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Energy Research and Development Division

FINAL PROJECT REPORT

Natural Gas Methane Emissions from California Homes

Edmund G. Brown Jr., Governor
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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Natural Gas Methane Emissions from California Homes is the final report for the Natural Gas Emissions from Residential Buildings in California project (Contract Number 500-13-008) conducted by the Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Methane emissions from the natural gas system likely contribute a small but meaningful fraction of California’s greenhouse gas emissions. This work estimates statewide mean methane emissions from residential natural gas consumption using measurements of inactive, house leakage (pipe-fitting leaks and combustion appliance pilot light flames) and, separately, a subset of operating combustion appliances in 75 California homes that participated in energy efficiency retrofit programs.

The measurements show inactive house emissions mostly near the limit of detection but with a small number of emissions above 10 grams of methane daily. Pilot lights are found to be potentially significant contributors to inactive emissions. Similarly, measurements of combustion efficiency for operating appliances show a majority of values near zero but with small detected emissions for stovetops and water heaters that are also fit with gamma distributions. One exception is forced air furnaces, which were nearly all low emitters. The team also found that emissions from pilot lights likely constitute a significant fraction of inactive house emissions, and flames in dominant domestic water heaters when in steady operation.

Total emission estimates, 35.7 Giga gram methane per year, corresponds to 15 percent and 2 percent of the natural gas sector total methane emissions and state total methane emission, respectively, from the most recent state inventory for 2015. While methane emissions from houses are small compared to most other sources, California’s ambitious climate goals (for example, 80 percent reduction by 2050) suggest value in testing and repairing obvious leaks in residential gas lines, modernizing combustion appliances to move away from pilot lights, and gradually increasing the use of nonfossil energy sources for residential space and water heating and cooking.

Keywords: Building, emissions, greenhouse gas, methane, natural gas, residential

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Methane (CH_4) is an important short-lived climate pollutant responsible for roughly 10 percent of California's total anthropogenic (human activity) greenhouse gas (GHG) emissions, making the control of this gas crucial for attaining California’s climate change goals. While methane from the natural gas system constitutes a smaller portion of California’s total anthropogenic GHG emissions, after-meter emissions from the residential sector (and other subsectors) remain uncertain yet potentially amenable to straightforward mitigation.

Project Purpose

The research team initiated this project with the goals of providing a quantitative assessment of California’s statewide methane emissions due to residential natural gas consumption and identifying promising actions to help reduce these emissions in the future.

Project Process

To accomplish the goals identified above, the research team planned and conducted a project to:

- Identify and select a sample of houses that approximate the characteristics of California’s single-family homes.
- Measure the housing samples to separately quantify both continuous emissions (that is, leaks from pipes and fittings and pilot lights) and episodic emissions from operating combustion appliances.
- Perform ancillary measurements as necessary to fill measurement gaps.
- Apply modern statistical methods to extrapolate measured results to the California housing stock.
- Identify key points of leverage for future mitigation.

Project Results

Based on analysis of California’s housing stock, an energy efficiency retrofit contractor recruited 75 California houses in the 2016-2017 period. Total inactive methane emissions, meaning emissions measured without any active operation of natural gas appliances, from the combination of leaks and emissions from pilot lights were estimated in each house using measurements of the indoor methane enhancement relative to outdoor air at a controlled ventilation air flow rate. The methane emitted from a subset of operating combustion appliances was estimated as the product of appliance gas use times the ratio of methane to carbon dioxide (CO_2) in combustion exhaust. In addition to the 75 homes and associated appliances, the authors measured methane emissions from three tankless (on-demand) gas water heaters as a function of hot water demand.

Using the combination of measurements, the research team determined distributions for both inactive house and appliance emissions. Researchers then used a statistical method, to estimate the distributions of inactive emissions, and appliance measurements were combined with Energy Commission data on sector-specific (in other words, water and space heating, cooking, and so forth) gas use to estimate appliance emissions. The state-wide estimate shows methane emitted from inactive house leakage was 23.4 (13.7 – 45.6, at 95% confidence) gigagram (Gg) CH_4 (or 0.6 (0.4 – 1.2) teragram (Tg) CO_2eq using 100-yr global warming potential of 25). Methane has 100-year global warming potential of 25 meaning that releasing one unit mass of methane into the atmosphere is about equivalent to releasing 25 unit mass of carbon dioxide,

Emissions from steady operation of appliances and their pilots is 13.3 (6.6 – 37.1) Gg CH_4/yr, an order of magnitude larger than current inventory estimate, with transients likely increasing appliance emissions further. This estimate of emissions from combustion appliances is more than an order of magnitude greater than the residential natural gas combustion emission (0.01 Tg CO_2eq) from the most recent state inventory for 2015.

Taken together, the estimated emissions from combustion appliances is more than an order of magnitude larger than the residential natural gas combustion emission (0.01 Tg CO_2eq) from the most recent state inventory for 2015. Together, total CH_4 emissions from residential sector natural gas consumption are 35.7 (21.7 – 64.0) Gg CH_4/yr (and 0.9 (0.5 - 1.6) Tg CO_2eq), equivalent to 0.5% (0.3 - 0.9%) of residential consumption. This result was roughly consistent with previous top-down analysis of natural gas methane emissions for the San Francisco Bay Area, a region without significant oil or gas production. Roughly speaking, the economic value of emitted natural gas can be estimated as the product of the 0.5 percent of California's residential natural gas consumption of about 500 giga cubic feet per year (Gcft/yr) times an average price of ~$12 per million cubic feet (Mcft), or about $30 million/yr.

Inspecting combustion sources more closely suggested that methane emissions from a combination of pipe leaks occurred in only a subset of houses, but pilot light flames likely constituted a significant fraction of inactive house emissions, and emissions per unit heating value from domestic (tank) water heaters were somewhat higher than those of modern tankless (on-demand) water heaters.

These results suggest that low-cost mitigations might include:

- Expanded use of electronic ignitions in new combustion appliances.
- Increased consumer adoption of low-emitting tankless water heaters for retrofits and new installations.

- Inspection and repair of leaks of accessible pipe fittings (for example, at point of sale or during energy retrofits).

Finally, while methane emissions from residential natural gas consumption are small compared to most other sources of anthropogenic, or human-caused, methane, California's ambitious climate goal to reduce greenhouse gas emissions 80 percent below 1990 levels by 2050 will require aggressive targeting of all GHG emissions, suggesting value in upgrading building natural gas infrastructure, modernizing combustion appliances, and gradually moving toward nonfossil renewable energy sources coupled with high-efficiency technologies for residential space and water heating and cooking.

Benefits to California

This research provides additional information for the California Air Resources Board to update the greenhouse gas inventory. The Air Resources Board used the results from this study to update the residential sector emissions for 2018 greenhouse gas inventory. The research also provides California ratepayers with an estimate of the amount of methane emitted from California homes and outlines steps that can be taken to reduce those emissions with only minor adjustments to home maintenance and real estate transactions. Assuming that roughly half of the leaks and emissions estimated above can be reduced, the avoided cost of fuel use will save ratepayers roughly $15 million a year. This will also reduce greenhouse gas emission by half a million metric tons CO_2 equivalent, which is 0.15% of the 2050 reduction needs. The work also demonstrates methods that could be adapted to business and industry as California progresses toward healthy local environments in a carbon-neutral society.

CHAPTER 1: Introduction

1.1 California Total and Natural Gas Methane Emissions

Methane (CH_4) is an important greenhouse gas (GHG) in meeting California's climate change goals for GHG emission reductions. However, quantifying CH_4 emissions in California is challenging due to various emission sources, temporal (for example, daily to seasonal) variability, and spatially diverse emissions. Recent measurement-based top-down studies (such as Jeong et al., 2013; 2016; Wecht et al., 2014; Turner et al., 2015) showed the bottom-up approach (for example, state CH_4 emission inventory) underestimates CH_4 emissions. The top down approach uses atmospheric methane concentration level and inversion modeling to estimate methane leaks. The bottom-up approach uses component level emission measurements and emission factors to estimate total methane leaks. For example, Jeong et al. (2016) conducted a full annual analysis for regional CH_4 emissions using measurements across California and estimated that actual CH_4 emissions are 1.2 to 1.8 times larger than the 2013 state inventory (1.64 Teragram(Tg) CH_4/yr). Compared with statewide total emissions estimated from recent top-down studies, CH_4 emissions from the residential natural gas (NG) sector constitute a small part of the state total. However, residential natural gas CH_4 emissions can make up a potentially significant portion of the natural gas distribution sector GHG emissions in urban areas. Jeong et al. (2017) used CH_4 and volatile organic compounds (VOCs) measurements for source apportionment of CH_4 emissions in the San Francisco Bay Area (SFBA), where the natural gas distribution sector is the dominant potential source of leakage, with little natural gas transmission or production. They estimated that actual natural gas CH_4 emissions are roughly twice the bottom-up inventory for SFBA. The result from Jeong et al. (2017) suggests that residential natural gas CH_4 may be an important component in reducing urban natural gas emissions, as well as reconciling the discrepancy between top-down and bottom-up CH_4 emission estimates.

1.2 California Residential Building Stock and Gas Consumption

This study aimed to recruit a representative sample of single-family detached houses in California for estimating the postmeter methane leakage from the California housing stock. Roughly two-thirds of housing units in California are single-family units, and most are detached homes (2011-2015 American Community Survey, U.S. Census Bureau, 2016). For this reason, this study recruited a sample of single-family detached homes with different characteristics in terms of geographical location, year built, and square footage. Sampled homes included single- and multistory, common foundation types (such as slab or crawlspace), and one or more appliances that use natural gas: space heating, water heating, cooking, clothes drying, and others.

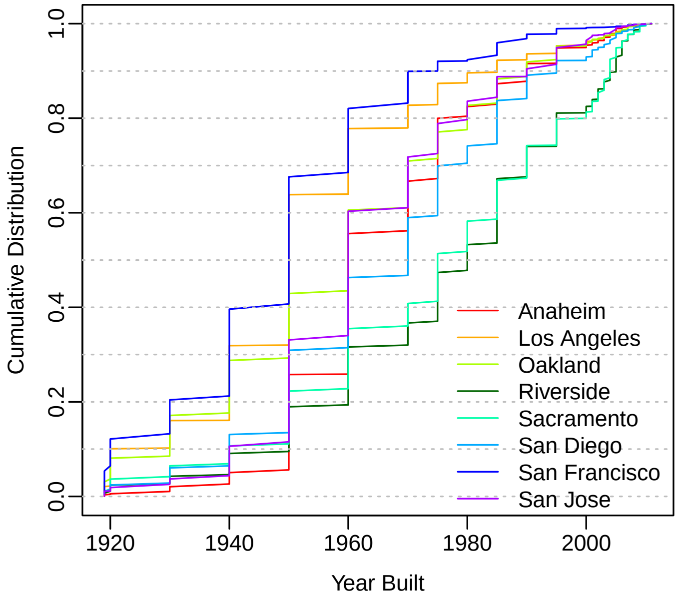
Figure 1 to Figure 5 show the distributions of key characteristics of single-family detached houses surveyed by 2011 American Housing Survey (Selected Metropolitan Areas data) (U.S. Census Bureau, 2014) from eight populated areas in California:

- Anaheim-Santa Ana
- Los Angeles-Long Beach
- Oakland-Fremont-Hayward
- Riverside-San Bernardino-Ontario
- Sacramento-Arden-Arcade-Roseville
- San Diego-Carlsbad-San Marcos
- San Francisco-San Mateo-Redwood City
- San Jose-Sunnyvale-Santa Clara.

The 2011 American Housing Survey surveyed a sample of about 4,500 homes in each of the population areas to provide detailed information on housing characteristics, including fuel use type (such as natural gas, electricity) by each major appliance, which is relevant to this study.

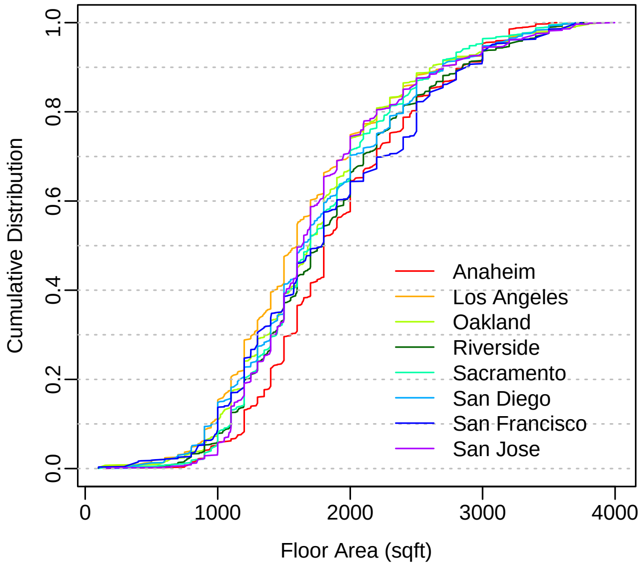
Three-quarters of Californians live within the eight populated areas listed above. Among them, about one-third of the population lives in the northern part of the state (Oakland-Fremont-Hayward, Sacramento-Arden-Arcade-Roseville, San Francisco-San Mateo-Redwood City, and San Jose-Sunnyvale-Santa Clara), and two-thirds live in the southern part of the state (Anaheim-Santa Ana, Los Angeles-Long Beach, Riverside-San Bernardino-Ontario, and San Diego-Carlsbad-San Marcos). This study also included a few homes from the Central Valley (Fresno, Kern, and San Joaquin, Stanislaus, and Tulare) region of California, where about 10 percent of the state population lives.

Figure 1: Year Built of California Single-Family Detached Homes



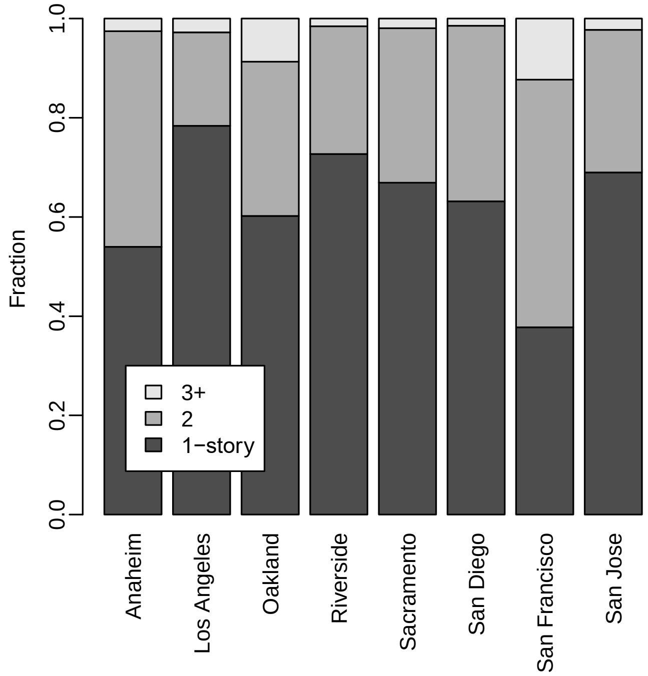
Source: Data from American Housing Survey 2011 (U.S. Census Bureau, 2014).

Figure 2: Floor Area of California Single-Family Detached Homes



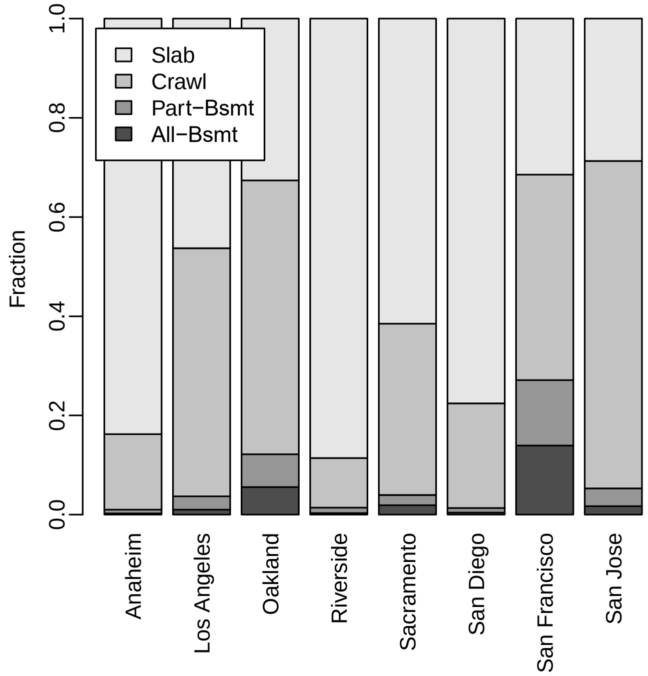
Source: Data from American Housing Survey 2011 (U.S. Census Bureau, 2014).

Figure 3: Number of Stories of California Single-Family Detached Homes



Source: Data from American Housing Survey 2011 (U.S. Census Bureau, 2014).

Figure 4: Foundation Types of California Single-Family Detached Homes



Source: Data from American Housing Survey 2011 (U.S. Census Bureau, 2014).

Key observations from the American Housing Survey 2011 (U.S. Census Bureau, 2014) data are summarized as follows:

- **Year built**: Houses tended to be newer in the Riverside and Sacramento areas, compared to houses in the Los Angeles and San Francisco areas. Houses from the other four surveyed areas (Oakland, San Jose, Anaheim, and San Diego, ordered from older to newer) were built somewhere between the Los Angeles/San Francisco and Riverside/Sacramento groups. Overall, about 60% of the houses in California were built between 1950 and 1990.
- **Floor area**: Floor area distributions were similar across all surveyed areas, where 80% of the houses had floor areas between 1,250 and 3,000 square feet (ft^2).
- **Number of stories**: About 60% of the houses are single-story. San Francisco had the largest number of two-story houses, while the number of two-story houses in Los Angeles was the smallest.
- **Foundation type**: Crawlspace and concrete slab were the two most common foundation types. Houses in Anaheim, Riverside, San Diego, and Sacramento were predominately built on a concrete slab. Crawlspace was more common in houses in Los Angeles, Oakland, San Francisco, and San Jose.
- **Heating fuel**: There were five use types of gas fuel[1] reported in the 2011 American Housing Survey data: space heating, water heating, cooking, clothes dryer, and air conditioning. Few homes use gas for air conditioning, so it was not plotted. Most surveyed homes used gas as their space heating fuel or water heating fuel or both. More than half of the homes also used gas for cooking. In Anaheim, Los Angeles, Riverside, and San Diego, gas clothes dryers were more common than electric ones. But less than half of the homes in San Francisco, Oakland, San Jose, and Sacramento used a gas clothes dryer. There were higher percentages of survey respondents (9%) who were uncertain about the fuel use of their clothes dryers (compared to <1% for the other appliances). Thus, the fractions of homes with gas versus electric clothes dryers shown in Figure 5 were more uncertain in comparison. Taken together, it was common to find homes (80%) in Anaheim, Los Angeles, Riverside, and San Diego that used gas in three out of four fuel uses. In San Francisco, Oakland, San Jose, and Sacramento, only about 60% of homes used gas in three out of four fuel uses because gas clothes dryers were less common.

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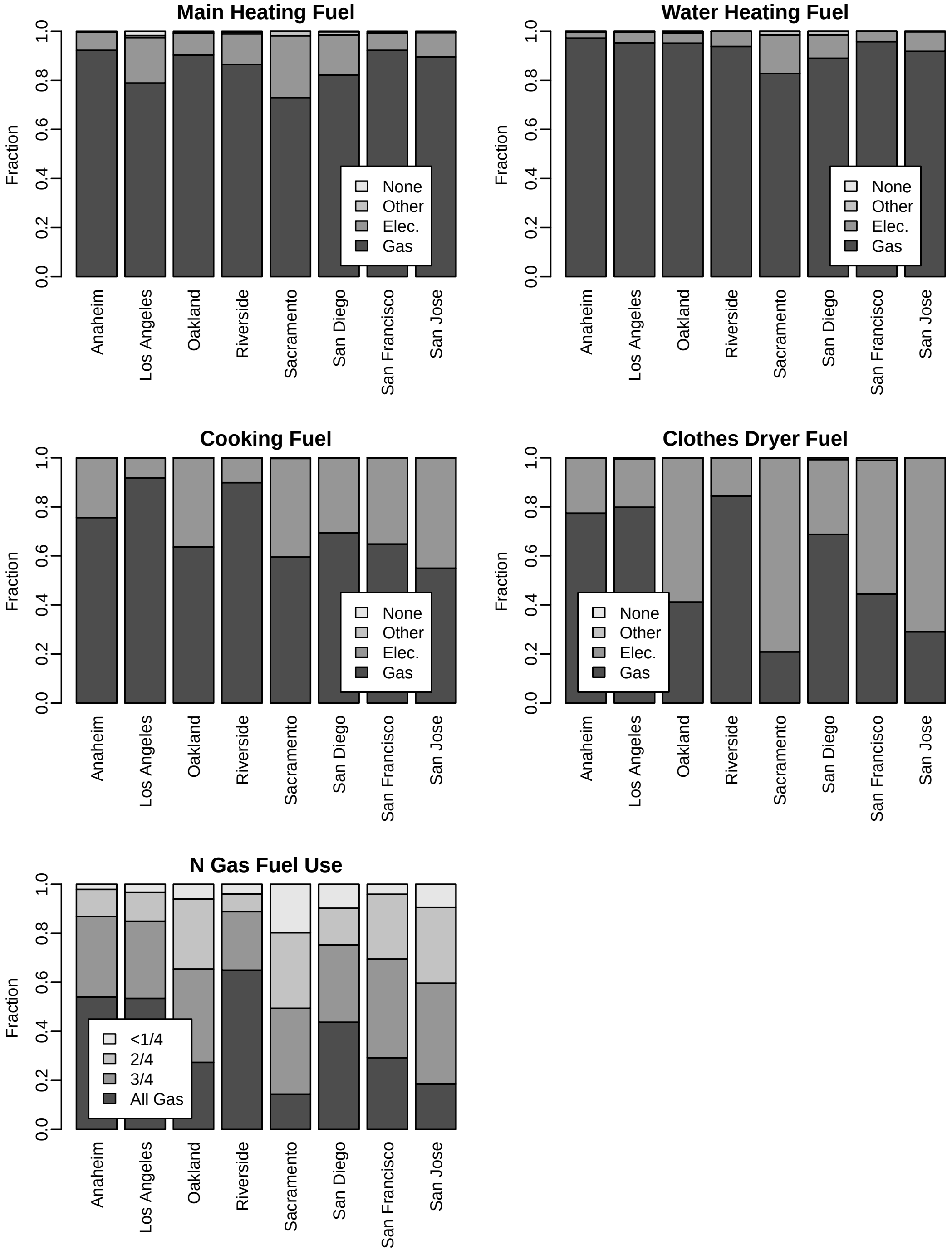
[1] Most households that live in single-detached houses answered yes to the question: “Do you use gas in your home?” However, a small fraction of those who answered "yes" may use liquid propane instead. This analysis excludes survey responses that answered “bottled gas” instead of “piped gas” as their source of the gas fuel.

Figure 5: Fuel Use in California Single-Family Detached Homes


Main Heating Fuel

Water Heating Fuel

Cooking Fuel

Clothes Dryer Fuel

N Gas Fuel Use

Source: Data from American Housing Survey 2011 (U.S. Census Bureau, 2014). The bottom plot shows the number of natural gas uses (out of a maximum of N = 4 from space heating + water heating + cooking + clothes dryer) in California single-family detached homes.

CHAPTER 2:
Methods

2.1 Distribution of Buildings Selected for Measurement

Based on the above analysis of the key characteristics of single-family detached houses from eight metropolitan areas in California surveyed by 2011 American Housing Survey (U.S. Census Bureau, 2014), the research team planned to recruit homes that spanned a spectrum in terms of the following parameters:

- Year built: <1970, 1970–1990, and >1990
- Floor area: <1,500, 1,500–2,500, and >2,500 ft^2
- Number of stories: 1- and 2-story
- Foundation type: Crawlspace and slab
- Number of gas appliances: 2 (e.g., space heating + water heating only), 3 (+ gas cooking), 4 (+ gas clothes dryer)

Richard Heath & Associates Inc. (RHA) recruited homes following a human subject protocol approved by the Lawrence Berkeley National Laboratory Institutional Review Board. A human subject protocol must be developed and approved by the laboratory for all studies that involve human subjects. RHA recruited homes to participate in this study from its existing customers and professional contacts. Eligibility criteria include owner-occupied, single-family detached homes that use natural gas for at least two of the following purposes: space heating, water heating, cooking, and clothes drying. The head of household had to speak English to understand study requirements and to communicate with the field technician. Participants received a small financial incentive ($75) for taking part in this study.

In addition to the field measurements of methane leakage, the field technicians noted conditions of the gas appliances and gas leaks if observed. (See Appendix A). None of the participating homes had a major gas leak that would be considered unsafe. In a small number of cases, the field technicians advised homeowners to contact their gas utility regarding an existing condition with their gas appliances. RHA's field technician also used an electronic combustion gas leak detector (such as Sensit or similar) or a soap solution to detect bubbles, or both, indicating minor gas leaks near a subset of combustion appliances, though researchers did not have sufficient time to test all exposed gas pipes within each house or any inaccessible pipes or fittings.

Study participants completed an occupant survey that provided additional information about the home. (Appendix B) Most households in California have two to four persons (U.S. Census Bureau, 2014). The median gas utility bill is $60 monthly. The research team summarized selected parameters collected from the occupancy survey for the study homes.

2.1.1 Gas Appliances With Pilot Light Flames

Incomplete combustion in gas appliances, including pilot lights, may contribute significantly to the overall methane emissions from homes. The typical number of pilot lights in California homes are estimated. Using the *2009 California Residential Appliance Saturation Study* (RASS) (Energy Commission, 2010) the largest number of pilot lights found is likely to come from gas fired water heaters with storage tanks because about 72% of the housing units in California have storage tank water heaters, although some newer water heaters use electronic ignition instead of a standing pilot. Assuming that a small fraction of gas storage water heaters (10% to 20%) use electronic ignition, the percentage of housing units in California that has a gas storage water heater with pilot lights may be in the range between 56% and 63%. California's Title 24 Building Energy Efficiency Standard has prohibited the use of pilot lights in a variety of appliances.

The *2009 RASS* also provided some data on use of pilot light in homes that use gas for space heating. Survey results suggest 1.26 million homes have a pilot light in their main heater, but the pilot light is on in winter only. As expected, there is a decreasing trend of pilot light use from 18% among homes that are built before 1975 to 3% among homes built after 2000. This corresponds to roughly 10% of California homes that have a pilot light used at least in winter. The 2009 RASS also provided data on homes that leave pilot light on all year. However, the team found the data to be unreliable because approximately 40% of survey respondents answered yes to having pilot light, regardless of year built. Instead, 10% pilot lights were used as the estimate for space heating.

Similarly, Title 24 specifies that cooking appliances may not use continuously burning pilot lights (with minor exceptions for those lacking electrical service or with very low gas use below 150 Btu/hr). From the *2009 RASS*, there were approximately one million cooktops and 0.83 million gas ovens that were from early 1990 or older. These older gas cooktops and ovens, corresponding to roughly 6-8% of 12.93 million occupied homes in California, are likely to have pilot lights. It was assumed 5% of the cooking appliances have pilot lights, with some older cooktops and ovens surveyed by RASS ten years ago would likely have been replaced by newer models without pilot lights. For cooking appliances with pilot lights, it is reasonable to assume two to four pilot lights per appliance (such as oven and broiler may each have a separate pilot light and a cooktop may have two pilot lights with one on each side). Summing across appliance types a total of 0.82-1.26 pilot lights were estimated in the average California home (Table 1).

Table 1: Estimated Number of Pilot Lights in California

Appliance Type	Houses with pilot lights (%)	Pilots per appliance	Pilot lights per house
Water Heating	56-63	1	0.56–0.63
Space Heating	10-30	1	0.1-0.3
Cooking	9	2–4	0.18-0.36
Pool, Spa	10	1	0.3
Clothes Dryer	0	0	0
Total			**0.82-1.26**

Source: *2009 California Residential Appliance Saturation Study* (Energy Commission, 2010).

Methane emissions from appliances are estimated by combining state-wide natural gas consumption with measurements of the ratio of CH_4 to CO_2 in exhaust gas. Natural gas consumption data for different appliance types are necessary to estimate emissions. Data for the total residential natural gas consumption is used from the Energy Commission (CEC, 2017), where residential natural gas consumption for 2015 is 4,126 million therms. Tthe U.S. Energy Information Administration (EIA, 2017) reports a similar total (401,172 million cubic feet or 4,160 million therms). Assuming 95% CH_4 content in the distributed natural gas, the total natural gas consumption from the Energy Commission is equivalent to 7.2 Tg CH_4/yr. The team estimated natural gas CH_4 consumption by appliance type using the 2009 RASS data as shown in Table 2. Estimates of gas use for pilot lights by appliance type (EERE, 2008) were combined with the data from Table 1 to estimate gas used by pilots and the fraction of gas used in normal appliance operation in Table 2.

Table 2: Gas Use by California Appliances and Pilot Lights

Appliance Type	Total gas by appliance (gG-gas/yr))	Typical gas flow rate to pilot* (Btu/hr)	Gas used by pilots (gG-gas/yr)	Fraction of gas burned in normal operation
Water Heating	3714	400	533	0.86
Space Heating	2805	400	89	0.97
Cooking	531	200	120	0.77
Pool, Spa	303	400	89	0.71
Clothes Dryer	227	-	0	1.00
Total	7580		741	

Source: 2009 California Residential Appliance Saturation Study (Energy Commission, 2010).

2.1.2 Whole Building Emissions

Methane emissions from interior leaks and quiescent appliances (with only pilot lights burning) were measured using a mass balance approach shown in Figure 6. Here, the home was depressurized using a calibrated fan while measuring the CH_4 concentration in the outdoor air drawn into the house and in the indoor air being exhausted. The enhancement of indoor CH_4 relative to outdoor "background" air combined with the known flow rate of air was used to estimate indoor CH_4 emissions using the following formula.

Considering the building shell as a well-mixed control volume, the research team expressed the time rate of change of CH_4 concentration in the indoor air as the difference of inflow minus outflow of CH_4 normalized by the building volume,

$$dC_i /dt = Q/V (C_o - C_i) + L/V, \qquad 1)$$

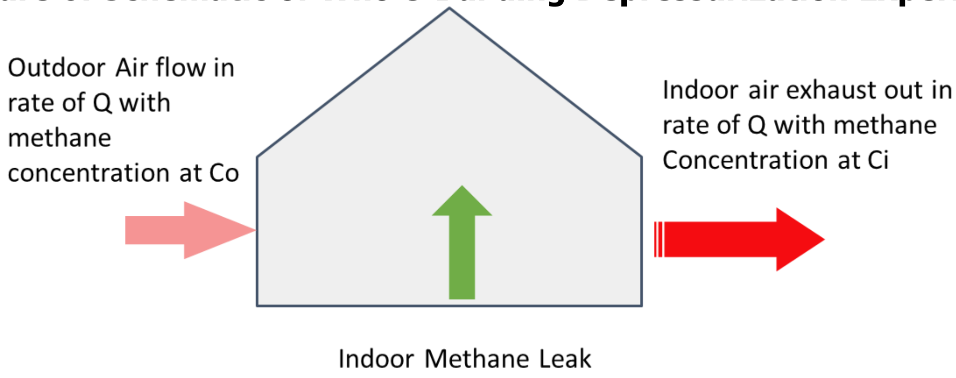
where C_i and C_o are the indoor and outdoor mixing ratios, respectively, Q is the total air flow rate; V is the building volume; and L is the interior CH_4 leak rate. For a case where the methane leak increased from zero to L at time t=0, this first order linear differential equation has a solution of the form,

$$C_i (t) = C_o + L/Q (1- \exp(-t/\tau)), \text{ where } \tau = V/Q, \qquad 2)$$

which at long times yields a steady-state solution (when $t >> \tau$) for L as,

$$L = Q (C_i - C_o) \qquad 3)$$

Figure 6: Schematic of Whole-Building Depressurization Experiment

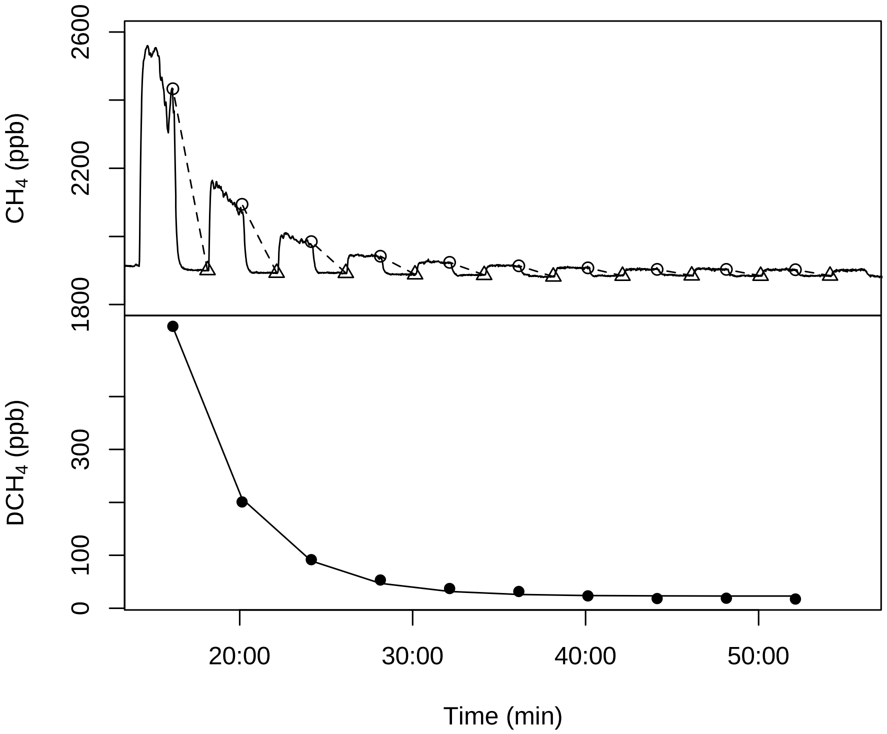


Schematic shows air flows into and out of house during building depressurization experiment. Here the air flow, Q, of outdoor air enters the home, mixes with indoor methane leaks from gas pipes and pilot light emissions, and is then exhausted at slightly higher CH_4 concentration.

Source: Lawrence Berkeley National Laboratory

Figure 7 shows example time series of indoor and outdoor CH_4 during a building depressurization experiment. For typical residential U.S. buildings subjected to a 50 Pascal (Pa) depressurization using a blower door, one may expect on the order of 10 air changes per hour (ACH), therefore, a near-steady-state condition ($t = 3\tau$) after ~ 18 minutes. To provide alternating indoor and outdoor measurements, air supplied to the gas analyzer was switched between the indoor air at the blower door and outdoor air every two minutes using a three-way solenoid valve. To allow for instrument settling, one minute of data was removed immediately following the valve switches, and the remaining minute of data was averaged to produce time series of C_i and C_o. In cases where the observed difference, C_i–C_o was clearly varying exponentially toward a steady state, the research team estimated L and τ using Eq. 2 in a nonlinear, least-square fit that included uncertainty estimates for L and τ. In cases with very small indoor-outdoor CH_4 differences, the authors did not observe an exponential decay in C_o–C_i In these cases, the research team estimated the mean value and standard error in L from Eq. 3 using the last 10 minutes of the building depressurization data, propagating observed variations in Q and $C_o - C_i$, together with the 5% absolute accuracy of the blower door calibration specified by the manufacturer.

Figure 7: Time Series of CH_4 During Example Building Depressurization



Top panel shows methane measured vs. time during example building depressurization experiment showing indoor (circles) and outdoor (triangles) averages connected by dotted lines for each measurement cycle. Bottom panel shows indoor-outdoor differences vs. time with and best fit exponential decay curve.

Source: Lawrence Berkeley National Laboratory

Because the typical (~50 Pa) depressurization used to generate the desired air exchange rate will cause backdrafting of combustion appliance emissions, the research team did not operate combustion appliances when measuring whole-building emissions separately. Instead, the team measured emissions from operating combustion appliances separately. The whole-building measurements were assumed to capture the combination of leakage from all plumbing fittings and operating appliance pilot lights only.

For the 75 home whole-building emission measurements reported in this study, the research team used a commercial blower door system[2] to depressurize the house, with

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[2] The Energy Conservatory Inc., DG-1000

interior doors open and small domestic fans in long hallways to increase coupling between interior spaces. The team measured methane with a portable total CH_4/CO_2 gas analyzer[3], which has a typical CH_4 measurement precision of ~0.3 parts per billion (ppb) for data collected at one sample per second, with the CH_4 and CO_2 volumetric mixing ratios reported in total (moist) air. The time response of the instrument to step changes in CH_4 was measured to have a 1/e response time of ~10 s, sufficient to obtain near-steady-state readings when switching even for large changes in concentration after waiting for one minute to settle.

Following the building depressurizations, the research team also tested the experimental configuration in each house by measuring the step increment in C_i after releasing an additional 5 standard cm^3 per minute (sccm) of CH_4 at a location roughly 3-5 m from the blower door. Here, a mixture of 4 +/- 0.1 % CH_4 in air was released for roughly 10 minutes from a compressed gas cylinder through a regulator at a flow rate of 125 +/- 15 sccm, set using a calibrated rotometeric (ball gauge) flow meter. The research team estimated the uncertainty in the flow rate from typical drifts in the flow meter over time under experimental conditions. In practice, the estimated total CH_4 emissions due to the combination of the house and the additional source, $L_{house+cal}$ was estimated using Eq. 3, and the additional leak was then estimated from the difference as $L_{cal} = L_{house+cal} - L_{house}$. In the majority of cases, the estimate of L_{cal} was within two standard errors of 5 sccm, though a subset were discrepant, so the authors examine the sensitivity of excluding that subset in the results of the following analysis section.

In addition to the main study, which employed a total CH_4 and CO_2 gas analyzer, the research team separately measured a subset of seven homes in the San Francisco Bay Area (Fischer et al., 2017). Here, the authors used an isotopic methane gas analyzer (Picarro G2132-*i*), which provided total methane, the $^{13}C/^{12}C$ stable isotope ratio, and CO_2 mixing ratio, with a measurement precision for the $^{13}C/^{12}C$ ratio of ~ 0.3 per mil, which was sufficient to distinguish contributions to observed indoor CH_4 enhancements due to natural gas CH_4 (where δ_{NG} ~ -30 to -35 per mil) from those due to biogenic CH_4 (e.g., sewer gas where δ_{bio} ~ -45 to -60 per mil) when the indoor enhancement was strong enough and sufficient data were averaged together. The source signature of indoor CH_4 sources, δ_L, was estimated by measuring the $^{13}C/^{12}C$ ratios of indoor CH_4, δ_{in}, and outdoor air, δ_{out}, and applying a two-component mass balance model

$$Q\ C_i\ \delta_i = Q\ C_o\ \delta_o + L\ \delta_L \qquad 4)$$

Here, the authors combine Eqs. 3 & 4 to yield

$$\delta_L = Q/L\ (C_i\delta_i - C_o\delta_o) = (C_i\delta_i - C_o\delta_o)/(C_i - C_o) \qquad 5)$$

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[3] Los Gatos Research, UGGA

For these tests, the research team measured indoor and outdoor CH_4 for roughly 10 minutes each for the seven houses and estimated δ_L. Six of the seven houses yielded values for δ_L consistent with natural gas methane (ranging from -15 +/- 21 to -32 +/- 7 per mil), while two had very small indoor CH_4 enhancement and, hence, very large (+/- 35 per mil) uncertainty in δ_L. From this, the authors concluded that measureable CH_4 enhancements were due to natural gas sources for most of the houses tested in the Bay Area and assume that the same was true for the houses measured in the 75-house study. The research team believes this assumption is reasonable because the evidence from the Berkeley houses does not suggest any cases with significant biological methane emissions.

2.1.3 Appliance Emissions

Emissions from operating appliances can be difficult to capture. For this reason, the authors applied an alternate method that assumes that most of the gas supplied to an appliance is combusted to CO_2. Under this assumption, one can reasonably approximate methane emission as the product of the fractional enhancement in CH_4 relative to enhancement of CO_2 in exhaust gas times the total gas consumption rate

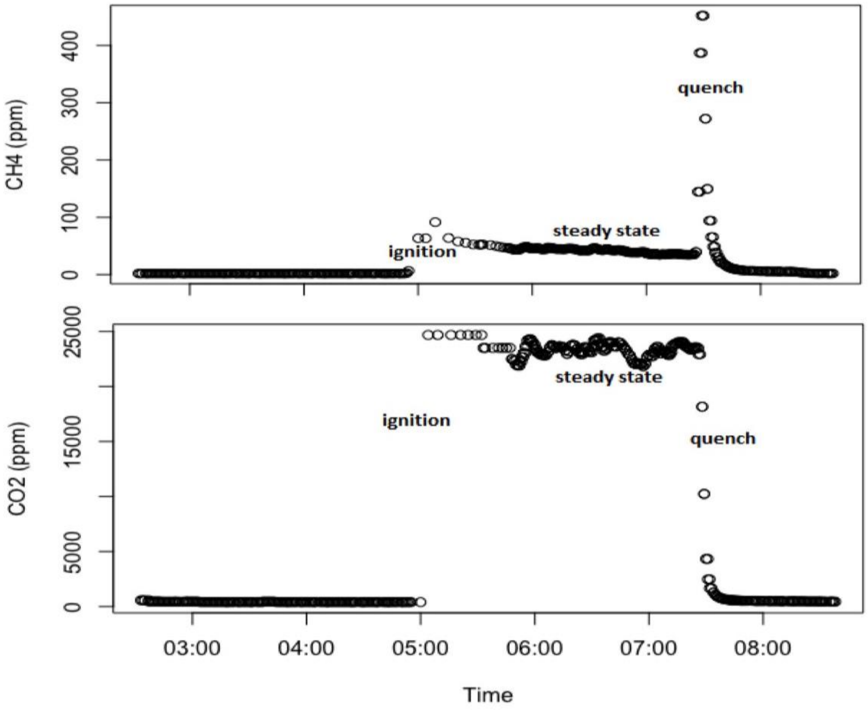
$$E = Q_g * \Delta\mathrm{CH}_4{:}\,\Delta\mathrm{CO}_2 \qquad 6)$$

where the ratio of enhancements is ΔCH_4: ΔCO_2 = (CH_{4exh}- CH_{4bg})/(CO_{2exh} – CO_{2bg}), where CH_{4exh} and CO_{2exh}, CH_{4bg} , and CO_{2bg} are the concentration of CH_4 and CO_2 in exhaust and background air, respectively, and Q_g is the gas consumption rate estimated from repeated gas meter readings. For example, Figure 8 shows the time series of measured CH_4 and CO_2 during appliance ignition, steady-state operation, and shutdown. Here, the background CH_4 and CO_2 are near 2 and 400 parts per million (ppm), respectively. During ignition, the CH_4 concentration goes up to 100 ppm, then falls to near 40 ppm during operation, and then spikes again when the appliance is quenched. By comparison, the CO_2 concentrations are comparatively more constant during ignition, operation, and quench, consistent with most of the gas being combusted. In practice, the gas use rate is measured by recording the time required for the fine meter dial (such as 2 cubic feet (cft)) to make one or more complete revolutions over the period when an appliance is operating. Here, quiescent gas use (from pipe leaks and pilot lights) is subtracted by making a baseline gas use measurement before operating the appliances.

Because of the high concentrations of CO_2 and to a lesser extent CH_4 in the combustions gas, the research team also estimated the systematic error due to calibration of the gas analyzer at high CH_4 and CO_2 values expected in the partly diluted streams of combustion exhaust gas. Here, the team premixed a cylinder of ambient air with additions of more concentrated CH_4 and CO_2 totaling 800 ppm CH_4 and 20,000 ppm CO_2. The estimated accuracy of the $\Delta CH_4{:}\Delta CO_2$ ratio was 5%, based on the accuracy the pressure sensors used to mix the CH_4, CO_2, and ambient air into the calibration cylinder. Using this standard, the authors found the Los Gatos Research

(LGR) analyzer yielded a ΔCH_4:ΔCO_2 ratio within 11% of that expected and assigned an overall uncertainty of 11% to the estimates of appliance emission estimates. However, this source of uncertainty was small compared to the uncertainty range obtained from sampling the distributions of ΔCH_4:ΔCO_2 ratios obtained from the appliances tested in the field described in the results and analysis (Figure 8).

Figure 8: Example Time Series From Appliance Heating Cycle



Measured CH_4 (upper) and CO_2 (lower) showing ambient air followed by appliance exhaust during ignition, steady-state operation, and quench, followed by another ambient air measurement.

Source: Lawrence Berkeley National Laboratory

2.1.4 Tankless Water Heaters

Tankless (on-demand) water heaters are more energy-efficient than conventional tank heaters but represent a small fraction (< ~ 10%) of the gas water heaters in California. To characterize the effect of including methane emissions on overall climate efficacy, the research team measured three tankless heaters identified in Table 2 separately from the 75-house study. As with other combustion appliances, the team measured emissions using the ΔCH_4: ΔCO_2 ratio method but included careful measurements of gas supplied to the appliances at 2-3 heating powers levels, which the team generated by setting the amount of water being drawn from the heaters. All three of these on-demand heaters used electronic ignitions (Table 3).

For the tankless water heater testing, the research team used the Picarro (G2132) analyzer to measure mixing ratios in exhaust gas and supply air. As with the LGR analyzer used for the main house study, the team calibrated the Picarro against a premixed standard containing 800 ppm CH_4 and 20,000 ppm CO_2. Here, the team found the analyzer was accurate to within 7% of the estimated ΔCH_4: ΔCO_2 ratio, which was marginally consistent within the 5% accuracy of reading the pressure sensor used to create the premixed standard.

Table 3: Water Heaters Measured and Rated Gas Consumption

Make	Model	Rated Gas consumption (kW = 3.4 kBtu/hr)
Rheem	ECOH200DVLN 1	3.2-52.8
Rinnai	REU-2424W-US 1	5.6~52.7
Takagi	T-K3-SP 1	3.2~55.7

Source: Lawrence Berkeley National Laboratory

For the tankless water heater testing, the research team used the Picarro (G2132) analyzer to measure mixing ratios in exhaust gas and supply air. As with the LGR analyzer used for the main house study, the team calibrated the Picarro against a premixed standard containing 800 ppm CH_4 and 20,000 ppm CO_2. Here, the team found the analyzer was accurate to within 7% of the estimated ΔCH_4: ΔCO_2 ratio, which was marginally consistent within the 5% accuracy of reading the pressure sensor used to create the premixed standard.

2.2 Statistical Estimation of California Emissions

The authors estimated statewide house leakage CH_4 emissions by multiplying the inferred average house leakage rate from these measurements by the number of housing units in California. The authors used the number of housing units from the *Population and Housing Estimates for Cities, Counties, and the State* dataset prepared by California Department of Finance (CDF, available at http://www.dof.ca.gov/Forecasting/Demographics/Estimates/E-5/, accessed on October 13, 2017). The authors used the total number of housing that is categorized as "Occupied." The number of occupied housing units was 12.93 million units for 2016, of which 65% are single-family units when a vacancy rate of 7.5% from the CDF dataset is applied. This housing total estimate included single detached and multifamily units. While not explicitly included in this study, the research team assumed methane emissions from multi-family housing can be estimated based on results from single-family homes, because they share many similar characteristics for natural gas plumbing and appliances.

Before estimating the average methane emissions from residential housing units across California, the research team examined the data for correlations between emissions and house age or broad geographic location. As noted in the results, the team did not find that significant ($p < 0.1$) relationship either between whole-house leakage and house age, or between whole-house leakage or appliance emissions between Southern California and Northern/Central California. Thus, the authors estimated statewide average CH_4 emissions from all house leakage and appliance measurements without subdividing by age or geographic location.

The measurement data are nonnormally distributed, and the associated central estimates cannot be calculated by taking simple averages. To estimate the statewide average house leakage and appliance emission rates, the authors used a Bayesian method combined with Markov chain Monte Carlo (MCMC) techniques, which comprise a class of algorithms for sampling from a probability distribution. The research team also estimated emissions using a simple bootstrapping method with resampling to be compared with the Bayesian method. The bootstrapping method assumed that the measurements are the best available samples that represent the unknown population without a normality assumption (Desharnais et al., 2014). For the Bayesian method, the authors took a parametric approach in which a probability distribution that represents the data was identified, and parameters (e.g., mean) were estimated based on the probability distribution. The Bayesian method assumed that the measurement data can be approximated by a gamma distribution (Chapter 3). The research team then fit the data to the gamma to estimate the parameters (such as mean). Because the Bayesian method with the MCMC technique yielded more conservative estimates from the assumed gamma distribution relative to the bootstrapping method, the team focused on results from the Bayesian method.

The posterior probability distribution to estimate both house leakage and appliance CH_4 emissions can be expressed as

$$p(s, r|\boldsymbol{y}) \propto p(\boldsymbol{y}|s, r)p(s)p(r) \qquad 7)$$

where **y** is the measurement vector, and *s* and *r* are the shape and rate parameters of the gamma distribution, respectively. The first term on the right-hand side is the likelihood function, and the remaining terms represent the prior distributions for the gamma distribution parameters (i.e., *s* and *r*). Equation 7) shows that the posterior probability is proportional to the likelihood function and prior distribution for the parameters.

For the likelihood function, the authors use

$$p(\boldsymbol{y}|s, r) \sim Gamma\ (s, r) \qquad 8)$$

where *Gamma* is the gamma probability distribution. *s* and *r* can be reparameterized by mean and standard deviation, which are the variables of interest, as

$$s = \frac{\mu^2}{\sigma^2}, r = \frac{\mu}{\sigma^2} \qquad 9)$$

As described, the research team needed to infer leakage rate and CH_4:CO_2 ratio to estimate whole-house leakage and appliance emissions, respectively.

In the Bayesian approach, the research team needed to specify the prior for μ and σ. The authors were interested in inferring μ and σ and needed to provide the prior distributions for μ and σ, although input parameters for the gamma distribution are *s* and *r,* they used Eq. 9 to convert u and σ to *s* and *r*. Because the authors lacked enough information on the prior distributions of μ and σ for both whole house leakage and appliance emissions, they used uniform prior as

$$\mu \sim unif\ (0, L_\mu),\ \sigma \sim unif\ (0, L_\sigma) \qquad 10)$$

where *unif* is the uniform distribution with the upper limits of L_μ and L_σ for μ and σ, respectively. For the whole-house leakage, the research team used 100 sccm (> two times the maximum measurement) for both L_μ and L_σ based on the measurements, providing large upper limits from which the team can sample. For appliance emissions, the authors needed to estimate CH_4:CO_2 ratios, which were then multiplied by natural gas consumption to obtain CH_4 emissions from appliances. Thus, the research team used 1.0 for L_μ, which is the maximum value for the CH_4:CO_2 ratio. The team used 0.5 for L_σ, which is half of the maximum CH_4:CO_2 ratio. In a sensitivity test, the team used 1.0 for L_σ and found the same result to the case where the team used 0.5 for L_σ.

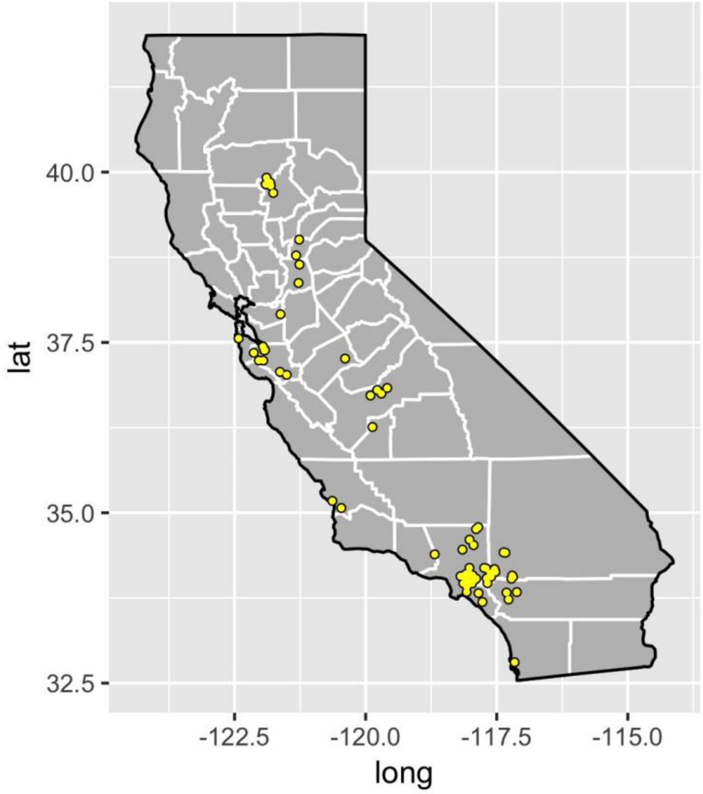
To build MCMC samplers for the posterior distribution shown in Equation 7), the authors used the JAGS system ("just another Gibbs sampler," Plummer, 2003) with the R statistical language (https://cran.r-project.org/). JAGS has been widely used for statistical inference applications, including a recent atmospheric study for estimating statewide CH_4 emissions (Jeong et al., 2016). The research team generated posterior distributions from 50,000 MCMC samples. Throughout this study, the team used 50,000 MCMC samples for all posterior distribution calculations. This study used the highest (posterior) density interval (HDI) for confidence intervals. The 95% HDI was calculated using the R HDInterval package (https://cran.r-project.org/web/packages/HDInterval/index.html, accessed on October 20, 2017). The team calculated HDI estimates such that all points within HDI have a higher probability density than those outside it (Kruschke, 2015).

CHAPTER 3:
Results

3.1 Distribution of Buildings Selected for Measurement

Figure shows the location of the 75 homes sampled in this study, 30 are in Northern California and the Central Valley (including Fresno), and 45 are located in Southern California and Central Coast (including San Luis Obispo).

Figure 9: Locations of Sampled Homes



Data points show the approximate location of 75 sampled homes (latitude and longitude of zip centroid), not the exact street address of homes.

Source: Lawrence Berkeley National Laboratory

Sampled homes span a range of characteristics in terms of year built, floor area, number of story, and foundation types. A large fraction of the 75 sampled homes (39%, Table 4) were built between 1950 and 1990, with a similar number of older and newer homes on both ends of the distribution. This is similar to the distribution of year built of California single-family detached homes from the American Housing Survey 2011 (60% of homes built between 1950 and 1990).

The physical dimensions of sampled homes (floor area and number of story) were similar in distributions compared to the American Housing Survey 2011 data. About half of the homes (55%, Table 5Source: Lawrence Berkeley National Laboratory

Table) ranged between 1,500 and 2,500 ft^2. Most of the sampled homes (71%, Table 6) were single-story.

Similar to data on foundation types from American Housing Survey 2011, crawlspace and slab were equally common among the sampled homes in Northern California/Central Valley). The slab type was more common than crawlspace for the sampled homes in Southern California/Central Coast.

Table 4: Year Built of Sampled Homes

Year Built	Percentage (%)	Number of Homes
1949 and older	**24**	**18**
1950 – 1990	**39**	**29**
1991 and newer	**37**	**28**
Total	**100**	**75**

Source: Lawrence Berkeley National Laboratory

Table 5: Floor Area of Sampled Homes

Floor Area (ft^2)	Percentage (%)	Number of Homes
<1500	27	20
1500 – 2500	55	41
>2500	19	14
Total	100	75

Source: Lawrence Berkeley National Laboratory

Table 6: Number of Story for Sampled Homes

Number of Story	Percentage (%)	Number of Homes
1	71	53
2	27	20
3	3	2
Total	100	75

Source: Lawrence Berkeley National Laboratory

Table 7: Foundation Type of Sampled Homes

Foundation	Northern California/Central Valley		Southern California/Central Coast	
	Percentage (%)	Number of Homes	Percentage (%)	Number of Homes
Slab	54	15	79	33
Crawlspace	46	13	21	9
Missing Data	--	2	--	3
Total	100	30	100	45

Source: Lawrence Berkeley National Laboratory

On average, the sampled homes had four gas appliances (Table 8). All sampled homes had a gas water heater. All except one home used gas for space heating. Storage tank water heaters were the most common (N = 70), while the remaining five homes used tankless water heaters. Most homes had a central forced air gas furnace (N = 72), while two homes used a gas wall furnace; one home did not use gas for space heating. Most of the sampled homes also used a gas cooktop (N=64) and a gas clothes dryer (N=53). About half of the homes had a gas oven (N=37).

Table 8: Number of Gas Appliances

Number of Gas Appliances	Percentage (%)	Number of Homes
2	5	4
3	15	11
4	41	31
5	35	26
6	4	3
Total	100	75

Common gas appliances include gas water heater (100%), central air gas furnace (95%), gas cooktop (85%), gas clothes dryer (71%), and gas oven (49%).

Source: Lawrence Berkeley National Laboratory

As part of the field survey, technicians observed minor gas leaks in pipe fittings near a subset of appliances in a small number of the homes (N=10, Table). Minor gas leaks were most commonly found near the gas water heater (N=6), followed by the gas cooktop (N=3), gas furnace (N=2), and gas oven (N=1), though not all appliances were tested in all houses. No gas leak associated near the gas clothes dryer was observed.

However, not all pipes and fittings were tested, so these results represent a lower limit to the number of leaks.

Table 9: Number of Minor Gas Leaks Detected by Field Technician

Number of Minor Gas Leaks	Percentage (%)	Number of Homes
0	87	65
1	12	9
>1*	1	1
Total	100	75

***Minor leaks were detected at three gas appliances in one house.**

Source: Lawrence Berkeley National Laboratory

Most study homes (71%) had between two and four occupants. Study participants reported higher income overall (85% reported household income >$75,000) compared to California's median statewide household income of $61,818 (2011–2015 data in 2015 dollars, U.S. Census Bureau, https://www.census.gov/quickfacts/CA, accessed on November 27, 2017). The median gas bill amount reported by study participants was $85 per month in January and $21 per month in August. These reported billing amounts were in rough agreement with the median amount of $60 per month according to 2011 American Housing Survey data.

A significant percentage (30%) of study participants reported having problems with cooktop gas burner ignition, which likely contributed to methane emissions. Twenty-four percent of study participants reported occasional problems with the cooktop burner ignition, and 6% of study participants reported such problems more frequently ("sometimes"). Other commonly reported issues with gas appliances, with at least 15% of study participants reporting problems occurring occasionally or more frequently include:

- Gas dryer not drying well (18%).
- Gas furnace used for space heating cycles on and off too frequently (17%).
- Gas water heater not providing enough hot water (16%).
- Gas water heater having slow recovery time (16%).
- Gas odor associated with gas cooktop or oven or both (15%).

Other problems were reported less frequently by study participants (Appendix B for list of survey questions on national gas appliances). For example, about 5% of study participants replied yes to the questions about whether the pilot light goes out in their gas furnace, gas water, gas cooktop, or gas oven.

3.2 Building Measurements

Estimated methane emissions from the quiescent buildings and appliance measurements from the 75 homes are reported in Appendix C and summarized in the next section. In addition, a table combining the measurement results with the results of the field survey completed by measurement technicians is available as a separate attachment in Microsoft Excel® format. In addition to the quiescent whole-house building emission measurement, the ΔCH_4:ΔCO_2 enhancement ratio was separately measured for two operating combustion appliances in each house.

3.2.1 Quiescent Whole-House Emissions

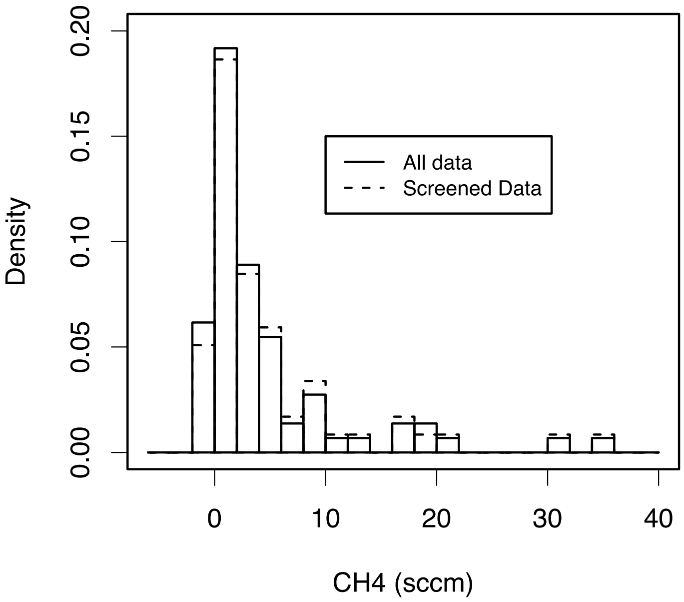
Emissions from quiescent buildings are shown as a histogram in Figure 10, ranging from near zero (nondetection) to a maximum near 36 sccm CH_4, with median and mean values of 2.0 and 4.5 sccm, respectively. The distribution of the data is clearly non-Gaussian with a long tail that will be characterized in the following analysis section. As described in the methods, the team screened the data when the estimated calibration gas flow did not match the known release rate to within two times the estimated measurement error (10 houses) but found the differences in distribution and summary statistics were indistinguishable compared to the observed spread in emissions. In addition, instrument problems caused measurements to fail for two houses. As noted above, field technicians inspected pipe fittings near a subset of appliances but found only 10 leaks. While whole-house leakage did not vary significantly across this sampling of leaks, the authors suspect this likely underestimates the number of houses with leaks because the field survey technicians did not inspect all pipes and fittings within each house.

3.2.2 Combustion Appliance Measurements

Two combustion appliances were measured in each home. As shown in Appendix C, the appliances measured included domestic water heaters with tanks (DWH), tankless water heaters (TWH), furnaces, stovetops, wall furnaces, and domestic water heaters and furnace pilot lights (DWH pilot, furnace pilot). Except for pilot lights (which had low gas use and were not switched on and off), the gas use during operation was measured separately for each combustion appliance. Because of instrument or operator errors, a subset of appliance measurements did not yield valid data and are marked as NA.

Summary statistics for valid emission measurements by appliance type are shown in Table 11. Less than half of the measurements (1 of 6 furnaces, 16 of 56 domestic water heaters, and 23 of 51 stovetops) had ΔCH_4:ΔCO_2 enhancements greater than zero as indicated by Ntot and Nzero, respectively. Here, the cases identified as zeros had either no measurable CH_4 enhancement or showed CH_4 depleted in the exhaust gas relative to air supplying the appliance, indicating that the flames consumed part of the methane present in the supply air.

Figure 10: Histogram of Measured Quiescent Whole-House Emissions



Measured emissions are shown for all data (solid line) and the houses screened (dashed line) where measured CH_4 gas addition matched the control value (5 sccm) to within a factor of 2 times the estimated measurement error. Note: 1 sccm = 1.03 g CH_4/day.

Source: Lawrence Berkeley National Laboratory

For the cases with positive $\Delta CH_4:\Delta CO_2$ enhancement, values ranged generally between 0.015% and 0.5% and a few higher values between 1% and 3%. Furnaces were an exception, with one nonzero value of 0.03% observed out of six furnaces measured, consistent with a small number of measurements made as part of a previous Energy Commission study (Fischer et al., 2017). Based on the low values in the small number of furnaces measured, the authors assumed furnaces make what amounts to a minor correction to CH_4 from furnace exhaust in the statewide analysis section below. Because of the large number of zero values, the resulting distributions of $\Delta CH_4:\Delta CO_2$ ratios are highly non-Gaussian, meaning that they do not follow a normal distribution. (See histograms in the following section.) There was no significant relationship between the measured $\Delta CH_4:\Delta CO_2$ enhancement ratios and appliance age for domestic water heaters or stovetops (Table 10).

Table 10: Summary Statistics for Combustion Appliance ΔCH_4:ΔCO_2 Enhancement Ratios (%)

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	Ntot	Nzero
Tank WH	0.000	0.000	0.000	0.136	0.100	1.000	62	40
Tank WH pilot	0.150	0.400	0.500	0.530	0.800	0.800	5	0
Dryer	0.000	0.000	0.035	0.068	0.103	0.200	6	2
Furnace	0.000	0.000	0.000	0.005	0.000	0.030	6	5
Furnace Pilot	0.230	0.515	0.800	0.677	0.900	1.000	4	0
Stovetop	0.000	0.000	0.000	0.242	0.100	3.000	54	28
Tankless WH	0.050	0.065	0.080	0.077	0.090	0.100	5	0
Wall Heater	0.000	0.250	0.500	0.500	0.750	1.000	2	1

Source: Lawrence Berkeley National Laboratory

Pilot light flames are an important exception to the above results, with all measured pilot lights exhibiting positive ΔCH_4:ΔCO_2 enhancement ratios. Because the number of total pilot light measurements was small, the distributions of water heater and furnace pilot lights cannot be distinguished. Grouping them together yielded mean and median ΔCH_4:ΔCO_2 enhancement ratios of 0.059% and 0.065%, and standard deviation 0.03%, respectively. Based on these results, the authors included pilot lights as a separate category of combustion appliance and evaluate the associated importance for California's total residential CH_4 emissions in the following discussion.

3.2.3 Separate Measurements of Three Tankless Water Heaters

In addition to the 75-house study, the research team measured three tankless water heaters, one at LBNL and two at researchers' homes in the San Francisco Bay Area. For each heater, the team measured the ΔCH_4:ΔCO_2 of exhaust gas at 2-3 gas flow rates, adjusted by varying the flow of cold water to the unit. In each case, the team repeated the measurement three times for each gas flow rate to estimate the variability in the measurements, which the authors report as standard deviation of 3.

The average and standard deviation of ΔCH_4:ΔCO_2 and CH_4 emission rates obtained from steady state operation of the tankless heaters are summarized in Table 11 and displayed in Figures 11 and 12. The results show that the ΔCH_4:ΔCO_2 ratios vary from 0.07% to 0.15% depending on the model of the water heater itself over the range of gas consumption measured. Because of the high gas flow to the tankless heaters, the corresponding CH_4 emissions varied from 17 to 68 sccm (1 sccm = 1.03 g CH_4/day). The ratio and gas flow were measured for three startup and shutdown cycles. The researchers estimate the uncertainty of each by calculating the standard deviation of the three replicate measurements. The standard deviations were equal to 5-10% of the mean values. Moreover, the most modern unit exhibited the lowest ΔCH_4:ΔCO_2 ratios.

While two units (Rheem and Rinnai) exhibited $\Delta CH_4:\Delta CO_2$ ratios declining with input gas flow (such that CH_4 emissions are relatively constant with input power), the third unit showed roughly constant or slightly increasing $\Delta CH_4:\Delta CO_2$ ratio with gas flow. The $\Delta CH_4:\Delta CO_2$ ratios measured for these three heaters were consistent with the range of values (0.05-0.1%) obtained for tankless heaters measured in the 75-home sample.

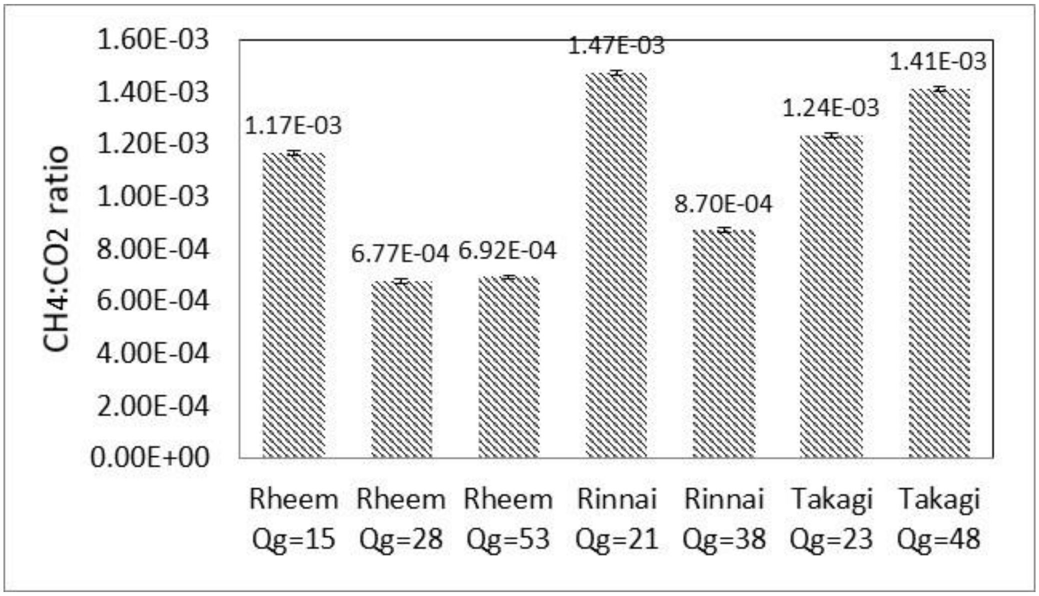
With respect to water heater cycling, additional methane emissions estimated for the combination of ignition and quench of these heaters varied from roughly 10 to 105 (+/-10) additional seconds of steady-state operation. This result suggests that hot water use involving many short (<2 minutes) heating cycles could emit roughly twice the CH_4 per unit of water supplied than for longer heating cycles, offsetting some of the advantage over tank water heaters with pilot lights.

Table 11: Measured Performance of Tankless Water Heaters During Steady Operation

Unit	Gas flow (lpm)	Avg· ΔCH_4: ΔCO_2	Stdev $\Delta CH_4:\Delta CO_2$	Avg Emission (sccm)	Stdev Emission (sccm)
Rheem	15.28	1.17E-03	1.47E-05	17.87	1.99
Rheem	27.82	6.77E-04	7.64E-06	18.83	0.75
Rheem	52.64	6.92E-04	8.04E-06	36.41	0.31
Rinnai	20.92	1.47E-03	3.01E-05	30.85	0.63
Rinnai	38.31	8.70E-04	8.90E-06	33.32	0.34
Takagi	22.94	1.24E-03	1.72E-05	28.38	1.92
Takagi	47.63	1.41E-03	3.43E-06	67.30	2.14

Source: Lawrence Berkeley National Laboratory

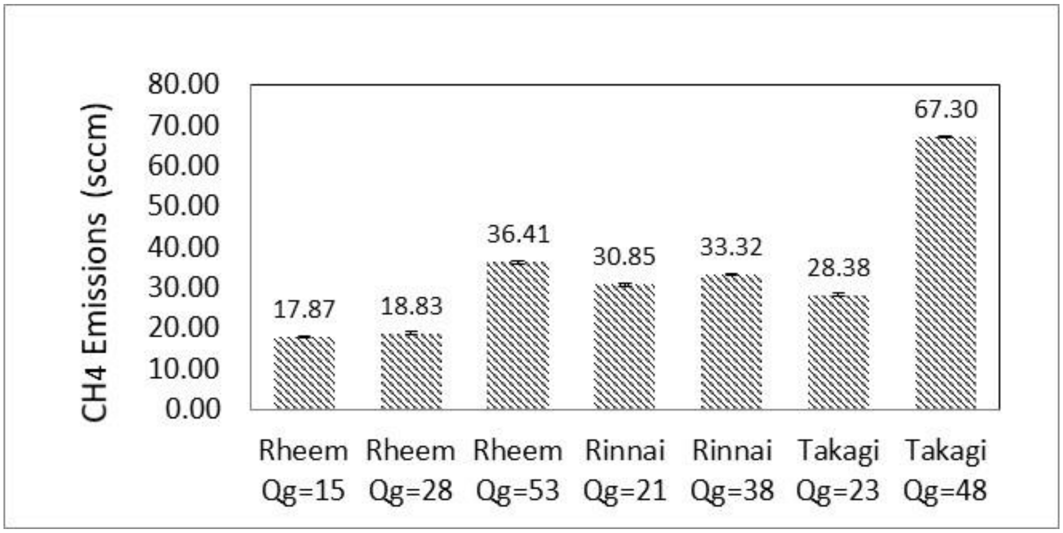
Figure 11: Tankless Heater ΔCH_4: ΔCO_2 Ratio by Model and Gas Supply Flow Rate



Ratios of emitted CH_4 to CO_2 for three tankless water heaters operated at different power levels from Table 12.

Source: Lawrence Berkeley National Laboratory

Figure 12: Tankless Heater CH_4 Emissions by Model and Gas Supply Flow Rate



Methane emissions for three tankless water heaters operated at different power levels from Table 12. Note: 1 sccm = 1.03 g CH_4/day.

Source: Lawrence Berkeley National Laboratory

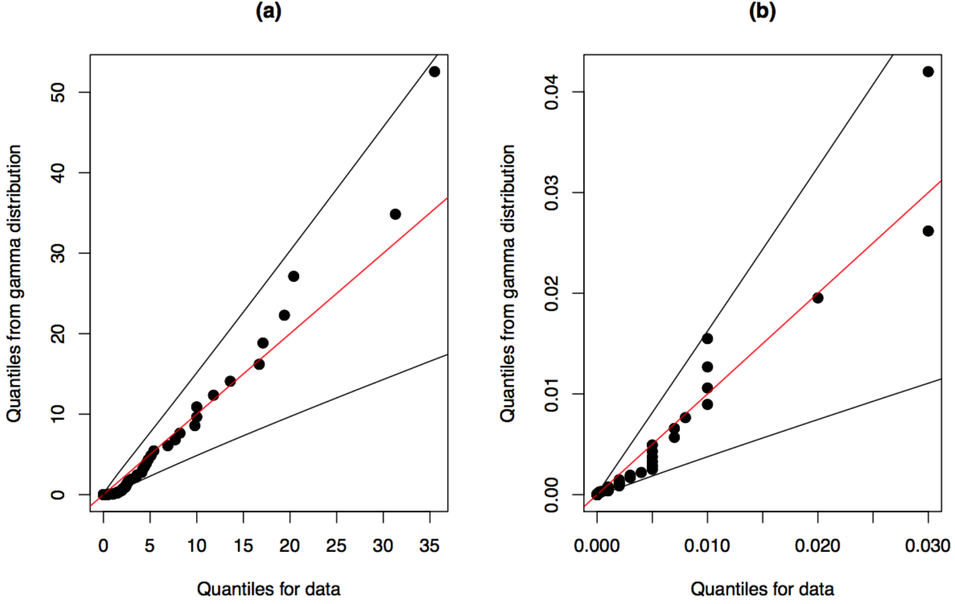
3.3 Statistical Estimation of California Emissions

3.3.1 Probability Distribution Fitting

The authors fit the measurements for quiescent house leakage and appliance emission rates to several nonnegative probability distributions (such as log-normal, gamma). For this purpose, a quantile-quantile (Q-Q) plot is typically used to compare the quantiles of measured data with the quantiles from theoretical distributions. In this work, the authors set all zero values to an infinitesimal positive definite value (1e-9). They then assessed the underlying distributions by fitting the observed quantiles (house leakage rate and appliance emission observations) to quantiles of theoretical distributions (for example gamma). For the Q-Q plot fitting, they used an R statistical package, qualityTools (https://cran.r-project.org/web/packages/qualityTools/index.html, accessed on October 1, 2017).

Based on the fitting results, the research team found that the data are best represented by the gamma distribution. Figure 13(a) shows the fit result of the leakage rate measurements to the gamma distribution. For this fit, the team removed 14 data points based on the quality control using the measured calibration flow. (Chapter 2 for details.) Similarly, Figure 13(b) shows the fit of the measurements for appliance emission rates (ΔCH_4: ΔCO_2 ratio) to a gamma distribution. Assuming gamma distributions from this fit result, the team estimated the emissions by inferring central estimates (with uncertainty) of the gamma distributions for both the house leakage rate and appliance emission rate. Because this gamma distribution is related to the observations, the team used it as a likelihood function of the Bayesian inference. (Section 2.3 for the details of the likelihood function.)

Figure 13: Gamma Q-Q Plot for (a) Measured Whole House Leakage Rates (in units of sccm) and (b) Measured ΔCH4: ΔCO2 Emission Ratios for Appliances (fractions)



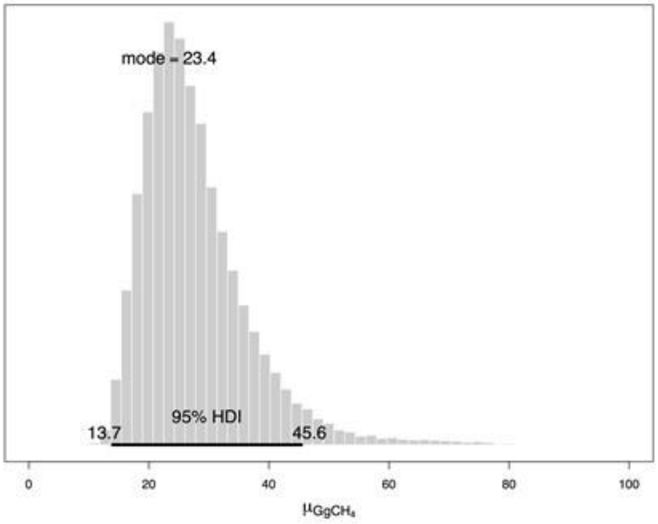
Black circles represent the quantiles of the data (data sorted in ascending order), and the red line in each plot represents a line that passes through the first and third quartiles. The confidence bounds (black lines) are shown at the 95% level. The units in the plots are in measurement units.

Source: Lawrence Berkeley National Laboratory

3.3.2 Emissions From House Leakage

Using the Bayesian method and measurements, the research team estimated mean CH_4 emissions from quiescent house leakage and pilot light emissions in California. Figure 14 shows the posterior distribution (with summary statistics) for the mean CH_4 emissions from house leakage, which was estimated using the Bayesian method treating the unknown mean CH_4 emission as a random variable. As shown in Figure 14, the posterior estimate for mean whole-house emissions is 23.4 (13.7 – 45.6, hereafter 95% confidence) Gg CH_4/yr when using only measurements from houses where the calibration prescribed calibration flow is obtained. (Section 2.) This result is not sensitive to removing data, as shown in Figure 15, where emissions estimated using all measurements yields whole-house emissions of 20.9 (12.5 - 37.5) Gg CH_4/yr. The slightly smaller confidence interval (specifically HDI) is likely due to including more data. For comparison with the Bayesian method, using the data directly in a bootstrap method yielded a narrower confidence interval of 15.3 - 31.7 Gg CH_4/yr.

Figure 14: Posterior Distribution for Estimated Mean Quiescent House Leakage CH_4 Emissions Obtained Using Measurements Passing Quality Control Test



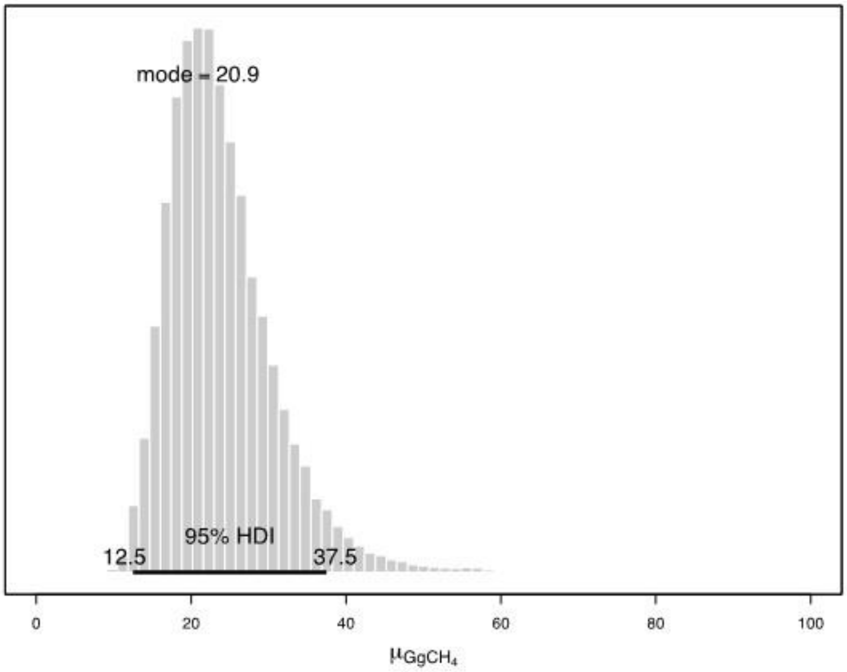
The posterior distribution represents whole-house quiescent leakage (Gg CH_4/yr) including pipe leaks and emissions from pilot lights. The distribution was estimated using the subset of measurements that pass the quality control test using calibrated leak measurements described in the methods section.

Source: Lawrence Berkeley National Laboratory

The whole-house measurements captured leakage from fittings and emissions from pilot lights. Here, the research team provides an estimate of the likely contribution of pilot lights to typical whole-house emissions as the product of the number of pilot lights in an average house, the amount of gas consumed by a pilot light, and the fraction of methane emitted unburned from the CH_4:CO_2 enhancement ratio measured for pilot lights in this study. As previously described, the team assumed the number of pilot lights per house and the gas use for pilot lights in Table 2. Combining this with the estimate in Table 11 for the ΔCH_4:ΔCO_2 ratio for pilot lights (0.6+/-0.3), the team estimated pilot light emissions are 4.7 (3-10) Gg CH_4/yr, where the uncertainty was assumed to be dominated by uncertainty in the ΔCH_4:ΔCO_2 ratio, though the team acknowledged that gas consumption and number of lights were also uncertain.

Compared with the whole-house measurements, the mean estimate for pilot light emissions accounted roughly 25% of the estimated quiescent house leakage. This estimate for the relative contribution of pilot lights to the whole-house leakage was based on a simple estimate of the pilot light gas use and a limited number of measurements for pilot lights from the samples. Although the approach was simple and data were limited, this result suggests that further studies on pilot light emissions may be important, given the relatively large contribution of pilot lights to the whole-house leakage (Figure 15).

Figure 15: Posterior Distribution for Estimated Mean Quiescent House Leakage CH_4 Emissions Obtained With All Whole-House Measurements



The posterior distribution represents whole-house quiescent leakage (Gg CH_4/yr), including pipe leaks and emissions from pilot lights. The distribution is estimated using the all whole-house measurements.

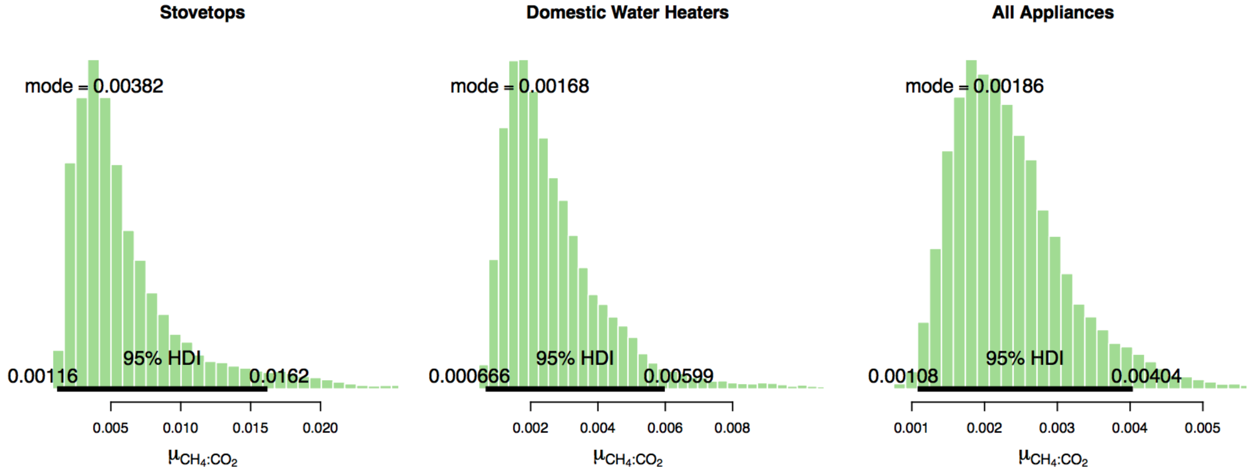
Source: Lawrence Berkeley National Laboratory

3.3.3 Emissions From Residential Appliances

The research team estimated residential CH_4 emissions from appliances by grouping measurements by the appliance type and measurements of the $\Delta CH_4:\Delta CO_2$ ratio combined with gas usage by appliance type. Here, the authors note that NG use by pilots is subtracted from the total NG consumption by appliance class before estimating CH_4 emissions from operating appliances. Figure 16 shows the posterior distributions for the estimated mean $\Delta CH_4:\Delta CO_2$ ratios by the appliance type fit to gamma distributions. Other appliance types were estimated as point estimates.

Comparing the posterior mean $\Delta CH_4:\Delta CO_2$ ratio for conventional domestic water heaters (0.17% (0.067-0.6%) with the range of measured $\Delta CH_4:\Delta CO_2$ ratios for tankless heaters (0.05-0.15%), tankless heaters appear to burn more efficiently than the flames of the tank heaters. This observation, with the fact that the majority of existing tank heaters use pilot lights, suggests that tankless heaters may be superior from a methane emissions and an energy efficiency perspective.

Figure 16: Posterior Distributions for Mean $\Delta CH_4:\Delta CO_2$ Enhancement Ratios



The posterior distributions were generated for stovetops, domestic water heaters, and all appliances, respectively.

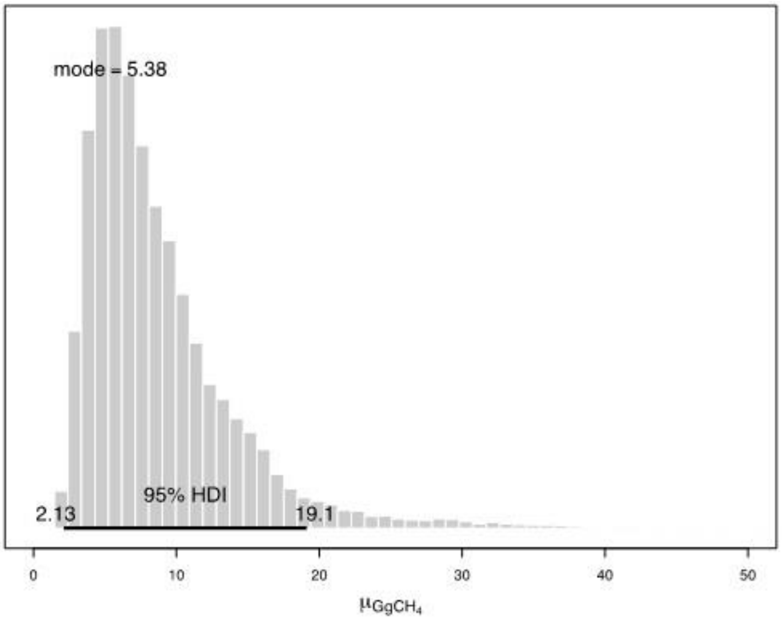
Source: Lawrence Berkeley National Laboratory

CH_4 emissions from appliances were estimated (Eq 6.) as the product of the $\Delta CH_4:\Delta CO_2$ ratio and the natural gas use for each appliance type from Table 4. As shown in Figure 17, emissions from domestic water heating were 5.4 (2.1 – 19.1) Gg CH_4/yr (at 95% confidence). For the stovetop, total CH_4 emissions were estimated to be 1.6 (0.5 – 6.6) Gg CH_4/yr (Figure 18). Although the mean $\Delta CH_4:\Delta CO_2$ ratio was higher for the stovetops (mode = 0.0038) than for the water heater (mode = 0.0017), the natural gas use for the cooking was only 14% of the water heating.

Total CH_4 emissions estimated by appliance types are summarized in Table 12. The largest single category is emissions from domestic water heating which total 5.4 (2.1 – 19.1) Gg CH_4/yr (at 95% confidence). For comparison, emissions from cooking are estimated to be 1.6 (0.5 – 6.6) Gg CH_4/yr. Although the mean $\Delta CH_4:\Delta CO_2$ ratio is higher for the stovetops (mode = 0.0038) than for the water heater (mode = 0.0017), the NG use for the cooking is only ~ 14% of that of the water heating. Estimating emissions from joint MCMC sampling of water heating and cooking together yields emissions of 7.5 (3.3 – 22.7) Gg CH_4/yr. Joint sampling for the sum of water heating and cooking does not yield the same result as that from the linear sum of individual sampling results due to non-Gaussian likelihood distributions and sampling uncertainty (inherent in working with samples).

The other appliance types are estimated to have comparatively much smaller emissions (furnaces, spas, etc.). The lower 25% and upper 75% estimates for $\Delta CH_4:\Delta CO_2$ ratio together are used with gas consumption to estimate the central value as the geometric mean of the lower and upper estimates. For example, this results in estimated emissions of 0.4 (0.04 – 1.1) Gg CH_4/yr for space heating. In areas where a significant fraction of space heating is done with inefficient heaters (such as wall furnaces), these emissions will likely be higher. Emissions from spa/hot tubs, and clothes driers are estimated to contribute small but uncertain amounts to the combustion related emissions. Lacking better information, emissions were summed for these classes linearly with a total estimate of 1.1 (0.4 – 3.4) Gg CH_4/yr for space heating, pools and spas, and clothes driers together linearly.

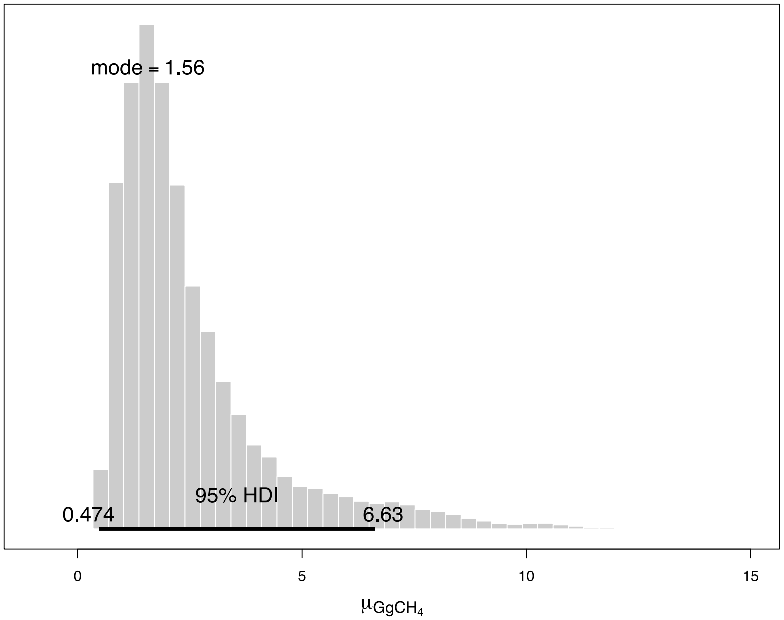
Figure 17: Total Estimated CH_4 Emissions (Gg CH_4/ yr) From California Domestic Water Heaters



The posterior distribution representing emissions (Gg CH_4/yr) for water heating not including pilot lights

Source: Lawrence Berkeley National Laboratory

Figure 18: Total Estimated CH_4 Emissions (Gg CH_4/ yr) From California Stovetops (Cooking)



The posterior distribution representing emissions from cooking (Gg CH_4/yr) based on stove tops not including pilot lights.

Source: Lawrence Berkeley National Laboratory

Table 12: Estimated Quiescent CH_4 Emissions from California Homes and Combustion Appliances

Estimation Type	**Description**	**Lower CH4:CO2 ratio *** (%)	**Lower CH4 emitted** (Gg CH_4/yr)	**Central CH4: CO2 ratio *** (%)	**Central CH4 emitted** (Gg CH_4/yr)	**Upper CH4:CO2 ratio *** (%)	**Upper CH4 emitted** (Gg CH_4/yr)	**Lower CH4 MCMC** (Gg CH_4/yr)	**Central CH4 MCMC** (Gg CH_4/yr)	**Upper CH4 MCMC** (Gg CH_4/yr)
Quiescent Whole-House	Whole-House Leakage							13.7	23.4	45.6
Appliance Combustion	Space Heating	0.005	0.1	0.014	0.4	0.04	1.1			
	Water Heating	0.07	2.2	0.205	6.5	0.6	19.1	2.1	5.4	19.1
	Cooking	0.11	0.5	0.420	1.7	1.6	6.6	0.5	1.6	6.6
	Pool&Spa	0.07	0.1	0.205	0.4	0.6	1.3			
	Clothes Dryer	0.005	0.0	0.032	0.1	0.2	0.5			
MCMC-Appliance Combustion**	Water Heating + Cooking							**3.3**	**7.5**	**22.7**
Total MCMC**	Water Heating + Cooking + Whole-House Leakage							**21.3**	**34.6**	**60.6**
Minor Appliances***	Space Heating + Pool/Spa + Dryer		**0.4**		**1.1**		**3.4**			

*** Ratios for water and cooking values taken from fitted distributions, others are minimum value greater than zero or max of observed values, with pool and spa assumed the same as heaters for domestic water. ** Note: MCMC sampling of joint distributions yield estimates that differ from the linear sum over individual distributions. *** Total emissions reported in text are estimated by summing minor appliances linearly with MCMC result**

CHAPTER 4: Discussion and Recommendations

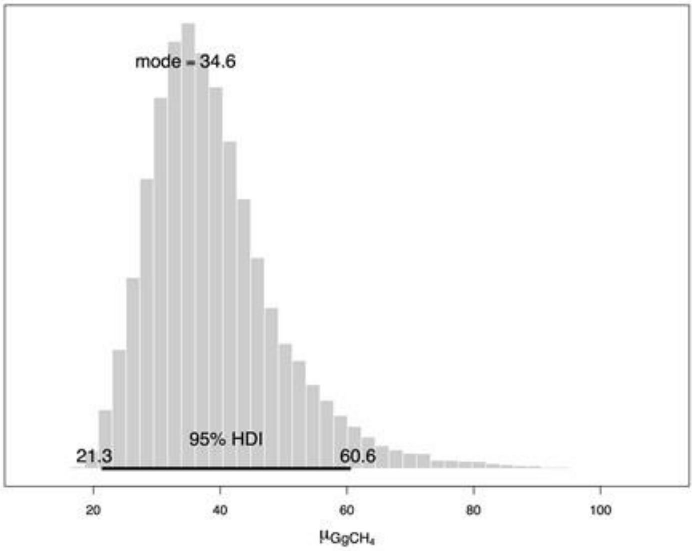
4.1 Residential Emissions Compared With Regional Studies

The authors estimated total natural gas CH_4 emissions from California residential gas consumption by combining emission estimates from quiescent house leakage and residential combustion appliances. As mentioned in the results section, the research team did not detect any statistically significant variation in measured emissions for either whole-house or appliances by house age or broad geographic location (between Southern and Northern California.)

Methane emissions from California residences are estimated for the combination of quiescent house leakage and operating combustion appliances combining MCMC emission samples from these two sectors (Figure 19). Including the additional emissions from minor appliances (see Table 12) linearly, total CH_4 emissions from residential sector NG consumption is 35.7 (21.7 – 64.0) Gg CH_4/yr (and 0.9 (0.5 - 1.6) Tg CO_2eq, using the global warming potential of 25 gCO_2eq/gCH_4 adopted by the CARB GHG inventory), equivalent to 0.5% (0.3 - 0.9%) of residential consumption. This is equivalent to roughly 15% of estimated the California inventory for NG related CH_4 emissions (6.4 Tg CO_2eq), and 2% of total inventory CH_4 emissions (39.6 Tg CO_2eq) in 2015 (CARB, 2017). In terms of cost to consumers, if a 0.5% of California's residential NG gas consumption is emitted at an average price of ~ $12/Mcft in 2016 (EIA, 2018), the economic value of lost gas is approximately $30 million/yr that could be applied to reducing sources of post-meter CH_4 emissions.

In comparison with regional studies, it is difficult to uniquely attribute the residential portion of CH_4 emissions estimated in regional atmospheric inversion studies of California because of the presence of other fossil-fuel related (for example petroleum and gas production, transmission, and distribution) and also biological (such as livestock, landfills, etc.) CH_4 sources. For example, the Los Angeles area and South Coast Air basin have numerous petroleum production and gas storage activity (Jeong et al., 2016). However, previous work for the Energy Commission applied multi-species measurements in a source-specific inversion to show that total natural CH_4 emissions from the San Francisco Bay Area (which contains no significant petroleum or gas production) are equivalent to 0.3–0.5% of total gas consumption (Jeong et al., 2017). This estimate of the emitted fraction of residential NG consumption is hence slightly higher than, but likely consistent with, the regional inversion estimate if emissions from residential portion of gas delivered through distribution and transmission pipelines are small compared to the residential emissions, and the emitted fraction of gas used by commercial buildings and industrial activities is similar to or smaller than that for residential. These later questions are being addressed in current research for the Energy Commission (PIR-15-003 and PIR-15-017).

Figure 19: Combined Total Residential CH_4 Emissions (Gg) Combining Whole House Leakage and Major Residential Appliances



Source: Lawrence Berkeley National Laboratory

Summing linearly across all aspects of combustion appliances, CH_4 emissions from major operating appliances (7.5 (3.3 – 22.7) Gg CH_4 /yr), minor appliances (1.1 (0.3-4.4 Gg CH_4 /yr), and pilot lights (4.7 (3-10) Gg CH_4 /yr) yields 13.3 (6.6 – 37.1) Gg CH_4 /yr, which is roughly equivalent to 0.17 (0.08-0.47) % of total gas consumed. Converting combustion related CH_4 emissions to 100-yr CO_2 equivalent units the estimate of 0.33 (0.15 – 0.89) Tg CO_2eq is more than an order of magnitude larger than residential natural gas combustion emissions (0.01 Tg CO_2eq) reported in the 2015 state GHG inventory. Nearly 30% of the total appliance emissions are estimated from pilot lights, suggesting a value in moving toward electronic ignitions. Last, appliance emissions may be larger than the steady state measurements reported for 75 homes suggest because of emission transients during burner startup and shutdown as found in the separate measurements of tankless water heaters. This suggests that future work should include measurement of transient emissions across a sample of appliance types and manufacturers should consider design of new products that minimize CH_4 emissions during startup and shutdown.

For this estimate, the team aggregated MCMC samples from house leakage and appliances (water heater and stovetop), taking advantage of the Bayesian MCMC method that allows for constructing a distribution from different sets of MCMC samples.

4.2 Recommendations

Comparing the estimated CH_4 emissions for different quiescent leakage and combustion appliances suggests that 1) quiescent emissions from a combination of pipe leaks occur in a subset of houses but that emissions from pilot lights may constitute a significant fraction of quiescent house emissions, 2) emissions from combustion appliances are likely dominated by water heating, and 3) tankless water heaters with electronic ignitions appear to emit similar or less CH_4 than conventional domestic (tank) water heaters with pilot lights per unit of gas consumed. With these considerations, it appears appropriate to suggest:

- Using electronic ignitions (rather than pilot lights) in new combustion appliances. This could reduce emission by 8 Gg methane per year, saving about $3 million on fuel.
- Adopting test standards and use of low-emitting tankless water heaters for retrofit and new installations.
- Inspecting and repairing leaks of readily accessible pipe-fittings (such as at point of sale or during energy retrofits). This could potentially reduce 16 Gg methane emission per year, about $15 million saved on fuel.

- Finally, while CH_4 emissions from houses are small compared to most other sources of anthropogenic CH_4, California’s ambitions climate goals (for example 80% reduction by 2050) require aggressive reductions to GHG emissions, suggesting value in maintaining/upgrading building infrastructure, modernizing combustion appliances, but also gradually transitioning to renewable non-fossil energy sources and high-efficiency technologies (for example heat pumps, induction heating) for residential water and space heating and cooking (Hong et al., 2016; Sheikh, 2016).

LIST OF ACRONYMS

Term	Definition
CH_4	Methane
GHG	Greenhouse gas
MCMC	A Markov chain Monte Carlo (MCMC) method is an algorithm used for sampling from a probability distribution.
NG	Natural gas
Q-Q plot	The Q-Q plot is used to determine if two sets of samples come from the same probability distribution.
sccm	standard cubic centimeter per minute
SFBA	San Francisco Bay Area
therm	The therm is a unit of heat equivalent to 100,000 British thermal units (Btu).

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APPENDIX A:
Field Survey Form

Home ID: ______________ City: ____________________ 3-Digit Zip Code: _________

Field Technician: ____________________ Date/Time of Arrival: __________________

1. Basic House Characteristics

Conditioned Floor Area: ________________ Number of Story: _______________

Ceiling Height: _______________________ House Height: _________________

Year Built: __________________________ Year Moved in: ________________

Number of Bedrooms: _________________

Number of Full Bathrooms: _____________ Half Bathrooms: _______________

Garage: ☐ Attached ☐ Detached ☐ None ☐ Other. Specify: ______________

Foundation Type: ☐ Vented Crawlspace ☐ Unvented Crawlspace

☐ Slab ☐ Other. Specify: _______________________

Front Orientation (N / E / S / W): _________________________

Air Conditioning: ☐ Central System ☐ Room Units. Number: _________ ☐ None

Heating Equipment	Main	Supplementary
Forced warm-air furnace with ducts and vents to individual rooms		
Electric heat pump		
Built-in electric baseboard heating OR electric coils in floors, ceilings, or walls		
Floor, wall, or other pipe-less furnace built into the building		
Steam or hot water system with radiators OR other system using steam or hot water		
Room heaters burning kerosene, gas, or oil		

Heating Equipment	Main	Supplementary
☐ Vented ☐ Unvented		
Portable electric heaters		
Wood-burning stove, pot belly stove, Franklin stove		
Cooking stove		
Fireplace ☐ With inserts ☐ Without inserts		
Other. Specify:		

Sketch House Layout ☐ 1st Story ☐ 2nd Story ☐ Other. Specify: ______________

Indicate locations of gas appliances in sketch: **F** = furnace, **W** = water heater, **D** = clothes dryer, **C** = cooktop, **O** = oven, **R** = other. Specify: _________________________

2. Gas Appliances

2.1 Furnace

☐ Natural gas ☐ Electric ☐ Other. Specify: _________________

Make: ___________________________ Model: ___________________________

BTU Rating: _____________________________________ ☐ EnergySTAR

Year Installed: ____________________________________ ☐ Unknown

Last Serviced: ____________________________________ ☐ Unknown

Location: ____

Describe Condition: Good / Fair / Poor ____

NG odor detected? Yes / No _________________________________

Leak detected? Yes (Bubble / NG meter) / No____________________

____

2.2 Water Heater

☐ Natural gas ☐ Electric ☐ Other. Specify: _________________

☐ Storage ☐ Tankless ☐ Heat pump ☐ Solar

☐ Other type. Specify: ___________________________

Make: ______________________________ Model: ______________________________

BTU Rating: ____ ☐ EnergySTAR

Year Installed: ____ ☐ Unknown

Last Serviced: ____ ☐ Unknown

Location: ____

Describe Condition: Good / Fair / Poor ____

NG odor detected? Yes / No _____________________________________

Leak detected? Yes (Bubble / NG meter) / No______________________

____

2.3 Cooktop

☐ Natural gas ☐ Electric ☐ Other. Specify: ___________________

Make: ______________________________ Model: ______________________________

BTU Rating: ____ ☐ EnergySTAR

Year Installed: ____ ☐ Unknown

Last Serviced: ____ ☐ Unknown

Location: ____

Describe Condition: Good / Fair / Poor ____

NG odor detected? Yes / No _____________________________________

Leak detected? Yes (Bubble / NG meter) / No______________________

____

2.4 Oven / Range

☐ Natural gas ☐ Electric ☐ Other. Specify: ___________________

Make: ______________________________ Model: ______________________________

BTU Rating: ____ ☐ EnergySTAR

Year Installed: ____ ☐ Unknown

Last Serviced: ____ ☐ Unknown

Location: ____

Describe Condition: Good / Fair / Poor ____

NG odor detected? Yes / No ___________________________________

Leak detected? Yes (Bubble / NG meter) / No_____________________

____

2.5 Clothes Dryer

☐ Natural gas ☐ Electric ☐ Other. Specify: _________________

Make: ____________________________ Model: ____________________________

BTU Rating: _______________________________________ ☐ EnergySTAR

Year Installed: ______________________________________ ☐ Unknown

Last Serviced: ______________________________________ ☐ Unknown

Location: ____

Describe Condition: Good / Fair / Poor ____

NG odor detected? Yes / No ___________________________________

Leak detected? Bubble / NG meter _____________________________

____

2.6 Other natural gas appliance. Specify: ____

Make: ____________________________ Model: ____________________________

BTU Rating: _______________________________________ ☐ EnergySTAR

Year Installed: ______________________________________ ☐ Unknown

Last Serviced: ______________________________________ ☐ Unknown

Location: ____

Describe Condition: Good / Fair / Poor ____

NG odor detected? Yes / No ___________________________________

Leak detected? Yes (Bubble / NG meter) / No_____________________

____

3. Structure Conditions

3.1 Heating

- ☐ Uncomfortably cold because heating equipment broken down.
- ☐ Having unvented gas, oil, or kerosene heaters as the primary heating equipment.

3.2 Electric

- ☐ Exposed wiring.
- ☐ Broken fuses or tripped circuit breakers.

3.3 Upkeep

- ☐ Water leaks from the outside, such as from roof, basement, windows, or doors.
- ☐ Water leaks from inside structure, such as pipes or plumbing fixtures.
- ☐ Holes in the floors.
- ☐ Holes or open cracks in the walls or ceilings.
- ☐ More than 8 inches by 11 inches of peeling paint or broken plaster.
- ☐ Signs of mice or rats.

3.4 Indoor Environmental Quality

- ☐ Smoking in home.
- ☐ Musty smells in home.
- ☐ Mold present in home. Describe location(s): ___________________________________

3.5 Structure Exterior

- ☐ Sagging roof that can be seen without climbing on the roof.
- ☐ Missing roof materials include rotted, broken or missing shingles, tiles, slates, etc.
- ☐ Holes that expose the inside of the unit to the elements.
- ☐ Missing materials on the walls and chimney.

- ☐ Boarded-up windows or doors, covered by board, brick, metal or other material.
- ☐ Broken windows with at least several panes are missing or broken.
- ☐ Foundation defects include large cracks, holes, and rooted, loose or missing material.

3.6 Other. Describe: ____

____

4. Overall Assessment

4.1 In your opinion, does the home receive adequate maintenance?

☐ Adequate ☐ Moderately inadequate ☐ Severely inadequate

Describe: ____

____

4.2 On a scale of 1 to 10, how would you rate this unit as a place to live?

Worst 1	2	3	4	5	6	7	8	9	Best 10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

4.3 On a scale of 1 to 10, how would you rate this neighborhood?

Worst 1	2	3	4	5	6	7	8	9	Best 10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Definitions

Heading Equipment:

- Warm-air furnace refers to a central system that provides warm air through ducts leading to various rooms.

- Steam or hot water system refers to a central heating system in which heat from steam or hot water is delivered through radiators or other outlets. It also includes solar heated hot water that is circulated throughout the home.

- Electric heat pump refers to a heating and cooling system that utilizes indoor and outdoor coils, a compressor, and a refrigerant to pump in heat during the winter and pump out heat during the summer. Only heat pumps that are centrally installed with ducts to the rooms are included in this category. Others are included in wall units.

- Built-in electric units refer to units permanently installed in floors, walls, ceilings, or baseboards.

- Floor, wall, or other built-in hot-air unit without ducts delivers warm air to the room right above the furnace or to the room(s) on one or both sides of the wall in which the furnace is installed.

- Room heater with flue refers to non-portable room heaters in the wall or free standing heaters that burn liquid fuel, and which are connected to a flue, vent, or chimney to remove smoke and fumes.

- Room heater without flue refers to any room heater that burns kerosene, gas, or oil, and that does not connect to flue, vent, or chimney.

- Portable electric heater refers to heaters that receive current from an electrical wall outlet.

- Fireplaces with inserts have a fan-forced air circulation system to force the heat into the room.

- Fireplaces without inserts refers to glass door fire screens or fire backs inserted in the back of the fireplace to passively reflect heat.

- Cooking stove refers to gas or electric ranges or stoves originally manufactured to cook food.

- Stove refers to any range or stove that burns solid fuel including wood burning, pot belly, and Franklin stoves.

- Other includes any heating equipment that does not fit the definition for any of the previous definitions.

Cooling Equipment:

- Air conditioning is defined as the cooling of air by a refrigeration unit. This definition excludes evaporative coolers, fans, or blowers that are not connected to a refrigeration unit.

- A "room unit" is an individual air conditioner which is installed in a window or an outside wall and in generally intended to cool one room.
- A "central system" is a central installation which air-conditions the entire housing unit. A central installation with individual room controls is a central air-conditioning system.

Descriptions of exterior structure deficiencies*:

- A roof is sagging if it is substantial and can be seen without climbing on the roof.
- Missing roof materials include rotted, broken or missing shingles, tiles, slates, etc., may have been caused by extensive damage from fire, storm or serious neglect.
- Holes are missing materials that expose the inside of the unit to the elements.
- Missing materials on the walls and chimney may have been caused by fire, storm, flood, neglect or vandalism. Missing materials may <u>or</u> may not expose the inside of the unit to the elements.
- Boarded-up windows or doors may be covered by board, brick, metal or other material.
- Broken windows are if several panes are missing or broken.
- Foundation defects include large cracks, holes, and rooted, loose or missing material.

[*] Do not report the above defects if the conditions are due to construction activities, unless it is obvious that the work has been abandoned.

APPENDIX B:
Occupant Survey Form

Richard Heath & Associates, Inc.
1390 Ridgewood Drive #10
Chico, CA 95973
www.rhainc.com

[Date]

Dear Homeowner,

Thank you for participating in a research study on measuring emissions of natural gas from homes in California. Richard Heath & Associates, Inc. (RHA) is working with Lawrence Berkeley National Laboratory to collect this data for estimating methane leakage rates from residential use.

This survey is developed by researchers at Lawrence Berkeley National Laboratory to gather data about your home and household. Please answer questions to the best of your knowledge. You may skip questions that you do not want to answer.

You can return this survey to the field technician. Alternatively, you may return this survey to RHA by mail.

You will receive $60 for completing the in-home visit. In addition, you will receive $15 for completing this survey. Your completed survey must be postmarked within two weeks of the in-home visit to receive the full amount of $75.

If you have questions about the survey, please contact:

Rengie Chan, Ph.D.
Study Lead, Lawrence Berkeley National Laboratory
Tel: (510) 486 6570 Email: wrchan@lbl.gov

Your survey data will help us interpret the methane measurements and estimate the statewide leakage rates for California.

We thank you for your time and participation.

Sincerely,

[Name]

Technical Director
Tel: (530) 892 2887
Email: NAronson@rhainc.com

Home ID: ______________________ Date: ________________________

1. Natural Gas Usage

a. Do you receive a bill for natural gas used? ☐ Yes ☐ No ☐ Don't know

b. Is any of the following also included in your natural gas bill? Check all that apply.

☐ Electricity
☐ Fuel oil
☐ Garbage and trash
☐ Water and sewage
☐ Other. Specify: ___________________________
☐ Don't know
☐ Natural gas is billed separately

c. How much was your most recent natural gas bill? You may refer to your billing history, or give your best estimate.

$ __________________________

d. What month was that bill for?

☐ January
☐ February
☐ March
☐ April
☐ May
☐ June
☐ July
☐ August
☐ September
☐ October
☐ November
☐ December

e. What were the typical monthly costs for natural gas for the month of January? You may refer to your billing history, or give your best estimate.

$ __________________________

f. What were the typical monthly costs for natural gas for the month of August? You may refer to your billing history, or give your best estimate.

$ __________________________

2. Home Improvement Activities

2a. In the last two years, were the gas lines in your home modified, repaired, or added?

☐ Yes ☐ No ☐ Don't know

2b. If you answered “Yes”, who did most of the work that involved the gas lines?

☐ Plumber or other contractor
☐ Gas utility company
☐ Other professional installer
☐ Someone in my household
☐ Don’t know
☐ No work on gas lines

2c. In the last two years, have you added or replaced the following equipment in your home?

☐ Central air conditioning
☐ Clothes dryer
☐ Cooktop
☐ Dishwasher
☐ Duct work
☐ Fireplace
☐ Furnace
☐ Heat pump
☐ Oven
☐ Water heater
☐ Don’t know
☐ None

2d. Was your bathroom OR kitchen remodeled in the last two years?

	Bathroom	Kitchen
No work done	• ☐	• ☐
Minor work, such as painting or fixing a broken water pipe	• ☐	• ☐
Major alternations or improvements	• ☐	• ☐
Bathroom OR kitchen newly added	• ☐	• ☐
Don’t know	• ☐	• ☐

2e. In the past two years, has there been a major disaster that required you to make extensive repairs to your home?

☐ Earthquake
☐ Flood
☐ Landslide
☐ Lightning or fire
☐ Tornado, hurricane, etc.
☐ Other. Specify: ________________________________
☐ Don’t know
☐ None

3. Natural Gas Appliances

3a. Do you use natural gas to heat your home?

☐ Yes, use natural gas as main heating fuel
☐ Yes, use natural gas as supplemental heating fuel
☐ No
☐ Don’t know

3b. If you answered “Yes”, do you use a gas furnace to heat your home?
☐ Yes ☐ No ☐ Don’t know

3c. If you use a gas furnace to heat your home, how often do the following conditions occur?

	Never	Occasionally	Sometimes	Often
Gas furnace ignition problem	• ☐	• ☐	• ☐	▸ ☐
Gas furnace cycles on and off too frequently	• ☐	• ☐	• ☐	▸ ☐
Gas furnace does not produce enough heat	• ☐	• ☐	• ☐	▸ ☐
Gas furnace pilot light goes out	• ☐	• ☐	• ☐	▸ ☐
Other. Specify:	• ☐	• ☐	• ☐	▸ ☐

3d. Do you use natural gas for water heating?
☐ Yes ☐ No ☐ Don’t know

3e. If you use natural gas for water heating, how often do the following conditions occur?

	Never	Occasionally	Sometimes	Often
No hot water	• ☐	• ☐	• ☐	▸ ☐
Not enough hot water	• ☐	• ☐	• ☐	▸ ☐
Slow recovery time	• ☐	• ☐	• ☐	▸ ☐
Water heater burner pilot light goes out	• ☐	• ☐	• ☐	▸ ☐
Other. Specify:	• ☐	• ☐	• ☐	▸ ☐

3f. Do you use natural gas for cooking?
☐ Yes, use natural gas cooktop

☐ Yes, use natural gas oven

☐ No

☐ Don’t know

3g. If you use natural gas for cooking, how often do the following occur if any?

	Never	Occasionally	Sometimes	Often
Cooktop gas burner ignition problem	• ☐	• ☐	• ☐	▸ ☐
Weak cooktop gas burner flame	• ☐	• ☐	• ☐	▸ ☐
Noisy cooktop gas burner flame	• ☐	• ☐	• ☐	▸ ☐
Cooktop pilot light goes out	• ☐	• ☐	• ☐	▸ ☐

Oven gas burner ignition problem	• ☐	• ☐	• ☐	› ☐
Oven gas burner pilot light goes out	• ☐	• ☐	• ☐	› ☐
Gas odor	• ☐	• ☐	• ☐	› ☐
Other. Specify:	• ☐	• ☐	• ☐	› ☐

3h. Do you use natural gas for clothes drying?

☐ Yes ☐ No ☐ Don't know

3i. If you use a natural gas clothes dryer, how often do the following conditions occur?

	Never	Occasionally	Sometimes	Often
Drum spins, but no heat	• ☐	• ☐	• ☐	› ☐
Not drying well	• ☐	• ☐	• ☐	› ☐
Dryer getting too hot	• ☐	• ☐	• ☐	› ☐
Other. Specify:	• ☐	• ☐	• ☐	› ☐

4. Overall Assessment

4a. Is your building older, younger, or about the same age at the nearby buildings in your neighborhood?

☐ Older

☐ Younger

☐ About the same age

☐ Very mixed

☐ Don't know

☐ No other residential buildings

4b. On a scale of 1 to 10, how would you rate your home as a place to live?

Worst									Best
1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

4c. On a scale of 1 to 10, how would you rate your neighborhood?

Worst									Best
1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

5. Demographic Information

The next questions will help us interpret the results of the survey. All responses will be kept confidential.

5a. What is the number of persons living in this household?

0 to 17 years of age: _________________

18 to 65 years of age: ________________

Over 65 years of age: ________________

What is the total income of all member(s) of your household combined?

☐ Less than $35,000

☐ $35,000 to $49,999

☐ $50,000 to $74,999

☐ $75,000 to $99,999

☐ 100,000 to $150,000

☐ Greater than $150,000

APPENDIX C:
Emission Measurement Summary

Table C-1: Measured Methane Emissions for 75 Home Study

House	House Leak (sccm)	Leak err (sccm)	cal.flow (sccm)	cal.flow.err (sccm)	cal.qc	appl1 code	appl1 gas.use (cfm)	appl1 CH4:CO2 (x 1000)	appl2 code	appl2 gas.use (cfm)	appl2 CH4:CO_2 (x 1000)
NC001	1.8	0.9	5.0	0.9	0	DWH	0.55	4.0	NA	NA	NA
NC002	NA	NA	NA	NA	NA	DWH	0.6	0.0	Dryer	0.35	0.7
NC003	2.3	0.5	3.7	0.5	0	DWH	NA	10.0	Stove top	NA	NA
NC004	2.4	0.4	2.1	0.4	0	DWH	0.6	7.0	Dryer	0.42	2.0
NC005	31.3	1.9	2.1	2.9	0	DWH	0.59	3.0	Dryer	NA	NA
NC006	10.0	5.0	4.0	5.0	0	Tankless	1.02	1.0	Dryer	0.22	NA
NC007	6.9	3.0	5.0	3.0	0	DWH	0.6	NA	Stove	0.18	NA
NC008	1.3	0.1	4.6	0.3	0	DWH	NA	0.0	NA	NA	NA
NC009	4.2	0.5	4.1	0.7	0	DWH	NA	0.0	DWH pilot	0.01	5.0
NC010	3.0	0.7	3.1	0.8	0	DWH	NA	0.0	DWH pilot	0.01	8.0
NC011	NA	NA	NA	NA	NA	DWH	NA	0.0	DWH pilot	0.01	8.0

House	House Leak (sccm)	Leak err (sccm)	cal.flow (sccm)	cal.flow.err (sccm)	cal.qc	appl1 code	appl1 gas.use (cfm)	appl1 CH4:CO2 (x 1000)	appl2 code	appl2 gas.use (cfm)	appl2 CH4:CO2 (x 1000)
NC012	11.8	0.3	4.1	0.3	0	DWH	0.63	0.0	Stove	0.2	0.0
NC013	2.6	0.3	5.8	0.6	0	DWH	0.64	0.0	DWH pilot	0.01	1.5
NC014	2.8	0.4	16.0	0.4	1	DWH	0.44	0.0	DWH pilot	0.01	4.0
NC015	0.1	0.2	3.3	0.3	0	DWH	NA	0.0	Stove	0.18	0.3
NC016	2.1	0.5	3.3	0.5	0	DWH	0.53	2.0	Stove	0.2	2.0
NC017	3.6	0.4	2.6	0.6	0	Tankless	NA	NA	NA	NA	NA
NC018	1.0	1.0	3.3	1.0	0	Furnace	0.8	0.0	NA	NA	NA
NC019	2.0	0.6	4.9	1.1	0	Furnace	NA	0.0	Furnace Pilot	0.01	2.3
NC020	8.2	0.8	0.5	0.8	0	Stovetop	0.29	2.0	Stove	0.03	NA
NC021	1.5	1.2	3.8	1.2	0	Furnace	1.68	0.0	Furnace Pilot	0.01	10.0
NC022	7.7	0.9	3.7	0.1	0	Furnace	1.31	0.0	Furnace Pilot	0.01	NA
NC023	17.1	1.5	6.1	1.6	0	Furnace	1.32	0.0	Furnace Pilot	0.01	8.0
NC024	0.1	0.5	4.1	0.2	0	DWH	NA	NA	Dryer	0.36	NA
NC025	18.7	0.1	0.2	0.1	1	Furnace	0.58	0.3	Dryer	NA	0.0

House	House Leak (sccm)	Leak err (sccm)	cal.flow (sccm)	cal.flow.err (sccm)	cal.qc	appl1 code	appl1 gas.use (cfm)	appl1 CH4:CO2 (x 1000)	appl2 code	appl2 gas.use (cfm)	appl2 CH4:CO_2 (x 1000)
NC026	-1.6	0.5	0.5	0.7	0	DWH	0.57	0.0	Stove	0.2	7.0
NC027	0.6	0.1	0.0	0.1	1	DWH	0.54	0.0	Stove	0.26	0.0
NC028	2.0	0.6	0.4	0.8	0	DWH	0.57	0.0	Stove	0.27	3.0
NC029	0.5	0.2	-0.7	0.3	1	DWH	0.57	0.0	Stove	0.27	0.0
NC030	0.0	0.2	0.2	0.3	1	DWH	0.57	2.0	Stove	0.35	2.0
SC001	16.7	0.8	-0.8	0.9	0	DWH	0.67	0.0	Stove	0.28	0.0
SC002	1.5	0.4	4.1	0.4	0	DWH	0.66	5.0	Stove	0.22	1.0
SC003	20.4	2.3	5.1	3.5	0	DWH	NA	0.0	Stove	0.25	0.0
SC004	2.7	0.1	3.0	0.4	0	Tankless	0.67	0.5	Stove	0.32	0.0
SC005	2.5	0.0	3.7	0.6	0	DWH	0.53	5.0	Stove	0.28	0.0
SC006	19.4	1.1	5.3	1.2	0	DWH	0.53	10.0	Stove	0.13	20.0
SC007	1.9	0.0	3.3	0.3	0	DWH	0.33	0.0	Stove	0.19	8.0
SC008	0.4	0.3	4.8	0.4	0	DWH	0.46	0.0	Stove	0.21	0.1
SC009	35.5	4.0	7.3	4.1	0	DWH	0.47	0.0	Stove	0.17	1.0
SC010	2.7	0.1	36.7	2.5	1	DWH	0.98	5.0	Stove	0.2	0.0
SC011	1.6	0.8	0.9	0.8	0	DWH	0.55	0.0	Stove	0.2	0.0
SC012	1.1	0.0	5.1	0.2	0	DWH	0.53	1.0	Stove	0.16	0.2
SC013	0.1	0.1	20.9	1.4	1	DWH	0.38	1.0	Stove	0.14	0.0
SC014	2.8	2.4	97.8	2.8	1	DWH	0.51	0.0	Stove	0.26	0.0
SC015	1.0	0.8	9.5	0.9	0	DWH	0.66	0.0	Stove	0.29	0.0
SC016	10.0	0.8	5.9	1.1	0	DWH	0.66	0.0	Stove	0.11	30.0

House	House Leak (sccm)	Leak err (sccm)	cal.flow (sccm)	cal.flow.err (sccm)	cal.qc	appl1 code	appl1 gas.use (cfm)	appl1 CH4:CO2 (x 1000)	appl2 code	appl2 gas.use (cfm)	appl2 CH4:CO_2 (x 1000)
SC017	0.5	0.7	1.8	0.8	0	DWH	NA	0.0	Stove	0.11	0.0
SC018	9.8	0.4	5.6	0.8	0	DWH	0.66	0.0	Stove	0.11	0
SC019	0.4	0.1	0.6	0.2	1	DWH	0.4	0.0	Stove	0.29	5
SC020	2.4	0.2	5.4	0.9	0	DWH	0.59	5.0	Stove	0.18	0
SC021	4.1	0.3	0.5	0.3	0	DWH	0.59	0.0	Stove	0.18	0
SC022	0.5	0.1	0.5	0.1	1	Wall Heater	0.59	0.0	Stove	0.18	0
SC023	4.9	NA	-3.9	NA	NA	DWH	0.59	0.0	Wall Heater	0.52	10
SC024	13.6	0.5	3.5	2.2	0	DWH	0.18	0.0	Stove	0.59	0
SC025	-0.2	0.1	3.5	0.3	0	DWH	0.59	0.0	Stove	0.18	0
SC026	4.4	0.3	3.2	0.7	0	DWH	0.5	10.0	Stove	0.24	0
SC027	-0.1	0.1	0.3	0.2	1	DWH	0.5	1.0	Stove	0.24	0
SC028	5.4	1.0	3.5	1.1	0	DWH	0.54	0.0	Stove	0.24	0
SC029	0.6	0.2	9.2	0.9	0	DWH	0.54	0.0	Stove	0.24	0
SC030	1.1	0.0	3.4	0.3	0	DWH	0.53	0.0	Stove	0.23	0
SC031	4.8	0.3	1.6	0.4	0	DWH	0.53	0.0	Stove	0.23	0
SC032	0.5	0.2	3.7	0.4	0	DWH	NA	NA	Stove	0.19	NA
SC033	-0.5	0.1	0.6	0.1	1	Tankless	0.6	NA	Stove	0.12	0
SC034	-0.5	0.1	1.5	0.2	0	DWH	0.55	0.0	Stove	0.17	0
SC035	5.1	0.5	10.4	2.4	0	Tankless	0.69	0.8	Stove	NA	NA
SC036	0.5	1.4	6.2	1.6	0	DWH	NA	NA	Stove	0.19	NA
SC037	3.5	0.1	6.5	1.1	0	DWH	0.53	0.0	NA	NA	NA
SC038	4.6	0.4	3.8	0.6	0	DWH	NA	NA	Stove	0.26	0
SC039	-0.1	0.1	3.1	0.6	0	DWH	0.52	0.0	Stove	0.15	1

House	House Leak (sccm)	Leak err (sccm)	cal.flow (sccm)	cal.flow.err (sccm)	cal.qc	appl1 code	appl1 gas.use (cfm)	appl1 CH4:CO2 (x 1000)	appl2 code	appl2 gas.use (cfm)	appl2 CH4:CO2 (x 1000)
SC040	0.2	0.1	0.9	0.5	0	DWH	0.44	0.0	Stove	0.18	0
SC041	0.1	0.1	-2.3	0.2	1	DWH	NA	NA	Stove	0.25	NA
SC042	-0.1	0.1	4.6	0.1	0	DWH	0.51	0.0	Stove	0.13	0
SC043	0.4	0.1	2.8	0.2	0	DWH	0.53	5.0	Stove	0.15	10
SC044	-0.5	0.6	8.5	1.9	0	DWH	0.48	0.0	Stove	0.09	30
SC045	1.5	0.2	3.9	0.4	0	DWH	0.54	0.0	Stove	0.15	0