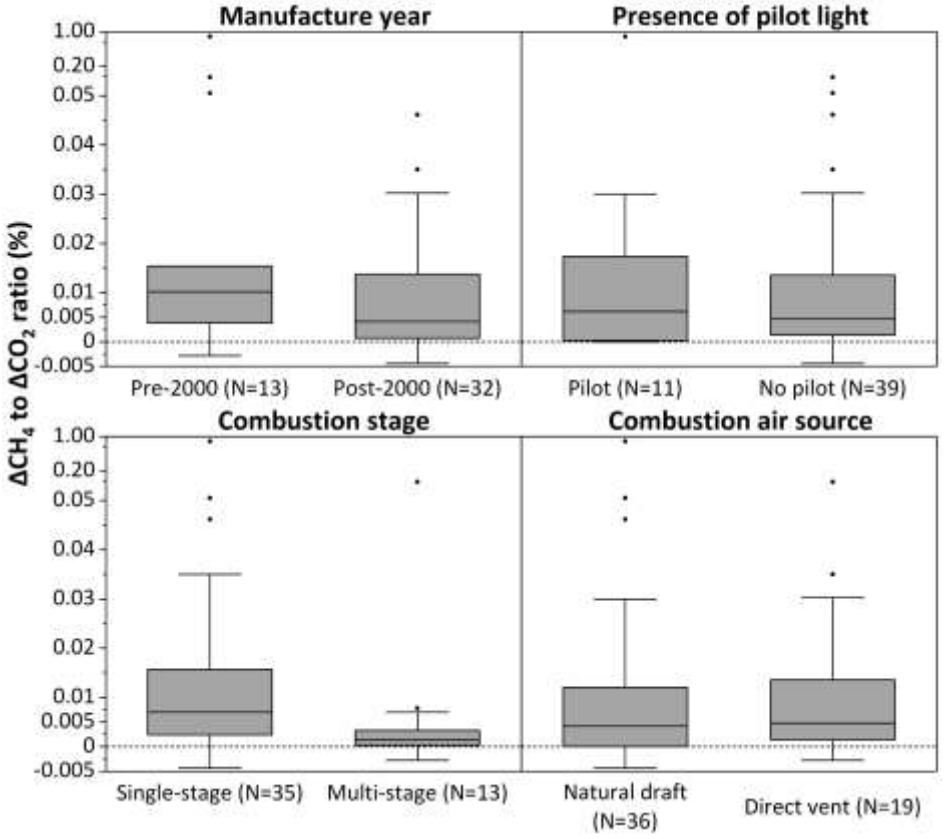


Figure S11. Operational ΔCH_4 to ΔCO_2 ratio (R_{SC}) distributions for forced-air furnaces (CFs) based on year of manufacture, ignition type, combustion stage, and source of combustion air.

Table S3. Bootstrapped mean and 90% confidence interval (CI) of emission factor (ng/J) for pilot lights and appliances' operational emission.

Emission source	Category	Emission factor (ng/J)	90% CI	
Idle emission	Pilot Light (N=39)*	75	56	100
Water heating	Storage Water Heater (N=131)	16	9	35
	Tankless Water Heater (N=27)	33	24	46
Space heating	Furnace - RTU and CF (N=70)*	4	2	13
	Furnace - WF (N=9)†	5	0	44
Cooking	Cooktop - Low (N=97)	197	118	370
	Cooktop - Medium (N=194)	40	29	60
	Cooktop - High (N=394)	60	51	75
	Oven - Preheat (N=84)	51	42	66
	Oven - Cycling (N=84)	142	95	354

*Out of 39 pilot lights measured by direct sampling, 28 are from storage water heaters, 8 from wall furnaces, and 3 from central furnaces. Out of 70 furnaces, 58 were standalone central furnaces (CFs) and 12 packaged unit furnaces (RTUs).

†90% confidence intervals values refer to the minimum and maximum, due to low sample size.

Table S4. Bootstrapped mean and 90% confidence interval (CI) of transient methane emissions from NG appliances.

Emission source	Category	Transient (mg CH_4 event^{-1})	90% CI	
Water heating	Storage Water Heater (N=48)	20	14	27
	Tankless Water Heater (N=21)	114	90	142
Space heating	Furnace - RTU and CF (N=27)	69	52	107
	Furnace - WF (N=2)†	15	14	16
Cooking	Cooktop - electronic ignition (N=304)	52	44	71

†90% confidence intervals values refer to the minimum and maximum, due to low sample size.

Table S5. Post-meter residential methane emissions (Gg CH_4 per year) by process in California. The values within brackets represent the 5^{th}-95^{th} percentile CI, which includes uncertainties in emission factors, burner firing frequencies, and numbers of appliances and homes with NG connections.

Category	Emission source	Pilot light emission	Operational emission	Transient emission	Total	Percent contribution (%)
Whole house	Quiescent leaks excluding pilot light				16.63 (11.48-25.08)	51.8
Water heating	Storage water heater	4.19 (2.69-6.53)	3.68 (1.95-8.12)	0.37 (0.21-0.64)	8.25 (4.85-15.30)	25.7
	Tankless water heater	NA	0.61 (0.42-0.88)	1.78 (1.06-3.12)	2.38 (1.47-4.00)	7.4
Space heating	Central furnaces	0.44 (0.28-0.59)	0.53 (0.26-1.90)	1.10 (0.74-1.92)	2.07 (1.28-4.41)	6.5
	Direct heating	0.25 (0.16-0.68)	0.20 (0-0.50)	0.03 (0.02-0.05)	0.34 (0.18-0.95)	1.1
Cooking appliances	Cooktop burners	NA	1.59 (1.26-2.09)	0.31 (0.19-0.48)	1.90 (1.45-2.58)	5.9
	Oven: pre-heat	NA	0.11 (0.08-0.14)	NA	0.11 (0.08-0.14)	0.3
	Oven: cycling	NA	0.40 (0.25-1.06)	NA	0.40 (0.25-0.47)	1.3

Table S6. Estimated California statewide methane emissions (Gg CH_4 per year) by housing type and source. The values within brackets represent the 5^{th}-95^{th} percentile CI, which includes uncertainties in emission factors, burner firing frequencies, and numbers of appliances and homes with NG connections.

Categories	Single-family detached	Townhouse	2-4 unit	5+ unit	Manufactured
Quiescent leaks excluding pilot	10.04 (6.93-15.14)	1.23 (0.85-1.86)	1.35 (0.93-2.04)	3.40 (2.34-5.12)	0.61 (0.42-0.92)
Water heating	6.86 (4.16-12.22)	0.66 (0.31-1.45)	0.71 (0.42-1.27)	2.03 (1.21-3.70)	0.37 (0.22-0.67)
Space heating	1.77 (1.08-4.02)	0.17 (0.09-0.42)	0.13 (0.08-0.26)	0.27 (0.17-0.49)	0.07 (0.04-0.16)
Cooking	1.57 (1.21-2.37)	0.23 (0.11-0.48)	0.20 (0.16-0.31)	0.33 (0.25-0.51)	0.08 (0.06-0.12)

Table S7. Percentage of data obtained from existing studies.

Service	Unit	Process	Fischer et al.[9,a]	Merrin and Francisco[10,a]	Lebel et al.[1,2,a]	Blum et al.[11,a]	Supplemental data[b]	SUMMATION[c]

Post-meter infrastructure	Whole-house	Leaks from distribution, & resting appliances	100%				
Water heating	Storage Water Heater	Pilot light	18%	82%			
		Sustained combustion	44%	20%	13%	8%	15%
		Transient			35%	21%	44%
	Tankless Water Heater	Sustained combustion	22%		63%		15%
		Transient			81%		19%
Space heating	Central Furnace	Pilot light	100%				
		Sustained combustion	9%	62%			29%
		Transient					100%
	Rooftop Packaged Unit	Sustained combustion	8%				92%
		Transient					100%
	Wall Furnace	Pilot light			100%		
		Sustained combustion		11%	67%		22%
		Transient					100%
Cooking	Cooktop Burner	Sustained combustion	8%	28%	48%	7%	9%
		Transient			67%	14%	19%
	Oven	Pre-heat			48%	22%	30%
		Burner cycling			48%	20%	32%

[a]Published sources.

[b]Supplemental data collected for 10 storage water heaters and 19 ranges / ovens during Lebel et al.[2] and Kashtan et al.[12] study campaigns.

[c]Data collected during SUper-eMitters of Methane detection using Aircraft, Towers, and Intensive Observational Network (SUMMATION) study in Bakersfield, California, California Energy Commission Agreement PIR-17-015.

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