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FINAL PROJECT REPORT

Ventilation and Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation

Gavin Newsom, Governor
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PREPARED BY:

Primary Authors:
Wanyu R. Chan
Yang-Seon Kim
Brennan D. Less
Brett C. Singer
Iain S. Walker

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720
Phone: 510-486-6570
http://www.indoor.lbl.gov

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PREPARED FOR:
California Energy Commission

Yu Hou
Project Manager

Dr. Jonah Steinbuck
Office Manager
ENERGY GENERATION RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation is the final report for the Healthy Efficient New Gas Homes (HENGH) project (contract number PIR-14-007) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

Conditioning air that enters California homes through building and ductwork leaks uses a substantial amount energy, typically about a third of all energy used for heating and cooling, so making energy use more efficient by sealing leaks is essential to achieving zero energy homes in California. At the same time, outdoor air contributes to healthy indoor air quality by diluting pollutants emitted inside the building. To ensure acceptable indoor air quality, California's Title 24 Building Standards require ventilation in new homes built since 2008. This report presents a comprehensive study of the effects of these requirements in recently built homes with natural gas appliances. The study included a survey on occupant satisfaction with air quality and ventilation-related activities like using range hood that affect air quality; a field study of homes built in 2008 or later; and simulations on how various ventilation rates might affect exposures to indoor pollutants as homes become more "air tight" in California.

The field study included 70 homes built between 2011 and 2017. The researchers monitored each home over roughly one week with the mechanical ventilation system operating and windows closed. The study found that the bulk of homes met most ventilation requirements and that ventilation fans on average moved 50 percent more air than the minimum specified in Title 24. Air pollutant concentrations were similar or lower than those reported in a study of recently constructed California homes done in 2007-08 before the minimum ventilation requirement. Measured concentrations were below health guidelines for most pollutants, indicating that indoor air quality is acceptable in new California homes when mechanical ventilation is used. However, labeling and controls for ventilation systems need to be improved.

Based on project findings, the researchers recommend that the core ventilation requirements of dwelling unit and local exhaust ventilation should remain in the Title 24 Building Energy Efficiency Standards for the foreseeable future.

Keywords: airtightness, cooking, formaldehyde, healthy buildings, nitrogen dioxide, particulate matter, range hood, Title 24

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Introduction

Many California homes waste energy to condition excessive outdoor air that enters through the building envelope (made up of the roof, subfloor, exterior doors, windows, and exterior walls). Although reducing this air infiltration saves energy, it also increases the risk of negative health effects because indoor air pollutant concentrations and exposure could increase. Previous California Energy Commission (CEC) research studies found that windows are not a reliable source of ventilation. Measured ventilation rates in many homes are below minimum levels based on the national ambient standard, and formaldehyde and $PM_{2.5}$ (particulate matter with diameter less than 2.5 micrometers) in many homes exceeds health guidelines.

In 2008, the CEC added ventilation requirements to the California *Title 24 Building Energy Efficiency Standards (Title 24)* to address adverse effects that could potentially result from sealing buildings to reduce air infiltration. Previous work in California highlighted contaminants of concern and documented contaminant levels. However, this work was done in homes built before the building standards required dwellings to have mechanical ventilation. Prior to this study, it was unknown whether ventilation requirements resulted in acceptable levels of contaminants and how ventilation requirements were being met.

This study measured the indoor air quality in California homes built to meet Title 24 ventilation requirements and assessed whether the requirements are having the desired effect of ensuring acceptable indoor air quality for California residents.

Project Purpose

The Healthy Efficient New Gas Homes project conducted by the Lawrence Berkeley National Laboratory (LBNL) examined the effects of new home mechanical ventilation requirements in the *2008 Title 24 Building Energy Efficiency Standards*. The project assessed whether code-required mechanical ventilation systems ensure acceptable indoor air quality. The project team also developed recommendations on how to achieve adequate ventilation while reducing infiltration and associated energy consumption.

The study measured operating characteristics of installed ventilation systems and other home parameters related to airflows between the house and outside, such as envelope and duct leakage. The field study obtained data from 70 homes and collected data about ventilation practices, indoor air quality, and occupant comfort. The field study focused on homes with natural gas appliances with gas service provided by California's investor-owned utilities.

The project team also implemented a web-based survey to obtain data on indoor air quality satisfaction and ventilation practices from a much larger sample of homes. The web-based survey collected data from homes built before and after the 2008 standards, starting with homes built in 2002. Participants in the field study homes also completed the survey.

Another major element of the project was a simulation-based analysis of potential energy benefits and indoor air quality implications of reducing infiltration and modifying ventilation requirements. The body of this report focuses on field study data and analysis. The survey and simulation studies are described in appendices.

Methods

LBNL designed and oversaw the field study protocol and conducted all data analysis. The study included measuring indoor air quality home characteristics, mechanical ventilation, and occupant activities in 70 occupied new California homes with natural gas appliances. The researchers took indoor air quality measurements for one week that included concentrations and changes over time of particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), carbon dioxide (CO_2), and formaldehyde. Measurements also included average concentrations over time of formaldehyde, NO_2 and total nitrogen oxides (NO_X).

The researchers estimated concentration of nitrogen oxide (NO) as the difference between NO_X and NO_2. The team conducted diagnostic tests to measure air leakage of the building envelope and the heating and cooling duct systems, along with airflows of all ventilation fans including those used to exhaust kitchens and bathrooms. The team monitored occupant activities for cooking and use of the range hood and other exhaust fans.

Project field teams were led by researchers from the Gas Technology Institute (GTI) with technical support from Pacific Gas and Electric Company (PG&E) and Southern California Gas Company's (SoCalGas) researchers as well as gas service technicians working under GTI guidance. The field teams completed data collection in 70 homes (48 homes in PG&E territory, and 22 homes in SoCalGas territory) between July 2016 and April 2018. LBNL obtained homeowner permission for this study, recruited study homes, provided technical oversight of data collection, and performed data analysis. LBNL also performed chemical analysis of all time-integrated formaldehyde and NO_2/NO_X samples and quantification of particulate matter filters.

Project Results

The web-based survey results from 2,648 respondents indicated that homes sampled in the field study were typical of new California homes in terms of house size and occupancy. About 90 percent of occupants rated indoor air quality as neutral, satisfied, or very satisfied and were generally more satisfied with indoor air quality than outdoor air quality. The web-based survey also found that occupants used range hoods vented to the outside more often than recirculating hoods, suggesting that occupants are aware of the difference in how effective these devices are. While most occupants were satisfied with indoor air quality, there were indications that increased bathroom exhaust venting and fewer home occupants correlate to fewer complaints of mustiness and odor. In addition, households with sensitive occupants (at least one person diagnosed with asthma or allergy) were more likely to use air cleaning devices. Homes with mechanical ventilation systems that survey respondents identified as providing fresh air were correlated with higher indoor air quality satisfaction.

Fifty-five of the field study homes met the dwelling unit ventilation requirement in Title 24 with a continuous exhaust fan that was either in the laundry room or a bathroom. Three homes—all in the same development—used a continuous exhaust fan in the attic that was connected to all bathrooms to meet dwelling and local exhaust ventilation requirements. The other mechanical ventilation systems identified were intermittent exhaust fans with operation interval controllers, supply fans connected to the central forced air system operating continuously, and supply ventilation provided intermittently by a central fan integrated system with a motorized damper. In most cases, the measured airflow of the exhaust fan exceeded the required ventilation needs. However, the field teams found the mechanical ventilation system operating in only 18 of the 70 homes in the study when the homes were first visited . The systems were not operated because occupants were unaware that the system existed and did not understand the controls, which were typically not labeled. Only 12 homes had a label that identified the control switch for the mechanical ventilation system. Field teams also found that fan runtime was set to run intermittently in half of the homes with a programmable controller. In the two homes where the thermostat was used as the controller, the fan was turned off.

The kitchen ventilation equipment in many homes appeared to meet most but not all of the Title 24 requirements. While most homes had a range hood or over-the-range microwave exhaust fan that met the minimum airflow requirement, many of the range hoods (and most of the over-the-range hoods) did so only at medium or high speed which is often louder than the acceptable noise level according to occupants. Some over-the-range hoods did not meet the airflow requirement even at the highest speed setting. An important caveat to this finding is that the over-the-range airflows could be low based on the measurement method that required taping over the air inlets on some over-the-range hoods, resulting in a lower airflow measurement.

Comparisons of indoor formaldehyde, NO_2, and $PM_{2.5}$ levels with those from a 2007-2008 study of new homes in California suggest that contaminant levels are lower in recently built (after 2008) homes. California's regulation to limit formaldehyde emissions from composite wood products appears to have substantially lowered the emission rate and concentration in new homes. Formaldehyde levels are still above California guidelines in the studied homes, but lower than other national and international guidelines. Lower outdoor $PM_{2.5}$ can only explain part of the substantially lower indoor $PM_{2.5}$ levels measured in the study compared to the previous study. Other contributors to lower indoor $PM_{2.5}$ are the use of higher efficiency air filters in central forced air systems; filtration of outdoor particles by the building envelope (as occurs when ventilation is provided with an exhaust fan); and possibly lower particle emission rates inside the home. Finding relatively low time-averaged NO_2 concentrations in this study is significant, since all homes in the study had natural gas cooking appliances. This finding suggests that the mechanical ventilation systems in these homes may be contributing to lower NO_2. CO_2 concentrations were highest overnight in bedrooms, while CO_2 concentrations measured in the main living space were not substantially different from those in the prior study.

These results suggest that under current occupant pollutant exposure guidelines, a more stringent airtightness limit will have marginal savings of roughly 1 percent of annual heating, ventilation, and air conditioning energy. If exposure increases by about 5-24 percent, then a saving of 3-5 percent is possible through air tightening. On average, the adopted 2019 fan sizing method for Title 24 performed similarly, in terms of energy and indoor air quality performance, to ASHRAE 62.2-2016 method under current airtightness conditions. The 2019 Title 24 fan sizing method gave weighted average exposure very near to 1.0 under both current and hypothetical airtightened scenarios, though exposure would increase roughly 5 percent under a hypothetical airtightness requirement in the energy code. The study shows the 2019 Title 24 fan sizing approach provides consistent results for occupant exposure to indoor air pollution across a wide range of climates and airtightness. The only exception is leakier homes in this study that have increased site energy consumption ranging from 70 to

1,400 kilowatt-hours per year. The previous Title 24 fan sizing methods from 2008 and 2013 did not have this consistency, and had occupant exposures 30-40 percent worse than the 2019 Title 24 method.

The field study found many recently constructed homes had ventilation equipment that had much more airflow capacity than the minimum requirements of Title 24 for when they were built. Most systems would meet the higher air flow requirements of Title 24-2019. Because the energy calculations performed for this study were based on ventilation systems that were not oversized and only met the minimum requirements, this implies that in practice, the additional energy consumption introduced by of the higher minimum mechanical airflow requirement may be less than the estimates presented above .

Technology Transfer

The results of the project have been published in several reports to the commission and available at the LBNL website (https://eta.lbl.gov/publications) and in an article for *Home Energy* magazine. Researchers have presented results to an international audience via papers and presentations at the past three International Energy Agency Annex 5 - Air Infiltration and Ventilation Center (AIVC) Conferences, and the final report has been published as a contributed report to the same conference (http://aivc.org/sites/default/files/AIVC_CR18.pdf). Researchers have published and presented conference papers at the following conferences: ASHRAE/AIVC IAQ, Indoor Air, International Society of Indoor Air Quality and Climate, AIVC Annual Conference, and Indoor Air Quality Association. Workshops using the results have been given at RESNET National conferences, Home Performance Coalition National Conferences, the Forum on Dry Climate Home Performance, the Leading Builders of America Code Council Meeting, and AIVC/ProClima workshops in New Zealand. The researchers are preparing journal manuscripts on the following topics: occupant survey results; analysis of field study data to describe indoor air quality results; the presence, performance, and use of mechanical ventilation; and the relationships between envelope leakage and fan sizing, with the implications for codes and standards.

Title 24 discussions have used project results as technical input for the topics of home airtightness and home ventilation requirements, as well as for potential future changes to ventilation system labeling requirements and kitchen ventilation in collaboration with the Home Ventilating Institute and ASHRAE Standard 62.2. The technical approaches developed for the Healthy Efficient New Gas Homes project are being used in a nationwide study funded by the U.S. Department of Energy Building America Program to perform similar monitoring in other regions of the United States, and LBNL is leading the field study design and data analysis for this national study. This dataset of new homes, together with data collected from the project, will greatly advance our knowledge of ventilation and indoor air quality in new homes and will be used to inform policy and standards (particularly ASHRAE Standard 62.2 and RESNET) at a national level.

Project Benefits

The field study of 70 homes built to meet the 2008 Title 24 mechanical ventilation requirements found acceptable indoor air quality in the homes when the mechanical systems were operating and windows were generally closed. The team concluded that these or similar requirements should continue to be included in Title 24 to ensure healthy indoor environments for California ratepayers. Finding that roughly 75 percent of the homes did not have their ventilation systems operating, and that many of those homes did not have code-required labels on ventilation controllers, suggests that indoor air quality may not be adequately protected in many homes. Corrective actions to mediate the statistically widespread prevalence of non-operation of mechanical ventilation in new homes will benefit occupants by reducing their exposure to indoor generated pollutants. At a minimum, the requirement to label switches controlling ventilation systems must be enforced. A more effective solution would be to have standardized labels used in all homes with indicators to show system operation.

There is little energy benefit associated with implementing a maximum air leakage requirement (for example, three air changes per hour at 50 Pascals) for new California homes on a statewide basis, mostly due to most new home starts being in mild climates and the requirements for minimum ventilation provided by mechanical systems. However, the climates zones with the harshest weather (Climate Zone 1 – North Coast and Climate Zone 16 – High Sierra) would have energy savings of several hundred kilowatt-hours per year.

CHAPTER 1: Introduction

1.1 Healthy Efficient New Gas Homes Study Overview

The Healthy Efficient New Gas Homes (HENGH) project led by Lawrence Berkeley National Laboratory (LBNL) aimed to study the impacts of new home mechanical ventilation requirements included in the 2008 Title 24 Building Standards (CEC, 2008). The ventilation requirements were added to the standards to address adverse impacts that could potentially result from air sealing envelopes to reduce infiltration and improve energy efficiency. The field study component of the project aimed to characterize installed ventilation system designs and rated airflows, to measure airflows, and to monitor ventilation equipment use and indoor air quality (IAQ) over a one-week period in a diverse sample of homes built to meet the 2008 or subsequent versions of the standards. The field study also collected data about ventilation practices and indoor air quality and comfort satisfaction of the home's occupants. The field study obtained data from 70 homes with natural gas appliances and service provided by one of California's investor-owned gas utilities.

Many California homes, including some that have been built in recent decades, waste energy to condition excessive outdoor air that enters via uncontrolled infiltration through the building envelope. Air leakage to and from forced air heating and cooling system ducts in unconditioned attics and garages results in additional energy losses. Though energy inefficient, the infiltration of outdoor air has traditionally served to dilute air pollutants emitted inside the building. Thus, while reducing infiltration and duct leakage saves energy, these measures also increase the risk of negative health impacts as indoor air pollutant concentrations and exposures may increase.

Starting in the mid-2000s, the California Energy Commission funded several research studies (for example, Price et al., 2007, and Offerman, 2009) that aimed to evaluate the potential IAQ impacts associated with envelope air sealing, and the potential to mitigate these through the use of mechanical ventilation systems. These studies found (a) that a majority of the households in new California homes reported not opening windows regularly for ventilation in some seasons, and a substantial minority of households reported not using windows to ventilate during any season; (b) that actual, measured ventilation rates in many homes were below target minimum levels; and (c) that the median measured formaldehyde concentration across study homes was four times the chronic reference exposure level set by the California Office of Environmental Health Hazard Assessment (OEHHA).

To address this issue, the 2008 California Building Energy Efficiency Standards[1] included requirements for mechanical ventilation to maintain acceptable IAQ, and ventilation requirements have been included in all subsequent versions of the standard. The first ventilation requirement was based on a version of ASHRAE Standard 62.2 that was specifically developed for California and set a minimum continuous mechanical airflow along with an

[1] In this document "Title 24" refers to California Title 24, Part 6, Building Energy Efficiency Standards.

option to ventilate intermittently at rates determined to provide equivalent dilution of indoor sources. The standards also include requirements for kitchen and bathroom ventilation.

The Energy Commission funded the HENGH study to evaluate the impacts of the mechanical ventilation system requirements that started in 2008. The intent was for HENGH results to inform considerations of ventilation requirements as California transitions to a building standard requiring all new homes to be zero net energy.

1.2 Prior Studies of Ventilation and IAQ in New California Homes

1.2.1 Mailed Survey of Ventilation Behavior and Household Characteristics

In the mid-2000s, the Energy Commission funded, via contract CEC-500-02-023, a study of ventilation behaviors, IAQ perceptions, and related household characteristics in recently built California homes. The study, reported in Price and Sherman (2006) and Price et al. (2007), had the following objectives:

- Determine how occupants use windows, doors and mechanical ventilation
- Determine occupant perceptions of and satisfaction with IAQ in their homes
- Determine the relationships among ventilation practices, perceived IAQ and house and household characteristics
- Determine barriers that prevent or inhibit the use of windows, doors, and mechanical ventilation systems.

The study was conducted using a paper survey form that was mailed to a statewide, stratified random sample of 4972 single-family detached homes in 2003 with 1448 responses received. The data were supplemented with 67 completed interviews from a "builder" (convenience) sample of 230 houses known to have mechanical ventilation systems. The data from the sample were analyzed for the entire state and also by region; associations between behaviors and household characteristics were investigated.

The results of this study showed that window opening was not a reliable method to ventilate homes. Windows were not used for a wide range of reasons including inclement outdoor weather, noise and security issues. Even among homes that did open windows, the use was generally sporadic and inconsistent.

1.2.2 Field Study of Ventilation and IAQ in California Homes Built 2002–2004

As a follow-up to the mailed survey, the Energy Commission and Air Resources Board jointly supported a field study of ventilation and IAQ performance in recently built California homes as described in Offermann (2009). Throughout this report the Offermann study is referred to as the California New Home Study or CNHS. The CNHS characterized ventilation equipment and relevant performance aspects of the home – such as envelope air leakage and garage to house air leakage – and measured air exchange rates, ventilation equipment use, and a suite of IAQ parameters over a 24-hour period in each home. The CNHS used the mailed survey database from the earlier mail out survey and supplementary procedures to recruit 108 homes, with most built in 2002-2004. At the time of the research team visits in the summer of 2007 through winter 2008, the homes ranged in age from 1.7 to 5.5 years. The study measured CO_2, CO, temperature, and relative humidity with time resolution. Formaldehyde, acetaldehyde, and 20 other volatile organic compounds (VOCs) were measured in 24-h integrated samplers inside all homes and outside of 40 homes. Measurements of time-integrated $PM_{2.5}$ and NO_2 were made inside 29 homes and outside at 11 homes. Time-integrated air exchange rates were measured in all homes over the 24-hour sampling period and in a subset of 21 homes over a two-week period. Use of windows and ventilation equipment was monitored over a week in almost all study homes. Twenty of the homes were visited in summer and winter seasons. Day-to-day variability was assessed by measurements conducted on three successive days in four of the study homes.

The air exchange rate (AER) of a home describes the rate of airflow in and out of the home as a fraction of the volume of air in the house. For the CNHS, the median AER was 0.26/h (i.e., about one quarter of the air in the home was exchanged with outside each hour) among the 107 homes with data from the main monitoring day and 0.24/h for the 21 homes with AER measured over two weeks. Approximately 2/3 of the homes had air exchange rates below the implicit target of 0.35/hour. Thirty-two percent of study homes had no window or door use for ventilation during the 24-hour monitoring period and 15 percent had no use during the preceding week. There were 48 seasonal measurements (winter and/or summer) for 26 homes that had provided data through the prior mailed survey. In 52 percent of homes, the actual week-average window use exceeded the high end of the usage estimated during the survey. And in another 10 percent of cases, there was measured use in homes that estimated no use of windows.

The two contaminants with measured indoor air concentrations that exceeded health guidelines were formaldehyde and $PM_{2.5}$. Indoor formaldehyde concentrations exceeded the OEHHA chronic reference exposure level (CREL) of 9 $\mu g/m^3$ in 98 percent of study homes and the median level of 36 $\mu g/m^3$ was four times the OEHHA CREL. While none of the homes had indoor $PM_{2.5}$ above the guideline exposure level of 65 $\mu g/m^3$ considered by Offermann, the team believed the U.S. EPA national ambient air quality annual standard of 12 $\mu g/m^3$ is a more relevant benchmark for in-home, time-averaged $PM_{2.5}$. The Offermann study reported a 75th percentile indoor $PM_{2.5}$ concentration of 14 $\mu g/m^3$ and a 50th percentile of 11 $\mu g/m^3$. Outdoors, the 75th and 50th percentile concentrations were 9.5 and 8.7 $\mu g/m^3$. Overall, these results suggest that a substantial minority of the homes in the Offermann study may have had indoor $PM_{2.5}$ above the NAAQS threshold and high indoor $PM_{2.5}$ was not solely due to high outdoor concentrations. A large fraction of the homes studied by Offermann also exceeded the Proposition 65 Safe Harbor Levels of acetaldehyde (93 percent). Concentrations of VOCs other than formaldehyde were lower than OEHHA CRELs in all cases, though several VOCs were present in at least some homes at levels that exceeded the Proposition 65 Safe Harbor Levels: trichloromethane (8 percent), tetrachloroethene (8 percent), 1,4-dichlorobenzene (12 percent), naphthalene (27 percent), benzene (63 percent).

1.2.3 Field Studies of Mechanical Ventilation System Performance

Published data on installed ventilation system performance suggest uneven implementation of code and standard requirements across states. A study of 29 homes in the state of Washington (Eklund et al., 2015) found that most had systems that were set, or that could be set to comply with the state standards for general mechanical ventilation. However, many of the systems were not operating at these design conditions as found. There were problems with incorrect settings (mostly systems not set to operate continuously or with adequate frequency) and maintenance issues, including some that required substantial expertise to resolve. A 21-home study conducted in Florida (Sonne et al., 2015) found that only 12 of the installed general ventilation systems were capable of operating and many of those had airflow rates well below design conditions. These two studies reported the following problems:

- Installation problems, for example, disconnected duct, blocked vent, poorly hung ducts, inadequate duct insulation, inoperable outdoor air exhaust duct damper, ERV/HRV system installed backward.
- Operational problems, for example, fan turned off, dirty filters, inadequate operation runtime.
- Difficult access to on/off controls, inaccessible intake/discharge vents (for example, on roof) with screens that require routine maintenance.

In contrast, a study of 15 new homes in California (Stratton et al., 2012) – including six which were occupied – found installed exhaust ventilation systems that exceeded the minimum airflow requirements (by 40 percent on average) and only 2 homes failed to meet the minimum dwelling unit ventilation requirement. About one third of the kitchen and bathroom exhaust systems failed to meet minimum requirements.

1.3 Title 24 Ventilation Requirements

Dwelling unit mechanical ventilation has been required in new homes and in additions of more than 1,000 ft^2 since the 2008 California Title 24 Building Energy Efficiency Standards. The standard also requires exhaust ventilation in each bathroom and either a venting range hood or an exhaust fan in the kitchen.

The local exhaust requirements can be met by continuously operating fans or "demand controlled" fans that are either operated manually or using a sensor, for example based on occupancy or humidity level. The fans must have certified airflow ratings or must be field verified to move a specified minimum amount of air at a rated maximum sound level. Bathroom fans must move at least 20 cubic feet per minute (cfm) or 10 liters per second (l/s) if continuous or 50 cfm (25 l/s) if demand-controlled. Enclosed kitchens can have a continuous exhaust fan moving air equivalent to at least five kitchen air volumes per hour. Non-enclosed kitchens must have a range hood that moves at least 100 cfm (50 l/s) or an exhaust fan that moves at least 300 cfm (150 l/s) or five kitchen air volumes per hour. Continuously operating exhaust fans – used either for dwelling unit or local exhaust – must be rated at 1 sone (a unit of subjective loudness for an average listener) or lower and demand-control exhaust fans must be rated at 3 sone or lower at the required airflows. Sone is a unit for loudness, with 1 sone being similar to a quiet refrigerator.

Initially, the only compliance path for dwelling unit ventilation was the Fan Ventilation Rate method (FVRM), as described in Section 4.6.2 of the 2008 California Title 24, Part 6 Building Energy Efficiency Standards Residential Compliance Manual. This calculation requires 1 cfm of mechanical airflow for every 100 ft^2 of conditioned floor area and an additional 7.5 cfm for each occupant (typically bedroom count + 1). This calculation and the kitchen and bathroom venting requirements are taken from ASHRAE Standard 62.2-2007. Required airflows calculated using the FVRM do not vary by location or airtightness, but only by house size and occupancy. The FVRM is currently used to size dwelling unit ventilation fans for the prescriptive reference homes used to demonstrate Building Standards compliance in CBECC-Res. While not explicitly stated in the Standard, this calculation assumes 2 cfm of natural infiltration per 100 ft^2 of conditioned floor area (per the ASHRAE Standard), which is a reasonable assumption for homes in the 5-7 ACH50 range of airtightness. For more airtight homes (particularly in mild California climates), this infiltration assumption is too high, leading to dwelling unit ventilation rates that are below current targets. Recognizing the incompatibility of the FVRM with low-infiltration, airtight new homes, the Energy Commission added a parallel compliance path in the 2013 standard cycle called the Total Ventilation Rate method (TVRM), calculated as follows. First, a Total Required Ventilation Rate is calculated (Q_{total}) similarly to the FVRM, but with a 3 cfm per 100 ft^2 conditioned floor area requirement (based on more recent versions of ASHRAE Standard 62.2 from 2013 onwards). Next, the Effective Annual Infiltration Rate is estimated based on the home's normalized leakage (as measured by blower door), geometry and geographic location (Q_{inf}). Finally, the Required Mechanical Ventilation Rate (Q_{fan}) is calculated as the difference between the Total Required Ventilation Rate and the Effective Annual Infiltration Rate. For airtight homes, this sizing method results in larger mechanical fan airflow requirements than the FVRM. For leaky homes, fan size can be reduced. Dwelling unit ventilation fan airflows differ by airtightness, house geometry and climate zone. The new 2019 Title 24 Building Energy Efficiency Standards have eliminated the FVRM for demonstrating compliance, and also adjusted the TVRM such that all homes will receive a dwelling unit ventilation fan sized as if the home were 2 ACH50. If air leakage is measured and is less than 2 ACH50, then the lower leakage rate is used in fan sizing calculations.

1.4 HENGH Field Study Objectives

The HENGH field study aimed to collect data on indoor air quality and ventilation system characteristics, installed performance and usage in California homes built to the 2008 or more recent version of the Title 24 Building Energy Efficiency Standards. The overarching goal of the field study was to collect data to improve understanding of whether the ventilation equipment being installed to meet the recent Title 24 requirements is effectively providing acceptable IAQ in new California homes. The study had the following specific data collection objectives:

- Collect field data from a diverse sample of homes that covers the areas of the state with substantial new home construction and including a range of climate zones.
- Characterize the dwelling unit/dwelling unit mechanical ventilation systems and measure their airflows for comparison to Title 24 requirements.
- Characterize all other mechanical systems (for example, bathroom exhaust fans) that may contribute to outdoor air exchange in the home and measure their airflows as feasible.
- Collect data on the use of kitchen and bathroom exhaust fans in relation to activities that release pollutants and moisture into these rooms.
- Measure concentrations of air pollutants inside and outside of the homes, including as feasible, time-varying monitoring of pollutants that are impacted by occupant activities.
- Obtain information about occupant activities and use of controls that may impact IAQ during the in-home monitoring period.

- Obtain monitoring data over a period of a week in each home to capture the cycle of activities that happen over this interval.
- Collect data on occupant satisfaction with IAQ and comfort conditions in the field study homes.
- Examine the relationships among ventilation equipment and use, measured and perceived IAQ, and house and household characteristics.
- Evaluate how to provide adequate ventilation in homes while reducing infiltration beyond the 2008 Title 24 standard, while still providing acceptable IAQ.

Since the focus of the study was to investigate whether the current requirements for mechanical ventilation provide sufficient protection, and it was known that a substantial fraction of California households do not routinely open windows for ventilation during at least some parts of the year, the study protocol was to measure IAQ in homes while windows were generally kept closed and with dwelling unit ventilation systems operating.

Prior to the field study, the project implemented a web-based survey to obtain data on IAQ satisfaction and ventilation practices in a much larger sample of modern California homes. The survey collected data from homes built both before and after the 2008 Building Energy Efficiency Standards. Details about the web-based survey are provided in Appendix A.

1.5 Simulation Study Objectives

Another major element of this project was a simulation-based analysis of potential energy benefits and indoor air quality implications of reducing infiltration and modifying ventilation requirements. This element of the study is described in Appendix B. The main goals of this simulation effort were to quantify the energy, ventilation and IAQ impacts of airtight residences under current and proposed IAQ compliance paths available in the Title 24 Building Energy Efficiency Standards and the ASHRAE 62.2 ventilation standard. Specifically, the team examined how different levels of envelope airtightness and methods of sizing dwelling unit ventilation fans would affect HVAC energy use and time-averaged concentrations of a theoretical, continuously emitted pollutant (as an IAQ indicator). The results of this work are designed to inform the questions of whether an airtightness requirement should be included in the Title 24 standard, and if so, should ventilation requirements be modified to compliment this requirement, to avoid causing harm.

The main objectives of the simulation study were (1) to evaluate the IAQ and energy impacts of different dwelling unit fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH50 airtightness requirement in the Title 24 Building Energy Efficiency Standards. Energy, ventilation and IAQ performance were simulated in two prototype homes compliant with the 2016 prescriptive provisions of the Title 24 Building Energy Efficiency Standards, across a subset of California climate zones (CZ 1, 3, 10, 12, 13 and 16), reflecting the variety of climate conditions in the state. Airtightness was varied between 0.6 and 5 ACH50, and dwelling unit ventilation fans were sized according to seven currently available or proposed compliance paths in Title 24 or ASHRAE Standard 62.2. Fan sizing methods either accounted for infiltration and fan type (i.e., balanced vs. unbalanced), or they used a fixed airflow approach, with no variability in the fan sizing by airtightness, climate zones, geometry and fan types. The simulations used the ASHRAE 62.2 relative exposure framework to assess IAQ. This framework considers IAQ by calculating the time-integrated concentration of a generic contaminant emitted at a constant rate under some alternative ventilation approach and compares that to the time-integrated concentration that would occur with a continuous, fixed airflow – in this case the target dwelling unit airflow required by ASHRAE Standard 62.2. This metric is described in the 62.2 framework and subsequently in this report as relative exposure. The results for individual cases were combined using a weighting based on the fraction of new homes constructed in the state's climate zones to get statewide estimates of performance.

CHAPTER 2: Methods

2.1 Field Study Overview

2.1.1 Overview of Data Collection Approach in Homes

The HENGH field study was designed by the research team from Lawrence Berkeley National Laboratory (LBNL) to achieve the objectives of obtaining measured IAQ and ventilation equipment usage data over a weeklong cycle of household activity, characterizing the installed ventilation equipment and measuring airflows, and obtaining information on perceptions and activities from the participant, in each study home. The detailed protocol is provided in a report (Chan et al., 2016, LBNL-1005819) that is available via the LBNL Energy Technologies Area (ETA) publications web site (https://eta.lbl.gov/publications). The final protocol was developed in part based on a pilot study conducted by LBNL in two homes in Northern California. The pilot study protocols and results are described in Appendix C, which is also published as a separate report (Chan et al., 2016, LBNL-1005818). Both the pilot study and final field study protocols were reviewed and approved by the LBNL institutional review board.

Each home in the HENGH field study was visited three times.

During the first visit, the research team obtained written consent from the study participant, checked that the home had the basic ventilation equipment required by the Title 24 Building Energy Efficiency Standards, and confirmed that the equipment was operable. If the dwelling unit ventilation fan was not operating, the researcher obtained consent from the participant to activate the system. The team confirmed that the participant met and understood all study requirements including the expectation that the dwelling unit ventilation system would operate throughout the week and the use of windows and doors would be limited to dealing with acute IAQ challenges (for example during major cleaning) and not opened for extended periods to provide extra ventilation beyond the mechanical system. The participant was asked about potential hazards and any locations within the home that the researcher should not enter, and potential indoor and outdoor locations for siting of air quality measurement stations were discussed. Characterization of the house, gas appliances, and ventilation equipment was also started on the first visit. The characterization included marking the locations of ventilation equipment and appliances on a house floor plan; photographing appliance and ventilation equipment as installed; and recording make, model, and performance ratings such as gas appliance burner fuel use rates and airflow rates for ventilation fans. A detailed list of parameters recorded in the characterization is provided in the LBNL report about the protocol. Each home also received a standard gas appliance safety inspection (NGAT) by a utility field service technician who performs this test routinely for utility customers. In a few homes, the inspection identified an issue that the gas service technician was able to fix on the spot, at the homeowner's request. Three homes failed NGAT because of a venting non-conformity identified for a fireplace or water heater. In two cases, a follow up visit was scheduled with a gas technician, and one-week monitoring was rescheduled at a later date. In the third case, the gas technician determined that the appliance could be used and monitoring could safely proceed without rescheduling. A few homes had problems with mechanical ventilation systems that were corrected prior to monitoring. In one home, the exhaust fan providing the dwelling unit ventilation was not connected to the terminal fitting at the roof; the homeowner contacted the builder and this was resolved before the next scheduled visit. In two other homes, exhaust fans providing the dwelling unit ventilation were unplugged. These were referred to the owner, who contacted the builder. In one of these homes, the builder simply came to plug-in the fan. In the other, the builder found that the fan was not working and replaced it with a new fan. At the request of two of the homeowners, air filters in the forced air heating and cooling systems were replaced by the research team prior to the one-week monitoring period in these homes. In addition, air filters were missing from both of the filter slots in one home. At the request of the homeowner, air filters were installed prior to the one-week monitoring period.

During the second visit, the team conducted equipment performance measurements, installed devices to measure indoor air quality and record equipment use over the week, and finished the house and equipment characterization. The performance measurements included a "DeltaQ" test to determine air leakage through the building envelope and through the HVAC and duct system, and airflow measurements of the following exhaust fans: kitchen range hood, exhaust fans in the three most used bathrooms, and exhaust fans in any toilet rooms. Air quality monitors and samplers were placed outdoors, at a central indoor location (usually the great room), in the master bedroom, and in up to three additional bedrooms. Monitors were installed to record the usage history for kitchen, bath and laundry exhaust fans and the clothes dryer, and temperature sensors were placed on the cooktop and an HVAC supply register to record their operation. Photographs were taken of the installations. Detailed descriptions of the measurement methods and devices and a complete list of the parameters monitored are provided in subsequent sections of the Methods. The research team provided the participant with a printed survey and a set of daily activity logs (see appendix D) and explained how to complete the forms. The survey included a subset of the questions from the online survey conducted as an earlier research task of HENGH, focusing only on perceptions and activities and excluding questions about equipment that the research team could determine themselves while on site. A few days into the monitoring period, a researcher called the participant to check if they had any issues or discomfort related to the research operating in the home or any questions.

During the third visit, the research team removed all equipment monitors and air quality samplers, collected the survey and activity logs and did an exit walkthrough with the participant to verify that all equipment was removed. The incentive – a $350 gift card to a national home improvement store – was provided to the participant upon completion of this visit and a signed record of incentive payment was obtained.

2.1.2 Research Team

The field study was a collaboration involving LBNL, the Gas Technology Institute (GTI), the Pacific Gas and Electric Company (PG&E), the Southern California Gas Company (SoCalGas), Misti Bruceri & Associates (MBA), and Chitwood Energy Management. LBNL designed the overall study and recruitment plan; developed the specific data collection protocols; conducted recruitment; analyzed IAQ samples; and compiled, reviewed and analyzed the data. GTI managed all elements of the field study including scheduling visits, preparing equipment, conducting quality assurance checks of the equipment, managing staff working in homes to implement data collection, and providing data to LBNL in electronic format. SoCalGas provided staff members from their engineering and technical services departments to collect data under GTI direction in homes in SoCalGas service territory, and also provided gas service technicians to conduct safety inspections in those homes. PG&E provided financial support for MBA to commit a technical staff person to work with the GTI field team in PG&E territory; PG&E also arranged for their gas service technicians to conduct safety inspections in these homes. Chitwood Energy Management worked as a subcontractor to GTI, providing technical support and guidance.

2.1.3 Eligibility

To be accepted into the study, the following criteria had to be met by the participant, the building and the household. The participant had to be 18 years of age and speak English sufficiently well to understand the consent form. The building had to be a single-family detached structure, located in California, and built in 2011 or later. The home had to have natural gas appliances and mechanical ventilation, suitable locations and electrical outlets for study instruments, and not have highly unusual filtration or ventilation systems. The household had to prohibit smoking and at least one adult resident had to be available to grant access to the study for each in home visit. The home had to be occupied by the owner and the participant had to agree to allow the study team access to the home to recover measurement devices if they decided to stop participating before the week of in-home measurements was complete.

The "built in 2011 or later" requirement was used as a proxy for homes built to comply with the 2008 version of Title 24. The study team assumed it would be difficult for potential participants to determine which version of Title 24 was applicable when their home was permitted. Records were obtained from CalCERTS/CHEERS for 23 homes to verify that they were certified to meet the 2008 or more recent standards. Even though Title 24 compliance documents were not available for the other homes, the presence of mechanical ventilation equipment in all 70 homes indicates that they were built to the 2008 or more recent standards.

2.1.4 Recruitment

The study was advertised and homes were recruited via several mechanisms.

The initial plan was to identify eligible and interested field study participants via the online survey (see Appendix A for details). After they completed the online survey, respondents who had indicated that their home was built 2011 or later and was a single-family detached structure were asked if they were interested in learning about "a follow-up study of indoor air quality and ventilation" that "involves research teams visiting homes to measure the performance of ventilation equipment, and to set up air quality and ventilation monitoring devices that will remain in place for a one-week period." Twenty-eight online survey homes built 2011 or later indicated interest in learning more about the study, but none of them ultimately participated. The low yield from these homes may have resulted from the long delay between the time when they completed the survey and indicated their interest (in 2015), and the time that the field study started to visit homes in SoCalGas service territory (in second half of 2017).

The second major approach was to advertise the study through various mechanisms and direct potentially interested individuals to visit a website that provided information about the study along with eligibility and participation requirements. The website had a page for interested individuals to provide their contact information. The online survey and an early version of the website noted that participants could receive an incentive valued at up to $230 for completing all elements of the study. Prior to the start of field monitoring, the incentive was increased to a $350 gift card to a home improvement store if they completed all study elements including the occupant survey and all daily activity logs. Participants also were offered a report summarizing the results of ventilation and IAQ measurements in their home. This report was prepared and provided to study participants by LBNL.

The most successful mechanism used to advertise the study was direct mailing of postcards to addresses of qualifying homes identified by searching the Zillow.com website for recently-sold, single-family homes built in 2011 or later. The postcards provided the basic study requirements, noted the incentive, and provided the study project website. Postcards were sent in several batches, each time targeting a different area with the study domain. During the last phase of recruitment, a $50 referral was offered to participants in order to meet the target number of study homes. Another mechanism that was tried without success was to offer incentives to home energy raters for any referrals that led to a consented study participant.

2.1.5 Screening and Selection

An LBNL researcher attempted to call each person who indicated interest through the survey or website. When a connection was made, the researcher first confirmed eligibility, then provided key information about the study and answered questions. During this call, study participants were informed that the field team could, in some cases, determine on site that a home is unsuitable for the field study. For example, this would occur if the field team could not clearly identify a dwelling unit mechanical ventilation system or not confirm that it is operable. If the ventilation system was merely turned off or if the runtime was improperly set, the field team would ask permission of the study participant to make a repair or adjustment. The potential participants were also informed that the research team would arrange with their local utility to conduct a safety inspection of their gas appliances and venting. Any critical safety issues would need to be resolved before proceeding. If a home were determined to be unsuitable by the research team or the participant decided to stop after the first visit, the participant would receive a $75 gift card.

If, at the end of the screening call, the person was still interested, and they and their home appeared to be eligible, LBNL provided the person’s contact information to GTI to schedule the first visit. In total, LBNL recruited 103 homes. In the majority of the homes referred by LBNL to GTI that did not complete the study, there were no house visits, either because the formerly interested person did not respond to three attempts by the GTI team to make contact or the person decided to not participate before the first scheduled visit. One consented participant withdrew after the first visit and prior to the scheduled second visit. One home was excluded when it became clear on the first visit that the home was built before 2011.

2.2 Field Data Collection Procedures

2.2.1 House, Mechanical Equipment and Appliance Characterization

Prior to the visit, the research team typically was able to obtain a floor plan from the builder's website; sometimes this was a mirror image plan or a basic plan that could have small modifications among constructed homes. If the floor plan was not obtained prior to the visit, a basic floor plan was sketched on site. The team used a paper form to record basic information about the house: floor area and ceiling heights; number of stories, bedrooms, full and half baths, and other rooms on each floor; attached garage and number of parking spots, etc. Photos were taken of the connecting walls and ceilings between the garage and house, attic, backyard, gas appliances and mechanical ventilation equipment, general layout and exterior of the house.

The following equipment was identified, characterized and located on the floor plan, and photos were taken to document the details of the installation and typically also the nameplate information:

- Dwelling unit mechanical ventilation system. Noted basic design (exhaust, supply, or balanced); type of control; make, model and rated flow; and fan settings.
- Other ventilation equipment: bath and toilet room exhaust fans, kitchen range hood, and any laundry exhaust fans. Noted make, model and rated flow, type of control for each fan; and for kitchen note if range hood is microwave or simple range hood.
- Heating and cooling system(s). Noted type of system (all were forced air), make and model, capacity (in tons and Btuh) and whether system was zoned. Noted dimensions and location of each return and locations of filter(s) if not at the return air grille. Noted location(s) and types of thermostats. For each filter in a forced air heating or cooling system, recorded make, model and performance rating and visually assessed condition of filter; also took photo. Identified and characterized thermostat and marked location on floor plan.
- Attic. Noted whether it was vented or unvented and the type of insulation. Photographed ductwork, gas furnace, exhaust fans, and vents.
- Gas-burning appliances. Noted make, model and firing rates of all burners or photographed nameplate. Noted locations on floor plans.

2.2.2 DeltaQ Test to Determine Air Leakage of Envelope and Forced Air System

Air leakage of the building envelope and forced air system was measured with the DeltaQ test (Method A of ASTM-E1554-2013) using a TEC Minneapolis Blower Door System with DG-700 digital manometer (energyconservatory.com). The DeltaQ test provides the air leakage associated with the forced air system at its normal operating conditions. The TEC system includes software to perform the DeltaQ test in an automated manner. This software operates the blower door fan, records airflow rate and envelope pressure difference and calculates the resulting envelope and duct leakage. The software also automatically checks to see if the results are adequate to compute the building envelope and duct system air leakage. The software allows the user to repeat the whole test or part of the test if necessary, such as if someone stepped on a pressure tube during the test or a door was inadvertently opened.

The DeltaQ test was developed as an efficient alternative to the traditional duct leakage measurement method, which uses a duct blaster fan connected to the HVAC distribution system (per ASTM Standard E1554), and measures the airflow required to achieve a specified, arbitrary pressure relative to the house (typically -25 Pa), while all supply and return registers are tightly sealed off. Measuring duct leakage to outside requires further use of a blower door to zero-out pressure differences between the ducts and occupied space. In contrast, the DeltaQ duct leakage test (also in ASTM E1554) measures the duct leak airflows to outside at normal HVAC system operating conditions, using only the blower door fan and requiring no sealing of registers. The DeltaQ test builds on the standard envelope tightness blower door measurement techniques by repeating the tests with the HVAC system air handler turned off and on. The DeltaQ test requires several assumptions to be made about duct leakage and its interaction with the duct system and building envelope in order to convert the blower door results into duct leakage at system operating conditions. DeltaQ repeatability testing has shown the duct leakage measurement to be accurate within 1 percent of the air handler total flow. Accuracy may be reduced under windy conditions. The team chose the DeltaQ test because it is more useful in considering the duct leak effects on IAQ as it gives the supply and return airflows at operating conditions. The metric used for duct leakage compliance is a total leakage airflow (supply + return) at a fixed pressure that does not give us the flow necessary for IAQ assessments.

2.2.3 Measurement of Ventilation Equipment Airflows

Airflows of bath and laundry exhaust fans were measured using a TEC Exhaust Fan Flow Meter (The Energy Conservatory). Range hood airflows were measured using a balanced-pressure flow hood method described by Walker and Wray (2001). A calibrated and pressure-controlled variable-speed fan (TEC Minneapolis Duct Blaster, The Energy Conservatory) was connected to either the exhaust inlet (preferred approach) or outlet. The Duct Blaster was connected at each site using a transition piece that was adapted onsite to cover the entire underside of the range hood. Using a pressure sensor, the Duct Blaster fan was controlled to match the flow of the exhaust fan while maintaining neutral pressure to the room at the exhaust inlet. The pre-calibrated speed versus flow relationship of the Duct Blaster provided the flow through the exhaust fan. For microwave range hoods, the top vent was covered with tape to ensure that the airflow measured at the bottom inlet represented the entire flow through the device.

Supply fan flow rates were not measured directly because the air inlets – at the attic level – could not be quickly and safely accessed by the field teams. It was also not feasible to measure flows using in-duct velocity probes because the supply ducts were encased in spray foam insulation in the attic in all four of the HENGH homes that used supply ventilation.

Natural infiltration airflow was calculated over the same period and mechanical airflow was summed using sub-additivity, as described later in the Methods, to estimate the overall house air exchange rate.

2.2.4 Equipment Use Monitoring

Cooktop and oven use were monitored using iButton temperature sensors attached to the surface of the cooktop, generally with one iButton adjacent to each burner. The temperature data were analyzed to find rapid increases in temperature that signal use of the cooking appliance.

Operation of exhaust fans, range hoods, clothes dryers, and the central forced air system were determined using one of the following methods: motor on/off senor, air velocity anemometer, or power meter. The field team determined which method to use depending on the accessibility and configuration of the appliances. Fans with multi-speeds (for example, range hood) were monitored using a vane anemometer to discern use at varied settings and to enable use of the setting-specific airflow (measured separately) to be used when calculating the overall airflow through the home.

State sensors that discern open vs. closed condition were used to monitor the most often used exterior doors and windows. Although study participants were asked to keep these openings closed during the one-week study period, it was deemed valuable to monitor as any extended natural ventilation could impact pollutant measurements.

Temperature and relative humidity were monitored at the supply air registers as an indicator of heating/cooling use.

2.2.5 Air Quality Measurements

Air pollutant concentrations and environmental temperature and relative humidity were measured at several locations indoors and also outdoors on the premises. The central indoor air quality station was generally in the great room, a large open room on the first floor of the house that includes the kitchen and family room, or in a dining room that was openly connected to the other rooms on the first floor. The parameters measured at each location are noted below.

IAQ parameters and measurement equipment at outdoor station

- $PM_{2.5}$, 1-min resolved, MetOne ES-642 photometer
- Formaldehyde, 1-week integrated, SKC UMEx passive sampler
- NO_2 and NO_X, 1-week integrated, Ogawa passive sampler
- Temperature and humidity, 1-minute resolved, Onset HOBO U23 Pro v2

IAQ parameters and measurement equipment at central indoor station

- $PM_{2.5}$, 1-min resolved, MetOne BT-645 photometer
- Formaldehyde, 30-minute resolved, GrayWolf Monitor FM-801[2]
- NO_2, 1-minute resolved, Aeroqual Series 500
- CO_2, temperature and RH, 1-minute resolved, Extech SD-800
- Formaldehyde, 1-week integrated, SKC UMEx passive sampler
- NO_2 and NO_X, 1-week integrated, Ogawa passive sampler
- Temperature and humidity, 1-minute resolved, Onset HOBO UX100-011

IAQ parameters measured and measurement equipment in master bedroom

- Formaldehyde, 30-minute resolved, GrayWolf Monitor FM-801
- CO_2, temperature and RH, 1-minute resolved, Extech SD-800

[2] This monitor is a rebranded Shinyei Multimode Formaldehyde Monitor

- Formaldehyde, 1-week integrated, SKC UMEx passive sampler

IAQ parameters and measurement equipment in other occupied bedrooms

- CO_2, temperature and humidity, 1-minute resolved, Extech SD-800

The measured IAQ parameters are summarized in Table 1. Specifications of the time-resolved monitoring equipment, as advertised by the nameplate manufacturers, are provided in Table 2.

Table 1: Measured Air Quality Parameters

Parameters	Measurement Device	Sampling Locations	Sampling Resolution
$PM_{2.5}$	MetOne ES-642	Outdoor	1-minute
	MetOne BT-645	Indoor (central)	1-minute
CO_2. T, RH	Extech SD-800	Indoor (central, master & other bedrooms)	1-minute
NO_2	Aeroqual NO_2 Monitor	Indoor (central)	1-minute
	Passive Ogawa Samplers	Outdoor Indoor (central)	1-week
Formaldehyde	GrayWolf FM-801 (Shinyei Multimode)	Indoor (central, master bedroom)	30-minute
	Passive SKC UMEx-100	Outdoor Indoor (central, master bedroom)	1-minute
T, RH	Onset HOBO U23 Pro v2 Onset HOBO UX100-011	Outdoor Indoor (central)	1-minute

Source: Lawrence Berkeley National Laboratory

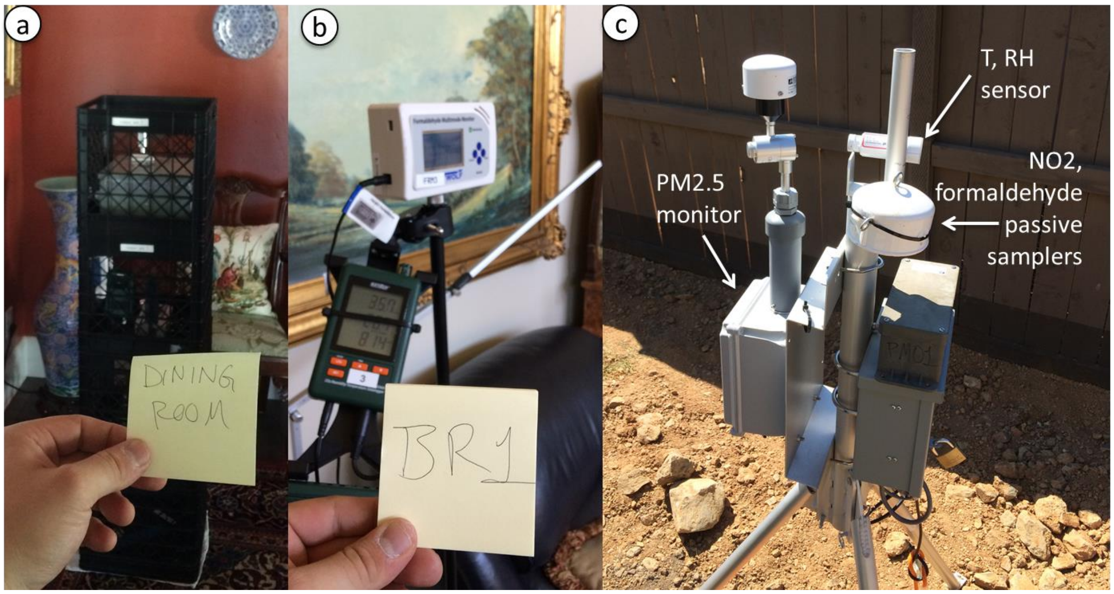
Table 2: Specifications of Air Pollutant Monitoring Equipment

Parameter	Device make and model	Range and Resolution	Accuracy	Other
Temperature	Onset HOBO UX100-011	Range: -20° to 70°C. Resolution: 0.024°C at 25°C	±0.21°C from 0° to 50°C	Response time: 4 min in air moving 1 m/s Drift: <0.1°C per year
Temperature	Extech SD800	0 to 50°C	±0.8°C	
Relative humidity	Onset HOBO UX100-011	Range: 1% to 95% (non-condensing); Resolution: 0.05%	±2.5% from 10% to 90%; up to ±3.5% at 25°C including hysteresis	Response time: 11 sec to 90% in airflow of 1 m/s Drift: <1% per year typical
Relative humidity	Extech SD800	Range: 10-90%	±4%RH below 70%; 4% of reading + 1% for 70–90% range	
Particulate matter, $PM_{2.5}$	MetOne ES-642 MetOne BT-645	Range: 0-100 mg/m^3. Resolution: 0.001 mg/m^3.	± 5% traceable standard with 0.6um PSL	
Carbon dioxide, CO_2	Extech SD800	Range: 0-4000 ppm; Resolution: 1 ppm	±40 ppm under 1000 ppm; ±5% (>1000ppm)	
Nitrogen Dioxide	Aeroqual 500 Series	Range: 0 to 1 ppm	± 0.02 ppm within 0 to 0.2 ppm range	
Formaldehyde	GrayWolf (Shinyei) Multimode Monitor	20 to 1000 ppb	± 4ppb for <40ppb, ± 10% of reading for ≥40ppb	30 min resolution; 20 ppb is lowest reliable value with stated accuracy

Source: Lawrence Berkeley National Laboratory

The central indoor monitoring equipment was deployed using a stacked crate system that protected the measurement equipment but allowed free airflow (Figure 1). The outdoor monitoring station was mounted on a tripod with air sampling occurring at roughly 2 m height. The target location for the outdoor station was at least 3 m from the nearest exterior wall of the house and any local sources such as a fire pit or grill. The ES-642 photometer was housed in a weatherproof enclosure designed and sold by the manufacturer (Met One Instruments, Inc.) that incorporates a sharp-cut cyclone to exclude particles larger than 2.5 μm aerodynamic diameter. The formaldehyde and NO_2/NO_X passive samplers were placed inside a 10 cm diameter PVC cap. This configuration is shown in Figure 1.

Figure 1: Examples of Air Quality Monitors



Air quality monitors used at indoor central station (a), master bedroom (b), and outdoors (c).

Source: Lawrence Berkeley National Laboratory

The standard software for the GrayWolf (Shinyei) formaldehyde monitor reports readings below 10 ppb as "<LOD". By special arrangement, GrayWolf provided modified software to provide readings below the nominal detection limit of the instrument.

The MetOne Instruments ES-642 and BT-645 are aerosol photometers that quantify the light scattered by the ensemble of particles passing through the measurement cell and translate that to an estimated $PM_{2.5}$ concentration based on a device-specific calibration relationship developed in the laboratory using a traceable reference of 0.6 μm diameter polystyrene latex (PSL) spheres. Since photometer response varies with aerosol size distribution and chemical composition, the accuracy of these devices for ambient (outdoor) or indoor $PM_{2.5}$ can vary substantially as the qualities of the aerosol vary. The recommended practice when using a photometer is to measure an environmental aerosol sample is to collect a filter sample in the same environment, preferably at the same time, and determine a location specific gravimetric $PM_{2.5}$ adjustment factor. In this study, The team checked the mass calibration factor and the time-response of the primary photometers by using Thermo pDR-1500 photometers with onboard filter sample alongside the MetOne monitors indoors and outdoors at eight homes. Due to power interruptions, data are available for only five of the outdoor deployments.

2.2.5.1 Calibrations and Quality Assurance for Time-Resolved Measurement Devices

All of the monitors used to collect time-resolved air quality data were purchased new at the start of the study, and thus were expected to conform to the manufacture specification for accuracy. The following additional procedures were implemented to check instrument cross calibrations.

The indoor and outdoor $PM_{2.5}$ monitors were co-located for roughly one hour during the instrument deployment visit at each home. In most cases the co-location was outdoors at the location of the outdoor monitor. Co-located comparisons were available from 45 homes. In two of the homes, the two monitors measured very different concentrations likely because the outdoor monitor had a heated inlet that was set to activate when relative humidity reached above 60 percent, and the indoor monitor did not. The heated inlet prevents condensation that could damage the instrument. The indoor monitor did not have a heated inlet because high humidity is generally not a concern when sampling indoor. At the two homes during the one-hour co-location test, the outdoor monitor measured high concentration of $PM_{2.5}$ (51 and 60 $\mu g/m^3$ at Home 063 and 068, respectively). Without the heated inlet, the co-located indoor monitor measured 111 and 78 $\mu g/m^3$, respectively. The two homes were sampled in winter (January 2018) in Tracy and Manteca CA, where high humidity condition in the morning likely explained this difference between the co-located indoor and outdoor $PM_{2.5}$ monitors. Excluding these two cases, the co-located indoor and outdoor $PM_{2.5}$ monitors agreed to within 1.9 $\mu g/m^3$ on average (median = 0.9 $\mu g/m^3$). In the remaining 43 homes, the outdoor monitor read somewhat lower concentration than the indoor monitor when the two were co-located more often (79 percent) than not (21 percent). This is likely because the heated inlet intended to prevent condensation resulted in some volatilization of the outdoor particles.

The Extech CO_2 monitors were co-located for 1 hour at each home or at a warehouse where the field team used for setup before the visit. The Extech were also calibrated at LBNL midway through the field study. During a break in the field study, the calibrations of all Extech CO_2 monitors were checked at LBNL by deploying the monitors in a well-mixed chamber with CO_2 concentrations varying between 400 and 1700 ppm. CO_2 concentrations were measured concurrently using an EGM-4 gas analyzer (PP systems, Amesbury, MA, USA). The EGM-4 was separately calibrated using standard gas of known CO_2 concentrations between 0 and 2500 ppm. CO_2 concentrations measured by the Extech were compared minute by minute against the EGM-4 data. On average, the difference in readings between the Extech monitors and EGM-4 was 7 percent of the CO_2 concentrations being measured by the EGM-4.

The Aeroqual 500 NO_2 monitor was calibrated before each visit with zero gas and a 1 ppm NO_2 standard gas. Monitor response was adjusted to match those values following manufacturer instructions.

2.2.5.2 Quality Assurance for Passive Samplers

Ogawa samplers were prepared according to manufacturer protocols. Prior to assembly for field deployment, all parts of the samplers were washed thoroughly with deionized water and allowed to dry thoroughly in a laboratory at LBNL. Sample pads were stored in the refrigerator in their original packaging until they were inserted into samplers. After samplers were assembled with new sample pads, they were placed in sealed amber plastic bags (Ziploc) and shipped to the field team in an insulated box with ice packs to keep them cool.

Four Ogawa samplers were deployed at each study home: one outdoors, two at the central indoor station (duplicates), and one field blank. The field blank was opened either at the indoor or outdoor station, then packaged and stored in a refrigerator for the monitoring week.

At least four UMEx 100 formaldehyde samplers were deployed at each study home: one outdoors, two in the central indoor station (duplicates) and one in the bedroom. In most of the sampled homes, a fifth formaldehyde sampler was opened indoors and packaged immediately to serve as a field blank. The formaldehyde blanks were stored in a refrigerator during the monitoring week.

2.2.5.3 Analysis of Passive Samplers

All passive samplers were shipped to LBNL for analysis. To avoid damage to the chemical samplers from extreme temperatures, samplers were mailed in an insulated shipping container with ice packs to keep them cool. The samples were extracted and analyzed following the protocols provided by each company (Ogawa & Company 2017; SKC, Inc. 2017). All Ogawa samples were extracted for analysis within 30 days from when the samplers were assembled.

For each NO_X and NO_2 sample the team subtracted the mass determined from the field blank at the same home before calculating the sample period concentrations of NO_X, NO_2 and NO as the difference between the adjusted NO_X and NO_2 concentrations. Analysis of 64-paired duplicates of indoor samples found that agreement in NO_2 concentrations was within 0.6 ppb on average (median = 0.3 ppb). When available, duplicates were averaged to provide a better estimate of the indoor concentrations of NO, NO_2, and NO_X.

The formaldehyde concentration determined by passive sampler at each home also was adjusted by the effective sample period concentration determined from the field blank at the same home. For the eleven homes that did not have a formaldehyde passive sample field blank, the team subtracted 0.15 micrograms, which is the mean mass determined from all available field blanks (and corresponds to 0.6 ppb for a 7-day collection period). Sixty-six paired indoor formaldehyde samples agreed to within 1.0 ppb on average (median = 0.7 ppb). When available, duplicates were averaged to provide a better estimate of the indoor concentrations.

The UMEx contains an internal blank within each sampler that can potentially be used for convenience instead of using a separate field blank sampler. However, analysis of the internal blank suggested that even it was not directly exposed to the sampling air, some formaldehyde was collected, possibly because the compartment isolating the internal blank was not completely airtight. The average analyte mass determined from internal blanks of indoor samples was 0.6 micrograms; this is 4 times the field blank value noted above.

Formaldehyde indoor emission rates E ($\mu g/m^3$-h) were calculated using a simple mass-balance equation assuming well-mixed, steady state condition. The same method was applied by Offermann (2009) to estimate indoor emission rates of formaldehyde and other VOCs.

$$E = (C_i - C_o) \times AER \quad (1)$$

Outdoor formaldehyde concentration (C_o, $\mu g/m^3$) was subtracted from the indoor concentration (C_i, $\mu g/m^3$) measured at the central location, assuming that there is no loss in formaldehyde as the outdoor air enters through the building envelope. Air exchange rate (*AER*, 1/h) is assumed to be the only mechanism that removals formaldehyde from the indoor air. Air exchange rate was estimated from natural infiltration airflow and mechanical airflow using sub-additivity, as described later in the methods

2.2.5.4 Weighing of Filters for Gravimetric $PM_{2.5}$ Determination

The filters used for gravimetric analysis were 37 mm diameter, 2.0 micron pore size Pall Teflo filters with ring. Prior to deploying to the field, each filter was preconditioned for 24 hours at controlled temperature and humidity conditions (47.5 +/- 1.5 percent RH and 19.5±0.5 ºC), according to EPA guidance for gravimetric measurements. The filters were passed over a deionizing source to remove any static charges and each filter was weighed twice using a Sartorium SE2-F balance. After pre-weighing, filters were loaded into the two pDR-1500 photometers and the devices were shipped to GTI prior to the scheduled deployment. At the conclusion of the week of side-by-side monitoring, GTI shipped the two pDR monitors back to LBNL. LBNL removed the filters, and repeated the preconditioning and weighing procedures noted above. The collected mass was determined as the difference in mass, post-sampling versus pre-sampling. The sample air volume was taken from the pDR software and the sample concentration was calculated as collected PM mass / sample air volume.

2.2.6 Survey and Activity Log

Participants were asked to complete a daily activity log, provided in Appendix D.

Field study participants also were asked to complete a survey that was adapted from the online survey conducted earlier in the project; the complete survey is provided in Appendix D. The field study survey reduced the number of questions about the mechanical equipment in the home as these data were collected already during the characterization work of the field team.

2.2.7 Data Compilation

Following the visits to homes, GTI researchers uploaded data files from all measurement devices, photos, and completed home characterization data forms to a secure server at GTI. The LBNL team copied these data onto a secure server at LBNL for compilation and analysis. The compiled LBNL database includes only de-identified data and may be made available to other researchers as specified in the approved IRB protocol.

2.2.8 Total Ventilation Rate Calculation

The total ventilation rate (Q_{total}) from mechanical fans and air infiltration was calculated following the procedure described in ASHRAE Handbook Fundamentals (2017). The calculation assumed that during the monitoring week, occupants followed instructions to keep windows and doors closed, so natural ventilation was negligible.

First, airflow rates from mechanical fans were added to calculate balanced ($Q_{balance\_mech}$) and unbalanced ($Q_{unbalance\_mech}$) airflow rates by comparing minute by minute the amount of exhaust and supply air from usage data collected from each home. Next, air infiltration ($Q_{infiltration}$) was calculated using the flow coefficient and pressure exponent of the building envelope, determined as part of the DeltaQ Test. Wind data were obtained from the nearest weather station[3]. Indoor and outdoor temperature were monitored onsite. Typical shelter class of 4 (urban building on larger lots where sheltering obstacles are *more than* one building height away) and 5 (shelter produced by buildings or other structures that are *closer than* one

[3] Data obtained from www.wunderground.com. During periods when wind was reported as "calm", 1 mph (mile per hour) was assumed for calculating air infiltration rate.

house height away) was used, as determined by reviewing photos of the house in relation to its surrounding. The total ventilation rate was calculated following Equation 2, which uses a superposition adjustment (∅) to account for the sub-additivity of unbalanced mechanical airflows with air infiltration.

- $Q_{total} = Q_{balance\_mech} + Q_{unbalance\_mech} + \emptyset Q_{infiltraiton}$ (2)
- $\emptyset = \frac{Q_{infiltration}}{Q_{unbalance\_mech} + Q_{infiltration}}$

2.3 Assessing Title 24 Fan Sizing and Airtightness Requirements for New California Homes using Simulations

The main objectives of the simulation study were (1) to evaluate the IAQ and energy impacts of different dwelling unit fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH50 airtightness requirement in the Title 24 Building Energy Efficiency Standards. The results for individual cases were combined using a weighting based on the fraction of new homes constructed in the state's climate zones to get statewide estimates of performance. The simulations included several fan sizing methods: the new requirements in 2019 Title 24, the fan ventilation rate method from the 2008 Title 24, the total ventilation rate method introduced in the 2013 Title 24 (with and without natural infiltration), the ASHRAE 62.2-2016 approach, and current builder practice based on the installed fan sizes found on the field testing part of this study.

The following discussion outlines the approach used on the simulation of fan sizing and air tightness requirements. More details are provided in Appendix B.

2.3.1 IAQ and Relative Exposure

IAQ impacts are assessed using the metric of relative exposure. The simulations used the relative exposure approach to assess IAQ where the concentration of a generic, continuously-emitted contaminant under some alternative ventilation approach is compared to the concentration that would occur with a continuous, fixed airflow – in this case the dwelling unit target airflow required by ASHRAE Standard 62.2 (Qtotal). The ratio of the exposure under the alternative ventilation scenario to the continuous fixed flow is the relative exposure. The metric of relative exposure is now the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard.

At a given time, a relative exposure equal to 1 means the two ventilation rates lead to identical pollutant concentrations. When averaged over a period of time (for example, annually), a value of 1 means the two rates provide equivalent chronic pollutant exposure. A relative exposure of one-half suggests the real-time ventilation rate is double the reference ventilation rate, and a relative exposure of two indicates a real-time ventilation rate that is half the reference rate. The annual average relative exposure during occupied hours must be less than or equal to one in order to satisfy ASHRAE 62.2-2016 requirements.

The relative exposure can be interpreted as a multiplier that could be applied to any generic contaminant emitted uniformly and at a constant rate from only indoor sources. For example, a value of 1.2 reflects a 20 percent increase in pollutant concentration relative to the concentration that would occur if the home's actual ventilation (Q_i) was at the target ventilation rate (Q_{total}). Or a value of 0.66 would reflect a 34 percent reduction in the pollutant concentration, relative to the concentration at the target ventilation rate.

In general, the pollutant concentration is inversely related to the ventilation rate. As a result, the increased airflow required to reduce the concentration by some fixed amount is much greater than the reduction in airflow needed to result in a similar increase in the concentration.

2.3.2 Airtightness, IAQ and Energy Consumption

Overall, reducing air leakage while mechanically ventilating to maintain equivalent IAQ is expected to save energy for two reasons: (1) it reduces the variability in the ventilation rate throughout the year, shifting airflows to milder weather conditions, and (2) this reduction in variability means the same exposure can be maintained with a lower total airflow. Both of these effects reduce the heating and cooling loads associated with ventilation, even when the same relative exposure is maintained.

2.3.3 Simulation Tool

The REGCAP simulation tool is used to predict the ventilation and energy performance. It combines detailed models for mass-balance ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. Two zones are simulated: the main house and the attic. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance.

2.3.3.1 Prototype Descriptions

Two Energy Commission prototype homes were simulated: one- and two-story, referred to throughout as "med" (or "medium") and "large", respectively. These were made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 Building Energy Efficiency Standards. Thermostat schedules were set to meet those specified in the 2016 Title 24 Alternative Calculation manual (ACM). Heating and cooling equipment was sized using Air Conditioning Contractors of America (ACCA) Manual J load calculation procedures. Current deviations from the Title 24 prescriptive path prototypes include no economizer fans, internal gains based on RESNET calculation method, HVAC equipment efficiencies and elimination of duct leakage to outside. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice.

The climate zones were chosen to capture a range of heating and cooling loads. The airtightness levels used in the simulations were 0.6, 1, 2, 3 and 5 ACH_{50}. The ventilation fan for Title 24 compliance was sized according to seven different calculation methods. Each case was simulated with both balanced and unbalanced dwelling unit ventilation fans. A baseline case with no dwelling unit ventilation fan operating was simulated for each combination of prototype, airtightness and climate zone. The ventilation energy use was the difference in total annual HVAC consumption between the fan and no fan cases, which includes changes in fan energy and thermal loads from air exchange.

2.3.3.2 Weighted Average Calculations

To scale these individual cases up to statewide estimates, weighting factors were developed that represent the best estimate of the current distribution of parameters, including climate zone, envelope airtightness, house prototype and ventilation fan type. A second series of weighting factors were developed to represent a proposed envelope leakage requirement of 3 ACH_{50}. The weighting factors are discussed further in Appendix B. Even though this is an imperfect approach to characterizing the entire new California single-family building stock, it provides a way to generalize and summarize these results, with a focus on where and how new homes are built in the state. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect of the larger energy impacts in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon).

2.3.3.3 Energy Use Normalization with Relative Exposure

When assessing energy savings from an airtightness requirement, the results conflate changes in airtightness with changes in the ventilation rate and relative exposure. To isolate the energy associated with ventilation and infiltration from other envelope loads, cases with no fan operation and no envelope leakage were simulated. The energy use for these cases was subtracted from the total to get the ventilation-only component. These ventilation-only energy use estimates for used to determine estimates of energy savings normalized by relative exposure. This is achieved by simply multiplying the ventilation-only energy estimates by the relative exposure in this case. For example, a relative exposure of 1.2 would lead to a 20 percent increase in energy use to correct to a relative exposure of 1. While this assumed linear relationship my not be exactly true in all cases it is the only way to achieve comparisons at the same relative exposure without considerable manual iteration. The total HVAC energy use was then calculated for each case by adding the adjusted ventilation energy use back onto the envelope-only HVAC energy use to provide an estimate of energy use for each case when they are forced to provide the same exposure.

2.3.3.4 Dwelling unit ventilation fan Size Calculation With Fixed Natural Infiltration

We assessed three fan sizing methods that have fixed assumptions for natural infiltration and do not include variability in house leakage. Their calculated fan airflows do not vary by the factors that affect infiltration: airtightness, house geometry and climate zone. These methods were chosen to reflect the most common approaches in California construction: two are directly from the Title 24 Building Energy Efficiency Standards and the third is based on field observations of installed systems (Builder Practice).

Fan Ventilation Rate Method (T24_2008)

The Fan Ventilation Rate method (referred to as ***T24_2008***) was added as a requirement in the Title 24 (2008) Residential Compliance Manual Section 4.6.2. It calculates dwelling unit ventilation fan airflow from conditioned floor area and occupancy, as shown in Equation 3. This was the fan sizing equation in the version of ASHRAE 62.2 at the time the Title 24 requirement was written. This fan sizing approach implicitly assumed a background infiltration rate equivalent to 0.02 cfm per ft^2 of conditioned floor area. This is an appropriate natural infiltration rate assumption for homes in the 5-7 ACH_{50} range, but it is inadequate for substantially more airtight homes. The ***T24_2008*** method results in fan sizes that do not vary by either airtightness or location. This fan sizing method continues to be available in the current 2016 Title 24, and it is the default sizing method for IAQ ventilation in the prescriptive and performance path homes.

$$Q_{fan} = \frac{A_{floor}}{100} + 7.5 \times (N_{br} + 1) \qquad (3)$$

Q_{fan} = calculated dwelling unit ventilation fan airflow, cfm
A_{floor} = conditioned floor area, ft^2
N_{br} = number of bedrooms

Total Ventilation Rate Method (Qtotal)

In 2013, the Total Ventilation Rate method was added to the Title 24 Building Energy Efficiency Standards as an alternative IAQ compliance path for airtight, low-infiltration homes. Homes using the Total Ventilation Rate method would typically calculate a fan size by subtracting an infiltration estimate from a dwelling unit target airflow. This is based directly on changes to ASHRAE 62.2 that explicitly changed the basic equations from fan sizing (based on an assumed natural infiltration airflow of 2 cfm/100 sq. ft. of floor area) to a total ventilation target. In this no-infiltration sizing method (referred to as ***Qtotal***), the dwelling unit fan airflow was set equal to the dwelling unit ventilation airflow target, as in Equation 4, where the fan airflow is equal to Q_{tot}.

$$Q_{tot} = 0.03\ A_{floor} + 7.5 \times (N_{br} + 1) \tag{4}$$

Current Builder Practice Method (BuilderPractice)

Field studies, including preliminary feedback from the HENGH field study, suggest that current builder practice in California homes is to install a dwelling unit ventilation fan that is oversized relative to the T24_2008 airflow requirement by roughly 40 percent[4]. This fan sizing is referred as ***BuilderPractice*** and use a 40 percent oversized fan in the simulations.

2.3.3.5 Dwelling Unit Ventilation Fan Size Calculation with House-Specific Natural Infiltration

Four dwelling unit fan sizing methods are examined that include house-specific natural infiltration estimates with varying levels of sophistication, all of which are based on the methods in the ASHRAE 62.2 ventilation standard. ASHRAE 62.2-2016 is structured to help ensure that all compliant homes have similar dwelling unit airflows that are consistent with the target airflow set by the standard (Q_{tot}). The team outlined the general process of calculating a dwelling unit target airflow (Q_{total}), a house-specific infiltration estimate (Q_{inf}), and the resulting requirement for the dwelling unit mechanical ventilation system (Q_{fan}). Where specific fan sizing methods diverge were highlighted from this general approach.

Total Ventilation Rate Method Including Infiltration (T24_2013)

The Total Ventilation Rate method is used and account for natural infiltration in the dwelling unit fan sizing; referred to as ***T24_2013***.

The target total ventilation airflow, comprising the combined natural and mechanical flows, is calculated using Equation 4. The natural infiltration airflow is estimated from blower door air leakage, house geometry and climate data using the procedures from ASHRAE 62.2-2016 (see Appendix B for more details).

[4] The 70 homes in the current study had an average measured fan flow 50% above the minimum requirement. However, all these data were not available at the time of performing the simulations and a 40% value was used based on the initial field study results and the results of Stratton et al. (2012) in 15 California homes.

ASHRAE 62.2-2016 Ventilation Standard Method (ASH622_2016)

The current ASHRAE 62.2-2016 ventilation standard (referred to as ***ASH622_2016***) builds on the T24_2013 calculation approach, but it adds a superposition adjustment (∅, see Equations 5 and 6) to account for the sub-additivity of unbalanced mechanical airflows with natural infiltration. Inclusion of superposition reduces the effective infiltration airflow, as explained earlier in Equation 2.

$$\emptyset = \frac{Q_{inf}}{Q_{total}} \tag{5}$$

where ∅ is the sub-additivity factor, having a value of 1 if the dwelling unit fan is a balanced system.

$$Q_{fan} = Q_{total} - \emptyset(Q_{inf}) \tag{6}$$

2019 Title 24 Method (T24_2019)

This fan sizing procedure is identical to the ASH622_2016 method, except envelope leakage is treated differently. IAQ fans in homes with envelope leakage greater than 2 ACH50 are sized using a default 2 ACH_{50} envelope leakage value. Homes with reduced envelope leakage below the 2 ACH_{50} limit use the actual leakage rate in fan sizing calculations. For very airtight homes, the calculated IAQ fan sizes are identical to those using the ASH622_2016 sizing procedure, while leakier homes have larger fan airflows, because of lower natural infiltration estimates resulting from the default leakage rate of 2 ACH_{50}.

2.4.3.6 Calculation of Relative Exposure

The relative exposure for a given time step is calculated from the relative exposure from the prior step (R_{i-1}), the target ventilation rate (Q_{tot}) and the current ventilation rate (Q_i) using Equation 7, unless the real-time or scheduled ventilation is zero, then Equation 8 is used.

$$R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t / V_{space}} \tag{7}$$

R_i = relative exposure for time-step i
R_{i-1} = relative exposure for previous time-step i-1
Q_{tot} = Total ventilation rate from ASHRAE 62.2-2016, cfm
Q_i = Ventilation rate from the current time-step, cfm
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, ft^3

$$R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}} \tag{8}$$

The real-time ventilation rate (Q_i) is the combined airflow of the dwelling unit ventilation fan and natural infiltration, predicted by the REGCAP mass balance model.

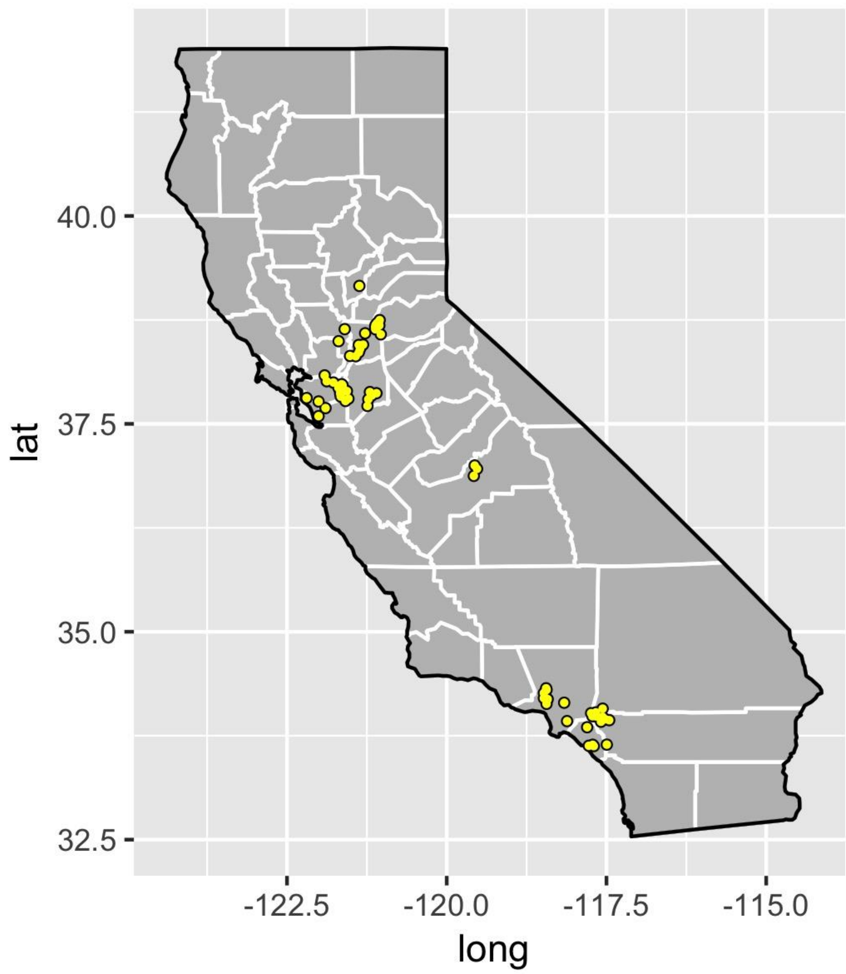
CHAPTER 3: Results

3.1 Characteristics of Field Study Homes

3.1.1 House Characteristics

Figure 2 shows the locations of the sampled homes. Forty-eight of the sampled homes were in PG&E service area and the other 22 were in SoCalGas service area.

Figure 2: Sampled Homes Locations



Source: Lawrence Berkeley National Laboratory

Table 3 shows the cities and climate zones where HENGH study homes were located. About 70 percent of new home construction in California is located within one of the 7 represented climate zones, based on the projected new housing by the Energy Commission Demand Analysis office for 2017 (the same data was used to calculate weighing factors for the simulation analysis, see Appendix B). Sampling occurred throughout the year, with summer (June through September) having the most samples, as shown in Table 4.

Table 3: Sampled Homes by Cities and Climate Zones (N=74)

IOU	Climate Zone	Cities (Number of homes)	Number of Homes	Total
PG&E	3	Discovery Bay (2), Hayward (2), Oakland (1)	5	48
	11	Marysville (1)	1	
	12	Brentwood (12), El Dorado Hills (10), Elk Grove (6), Manteca (4), Mountain House (2), Pittsburg (2), Davis (1), Dublin (1), Sacramento (1)	39	
	13	Clovis (3)	3	
SOCALGAS	8	Irvine (2), Downey (1), Lake Forest (1), Yorba Linda (1)	5	22
	9	Van Nuys (5), Alhambra (1)	6	
	10	Jurupa Valley (5), Chino (4), Corona (1), Eastvale (1)	11	

Source: Lawrence Berkeley National Laboratory

Table 4: Sampled Homes by Seasons

Season/Months	Number of Homes
Winter/Dec-Feb	16
Spring/Mar-May	13
Summer/Jun-Sep	27
Fall/Oct-Nov	14
Total	70

Source: Lawrence Berkeley National Laboratory

The earlier study by Offermann examined homes built between 2002 and 2004 and collected data from summer 2007 through winter 2008. This study sampled homes roughly a decade later, with most homes built between 2012 and 2016, and visited in fall 2016 through March 2018. The distribution of HENGH homes' construction years is shown in Table 5.

Table 5: Sampled Homes by Year Built

Year Built	Number of Homes
2011	1
2012	7
2013	13
2014	17
2015	15
2016	14
2017	3
Total	70

Source: Lawrence Berkeley National Laboratory

Tables 6 and 7 summarize the distribution of bedrooms and bathrooms. Almost all the homes had between three and five bedrooms.

Table 6: Sampled Homes by Number of Bedrooms

Bedrooms	Number of Homes
1	1
2	3
3	20
4	28
5	17
6	1
Total	70

Source: Lawrence Berkeley National Laboratory

Table 7: Sampled Homes by Number of Bathrooms

Bathrooms	Number of Homes
1–1.5	1
2–2.5	24
3–3.5	39
4–4.5	8
5–5.5	2

Source: Lawrence Berkeley National Laboratory

This study included a mix of one-story and two-story houses with a solitary three story home as summarized in Table 8.

Table 8: Sampled Homes by Number of Stories

Stories	Number of Homes
1	23
2	31
3	1

Source: Lawrence Berkeley National Laboratory

Most of the homes had floor areas in the rage of 2000 to 3500 ft^2, as shown in Table 9. The distribution of home sizes in the new study was very similar to homes in the Offermann study. For HENGH the Mean / Median / Interquartile (IQ) range were: 2657 / 2767 / 2096–3102 ft^2. In the Offermann study the Mean / Median / IQ range were: 2669 / 2703 / 2166–3152 ft^2.

Table 9: Sampled Homes by Floor Area

Floor Area (ft^2)	Number of Homes
<1500	4
1500–1999	8
2000–2499	12
2500–2999	12
3000–3499	13
≥3500	6

Source: Lawrence Berkeley National Laboratory

Offermann reported that homes were 1.7 to 5.5 years old when monitored in the CNHS study. HENGH homes were visited when slightly newer, with the majority being between 1 and 3 years at the time of monitoring (Table 10).

Table 10: Age of Homes When Sampled

Age of Home When Sampled	Number of Homes
<1	2
1	14
2	32
3	14
4	4
5	2
No Response	2
Total	70

Source: Lawrence Berkeley National Laboratory

All homes in the current study had gas cooktops. This is different from the Offermann study, in which 2 percent were gas and 98 percent were electric. The HENGH sample included many homes with electric ovens and/or clothes dryers.

Table 11: Appliance Fuel Use in Sampled Homes

Appliance	Number of Homes – Gas	Number of Homes – Electric
Cooktop	70	0
Oven	30	40
Clothes Dryer	42	28
Water Heater	70	0
Heating	69	1

Source: Lawrence Berkeley National Laboratory

Twenty-six of the 70 homes had a gas fireplace in the main living space and all were vented to outside (as required in California). One home had a second gas fireplace inside the master bedroom. Three homes had a gas fireplace outdoors, and three in an indoor/outdoor space, for example, a California Room.

3.1.2 Household Demographics

Data on household demographics were obtained via the survey. Table 12 shows that the most common household sizes were two or three residents and there were only three homes with a single resident. Summary data on the number of homes with occupants from each age group are provided in Table 13. Among the 70 homes sampled, 41 had no youths and 49 had no seniors, whereas only 8 homes had no (traditionally defined) working age adults.

Table 12: Number of Occupants in Sampled Homes

Number of Occupants	Number of Homes
1	3
2	29
3–4	23
5–6	9
7 or more	3
No response	3
Total	70

Source: Lawrence Berkeley National Laboratory

Table 13: Number of Occupants in Sampled Homes by Age Group

Number of Occupants Within Age Group (A)	Number of Homes with (A) Occupants in Age Group 0–17	Number of Homes with (A) Occupants in Age Group 18–65	Number of Homes with (A) Occupants in Age Group 65+
0	41	8	49
1	7	7	10
2	14	41	9
3	3	8	0
4	2	2	0
5	1	2	0
No response	2	2	2
Total	70	70	70

Source: Lawrence Berkeley National Laboratory

Table 14 indicates that the study sample comprised mostly college-educated heads of household, with about half having graduate degrees. The household earnings (Table 15) were also skewed toward higher earners, which is not surprising given the high cost of real estate in California.

Table 14: Education Level of Head of Household in Sampled Homes

Education Level	Number of Homes
Completed high school	1
Some college	5
Associate's degree	2
College degree	23
Graduate or professional degree	36
No response	3
Total	70

Source: Lawrence Berkeley National Laboratory

Table 15: Total Household Income in Sampled Homes

Income	Number of Homes
\$35,000–\$49,999	1
\$50,000–\$74,999	2
\$75,000–\$99,999	5
\$100,000–\$150,000	29
Greater than \$150,000	29
No response	4
Total	70

Source: Lawrence Berkeley National Laboratory

Study participants were the first owners in most of the homes, as indicated in Table 16. Many had their floor plans and appliance user manuals, and shared them with the research team.

Table 16: Responses to Survey Question: Are You the First Owner of the Property?

Survey Response	Number of Homes
Yes	53
No	9
No response	8
Total	70

Source: Lawrence Berkeley National Laboratory

Study participants answered two survey questions about their understanding of the operation of their own mechanical ventilation system. The responses are summarized in Table 17 and Table 18. A little more than half of the study participants responded that they understand how to operate their mechanical ventilation system, with 31 not knowing or not being sure. Only 29 said the system was explained to them at the time of purchase.

Table 17: Answer to Survey Question: Do You Feel You Understand How to Operate Your Mechanical Ventilation System Properly?

Survey Response	Number of Homes
Yes	38
No	12
Not sure	19
No response	2
Total	70

Source: Lawrence Berkeley National Laboratory

Table 18: Answer to Survey Question: Was the Operation of the Mechanical Ventilation System Explained to You When You Bought or Moved Into the Home?

Survey Response	Number of Homes
Yes	29
No	30
Don’t know	9
No response	2
Total	70

Source: Lawrence Berkeley National Laboratory

Study participants also answered questions about thermal comfort in winter and summer, air distribution, and moisture level.

- In winter / summer, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?
- How often do the following conditions affect comfort of occupants in your home?
  - Too much air movement
  - Not enough air movement
  - Indoor air is too dry
  - Indoor air is too damp
  - Indoor air as musty odor

The most commonly reported issues affecting occupant comfort a few times per week or more frequently are too cold in winter (29 percent), too hot in summer (31 percent), and not enough air movement (21 percent). Comparing responses from the 70 sampled homes with the larger sample of homes that completed the web-based survey (Table 19), fewer field study homes complained of being too hot in summer (31 percent versus 41 percent), but more of them complained of being too cold in winter (29 percent versus 20 percent).

Table 19: Comparison of Survey Responses From Field Study With Results From HENGH Survey

Issues Affecting Occupant Comfort a Few Times per Week or More Frequently	Field Study (N=70)	HENGH Survey (N=2271)
Too hot in summer	31%	41%
Too cold in winter	29%	20%
Not enough air movement	21%	18%
Too hot in winter	14%	10%
Indoor air too dry	9%	11%
Too cold in summer	4%	9%
Too much air movement	1%	5%
Musty odor	1%	3%
Indoor air too damp	1%	2%

See Appendix A for details about HENGH web-based survey.

Source: Lawrence Berkeley National Laboratory

These differences may be partly explained by the web-based survey respondents being predominantly from SoCalGas territory, where the winter is milder. Forty-three percent of web-based survey respondents reported never opening windows in summer (Table 20), presumably relying on air conditioning for cooling. In contrast, only 23 percent of field study homes reported never opening windows in summer; presumably this indicates that the field study homes are more likely to open their window in summer to cool the house. This may explain why fewer field study homes reported being too hot in summer, compared to web-based survey respondents. Interestingly, the percent reporting too cold in summer was roughly twice as high in the HENGH homes. Reported rates of other types of discomfort were similar between the two samples.

3.1.4 Self-Reported Window Use Under Typical Conditions

As part of the activity survey, participants estimated their typical window use by season. The results are generally consistent with the findings of the prior mailed survey (Price et al., 2007). In summer, fall, and spring, approximately half of the homes (47 percent on average) reported substantial window use (>2 hours per day on average); but during winter more than half (57 percent) reported not opening their windows at all. For context, it is important to note the finding of Offermann (2009) that actual window use exceeded seasonal projected use in the sample of homes for which both types of data were available.

Two study participants gave written feedback that keeping windows closed during the one-week monitoring period was a significant deviation from their normal use.

- "Closed windows was the most difficult given the good weather."
- "We really missed having our windows open, but other than that it was not bad."

Table 20: Self-Reported Window Use in Sampled Homes

Hours per Day	Summer Field Study	Summer Survey	Fall Field Study	Fall Survey	Winter Field Study	Winter Survey	Spring Field Study	Spring Survey
8+	17%	28%	24%	38%	3%	20%	27%	40%
2–8	29%	14%	26%	25%	10%	18%	19%	25%
1–2	29%	11%	27%	14%	26%	20%	30%	14%
0	23%	43%	19%	18%	57%	38%	20%	16%
No response	3%	4%	4%	4%	4%	5%	4%	5%

Percent of respondents saying that windows in their home were opened for the number of hours in the first column. See Appendix A for details about HENGH web-based survey.

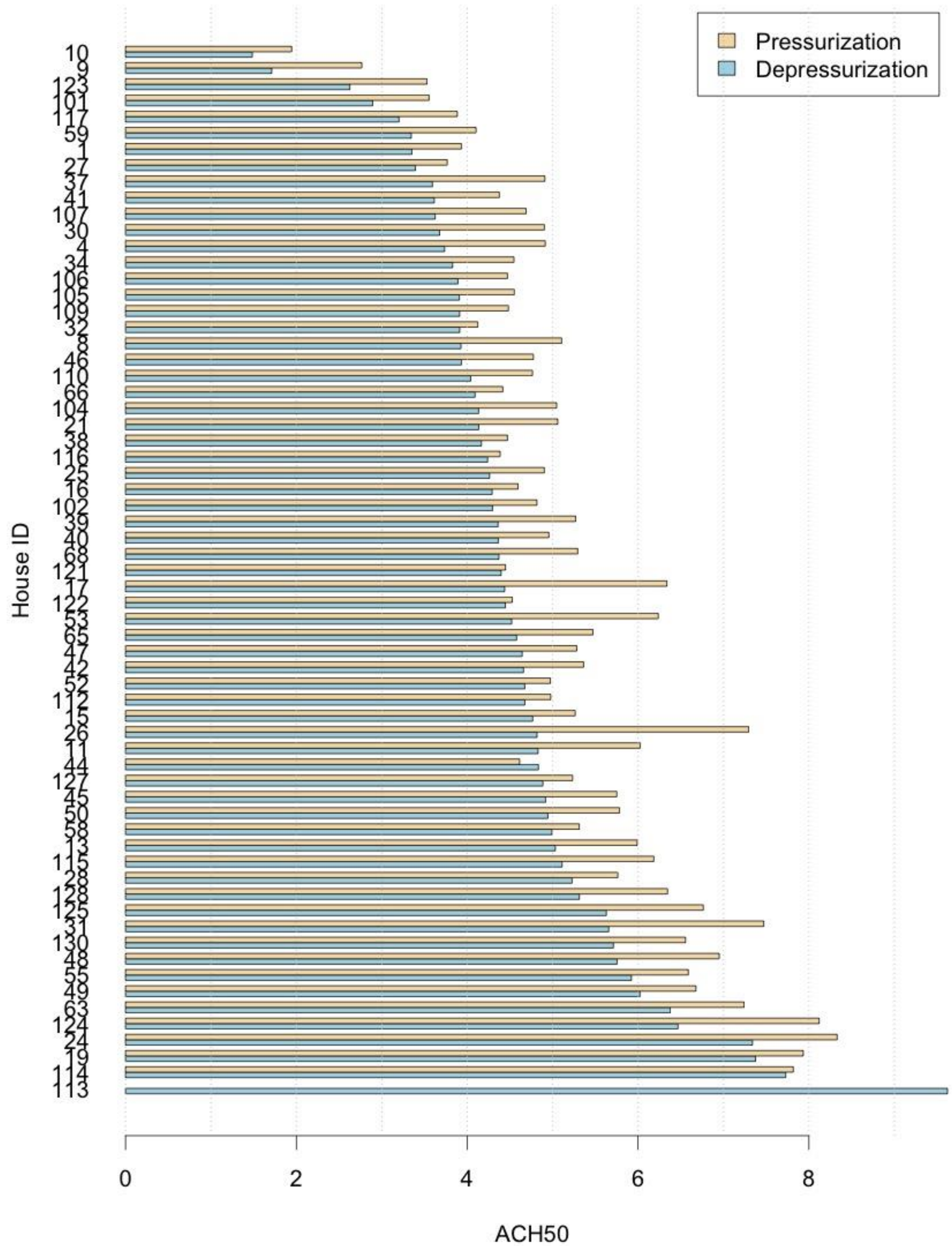
Source: Lawrence Berkeley National Laboratory

3.2 Envelope and Duct Leakage

Envelope leakage was measured using the DeltaQ test by first blowing air into a home (pressurization) then repeating the testing by sucking air out of the home (depressurization). The results were converted to ACH50 using the volume of the home and a calculated flow at

50 Pa. The results are shown in order from most leaky to most tight in Figure 3. Measured air leakage under pressurization was higher than depressurization by 20 percent on average. This result is not unusual and is due to "valving" of some envelope leaks, for example, from an exhaust fan damper being pushed open during pressurization. Most homes were between 3 and 6 ACH50 (Figure 4). Only four homes had envelope leakage less than 3 ACH50, the level required for compliance with the 2018 International Energy Conservation Code (ICC 2018).

Figure 3: Envelope Leakage Measured by DeltaQ Test

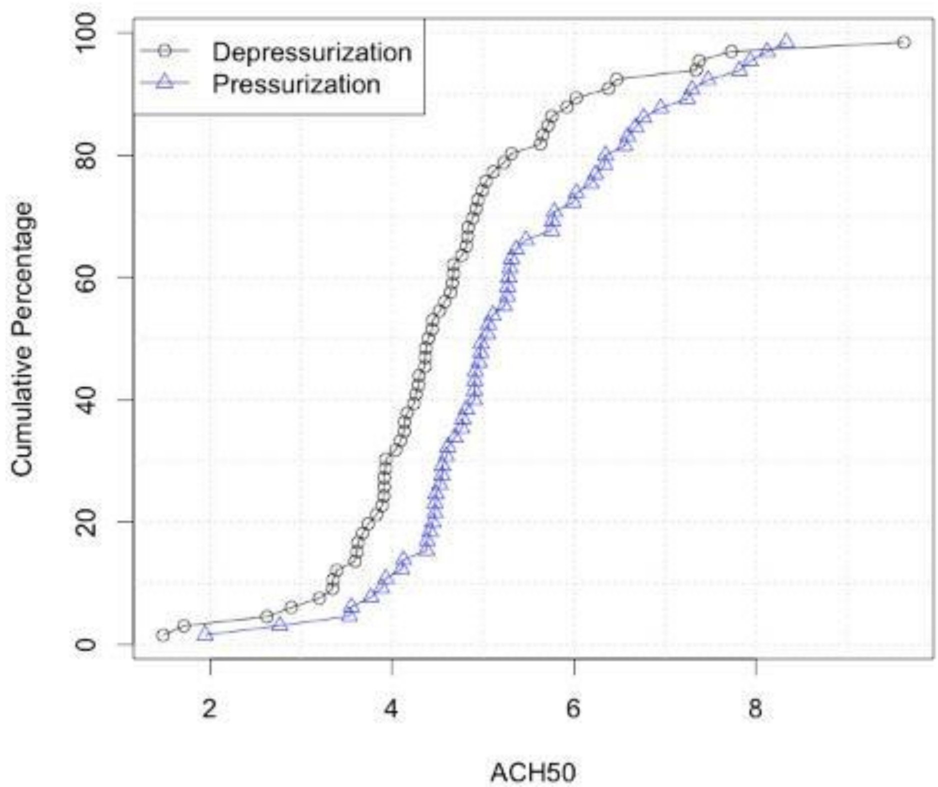


House 113 is an outlier in terms of its small floor area (675 ft^2). Air leakage measured during pressurization was nearly twice the value as measured during depressurization. A damper being pushed open during pressurization test could explain the large difference in the air leakage measured under the two test conditions.

Source: Lawrence Berkeley National Laboratory

It is noteworthy that the measured envelope air leakage of study homes built mostly in 2012 to 2016 is in the same range as air leakage of California homes built in the early 2000s, as reported on the online residential diagnostics database (resdb.lbl.gov) and in Chan et al. (2013).

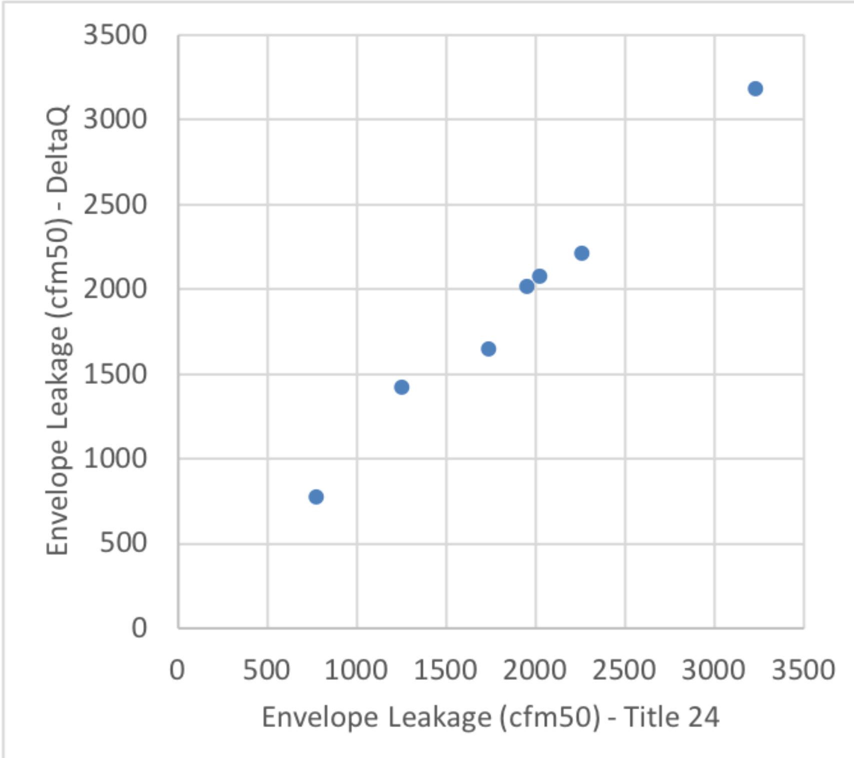
Figure 4: Distribution of ACH50 from Envelope Leakage Measurements



Source: Lawrence Berkeley National Laboratory

Title 24 compliance documents were obtained from CHEERS/CalCERTs for a subset of the homes (N=23). The measured envelope leakage was reported on the CF-1R form for only eight of these homes, as reporting is not mandatory. Figure 5 shows that envelope leakage measured in this study using the DeltaQ method corresponded closely to those reported in the Title 24 compliance records, which were likely measured by a standard blower door test. The two measurements of air leakage agreed with each other to within 5 percent in most of the 23 homes with data from both.

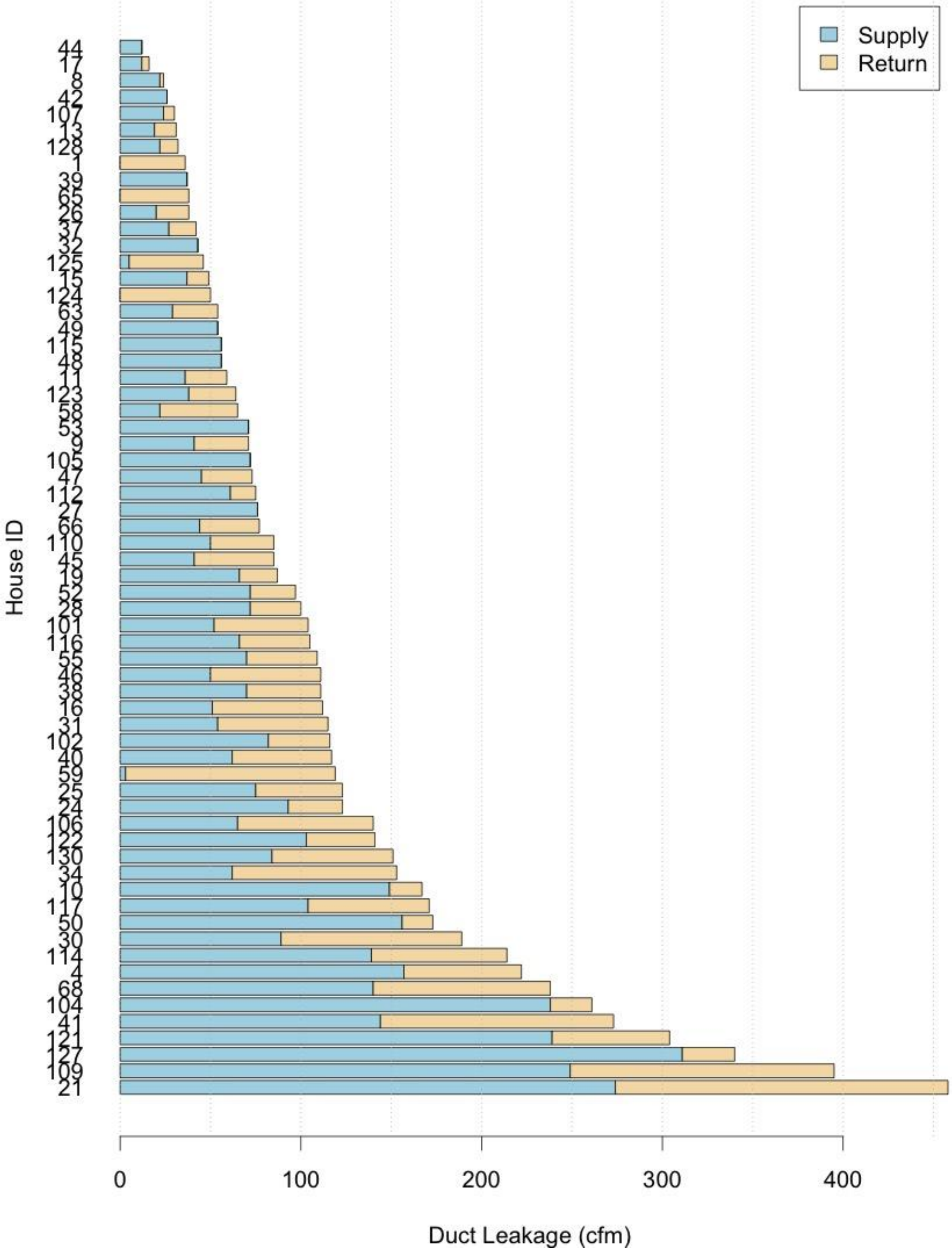
Figure 5: Comparison of Envelope Leakage Reported in Title 24 Compliance Records and Measured by DeltaQ Test



Source: Lawrence Berkeley National Laboratory

The DeltaQ test measures duct leakage at the operating pressure of the central fan system and measures supply and return leaks separately, as shown in Figure 6. Valid duct leakage measurements were obtained for 64 of 70 homes. Title 24 requires measurement of duct leakage at 25 Pa. Duct leakage measurements were available for all 23 homes from installation certificate (CF-6R) forms. Duct leakage measurements were also available from diagnostic testing results (CF-4R forms), but only for a subset of the homes (N=12). It is inappropriate to directly compare these two sets of measurements because they measure duct leakage under different equipment operating conditions.

Figure 6: Duct Leakage Measured by DeltaQ Test



Source: Lawrence Berkeley National Laboratory

3.3 Mechanical Ventilation System Characteristics and Flows

3.3.1 Dwelling unit Mechanical Ventilation

Sixty-four of the 70 homes had exhaust ventilation; the other six had supply ventilation. Table 21 shows the number of homes by ventilation system type, operation mode, and location(s) of exhaust or supply fan (if any).

Table 21: Dwelling Unit Ventilation System Type

System Type	Operation Mode	Fan Location(s)	Number of Homes
Exhaust	Continuous	Laundry Room	43
Exhaust	Continuous	Bathroom	9
Exhaust	Continuous	Attic	3
Exhaust	Intermittent	Laundry Room	5
Exhaust	Intermittent	Bathrooms (multiple)	4
Supply	Continuous	Attic	4
Supply	Intermittent	None*	2
Total			70

***These central fan integrated supply (CFIS) systems had a duct with motorized damper that connected the outdoors to the return side of the forced air system, but no supply fan.**

Source: Lawrence Berkeley National Laboratory

3.3.1.1 Supply Ventilation

In four (001, 003, 009, 010) of the six supply ventilation homes, a continuous supply fan in the attic drew in outdoor air and ducted it to the supply side of the forced air HVAC system through a filter (see Figure 7). Three of the homes had an on/off switch that controlled operation of the inline supply fan. In one home, the on/off switch had a "Whole House Ventilation Control" label (Figure 8, left). The fourth home had a programmable controller (Figure 8, left) that is not labeled.

Two homes (031, 055) had central fan integrated (CFIS) systems. These systems had a motorized damper open to draw outdoor air into the return plenum where airflow was induced by the operation of the forced air system blower rather than a separate fan. Outdoor air was not filtered for these systems because the filters were located at the return grilles and the outdoor air was introduced downstream of the grille. These systems were wired for control by a programmable thermostat; but the ventilation function was not programmed at either home and the intended (design) control algorithm was not apparent. (See Figure 9 for examples of CFIS control systems). As a result, these two homes were tested with the exhaust fan in the laundry room operating continuously during the one-week monitoring period to provide code-mechanical ventilation at a rate that exceeded the code requirement.

Figure 7: Supply Ventilation Filters

Photos of the supply air filter used in three homes.

Source: Lawrence Berkeley National Laboratory

Figure 8: Continuous Supply Fan Control

(left) Label reads: “Whole House Ventilation Control. Leave on except for severe outdoor air quality”. (right) Programmable controller used to control inline fan for supply ventilation.

Source: Lawrence Berkeley National Laboratory

Figure 9: Central Fan Integrated System

(top left) CFIS motorized damper and (top right) control module. (bottom) Thermostat showing ventilation control option was turned off.

Source: Lawrence Berkeley National Laboratory

3.3.1.2 Exhaust Ventilation

Of the 64 homes that met the Title 24 dwelling unit ventilation requirement with an exhaust system, 55 had continuous fan(s) and nine had fans connected to controllers for intermittent operation. The continuous exhaust fan was located in the laundry room in 43 homes and in the bathroom in nine homes. Three homes had a single continuous exhaust fan located remotely in the attic and connected to all bathrooms, as further described below. Five of the nine intermittent exhaust fans were located in the laundry room and the other four were in bathrooms.

A simple on/off switch was used in the majority of homes that had continuous exhaust fans. In one home with a laundry exhaust fan, the only control was at the breaker panel (Figure 10).

Figure 10: Continuous Exhaust Ventilation Controlled at Breaker Panel in One Home

Source: Lawrence Berkeley National Laboratory

Three homes had a single exhaust fan located remotely in the attic and connected to all bathrooms; this configuration satisfied both local exhaust and dwelling unit mechanical ventilation airflow requirements. However, these homes had no switch inside the house that occupants could use to turn the fan on or off. The three homes with this type of exhaust ventilation system were located in the same housing development. The inline fan used in these homes had a rated airflow of 240 cfm. In all three cases, the field team observed installation problems. In one of the homes, the exhaust vent was detached from the roof (Figure 11, left). In the other two homes, the exhaust fan was not plugged in (Figure 11, right). In one of these two homes, the exhaust fan did not work and had to be replaced. Study participants contacted the builder and the repair occurred prior to the one-week monitoring in all three cases. A general challenge of this type of system is the following: without balancing dampers and commissioning to set these dampers the airflows from each bathroom can be quite different from one another. Table 22 shows the measured airflow rates in various bathrooms connected to the single exhaust fan.

Figure 11: Continuous Exhaust Ventilation Provided by a Fan in Attic

Observed installation problem: (left) exhaust fan detached from roof, (right) exhaust fan not plugged in.

Source: Lawrence Berkeley National Laboratory

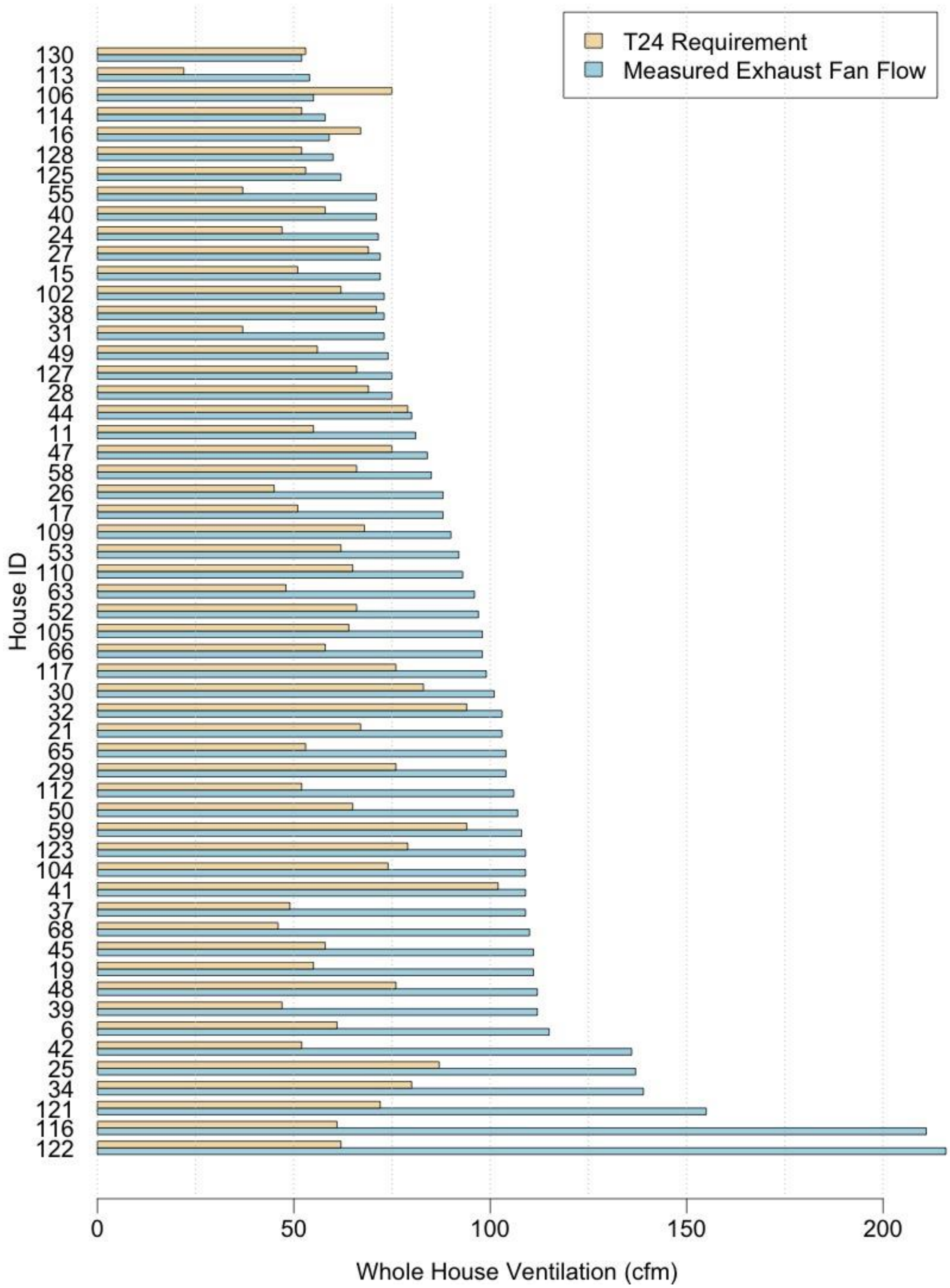
Table 22: Measured Airflow in Bathrooms Connected to a Single Continuous Exhaust Fan in Attic (cfm)

Room	House 116	House 121	House 122
Master Bathroom	49	25	39
Master Bathroom – Toilet	32	12	35
Full Bathroom 2	49	66	51
Full Bathroom 3	81	52	91
Total	211	155	216

Source: Lawrence Berkeley National Laboratory

Figure 12 shows the measured airflow of the dwelling unit continuous exhaust ventilation system rank ordered by measured airflow. In all but two cases (016, 106), the measured flows exceeded the Title 24 minimum requirement. The highest measured airflow rates were from the three homes (116, 121, 122) that used a single 240-cfm rated exhaust fan in the attic. The average minimum requirement was 63 cfm and the average installed flow was 96 cfm, or about 50 percent more than the minimum requirement. This is similar to the results in Stratton et al. (2012) for previous tests of new (built in 2010/2011) California homes.

Figure 12: Dwelling Unit Ventilation Fan Flow Rate

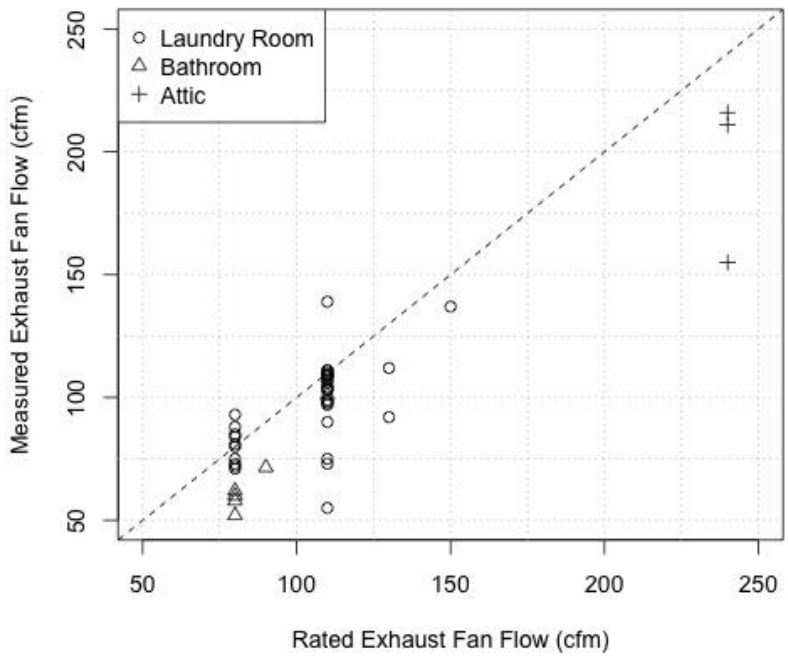


N=56, includes only continuously operating exhaust system with valid measured fan flow rate. Plot includes two homes with CFIS (031, 055) that were operated with laundry exhaust fan during the one-week monitoring period.

Source: Lawrence Berkeley National Laboratory

Figure 13 shows that the majority of the exhaust fans used to provide dwelling unit ventilation were rated at either 80 or 110 cfm. These were commonly available fan capacities provided by fan manufacturers. Note that the 110 cfm rated fans did not always achieve their rated flow, but still provided more flow than the minimum required by Title 24.

Figure 13: Rated and Measured Fan Flow Rate of Dwelling Unit Exhaust Ventilation



Source: Lawrence Berkeley National Laboratory

3.3.1.3 Labeling and Operating Condition of Dwelling unit Ventilation in Homes As-Found

On the initial visit, the mechanical ventilation system was running in 18 homes (26 percent). The system was turned off in 52 homes. A key predictor of whether the system was operating appears to be whether the system control switch was labeled, and how clear the label was. Table 23 presents a summary of the system status when the research team first arrived to the home, by control type and presence or absence of any identifying label.

Table 23: Dwelling unit Ventilation System Control

System Control	Label	System Status (as-found) – ON	System Status (as-found) – OFF
On/Off Switch	Yes	7	5
On/Off Switch	No	2	40
Programmable Controller	No	5	5
Thermostat	No	0	2
Breaker Panel	No	1	0
No Controller	No	3	0
Total		18	52

Source: Lawrence Berkeley National Laboratory

Title 24 and ASHRAE Standard 62.2 require that the controller of a dwelling unit ventilation system have an identifying and informative label. ASHRAE Guideline 24 provides the following example language for labeling:

> Manual switches associated with a whole-building ventilation system should have a clear label such as, "This controls the ventilation system of the home. Leave on except for severe outdoor contamination." In addition, guidance on operations and maintenance procedures should be provided to occupants.

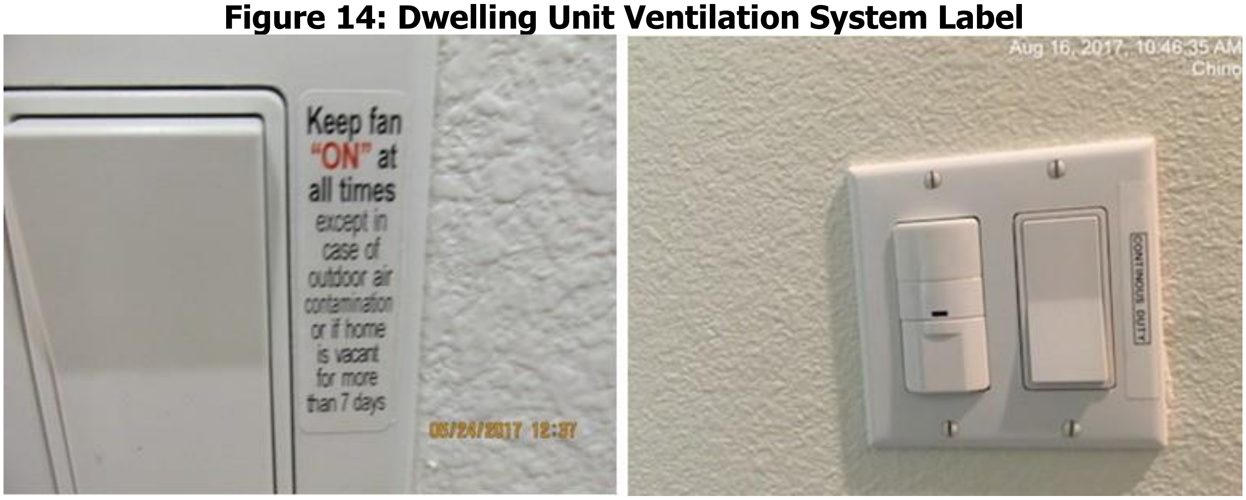
The Title 24 Residential Compliance Manual also provides suggested labeling language, such as "Ventilation Control", "Operate whenever the house is in use", or "Keep on except when gone over 7 days". The Compliance Manual recommends using more detailed labeling for intermittent systems to provide occupants with basic information on how to operate the timer. However, no specific wording is mandated in Title 24.

Only 11 homes had any label on the exhaust fan switch that identified it as controlling the dwelling unit ventilation system and all were on laundry room exhaust fans. In addition, only 1 in 6 homes that used supply ventilation had a labeled controller to identify its purpose.

The absence of labels is likely a contributing factor leading to systems being turned off. Furthermore, several of these labels were poorly worded, unclear and possibly confusing to occupants. A wide variety of labels were found (a couple of examples are illustrated in Figure 14). The following is a summary of the labeling "language":

- "Whole House Ventilation Control. Leave on except for severe outdoor air quality." (010, 026, 039, 049, 065; houses located in Davis, El Dorado Hills, Elk Grove, Manteca)
- "Keep fan "ON" at all times except in case of outdoor air contamination or if home is vacant for more than 7 days." (029, 048, 050; houses located in Brentwood, Elk Grove)
- "To maintain minimum levels of outside air ventilation required by the State of California, this fan should be on at all times when the building is occupied, unless there is outdoor air contamination." (053; house located in Hayward)
- "Continuous Duty" (105, 106, 109; houses located in Chino, Lake Forest)

Figure 14: Dwelling Unit Ventilation System Label



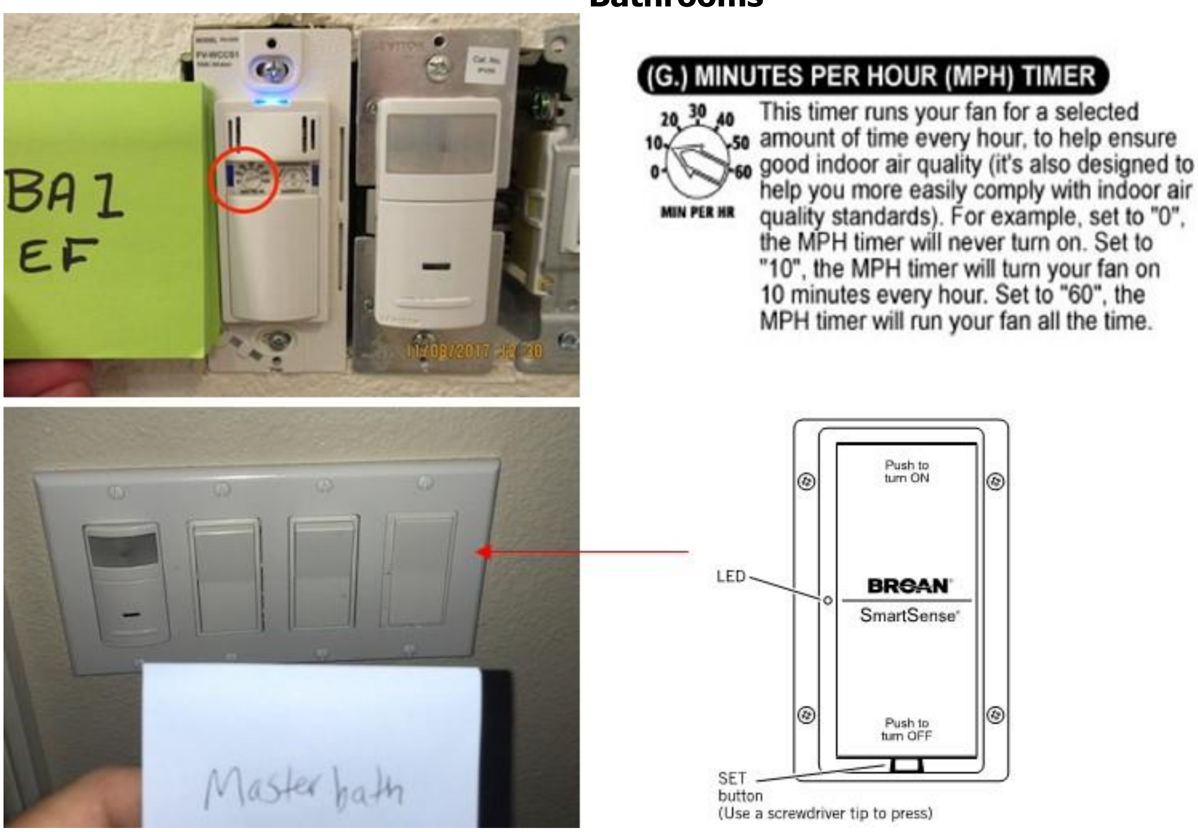
Source: Lawrence Berkeley National Laboratory

The wording of the dwelling unit ventilation system label, like the choice of the system installer, has a direct impact on the understanding of the study participants. In the three homes that had the message "Continuous Duty", all three systems were turned off.

In 7 out of 9 cases where a more descriptive message was used to explain the purpose of the dwelling unit ventilation system, the system (laundry exhaust fan) was running when the research team arrived to the house. There was only one case (065) where the study participant did not understand that the intent was for the fan to be on continuously. A study participant in House 053 understood the meaning of the label, but explained that s/he did not feel dwelling unit ventilation system was always necessary. Occupants in House 053 made it a habit to turn the laundry exhaust fan off. They reported that the exhaust fan makes the laundry room colder in winter as another reason to turn it off.

Programmable controllers of dwelling unit ventilation systems also appeared to be confusing to study participants, leading to these systems not being operated. The field team observed two types of programmable controllers used in bathrooms (Figure 15). These programmable controllers also have humidity control. In addition, five homes from the same community development (004, 005, 007, 008, 013) used a different type of programmable controller in the laundry room (Figure 16) that does not have humidity control. The field team did <u>not</u> adjust the fan runtime setting on the programmable controller for the one-week monitoring.

Figure 15: Programmable Controller Used to Control Exhaust Ventilation in Bathrooms

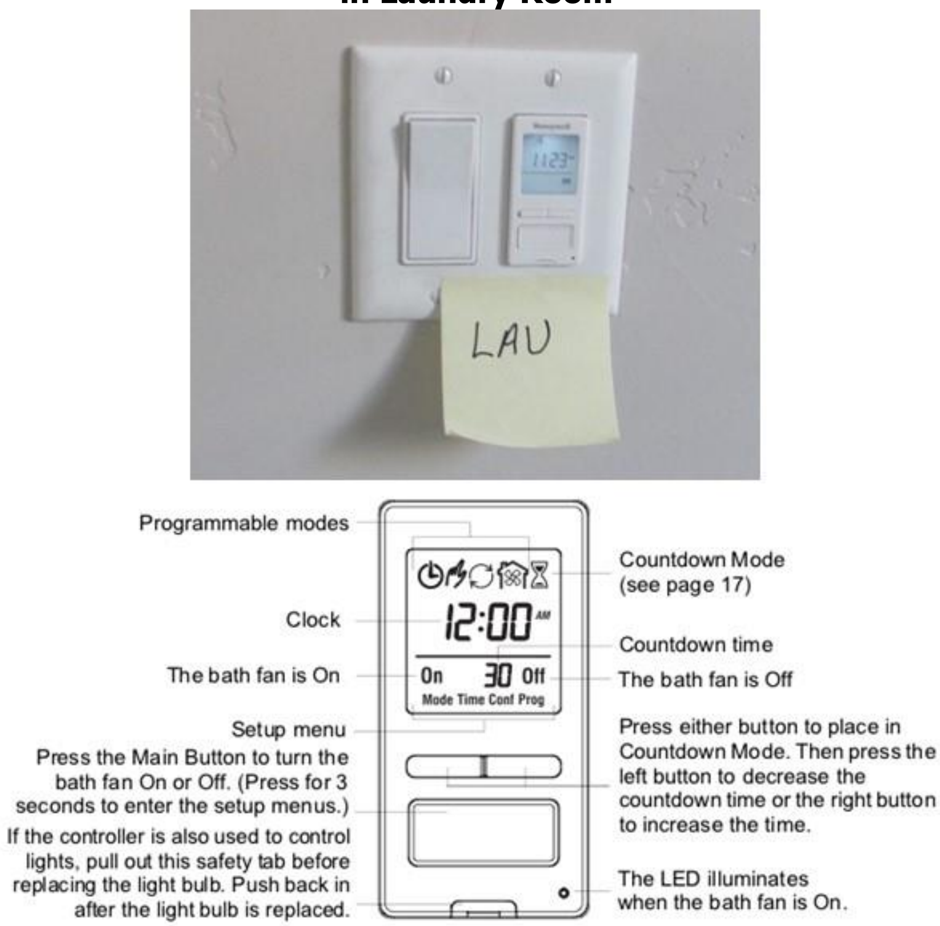


Schematics of programmable controller from online user manual: (top) Panasonic WhisperControls Adjustable Condensation Sensor used in home 046; (bottom) Broan SmartSense Intelligent Ventilation System used in home 101, 107 and 115.

Source: Lawrence Berkeley National Laboratory

Among the nine homes that used exhaust ventilation controlled by a programmable controller, only four (007, 101, 107, 115) had fans that were programmed to operate intermittently. Fans were set to run between 10 and 30 minutes every hour. Exhaust fans in the remaining five homes either did not operate at all during the one-week monitoring (005 and 046), operated constantly rather than intermittently for one week (013), operated constantly for a few days then turned off (008) or vice versa (004, i.e., off for a few days, then turned on). These results show that the runtime of intermittent exhaust fans was not properly set in many cases. The programmed setting can be easily overridden, leading to possible unintentional disabling of the ventilation system.

Figure 16: Programmable Controller Used to Control Exhaust Ventilation in Laundry Room



Schematics of programmable controller from online user manual Honeywell Programmable Bath Fan Control.

Source: Lawrence Berkeley National Laboratory

3.3.2 Kitchen Range Hood

In more than half of the kitchens (N=38) exhaust ventilation was provided by an over the range (OTR) microwave with exhaust fan. These measurements found that OTRs appeared to have much lower exhaust airflows then the 32 range hoods, as shown in Table 24; but as noted below, these data could be substantially biased by the method used to measure airflow for OTRs.

The field method for measuring OTR exhaust flow in this study involved taping over the air inlet at the top front of the OTR and measuring the inlet airflow at the bottom. Since airflow through the microwave unit is generally restricted, it is very possible that the total exhaust ventilation is reduced when the higher inlet is obstructed. The trend of OTRs having lower airflows than range hoods has been reported in previous laboratory and field studies (for example, Kim et al., 2018).

Table 24: Measured Kitchen Range Hood Fan Flow (cfm)

Fan Speed Setting	Range Hood	Microwave
Low		
Mean (cfm)	142	80
Median (5^{th}–95^{th} %tile) (cfm)	137 (59–292)	76 (33–141)
Medium		
Mean (cfm)	265	124
Median (5^{th}–95^{th} %tile) (cfm)	224 (81–625)	121 (78–184)
High		
Mean (cfm)	341	128
Median (5^{th}–95^{th} %tile) (cfm)	257 (138–806)	124 (37–216)

Source: Lawrence Berkeley National Laboratory

Most, but not all of the homes had kitchen exhaust devices that met the Title 24 minimum airflow requirement of 100 cfm as measured (Table 25); but many did so only at medium and high speed settings that may not comply with the 3 sone sound requirement. In general, the OTRs needed to operate at higher fan speeds to meet the 100 cfm requirement and only 24 percent of the OTRs met the airflow requirement at low speed. Nine (24 percent) of the OTRs did not move 100 cfm at any speed setting. In light of the potential bias noted above, the actual airflows of OTR units as installed deserves further attention.

Table 25: Fan Speed Settings at Which Range Hoods and Over-the-Range Microwave Exhaust Fans Moved at Least 100 cfm, as Required by Title 24.

Lowest Fan Speed Setting Moving at Least 100 cfm	Range Hood	Over-the-Range Microwave
Low	22	9
Medium	7	14
High	3	6
No setting that moved at least 100 cfm	0	9
Total	32	38

Source: Lawrence Berkeley National Laboratory

Make and model information were obtained for 66 of the 70 range hood or OTRs. Only 11 of the 66 were listed in the Home Ventilating Institute (HVI) online catalog as having certified airflows and sound ratings; these include three distinct range hood models in four homes and two distinct OTR models across seven homes. Table 26 shows the HVI-certified airflow and sound levels at high speed and low or "working" speed as well as the measured fan flows at all settings.

Table 26: Rated and Measured Performance of HVI-Rated Range Hoods and Over-the-Range Microwave Exhaust Fans.

HVI Rated Kitchen Ventilation	HVI Rated CFM	HVI Rated Sones	House ID	Measured Fan Flow (cfm)
Broan QP136SS	LS = 120, HS = 290	0.8, 5	027	132, 293
GE JV966DSS	WS = 160, HS = 590	0.4, 7.5	112	130, 224, 348, 434
			115	161, 266, 591, 780
KitchenAid KVWB606DSS	WS = 170, HS = 380	1.1, 5.5	010	138, 194, 227, 240
Whirlpool WMH31017	WS = 140, HS = 210	2, 5	001	77, 116
			019	68, 102
			028*	36, 42*
			046	84, 111
Whirlpool WMH53520	WS = 110, HS = 290	1.5, 7	015	58, 91, 97, 107
			040	82, 138, 130, 145
			101	79, 104, 102, 109

LS = low speed, WS = working speed, HS = high speed. Each row of measured fan flows represents one exhaust fan / home. *Suspect installation problem with venting.

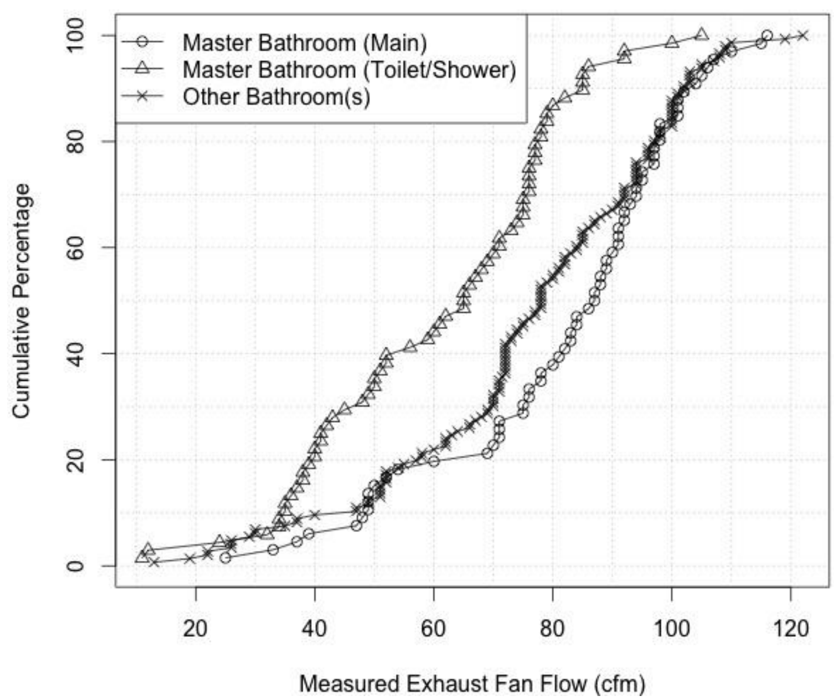
Source: Lawrence Berkeley National Laboratory

All four of the range hoods moved 100 cfm at the low fan setting, which also met the sound requirement of <3 sones. None of the OTRs met the airflow requirement at the working speed, which was the only setting rated at <3 sones. All but one of the OTRs moved at least 100 cfm on high speed. The one that did not move 100 cfm had such low airflows the team suspected that it may not have been installed properly for venting.

3.3.3 Bathroom Exhaust Fan

Most general bathroom exhaust fans met the requirement of 50 cfm minimum airflow for an intermittently operated fan. Figure 17 shows a cumulative distribution of the bathroom fan flow rates broken down into three categories: the main fan in the master bathroom; auxiliary fans in the master bath suite (for example in toilet room or shower; these are not required to meet the minimum airflow specifications if there is another fan in the bathroom), and exhaust fans in other bathrooms. Exhaust fans in the toilet room or shower tended to have lower measured airflows.

Figure 17: Bathroom Exhaust Fan Measured Flow Rates



Source: Lawrence Berkeley National Laboratory

The field team observed that in approximately two-thirds of homes (N=44) the main exhaust fan in the master bathroom had a humidistat control. The most common setting was 80 percent relative humidity for 20-minute runtime. However, lower relative humidity settings were also used: 30 percent (N=1), 50-60 percent (N=5), and 70-79 percent (N=6). Runtime was more consistently set between 15 and 20 minutes (N=18), with a few outliers: 5 minutes (N=2) and 40 minutes (N=1).

3.3.4 Mechanical and Total Ventilation Rate

Figure 18 summarizes the total mechanical ventilation airflow rate provided by all exhaust fans in homes and the estimated total outdoor airflow including air infiltration, during the week of monitoring. The mechanical fan flows were calculated by summing exhaust fan flows (dwelling unit exhaust fan, and other fans in bathroom, range hood, clothes dryer) weighted by their average usage time. Since it was not practical to directly measure the airflow of the clothes dryers in most homes, dryer airflow of 125 cfm were assumed based on a recent ENERGY STAR report[5]. The mechanical systems provided a large portion of total outdoor air in almost all homes and 78 percent on average.

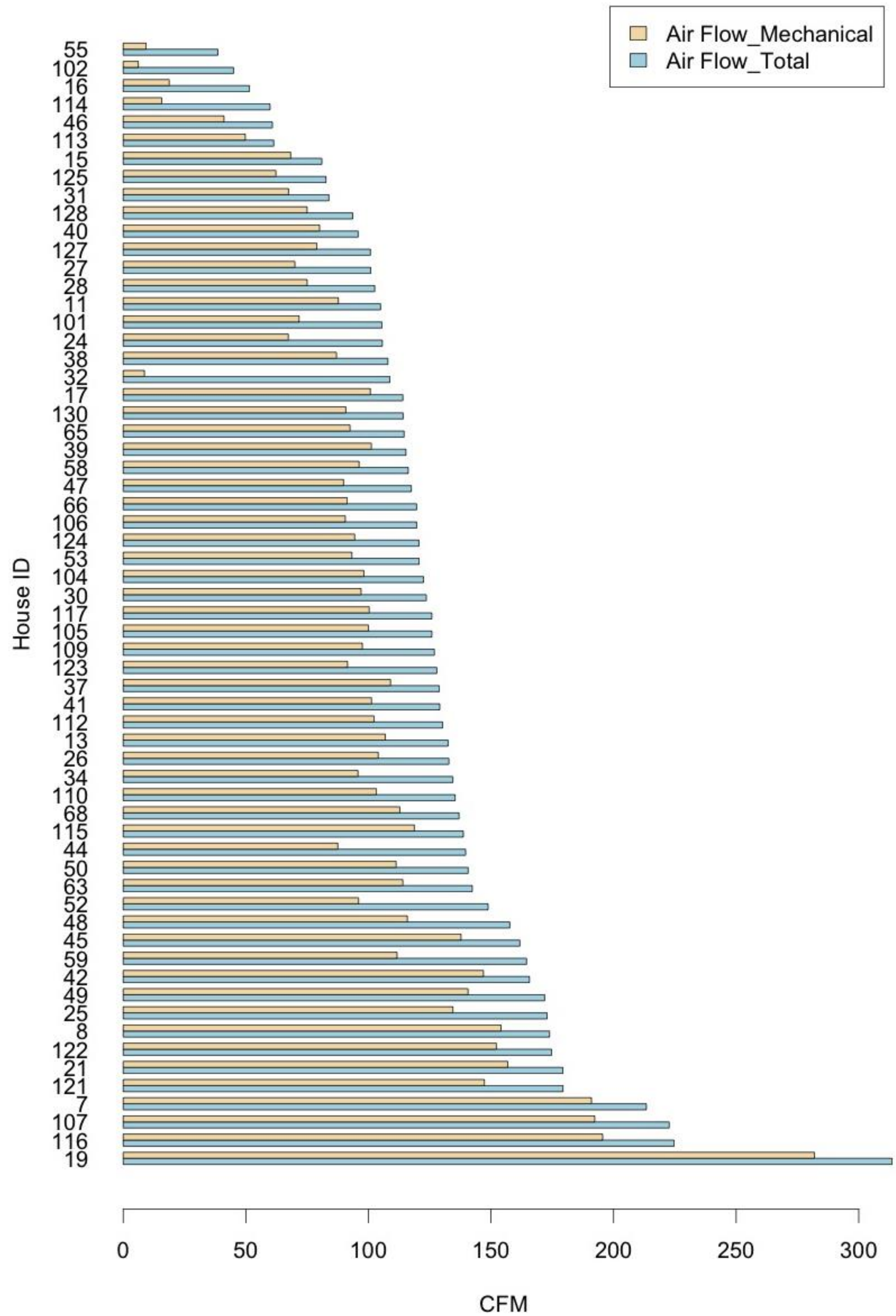
The total mechanical airflow was very low in five homes (016, 032, 055, 102, 114) in which the continuous exhaust fan that was supposed to provide dwelling unit mechanical ventilation was turned off by occupants during the monitoring week. Another home (046) had an intermittent exhaust fan that was not correctly programmed to provide sufficient ventilation.

Figure 19 presents the total estimated air exchange rate (AER) provided by all mechanical fan flows and air infiltration. There are six homes identified in Figure 19 where occupants reported to have opened their house-to-patio and/or garage door(s) for more than 3 hours per day on average during the one-week monitoring; in these homes natural ventilation may have increased the overall AER substantially beyond what is estimated based on mechanical fan flow and air infiltration alone.

Figure 19 also identified six homes in which the dwelling unit mechanical ventilation did not operate as designed to meet the Title 24 standard. Excluding results from these six homes suggest an AER estimate of about 0.35/h (mean = 0.37/h, median = 0.33/h), with most values between 0.20/h and 0.61/h, for homes complying with the standard. The air exchange rates estimated for homes operating with Title 24 compliant systems were higher than those measured by Offermann (2009) before the Title 24 standard was set in 2008. Offermann reported median AERs of 0.26/h for 107 homes measured during a single monitoring day and 0.24/h for 21 homes measured over a 2-week period.

[5] ENERGY STAR reports rated fan flow of clothes dryer typically range between 100 and 150 cfm. https://www.energystar.gov/sites/default/files/asset/document/ENERGY_STAR_Scoping_Report_Residential_Clothes_Dryers.pdf

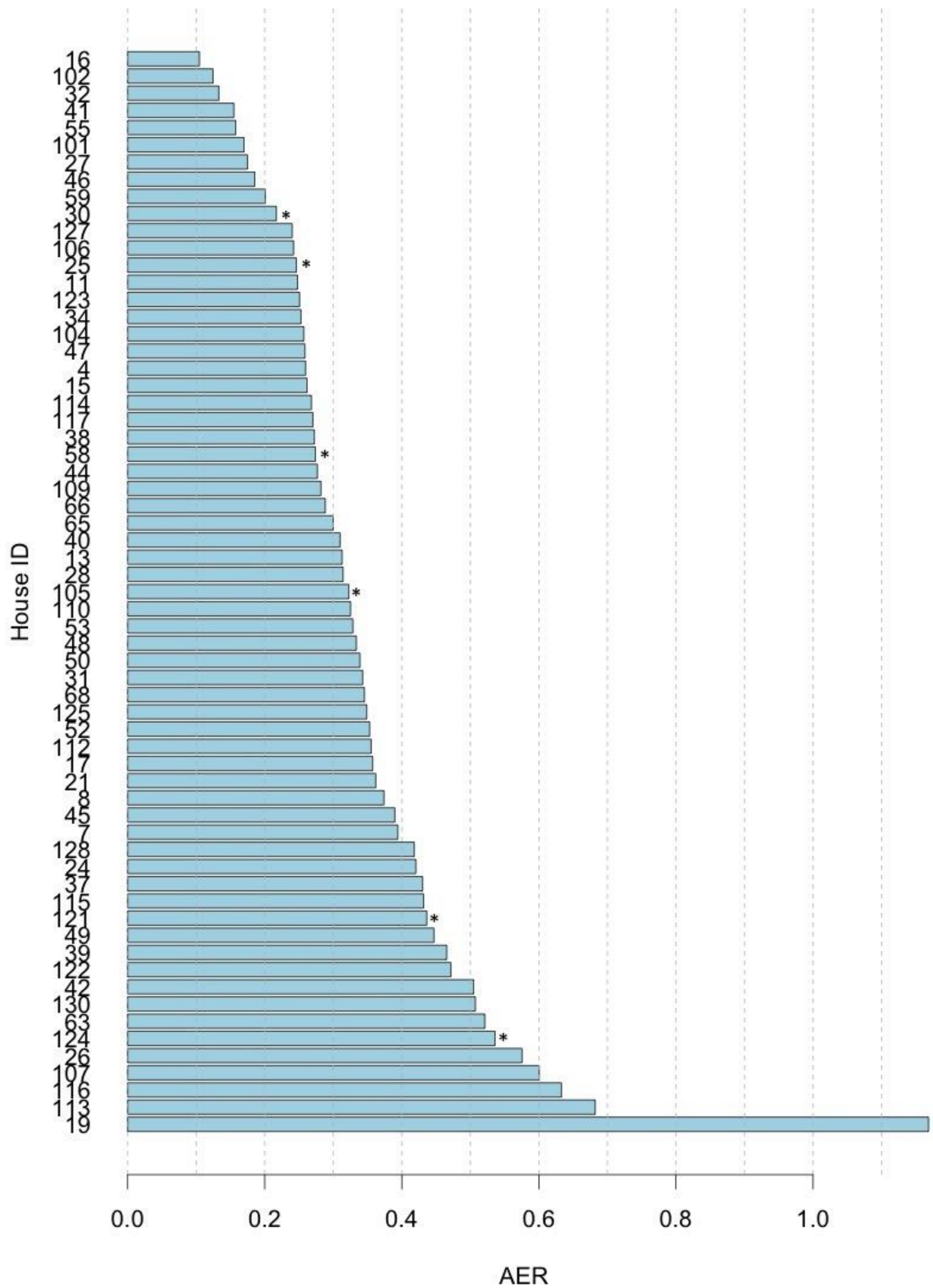
Figure 18: Mechanical and Total Ventilation Airflow Rate



N=63. This plot excludes four homes that used supply ventilation because the mechanical airflow could not readily be measured. The plot also excludes three homes with missing DeltaQ test result because building envelope airtightness is required to calculate air infiltration (part of total ventilation).

Source: Lawrence Berkeley National Laboratory

Figure 19: Total Estimated Air Exchange Rate



N=63. This plot excludes four homes that used supply ventilation because the mechanical airflow could not readily be measured. The plot also excludes three homes with missing DeltaQ test result because building envelope airtightness is required to calculate air infiltration (part of total ventilation). There are six homes (*) where opening of the house-to-patio and/or garage door(s) for more than 3 hours per day on average may have increased the overall AER substantially (see later section for more details on window and door use).

Source: Lawrence Berkeley National Laboratory

3.3.5 Air Filters in Central Forced Air Systems

The characteristics and conditions of air filters installed in the forced air systems when the field teams arrived to the house are summarized in Table 27 to Table 30. Many homes (68 percent) had more than one air filter (Table 27). Almost all filters (96 percent) were rated MERV 8 or higher, and 30 percent were rated MERV 11 or higher (Table 28). The field team recorded any information they could obtain about the length of time since the filters were last changed and visually assessed filter loading. If the last change date was not marked on the air filter, study participants were asked to recall when the filter was last changed. Nineteen of the 85 filters (22 percent) for which data were obtained had not been changed within the past 12 months (Table 29). Eighteen of the 67 homes (27 percent) had at least one filter that appeared overdue for replacement (assessed onsite by the field team as "very dirty") and roughly one fifth of all the air filters were assessed to be "very dirty" (Table 30).

Table 27: Number of Air Filters Characterized Per Home

Number of Air Filters	Number of Homes
1 Filter	22
2 Filters	34
3 Filters	10
4+ Filters	3
Total	69*

*** Statistics presented for homes with central forced air system only (one home, 113, has minisplit and no central forced air).**

Source: Lawrence Berkeley National Laboratory

Table 28: Air Filter MERV Ratings

MERV	Number of Air Filters
6	2
7	2
8	57
10	17
11	22
12	1
13	9
14	1
Total	111

Source: Lawrence Berkeley National Laboratory

Table 29: Time Since Last Air Filter Change

Marked or Estimated Time	Number of Air Filters
0 to 2 Months	33
3 to 5 Months	16
6 to 8 Months	17
12 to 15 Months	8
Never Changed	11
Total	85

Source: Lawrence Berkeley National Laboratory

Table 30: Condition of Air Filters Observed by Field Team

Air Filter Condition	Number of Homes	Number of Air Filters
Clean or Like New	20	39
Used or Dirty	29	65
Very Dirty	18	24
Total	67*	128

*** Total excludes one home (113) without a central forced air system (this home had a minisplit heat pump with no filter for air quality), one home (127) without any air filters installed in the return air registers, and one home (117) for which field observations were missing.**

Source: Lawrence Berkeley National Laboratory

3.3.6 Standalone Air Cleaners

The participant survey asked if a standalone (portable) air filter, air purifier, or air cleaner is used in the home. Fourteen replied yes. The percentage of homes that used air cleaners was higher in homes that also answered yes to whether anyone in the household has been diagnosed with asthma (33 percent versus 17 percent). Respondents reporting someone in the household with allergies were no more likely to have a standalone air cleaner compared to households without someone with allergies.

Table 31: Use of Stand Alone Air Cleaners in Homes With/out Occupants Diagnosed with Asthma or Allergies

Standalone Air Cleaners	Asthma Yes (N=18)	Asthma No (N=46)	Allergies Yes (N=37)	Allergies No (N=28)
Yes	6	8	8	6
No	12	38	29	22
Percentage of Homes with Standalone Air Cleaners	33%	17%	22%	21%

Among the homes that use standalone air cleaners, most study participants reported placing them in bedrooms.

Source: Lawrence Berkeley National Laboratory

Table 32: Placement of Stand Alone Air Cleaners

Standalone Air Cleaners	Number of Homes (N=14*)
Master Bedroom	6
Other Bedroom(s)	4
Living Room	3
Home Office	1
Laundry Room	2

*** Study participants have the option of selecting more than one location in survey.**

Source: Lawrence Berkeley National Laboratory

3.4 Occupancy and Activity

Results of self-reported occupancy from the daily activity log filled out by participants during the study period are summarized in Table 33 and Table 34. Most of the homes had one to three occupants at home at any given time when occupied. Most homes (88 percent of those responding) were occupied 16 or more hours per day on average.

Table 33: Self-Reported Average Occupancy (Number of People) When Home Was Occupied

Average Occupancy	Number of Homes
1 to <2 People	23
2 to <3 People	20
3 to <4 People	14
4 to <5 People	4
5 to <6 People	4
6 to <7 People	3
No Response	2
Total	70

Source: Lawrence Berkeley National Laboratory

Table 34: Self-Reported Average Number of Occupied Hours per Day During One-Week Monitoring

Number of Occupied Hours	Number of Homes
> 23 Hours	16
20 to <23 Hours	27
16 to <20 Hours	17
12 to <16 Hours	3
6 to <12 Hours	3
< 6 Hours	2
No Response	2
Total	70

Source: Lawrence Berkeley National Laboratory

3.4.1 Self-Reported Window Use During Monitoring

The results in Table 35 and Table 36 show that the occupants reported that they mostly complied with the request to keep windows closed during the test period. The majority of homes (N=47) reported no window use. Only 21 homes reported some window used. Three homes (006, 110, 116) that opened a window regularly did so only for short periods (5 to 25 minutes) each time. Of the 68 participants who answered the question about window use only 6 opened windows for more than 3 hours per week and only one household reported opening windows for more than 7 hours during the week. It is important to note that the question asked only about window opening and did include opening a patio door, which can provide substantially more natural ventilation than an open window.

Table 35: Self-Reported Window Use (Number of Times) During One-Week Monitoring Period

Number of Times	Number of Homes
0	47
1–2	12
3–5	4
6–10	2
10–20	2
25	1
No Response	2
Total	70

Source: Lawrence Berkeley National Laboratory

Table 36: Self-Reported Window Use (Total Length of Time) During One-Week Monitoring Period

Total Length of Time	Number of Homes
0	47
<1 Hour	10
1 to 3 Hours	5
3 to 7 Hours	5
21 Hours	1
No Response	2
Total	70

Source: Lawrence Berkeley National Laboratory

3.4.2 Monitored Exterior Door Opening

Monitoring data from state open/close sensors show that in the majority of the 63 homes with valid data exterior doors were closed most of the time: in 90 percent of homes the garage-to-house door was open for less than 30 minutes per day on average and in 70 percent of homes the house-to-patio door was open for less than 30 minutes per day on average. There were six homes where the house-to-patio door(s) was open for more than 3 hours per days and may have added to the overall AER substantially (025, 030, 058, 105, 121, and 124). Another four homes had the patio door open for 1 to 3 hours. Since the amount of patio door opening was not recorded (door could have been open any amount between a crack and fully open), the impact of the open patio door on air exchange is not known. In House 025 the garage-to-house door was also open for more than three hours per day on average.

Table 37: Average Duration of Door Opening Per Day During Monitoring Week

Average Duration of Door Opening Per Day	Door to Attached Garage (# homes)	Patio Door (# homes)
<30 Minutes	56	45
30 Minutes to 1 Hour	3	9
1 to 3 Hours	3	4
>3 Hours	1	6
Total	63	64

Source: Lawrence Berkeley National Laboratory

3.4.3 Self-Reported Cooking and Other Activities

Summary results for self-reported cooking activities are presented in Table 38 to Table 40. Of the 68 participants who provided information about cooking frequency, 50 percent said they used their cooktop 7 or more times per week, i.e. at least once per day on average; but only eight (12 percent) reported using the cooktop 15 or more times, i.e., more than twice per day on average. Ovens were used much less frequently and outdoor grills even less frequently. In 59 percent of the homes the average cooktop use lasted for 10–30 minutes and in another 29 percent the average cooktop use was between 30 and 60 minutes. Oven use was split more evenly between these times and outdoor grill use skewed even more to longer durations.

Table 38: Self-Reported Cooktop Use (Number of Times) During Monitoring Week

Number of Cooktop Use	Number of Homes
None	2
1–3 Times	16
4–6 Times	16
7–14 Times	26
15–21 Times	6
More than 21 Times	2
No Response	2
Total	70

Source: Lawrence Berkeley National Laboratory

Table 39: Self-Reported Oven and Outdoor Grill Use During Monitoring Week

Number of Uses	Oven (# homes)	Outdoor Grill (# homes)
None	16	52
1 Time	14	9
2–3 Times	21	7
4–5 Times	11	0
6–8 Times	6	0
No Response	2	2
Total	70	70

Source: Lawrence Berkeley National Laboratory

Table 40: Self-Reported Average Duration of Cooking Activities During One-Week Monitoring

Number of Uses	Cooktop (# homes)	Oven (# homes)	Outdoor Grill (# homes)
Less than 10 Minutes	3	3	0
10–30 Minutes	40	20	5
30–60 Minutes	20	24	8
>60 Minutes	3	5	3
No Usage Reported	2	16	52
No Response	2	2	2
Total	70	70	70

Source: Lawrence Berkeley National Laboratory

3.5 Air Quality Measurements

The following discussion summarizes the field test results and compares indoor air quality measurements from HENGH to the results reported in Offermann (2009), described as the CNHS (for California New Home Study).

3.5.1 Formaldehyde

Table 41 shows that in HENGH and CNHS homes the vast majority of formaldehyde was from indoor sources, and that HENGH homes had lower indoor formaldehyde compared to CNHS homes, despite being newer when tested[6]. The mean indoor formaldehyde concentration was lower in HENGH by about 45 percent and the median was lower by about 38 percent compared to CNHS.

Table 41: Comparison of HENGH and CNHS Passive Formaldehyde Measurements

Formaldehyde	HENGH	CNHS
Indoor	N=68	N=104
Mean (ppb)	19.8	36.3
Median (ppb)	18.2	29.5
Outdoor	N=68	N=43
Mean (ppb)	2.7	2.8
Median (ppb)	2.8	1.8

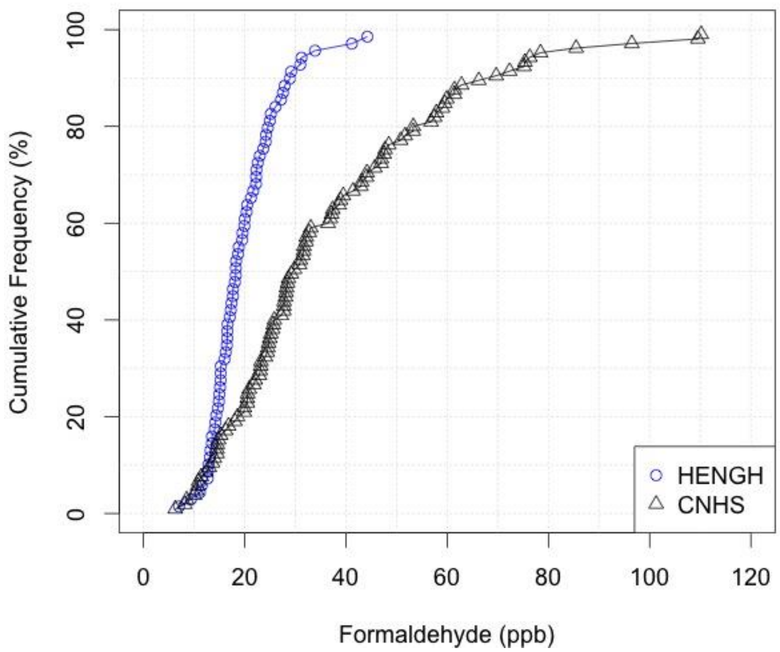
Source: Lawrence Berkeley National Laboratory

The six homes that had a patio or a house-to-garage door open for more than 3 hours per day on average did not have substantially lower formaldehyde and excluding those homes does not change the average indoor formaldehyde (mean = 19.9 ppb).

The distributions presented in Figure 20 show that 25 percent percent of the CNHS homes had formaldehyde concentrations higher than the highest formaldehyde level measured in any HENGH home.

[6] There is some evidence (for example, in Park and Ikeda, 2006) that formaldehyde emission rates are higher when homes are new.

Figure 20: Comparison of HENGH and CNHS Passive Formaldehyde Measurements



Source: Lawrence Berkeley National Laboratory

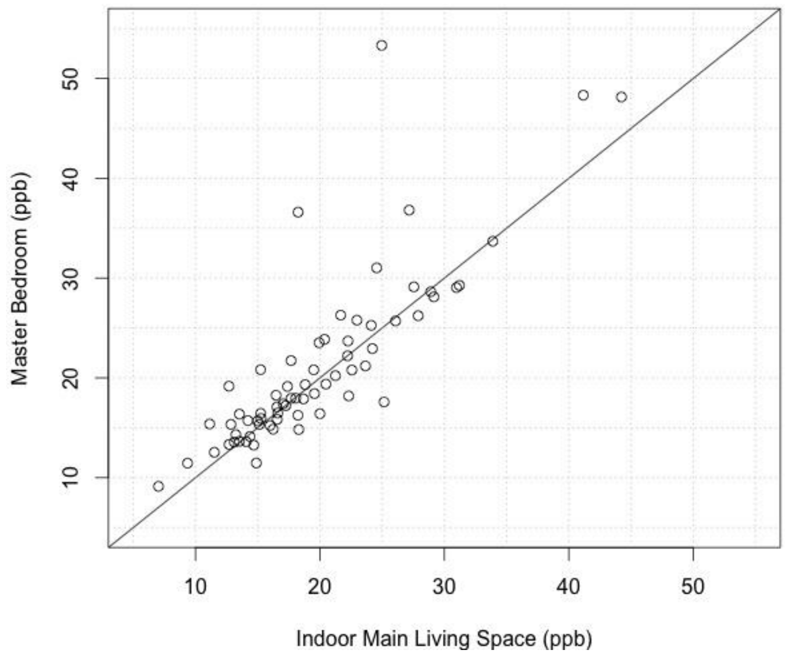
The substantial reduction in formaldehyde compared to the CNHS a decade earlier appears to result from both a lower emission rate and a reduction in homes that are severely under-ventilated. The mean indoor formaldehyde indoor emission rate calculated for homes in this study was 6.8 $\mu g/m^3$-h (based on 61 homes with all of the required component data) compared to a mean 13 $\mu g/m^3$-h calculated from 99 homes with the required component data in CNHS. The data required to calculate air exchange rate are indoor and outdoor formaldehyde concentrations and an estimate of the overall average air exchange rate over the week. For HENGH, only 61 homes had measured mechanical airflow and envelope air leakage (needed for calculating air infiltration rate) and valid indoor and outdoor formaldehyde concentrations. The CNHS estimated a wider range in formaldehyde indoor emission rates (10^{th} to 90^{th} percentile = 4.0 to 23 $\mu g/m^3$-h). The HENGH study found a narrower range (10^{th} to 90^{th} percentile = 3.2 to 11.4 $\mu g/m^3$-h). The reduction in indoor emission rate is likely a result from California's regulation to limit formaldehyde emissions from composite wood products that came into effect between the two studies. But it is important to note that this method of estimating AER based on mechanical airflow and air infiltration but excluding natural ventilation may have underestimated AER, and subsequently the formaldehyde indoor emission rate, by a small amount.

A potential indicator of the benefit of lower material emission rates is also apparent from the six HENGH homes that did not operate with code-compliant mechanical ventilation during the monitoring week, as discussed above in the section on air exchange rates. These included five homes in which occupants turned off the dwelling unit exhaust fan and a sixth in which the intermittent exhaust fan was not programmed correctly. Excluding these homes does not change the central estimate of indoor formaldehyde for HENGH: mean = 19.7 ppb, median = 18.2 ppb.

The lower formaldehyde concentrations measured by HENGH in comparison to CNHS are also partly the result of a higher baseline outdoor air exchange with mechanical ventilation. Many of the highest formaldehyde levels reported by Offermann were in CNHS homes that had air exchange rates below the minimum AER provided by mechanical ventilation systems in HENGH homes.

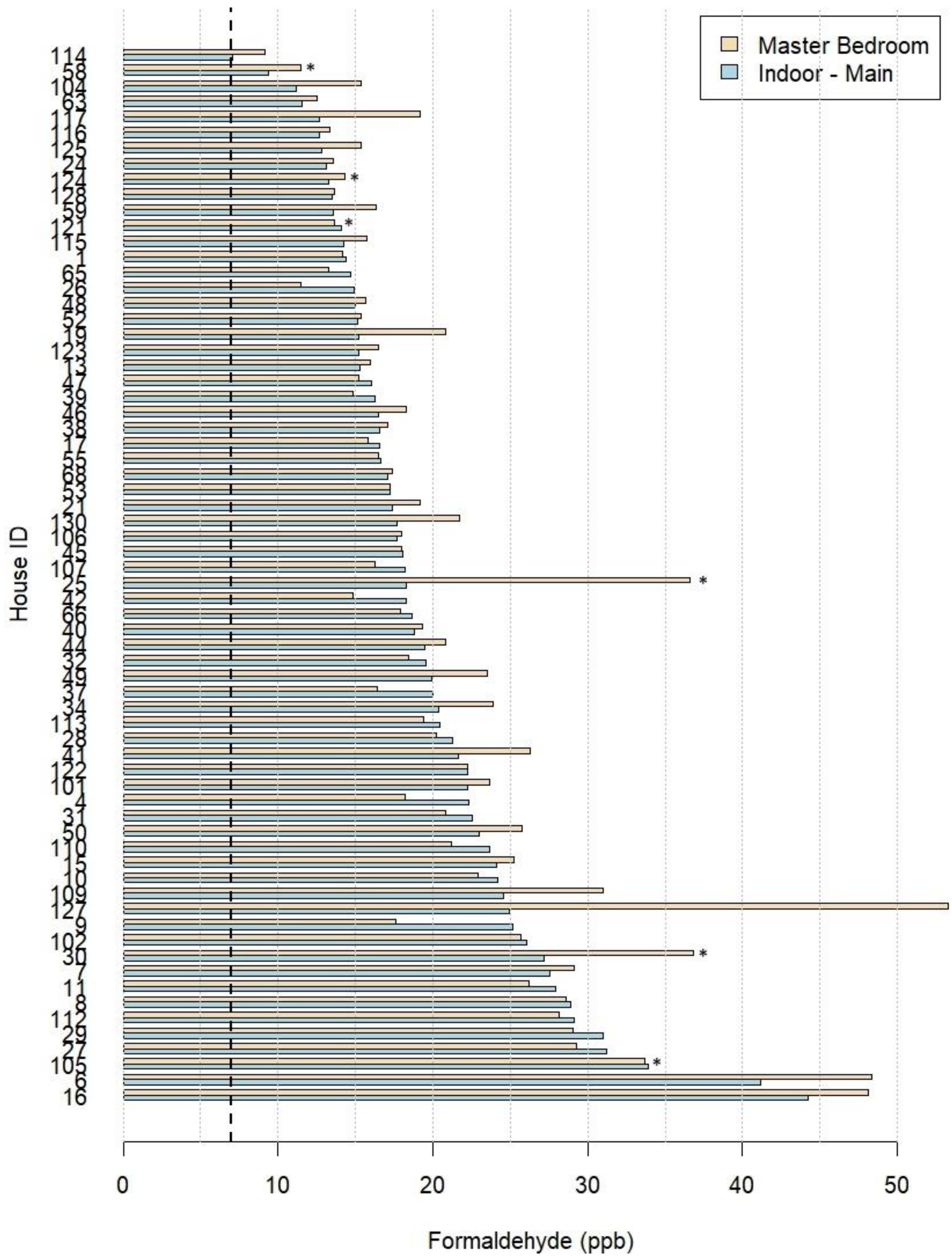
HENGH measured formaldehyde concentrations in the indoor main living space (for example, living room) and also in master bedroom. Generally differences were small between locations; but in some homes a higher concentration of formaldehyde was measured in the master bedroom compared to the central monitoring location.

Figure 21: One-Week Integrated Formaldehyde Measured with Passive Samples: Comparison of Concentrations at Bedroom and Central (Main) Indoor Locations



Source: Lawrence Berkeley National Laboratory

Figure 22: One-Week Integrated Formaldehyde Measured With Passive Samplers at Two Indoor Locations, Ordered by Concentration at Central (Main) Site

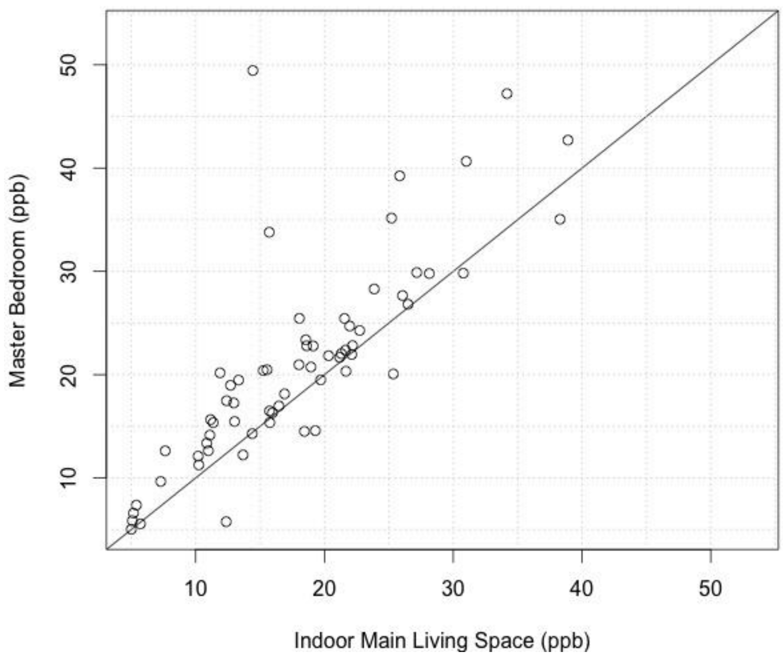


OEHHA REL (7 ppb) shown as dotted line. There are six homes (*) where opening of the house-to-patio and/or garage door(s) for more than 3 hours per day on average may have increased the overall AER substantially (see earlier section for more details on window and door use).

Source: Lawrence Berkeley National Laboratory

Indoor formaldehyde concentrations were also measured using time-resolved monitors that were co-located with the passive samples both at the indoor main living space and in the master bedroom. Figure 23 compares the one-week integrated formaldehyde concentrations measured by the time-resolved monitor at the two locations. Similar to results from passive samplers, higher formaldehyde concentrations were measured in the master bedroom of some homes, compared to the main living area.

Figure 23: One-Week Integrated Indoor Formaldehyde Concentrations from Time-Resolved Monitor



Source: Lawrence Berkeley National Laboratory

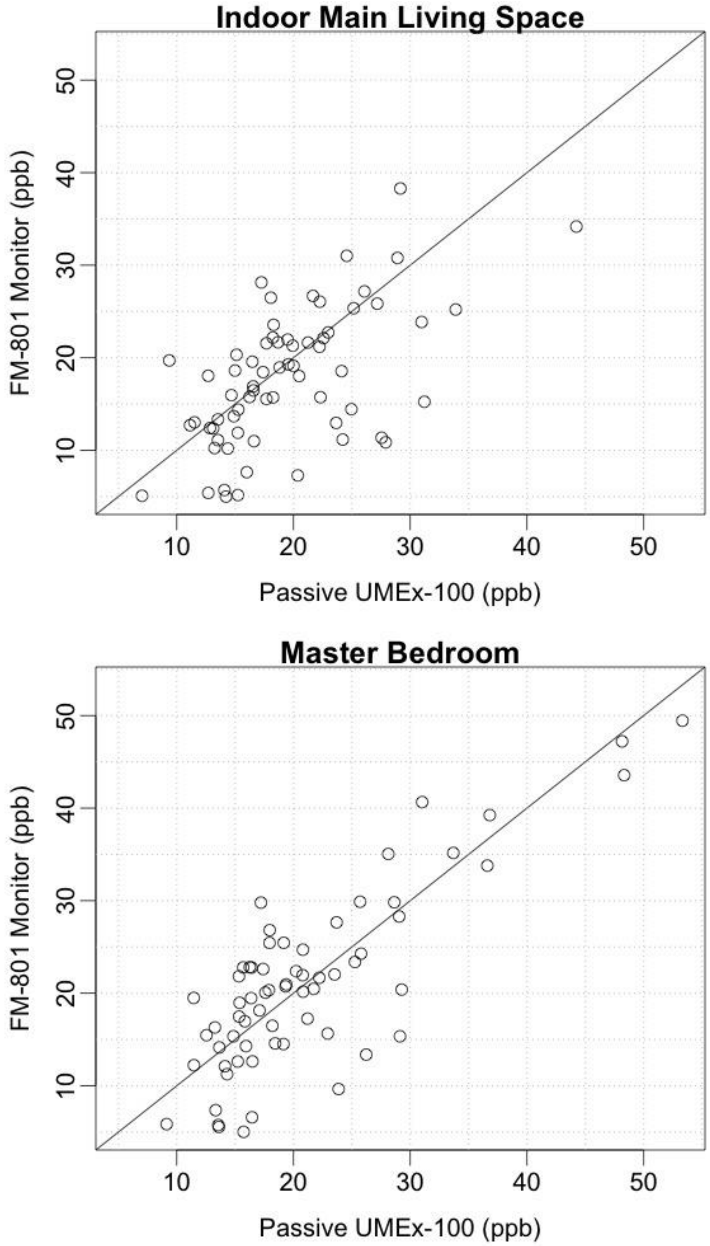
Table 42: Comparison of Time-Integrated Formaldehyde Measurements Using UMEx-100 Samplers and Gray-Wolf FM-801 Monitors

Formaldehyde	UMEx-100 Samplers	Gray-Wolf FM-801 Monitors
Indoor Main	N=68	N=67
Mean (ppb)	19.8	18.1
Median (ppb)	18.2	18.0
5th to 95th %tile (ppb)	11.9 – 31.1	5.5 – 30.9
Master Bedroom	N=68	N=66
Mean (ppb)	21.1	21.3
Median (ppb)	18.2	20.4
5th to 95th %tile (ppb)	12.8 – 36.7	6.0 – 42.2

Source: Lawrence Berkeley National Laboratory

Average formaldehyde concentrations measured by the real-time monitors provided similar aggregate results as the time-integrated passive samples (Table 42). However, considerable scattering was observed when comparing the time-average of the time-resolved to the time-integrated passive samples for each home (Figure 24). A better fit, in terms of R^2 from linear regression, was obtained for paired measurements from the master bedroom.

Figure 24: Comparison of Passive and Time-Resolved Formaldehyde Measurements



Comparison of passive and real-time formaldehyde measurements averaged over a one-week period. Linear regression gives R^2 = 0.33 for indoor main living space, and R^2=0.66 for master bedroom.

Source: Lawrence Berkeley National Laboratory

Future analysis of the real-time monitored formaldehyde and estimates of air change rates will evaluate effects of temperature and relative humidity on indoor formaldehyde emission rates, as suggested in previous research (Parthasarathy et al., 2011).

3.5.2 Fine Particulate Matter ($PM_{2.5}$)

$PM_{2.5}$ concentrations measured using real-time instruments (MetOne and pDR) were adjusted using gravimetric filter measurements to account for differences in particle size distribution between the field tests and instrument calibration. An adjustment factor (multiplier) was defined as follows:

$PM_{2.5}$ (real-time, adjusted) = $PM_{2.5}$ (real-time, unadjusted) x Adjustment Factor

Figure 25 shows indoor and outdoor adjustment factors calculated from filter measurements indoors at 8 homes and outdoors at 7 homes for the pDR and 5 homes for the MetOne photometers. The adjustment factors for indoor measurements were not insignificant: they accounted for ~20 percent underestimate from MetOne, and ~10 percent overestimate from pDR, on average. The calculated adjustment factors were applied to all indoor measurements.

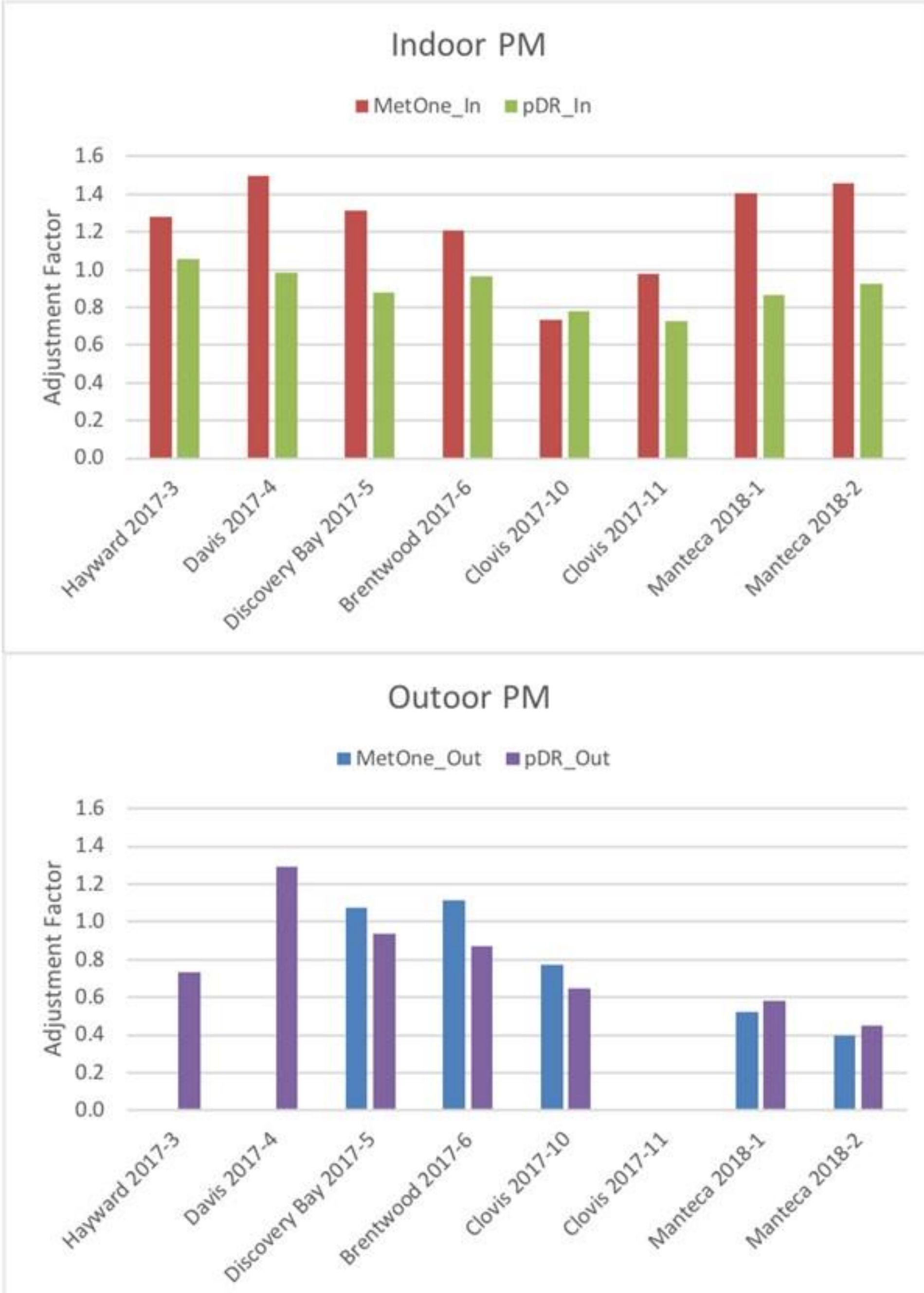
Table 43: $PM_{2.5}$ Adjustment Factor Using Filter Measurements

$PM_{2.5}$ Instrument	Indoor	Outdoor
MetOne	1.23	0.78
pDR	0.90	0.79

Source: Lawrence Berkeley National Laboratory

No adjustments were made for the outdoor measurements, even though Table 43 suggests that both MetOne and pDR may have overestimated the outdoor $PM_{2.5}$ concentrations. This is because unlike the adjustment factors estimated for indoor measurements (Figure 25), where MetOne consistently underestimated indoor $PM_{2.5}$ concentrations, and pDR consistently overestimated indoor $PM_{2.5}$ concentrations, the outdoor adjustment factors were more variable from home to home. The larger variability is thought to result from variations in particle size, mass distribution and compositions of outdoor $PM_{2.5}$, as well as environmental conditions when the data were collected. Consequently, applying a single adjustment factor to outdoor $PM_{2.5}$ measurements would not have improved accuracy of the results. Future analysis could compare outdoor MetOne data with the $PM_{2.5}$ concentrations reported at nearby ambient air quality monitoring stations.

Figure 25: PM2.5 Adjustment Factors Calculated from Filter Measurements



Column labels show city and year-month where real-time and filter measurements of $PM_{2.5}$ were collected.

Source: Lawrence Berkeley National Laboratory

Table 44 shows that the mean and median indoor $PM_{2.5}$ concentrations were much lower in HENGH than in CNHS. The median concentration outside of HENGH homes was also lower than the median outside of CNHS homes. The lower indoor $PM_{2.5}$ in HENGH compared to CNHS homes can only partly be attributed to the lower outdoor concentrations since the ratio of median HENGH/CNHS indoor concentrations is 0.48 and the ratio of median outdoor concentrations is 0.78. The ratio of median indoor to median outdoor concentration was approximately 0.5 for HENGH homes and approximately 0.8 in the CNHS. Other possible explanations include the benefits of higher performance air filters in HENGH homes and a potential benefit of filtration by the building shell associated with the exhaust ventilation systems, as reported by Singer et al. (2017). The higher quality air filters in HENGH homes compared to CNHS would only be a factor in homes that in which the forced air systems operated for a substantial fraction of time during the week of monitoring. An analysis of the potential factors that could have resulted in the lower indoor concentrations and indoor/outdoor ratios is planned and will be reported separately when it is available.

While 20 of the 67 HENGH homes with outdoor data had outdoor $PM_{2.5}$ exceed the CalEPA annual ambient air quality standard of 12 $\mu g/m^3$, only 12 of the 67 homes with indoor data had indoor concentrations exceed that benchmark (Figure 26).

Table 44: Comparison of HENGH and CNHS $PM_{2.5}$ Measurements

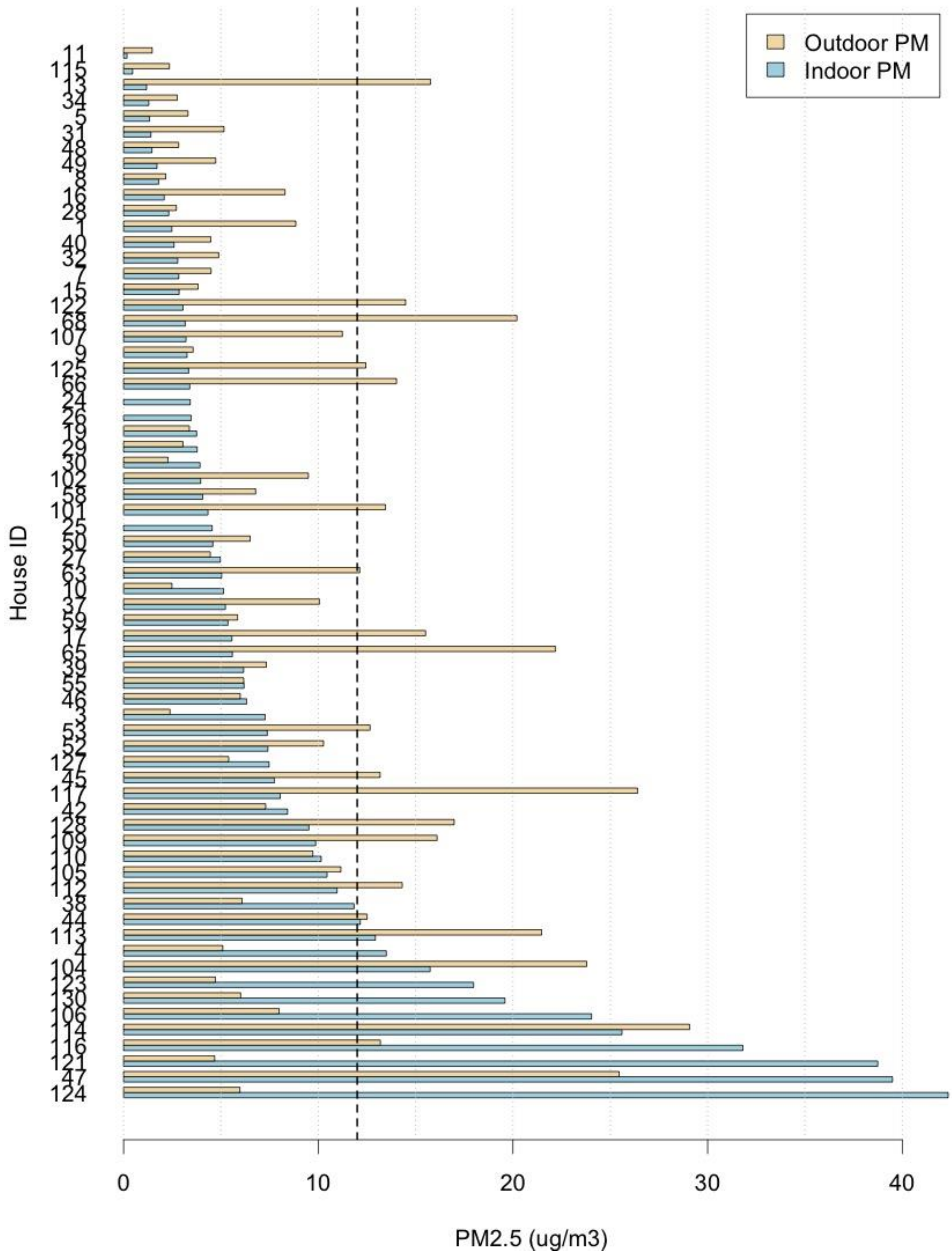
$PM_{2.5}$	HENGH	CNHS
Indoor	N=67	N=28
Mean ($\mu g/m^3$)	8.3	13.3
Median ($\mu g/m^3$)	5.0	10.4
Outdoor	N=67	N=11
Mean ($\mu g/m^3$)	9.3	7.9
Median ($\mu g/m^3$)	6.8	8.7

Source: Lawrence Berkeley National Laboratory

To examine the dependence of indoor $PM_{2.5}$ concentrations on outdoor concentrations, Figure 27 shows the ratio of indoor to outdoor $PM_{2.5}$ in relation to outdoor $PM_{2.5}$. Most homes (68 percent) showed an indoor/outdoor ratio less than unity. As expected, data suggested large variability in indoor/outdoor $PM_{2.5}$ ratios, with values ranging between 0.2 and 3.2 (5^{th} to 95^{th} percentile). The central estimates of indoor/outdoor $PM_{2.5}$ ratio are mean = 1.1 and median = 0.68.

In homes that were monitored when outdoor $PM_{2.5}$ concentrations were relatively high (>15 $\mu g/m^3$), the indoor/outdoor ratio (N=11) has a central tendency of about 0.55 (mean = 0.55, median = 0.56). Future analysis of $PM_{2.5}$ will seek to isolate contributions from indoor sources and calculate infiltration factors.

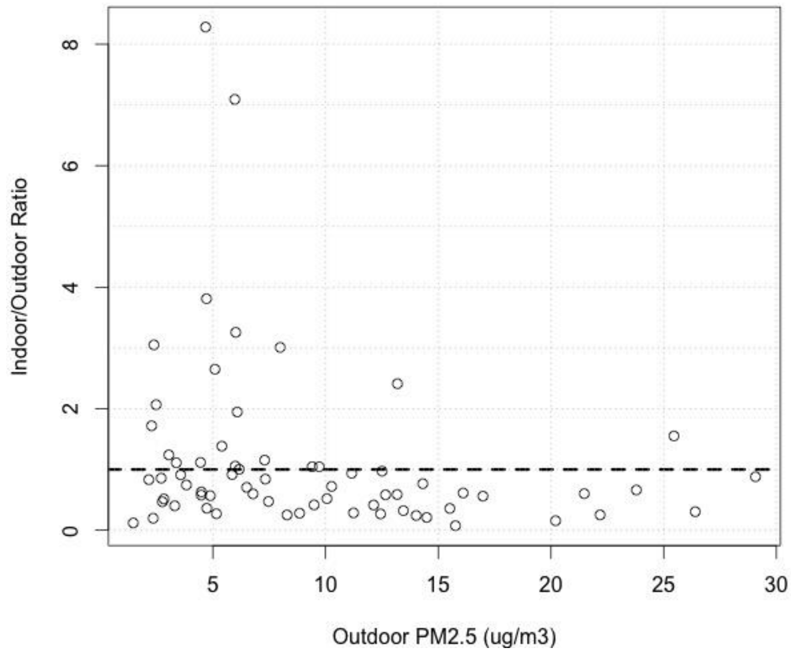
Figure 26: One-Week Average $PM_{2.5}$ Concentrations



CalEPA ambient air quality annual standard of 12 ug/m^3 showed as dotted line.

Source: Lawrence Berkeley National Laboratory

Figure 27: Indoor/Outdoor $PM_{2.5}$ Ratio



Source: Lawrence Berkeley National Laboratory

3.5.3 Nitrogen Oxides (NO_X) and Nitrogen Dioxide (NO_2)

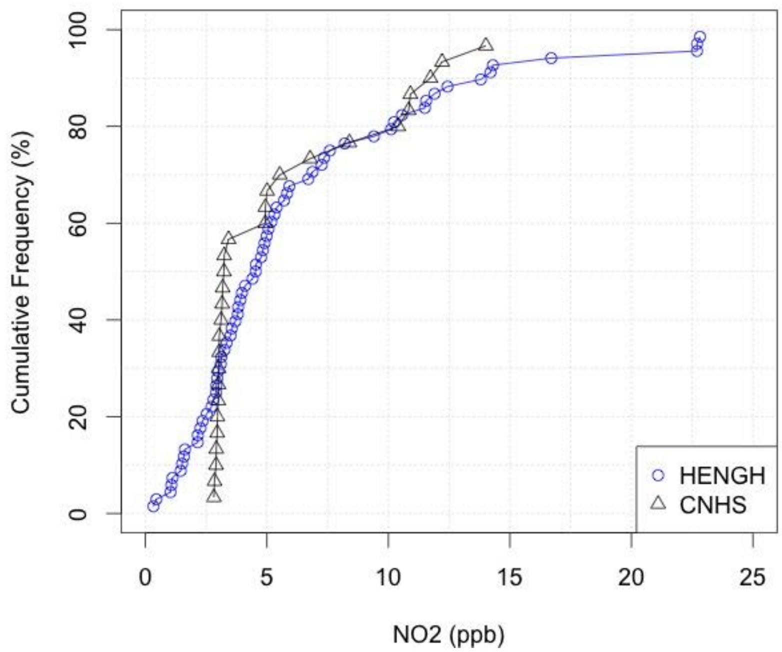
The indoor NO_2 concentrations measured in HENGH were slightly higher than those reported in CNHS homes as shown in Table 45 and Figure 28 while median outdoor levels were similar in the two studies (Table 45). There were seven HENGH homes with indoor concentrations NO_2 concentrations that were similar or higher than the highest measured in any CNHS home. All of the measured NO_2 concentrations were well below the US EPA 53 ppb annual ambient air quality standard for NO_2.

Table 45: Comparison of HENGH and CNHS One-Week Integrated NO_2 Measurements

NO_2	HENGH	CNHS
Indoor	N=67	N=29
Mean (ppb)	6.2	5.4
Median (ppb)	4.5	3.2
Outdoor	N=66	N=11
Mean (ppb)	5.6	3.5
Median (ppb)	3.7	3.1

Source: Lawrence Berkeley National Laboratory

Figure 28: Comparison of HENGH and CNHS One-Week Integrated NO_2 Measurements

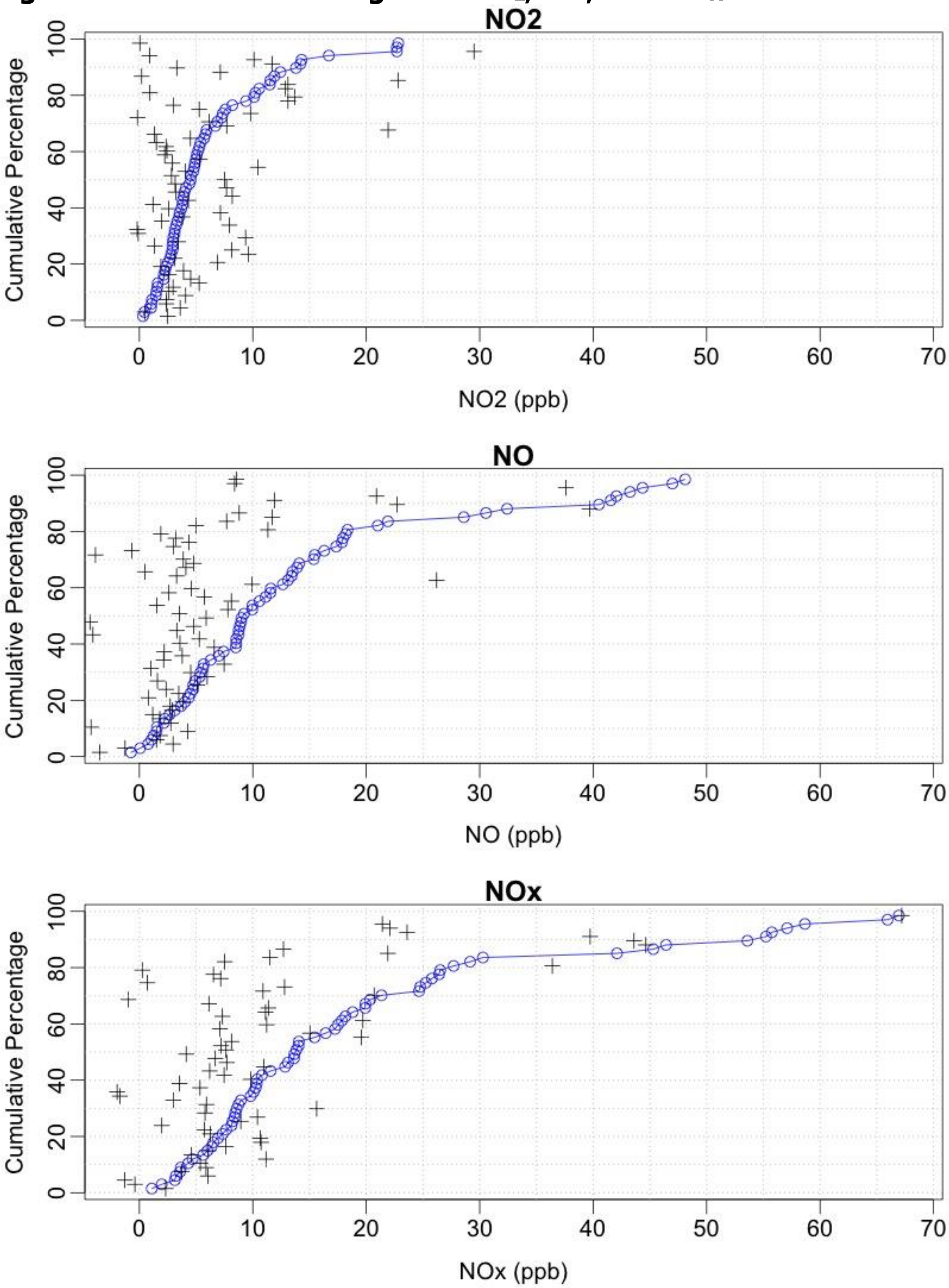


Source: Lawrence Berkeley National Laboratory

These results imply that the gas cooking appliances in the HENGH homes did not lead to widespread problems with indoor NO_2; this is in contrast to a recent study that found gas cooking is a significant source leading to elevated NO_2 in California homes that cook frequently with gas burners (Mullen et al., 2016).

Even though NO_2 concentrations measured by HENGH are similar to levels found in CNHS, the two studies differed in that HENGH homes all used gas for cooking, whereas almost all homes (98 percent) from the prior study used electric ranges. For NO and NO_X, Figure 29 shows that indoor concentrations were almost always higher than outdoors and that increased outdoor concentrations lead to increased indoor concentrations. For NO_2 deposition indoors results in indoor concentrations being substantially lower than outdoors when indoor sources represent a small contribution to total NO_2.

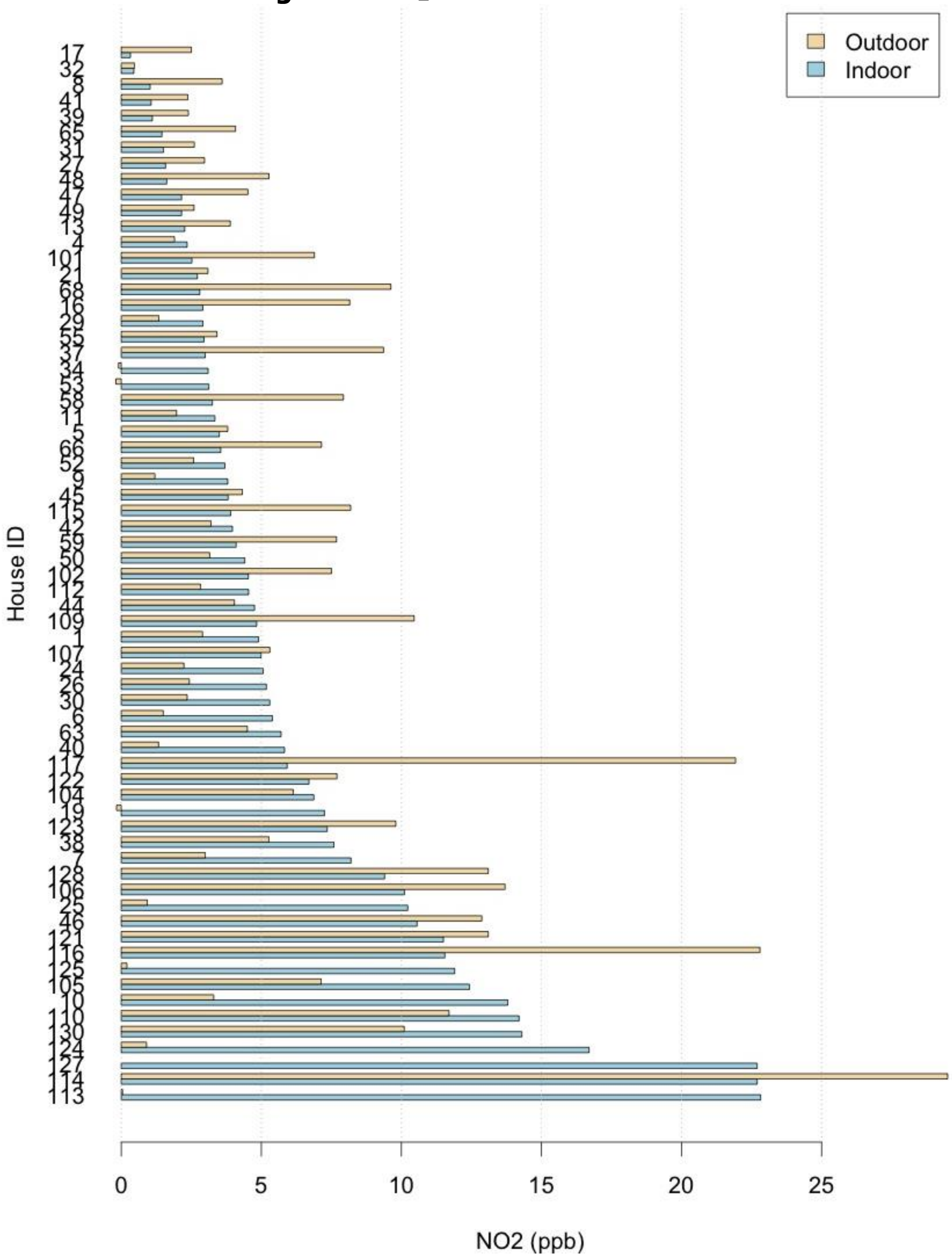
Figure 29: One-Week Integrated NO_2, NO, and NO_X Concentrations



Ranked ordered indoor NO_2, NO, and NO_X concentrations plotted as blue circles. Corresponding outdoor concentrations plotted as black crosses.

Source: Lawrence Berkeley National Laboratory

Figure 30: One-Week Integrated NO_2 Indoor Concentrations from Passive Samples



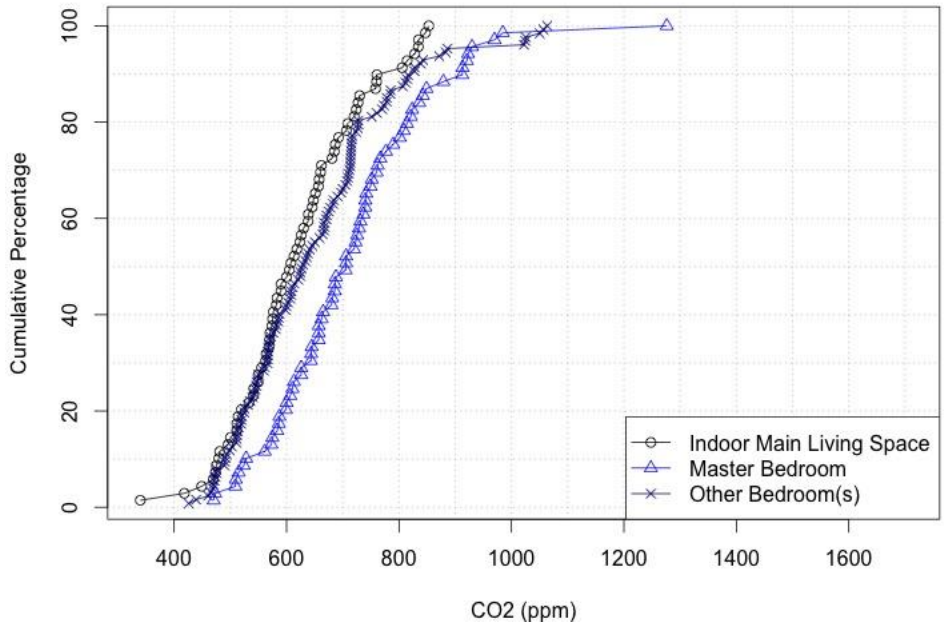
All NO_2 concentrations below USEPA annual standard of 53 ppb.

Source: Lawrence Berkeley National Laboratory

3.5.4 Carbon Dioxide (CO_2)

Figure 31 shows the distributions of average CO_2 concentrations over the monitoring period for various locations within the study homes. The highest time-averaged concentrations were in the master bedroom and the top 60 percent of the other bedroom locations were slightly higher than the main indoor living space.

Figure 31: CO_2 Measurements in Indoor Main Living Space and Bedrooms



Source: Lawrence Berkeley National Laboratory

Table 46 shows that the median of time-averaged CO_2 concentrations across HENGH homes was substantially higher than the median for the CNHS sample, but the means for the two studies were very similar.

Table 46: Comparison of HENGH and CNHS CO_2 Measurements

CO_2	HENGH	CNHS
Indoor	N=69	N=107
Mean (ppm)	620	610
Median (ppm)	608	564
10^{th} to 90^{th} %-tile (ppm)	481–770	405–890

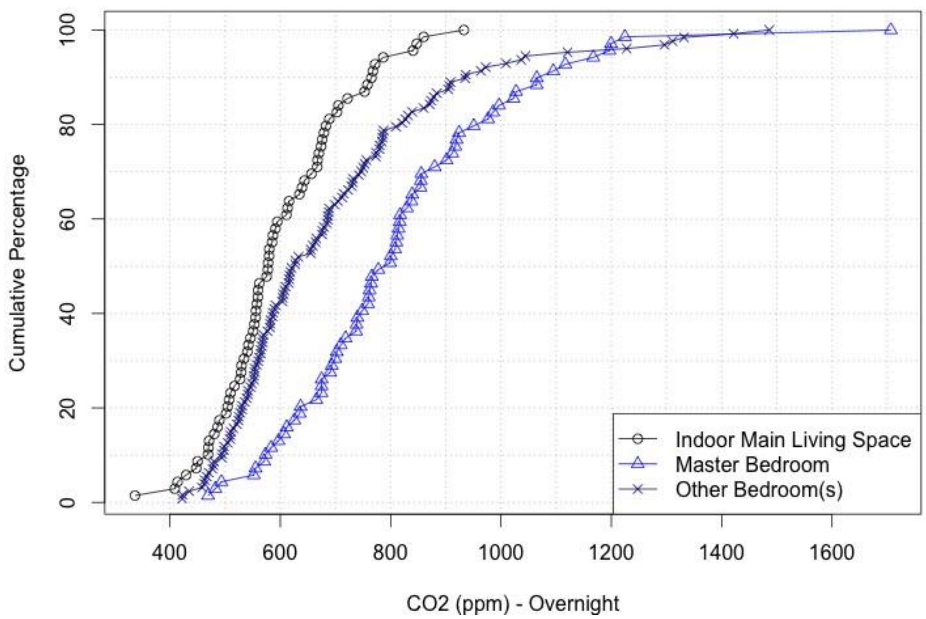
Source: Lawrence Berkeley National Laboratory

In the absence of a consensus limit for CO_2 in residences, the ASHRAE 62.1 guideline level of 1100 ppm (700 ppm above the outdoor background of roughly 400 ppm) was used as a benchmark[7] for CO_2. And considering that the ASHRAE guideline applies during occupied periods only, the average concentrations over an interval that include unoccupied periods should be solidly below this level. While only one home had time-averaged CO_2 above 1100 (in the master bedroom), several others had CO_2 above 1000 in other bedrooms. This suggests the possibility of concentrations exceeding 1100 during at least some occupied periods.

[7] ASHRAE 62.1 guideline level of +700 ppm above outdoor background (currently about 400 ppm) is largely based on odor concern in commercial buildings, which is not intended for residences.

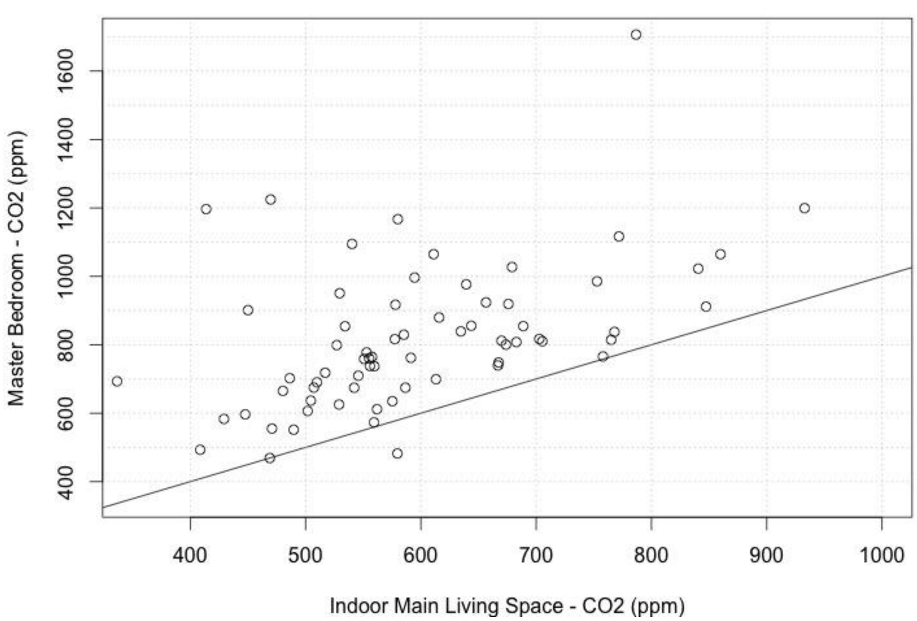
The difference in time-averaged CO_2 by indoor location results, unsurprisingly, from the bedrooms having much higher CO_2 overnight. Figure 32 shows the distributions of average CO_2 concentrations in each room, looking only at data from midnight to 5am (across all days with data during this time period). Six of the master bedrooms and 10 percent of the other bedrooms had mean CO_2 concentrations overnight in excess of 1100 ppm. Figure 33 compares the overnight CO_2 concentrations measured in the indoor main living space and master bedroom of the same homes.

Figure 32: Overnight (midnight-5am) CO_2 Measurements in Indoor Main Living Space and Bedrooms



Source: Lawrence Berkeley National Laboratory

Figure 33: Overnight (midnight-5am) CO_2 Measurements in Indoor Main Living Space and Master Bedroom



Source: Lawrence Berkeley National Laboratory

3.5.5 Temperature and Relative Humidity

Time-averaged indoor temperature and relative humidity measured in this study were similar to CNHS. The (24h) time-averaged indoor air temperature results reported for the CNHS study had the same median and mean of 22.4 ^{o}C, and a range of 17.1 to 28.2 ^{o}C across homes. The mean indoor air temperatures measured over the roughly weeklong monitoring periods in HENGH homes had the same median and mean of 22.9 ^{o}C, and a range of 17.8 to 27.1 ^{o}C across homes. CNHS reported 24-hour average indoor relative humidity with a median of 43 percent, a mean of 45 percent, and a range of 20 percent to 64 percent across homes. The mean relative humidity measured over the roughly weeklong monitoring periods in HENGH homes had the same median and mean of 45 percent, and a range of 28 percent to 60 percent across homes.

3.6 Fan Sizing and Air Tightness Requirements from the Simulation Study

The dwelling unit ventilation fan sizing methods with the poorest weighted average IAQ (highest relative exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method and the Total Ventilation Rate Method. These had weighted average relative exposures of 1.3 and 1.4, respectively. Of all sizing methods, the proposed *Title 24 2019* sizing method maintained relative exposure closest to 1.0. The ASHRAE 62.2-2016 method and the *Qtotal* method were the next best approaches. The ASHRAE 62.2-2016 fan/infiltration superposition method consistently under-ventilated and had average relative exposure of about 1.09, while the *Qtotal* method consistently over-ventilated, with relative exposures averaging about 0.93. *Qtotal* was the only sizing method that maintained exposure below 1.0 in all simulated cases. The best approaches from an IAQ standpoint were the *T24 2019* and *Qtotal* methods. They increased the weighted average energy use by 3 and 5 percent relative to the ASHRAE 62.2-2016 method. The difference in weighted average total consumption between any of these three sizing methods was roughly 300 kWh/year.

Most of the sizing methods had widely spread relative exposure values, meaning that most homes were either under- or over-ventilated relative to target rates in 62.2 and Title 24. This inconsistency increases the risk of either higher exposures to indoor emitted pollutants or excess energy consumption for individual homes, even when the weighted average results are acceptable. The ASHRAE 62.2-2016 fan sizing method, which accounts fully for infiltration and fan type (i.e., the differences between balanced and unbalanced fans), had the most consistent pollutant exposure and ventilation rates across all cases, irrespective of climate zone, fan type, airtightness or house prototype. This sizing method had average exposure of 1.09, due to biases in the exhaust fan sub-additivity calculations in ASHRAE 62.2-2016. If desired, the Energy Commission could adopt an alternative sub-additivity formulation that would eliminate most of this bias, and should reduce average exposure very close to 1.0. The adopted Title 24_2019 fan sizing method also had quite consistent exposure values, though it tended to over-ventilate leakier homes.

An airtightness requirement of 3 ACH50 in new California homes was found to have a predicted weighted average energy savings from 1 to 5 percent of total HVAC energy use, depending on what fan sizing method was used. Most of these savings were from reducing the ventilation rate and allowing higher concentrations of indoor emitted pollutants under the hypothetical airtightness requirement. The fixed airflow fan sizing methods saved more energy (roughly 3 to 5 percent) but worsened IAQ by increasing exposure by 5 to 24 percent. The energy savings are low because the majority of the projected new construction will be in mild climates, and because the interactions between unbalance mechanical ventilation and natural infiltration lead to small changes in total airflow when the flow is tightened to this 3 ACH50 limit. Energy use decreased as weighted average exposure increased, essentially trading potentially higher pollutant exposure for improved energy performance. The sizing methods that accounted for infiltration and/or fan type had substantially reduced weighted average energy savings (1 percent), while they marginally improved IAQ (reduced exposure by roughly 3 to 4 percent) under an airtightness requirement. These fan sizing methods are designed to ensure a similar dwelling unit ventilation rate across levels of airtightness, which they did with moderate success. Savings from an air leakage requirement were roughly double in the 2-story vs. 1-story prototype homes, because of their increased natural infiltration rates. Savings were also higher in climates with the harshest weather (CZ16 and CZ1), but the lack of new construction in these zones nearly eliminated their effect on the weighted average results. When HVAC energy consumption was normalized by exposure to ensure equivalent IAQ in all simulated cases, the energy savings for airtightening from 5 to 3 ACH50 were well below 1 percent for all fan sizing methods.

The adopted fan sizing method in the 2019 Title 24 energy code produces results that are relatively independent of regarding air leakage limits, because it provided weighted average exposure nearly equal to 1 under both airtightness scenarios (existing and airtightened). Weighted average exposure would increase 5 percent with an air leakage limit in the energy code, though it would still be less than exposure achieved using the ASH622_2016 sizing method. Relative to the ASHRAE 62.2-2016 method, the adopted T24 2019 fan sizing method over-ventilates leaky homes (3 and 5 ACH50), with increased site energy consumption ranging from 70 to, 1,400 kWh/year, when averaged across climate zones. These results suggest that unless occupant exposure to indoor generated contaminants is allowed to increase by 5-10 percent, then an airtightness limit will have very marginal savings of roughly 1 percent of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5 percent are possible through airtightening.

CHAPTER 4: Conclusions and Recommendations

Conclusions

The following conclusions may be drawn from the field study of homes constructed since the 2008 version of the Title 24 Building Energy Efficiency Standards first required mechanical ventilation.

1. The vast majority of homes appear to have ventilation equipment that exceeds the minimum airflow requirements for dwelling unit and bathroom ventilation, and dwelling unit ventilation systems appear to be substantially oversized (by roughly 50 percent on average in the study sample). The oversizing appears to result from use of standard sizes of exhaust fans, as most homes with exhaust ventilation had either an 80 cfm or a 110 cfm fan. This suggests that increasing ventilation requirements in future versions of Title 24 may have only a small impact on the ventilation equipment installed in homes.
2. The most common equipment used to meet the dwelling unit ventilation requirement appears to be a single exhaust fan (used in 60 of 70 study homes). The most common control for these exhaust systems appears to be continuous operation (55 homes) and the most common location for the exhaust fan was the laundry room (48 homes).
3. Having a clear label on the controller – as required by the Standard – appears to greatly increase the chance that the dwelling unit ventilation system will be operated. It was common for the dwelling unit ventilation system to be turned off as the systems were operating in only 18 of 70 study homes when the field team arrived. It was uncommon for ventilation control switches to have informative labels as required by the Standards, as control switches were labeled in only 12 of 70 study homes. Homes with clearly labeled control switches were much more likely to have ventilation operating.
4. Understanding about ventilation systems appears to be mixed: just over half of the participants in this study said they understood how to operate the ventilation system in their home and about half of those who could recall said that the ventilation system was explained to them when they bought the house.
5. The kitchen ventilation equipment in many homes appears to meet most but not all of the requirements, specifically not meeting the requirement of moving ≥100 cfm at a setting with a certified sound rating of ≤3 sones. While most homes had a range hood or over-the-range microwave exhaust fan (OTR) that met the 100 cfm minimum airflow requirement, many of the range hoods and most of the OTRs did so only at medium or high speed, and some OTRs did not meet the airflow requirement even at the highest speed setting. An important caveat to this finding is that the OTR airflows could be biased low based on the measurement method, which required taping over the air inlets provided at the front top of some OTRs. Not all kitchen ventilation equipment was HVI certified. There is a need for the Energy Commission to HERS verify compliance with the 62.2 requirement for the range hood fans to be HVI certified (as has been adopted in the 2019 Title 24 Part 6 standards).

6. Many homes had air filters in their forced air heating and cooling systems that should be at moderately to substantially effective at reducing PM2.5 when operated. Of the 132 filters identified in study homes, MERV performance values were discerned for 111. Of these all but four were MERV8 or better and 33 were MERV11 or better. Eighteen of the 67 homes had at least one filter that appeared overdue for replacement (assessed onsite by the field team as "very dirty") and roughly one fifth of all the air filters were assessed to be "very dirty." Nineteen of the 85 filters for which data were obtained had not been changed within the past 12 months.
7. A substantial minority of field study participants reported discomfort or dissatisfaction with some environmental condition on a weekly basis during at least some season(s): roughly 30 percent reported too hot in summer, roughly 30 percent reported too cold in winter, roughly 20 percent reported not enough air movement, roughly 15 percent reported too hot in winter and roughly 10 percent too dry.
8. Similar to the results of prior surveys, a majority of participants reported no daily window opening in winter and roughly 20-25 percent reported no window opening during other seasons. This indicates an ongoing need for mechanical ventilation, as a substantial fraction of the population will not open windows to provide natural ventilation on a regular basis.
9. The envelope air tightness of California homes built 2012-2017 appears roughly similar to airtightness of homes built in the early 2000s, with over 80 percent of the homes falling in the range of 3–6 ACH50 under depressurization conditions. Only four of the study homes had envelopes tight enough to meet the 3 ACH50 requirement of the 2018 International Energy Conservation Code.
10. When operated with compliant dwelling unit mechanical ventilation and with windows closed, recently constructed homes appear as a group to have much lower formaldehyde than homes constructed a decade earlier and ventilated according to the owner's preference (CNHS). HENGH homes had a mean of 20 ppb and median of 18 ppb whereas CNHS homes had a mean of 36 ppb and median of 29 ppb of formaldehyde. The lower formaldehyde appears to result from both lower emissions and greatly reducing the number of homes that are severely under-ventilated. The mean emission rate calculated from 61 HENGH homes with required data was 6.8 ▪g/m3-h. The mean of 99 CNHS homes with required data was 13 ▪g/m3-h.
11. The time-averaged concentrations of fine particulate matter (PM2.5) in the HENGH study homes (median of 5.0 ▪g/m3) were generally lower than those reported in a subset of the California new homes studied a decade earlier (CNHS, median of 10.4 ▪g/m3). And the ratio of indoor median to outdoor median decreased from roughly 0.8 for the CNHS homes to roughly 0.5 in the HENGH homes. If indoor emissions of PM2.5 were not greatly different, this result suggests that more recently constructed homes may be providing a higher level of protection from outdoor particles. Further analysis is needed to resolve the factors that could be leading to these results.
12. Despite having and using gas cooking appliances – cooktops were used 7 or more times in 38 homes and 15 or more times in 8 homes during the week long testing period – the time-averaged nitrogen dioxide (NO2) concentrations in study homes were not much higher than in the CNHS study, in which 98 percent had electric cooking

appliances. It is still possible that some HENGH homes may have had high concentrations of NO2 over short periods when cooking occurred. Time resolved NO2 data collected with a sensor-based IAQ monitor will be analyzed in the future to evaluate this question.

13. Our simulation results suggest that the adopted changes to fan sizing methods in the 2019 Title 24 results in the same exposures as achieved by meeting the IAQ ventilation requirements set forth in ASHRAE 62.2 -2016 across a wide range of homes and climates. Relative to the ASHRAE 62.2-2016 method, the adopted T24 2019 fan sizing method over-ventilates leaky homes (3 and 5 ACH50), with increased site energy consumption ranging from 70 to, 1,400 kWh/year, when averaged across climate zones. Due to imperfections in fan sizing methods, and the way that envelope infiltration and mechanical ventilation interact to produce the total ventilation for the home, we found that tightening homes led to increased pollutant exposures of 5-10 percent. If we adjust the energy savings to account for this small increase in exposure then the energy savings due to tightening are reduced, and the airtightness limit (suggested to be 3 ACH50) will have very marginal statewide weighted average savings of roughly 1 percent of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5 percent are possible through airtightening.

Recommendations

In light of the findings that acceptable indoor air quality was achieved in almost all homes built to meet the 2008 or more recent Title 24 Building Energy Efficiency Standards, and that IAQ was generally improved relative to homes constructed before mechanical ventilation was required, it is recommended that the core ventilation requirements of dwelling unit and local exhaust ventilation should remain in the Title 24 Building Energy Efficiency Standards for the foreseeable future.

In light of the finding that many of the range hoods and most of the over the range microwave exhaust fans could achieve the required 100 cfm of airflow only at medium or higher speeds (which are likely louder than 3 sones), and that some OTRs could not achieve 100 cfm even at the highest setting, it is recommended that builders pay more attention to selecting range hoods and OTRs that are certified by the Home Ventilating Institute as meeting the airflow and sound requirements and also take care to install low resistance ducting to maximize range hood and OTR airflow. The Energy Commission is also recommended to engage with HVI efforts to develop a certification for capture efficiency tests for range hoods and consider adding an explicit capture efficiency requirement for range hoods. An important caveat to this finding is that the OTR airflows could be biased low based on the measurement method, which required taping over the air inlets provided at the front top of some OTRs.

Recognizing that many homes were not using their dwelling unit mechanical ventilation systems when first visited by the research team, and the additional findings that the control switches in the majority of homes did not have clear labeling and those with clear labels were much more likely to be operating, it is recommended that the Energy Commission and the building industry work together to ensure that ventilation system controllers or switches in all new homes are equipped with *durable and understandable* labels describing their purpose and the importance of operating the dwelling unit mechanical ventilation system.

Confirming airflows in supply ventilation systems presents a general challenge for demonstrating compliance with ventilation standards. In this study, the team encountered four homes with supply ventilation systems that could not be measured to verify airflows without substantial effort. There were accessibility challenges with the exterior roof level inlets (which could only be reached with an extension ladder) and with ducts, which were encased in spray foam insulation. This indicates a need to find alternative measurement approaches to show compliance. One possibility is to add a requirement to the Title 24 Building Energy Efficiency Standards that ventilation equipment must incorporate an onboard diagnostic or technology to verify airflow as installed. The team recommends the Energy Commission coordinate with entities that develop field methods to measure airflow for ventilation systems (for example, RESNET Standard 380) to address this challenge.

Implementing the Title 24 2019 fan sizing approach had lower pollutant exposure and higher energy consumption than the ASHRAE 62.2-2016 method and gave consistent robust results with little variation in exposure across a wide range of homes and climates. If new home envelopes are tightened to below 3 ACH50 and ventilation fans are sized using the 2019 Title 24 requirements, exposure will increase by about 5 percent in new homes, while total HVAC energy use will be reduced by roughly 3 percent.

GLOSSARY

Term	Definition
ACH50	Air changes per hour at a pressure different of 50 Pascals between the living space and outdoors
AER	Air Exchange Rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CalCERTS	California's Home Energy Rating System (HERS) provider
CalEPA	California Environmental Protection Agency
CFM	Cubic feet per minute
CHEERS	California's Home Energy Rating System (HERS) Provider
CNHS	California New Home Study – the precursor to this study that investigated homes pre-mechanical ventilation requirements
CO_2	Carbon Dioxide
DeltaQ	DeltaQ Test – for measuring building envelope and duct leakage
EPIC	Electric Program Investment Charge
GTI	Gas Technology Institute
HENGH	Healthy Efficient New Gas Homes – the title of this study
IAQ	Indoor Air Quality
LBNL	Lawrence Berkeley National Laboratory
MERV	Minimum Efficiency Rating Value – a rating for air filters for removing particles. A higher value implies more removal of smaller particles.
NO	Nitrogen Monoxide – a byproduct of combustion
NO_2	Nitrogen Dioxide – a byproduct of combustion
NO_X	Various oxides of nitrogen – byproducts of combustion
Pa	Pascal
ppb	Parts per billion
PG&E	Pacific Gas and Electric Company
ppm	Parts per million
$PM_{2.5}$	Particle mass less than 2.5 microns in diameter – usually expressed as a concentration in mass per unit volume
OEHHA	Office of Environmental Health Hazard Assessment

Term	Definition
OTR	Over-the-range microwave
REL	Reference Exposure Level
RESNET	The National Home Energy Rating Network
SoCalGas	Southern California Gas Company
Title 24	California Building Energy Efficiency Standards
ug/m^3	Microgram per meter cube
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

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APPENDICES

APPENDIX A: IAQ Survey Results from the Healthy, Efficient, New Gas Homes Study

APPENDIX B: Title 24 Fan Sizing and Airtightness Requirements for New California Homes

APPENDIX C: Healthy Efficient New Gas Homes (HENGH) Pilot Test Results

APPENDIX D: Daily Activity Log and Occupant Survey

Appendices A through D are available upon request (Publication Number CEC-500-2020-023-APA-D) by contacting Yu Hou at Yu.Hou@energy.ca.gov.