Sustainable Energy & Environmental Systems Department
Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

Indoor Air Quality in California Homes with Code-Required Mechanical Ventilation

Brett C. Singer[1]
Wanyu R. Chan[1]
Yang-Seon Kim[1,2]
Francis J. Offermann[3]
Iain S. Walker[1]

[1] Residential Buildings Systems Group and Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[2] Department of Mechanical Engineering, Wichita State University, Wichita, Kansas, USA
[3] Indoor Environmental Engineering, San Francisco California, USA

April 2020

This work was supported by US Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Indoor Air Quality in California Homes with Code-Required Mechanical Ventilation

Brett C. Singer[1], Wanyu R. Chan[1], Yang-Seon Kim[1,2], Francis J. Offermann[3], Iain S. Walker[1]

[1] Residential Buildings Systems Group and Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA

[2] Department of Mechanical Engineering, Wichita State University, Wichita, Kansas, USA

[3] Indoor Environmental Engineering, San Francisco California, USA

Acknowledgements

This work was supported by the California Energy Commission through Contract PIR-14-007 and the U.S. Department of Energy Building America Program via Contract DE-AC02-05CH11231. The Southern California Gas Company (SoCalGas) provided direct funding to the Gas Technology Institute (GTI) and staff resources to support an online survey and field data collection. The Pacific Gas & Electric Company (PG&E) funded Misti Bruceri & Associates (MBA) to provide a field technician. SoCalGas and PG&E deployed Gas Service Technicians to conduct appliance safety inspections in study homes. Data collection in homes was conducted by Luke Bingham, Erin Case, and Shawn Scott of GTI; Guy Lawrence of MBA; Eric Barba, Mary Nones, Ara Arouthinounian, and Ricardo Torres of SoCalGas; and Woody Delp of LBNL. Rick Chitwood assisted with data collection and guidance on measuring airflow in supply ventilation systems. Max Sherman (retired from LBNL) helped develop the project and served as the initial Principal Investigator. Genese Scott of SoCalGas helped with online survey recruitment. Marion Russell of LBNL led the chemical analysis of air samples. Kelly Perce transferred survey and activity log data from paper to the survey database. The CalCERTS and CHEERS organizations provided Title 24 compliance records for many study homes. Neil Leslie, Larry Brand, and Rob Kamisky of GTI provided management support.

Abstract

Data were collected in 70 detached houses built in 2011-2017 in compliance with the mechanical ventilation requirements of California's building energy efficiency standards. Each home was monitored for a one-week period with windows closed and the central mechanical ventilation system operating. Pollutant measurements included time-resolved fine particulate matter ($PM_{2.5}$) indoors and outdoors and formaldehyde and carbon dioxide (CO_2) indoors. Time-integrated measurements were made for formaldehyde, NO_2 and nitrogen oxides (NO_X) indoors and outdoors. Operation of the cooktop, range hood and other exhaust fans was continuously recorded during the monitoring period. One-time diagnostic measurements included mechanical airflows and envelope and duct system air leakage. All homes met or were very close to meeting the ventilation requirements. On average the dwelling unit ventilation fan moved 50% more airflow than the minimum requirement. Pollutant concentrations were similar or lower than those reported in a 2006-2007 study of California new homes built in 2002-2005. Mean and median indoor concentrations were lower by 44% and 38% for formaldehyde and 44% and 54% for $PM_{2.5}$. Ventilation fans were operating in only 26% of homes when first visited and the control switches in many homes did not have informative labels as required by building standards.

Keywords: ASHRAE 62.2, Healthy Efficient New Gas Home Study, Carbon dioxide, Fine particulate matter, Formaldehyde, Nitrogen dioxide

Practical Implications

High performance home standards and building codes and regulations require mechanical ventilation equipment to help manage moisture and air pollutants emitted indoors. This paper demonstrates the success of a new construction residential ventilation requirement instituted in the state of California in 2008, with almost all studied homes having compliant ventilation equipment. The study found that the combination of mechanical ventilation and implementation of a standard that reduced the allowable formaldehyde emissions from manufactured wood products resulted in formaldehyde concentrations that were lower by 44% and 38% at mean and median levels than in homes built prior to the standards. This study affirms that new homes can be built to stringent efficiency standards while maintaining indoor air quality.

1. Introduction

Since 2008, California's statewide residential building code has included requirements for mechanical ventilation to protect indoor air quality (IAQ). Ventilation requirements were implemented to mitigate any negative impacts of reducing uncontrolled air infiltration by envelope air-sealing to reduce energy use. Lower air infiltration reduces dilution of pollutants emitted inside the home, leading to higher concentrations if no other actions are taken. Although mechanical ventilation in new homes has become commonplace in many developed countries, it is uncommon in the U.S., particularly in single-family dwellings. Many state and local building codes in the U.S. have implicitly relied on natural ventilation through leaky envelopes or for occupants to manage IAQ using natural ventilation.

The presumption that occupants effectively utilize natural ventilation to manage moisture and chronic exposure to formaldehyde and other pollutants from indoor sources in homes was examined in two large studies conducted in California in the mid-2000s. In 2003, a mail-based survey was sent to a statewide representative sample of homes built in 2002-2003 to query IAQ satisfaction, ventilation practices, activities, and equipment use that can impact IAQ[1]. Based on self-reported window use, the researchers assessed that most homes were substantially under-ventilated relative to the target of 0.35 h^{-1}, from the ASHRAE 62-1999 ventilation standard.

The California New Home Study (CNHS), conducted in 2006-2007, collected data in 108 homes built in 2002–2005[2]. The study included a thorough characterization of the building and thermal and mechanical equipment; measurements of envelope and garage-to-house air leakage; an occupant questionnaire that covered many of the same topics as the earlier mailed survey; monitoring of window use over a week; and measurements of air exchange and various IAQ parameters over a single 24-hour period. Sampling was roughly split between winter and summer and between Northern and Southern California. Monitoring was repeated in 4 homes to investigate day-to-day and seasonal variability. The study found that actual window use differed from what participants reported generally for the season in which measurements were made (i.e., 52% under-reported and 8.3% over-reported), indicating that self-reported window use in the mailout survey may have been biased low. The field study also found that air exchange rates (AERs) in the majority of new homes were below the target of 0.35 h^{-1} and that formaldehyde was substantially above state exposure guidelines in almost all homes. The results of these two studies suggested that new homes were not being adequately ventilated and that relying on occupants and natural ventilation is not an acceptable approach.

Starting with the 2008 statewide Title 24 Building Standards, California instituted mechanical ventilation requirements that were a hybrid of the requirements in the 2007 and 2010 versions of the ASHRAE Standard 62.2 for residential ventilation[3]. The California standard required exhaust fans in the kitchen and every bathroom and general ventilation for the dwelling unit that could be satisfied with a continuous or intermittent system, utilizing exhaust, supply or balanced airflows. A severe slowdown in new home starts in 2008-2010 delayed implementation as most homes built during these years had been approved under the prior building code. The ventilation requirements were not fully incorporated until at least 2010.

The Healthy Efficient New Gas Home (HENGH) study, described herein, was performed to evaluate IAQ in California homes built to meet the 2008 building standards for ventilation. The study focused on homes with natural gas because the sponsoring research program is financed by a surcharge on investor-owned, gas utility customers and because gas cooking burners are an important source of air pollutants[4, 5]. The study included a web-based survey of homes built since 2002, a simulation-based study of the energy impacts of ventilation, and the field study described in this paper. A report summarizing results of all three component studies is available[6].

This paper presents the methods and results of the HENGH field study and compares findings from homes built with mechanical ventilation in 2011-2017 to the CNHS homes built in 2002-

2005 mostly without mechanical ventilation. Homes studied in HENGH also were built with materials that complied with an air toxic control measure (ATCM) for composite wood products[7] that was implemented to reduce formaldehyde emissions.

The study goal was to provide empirical evidence of the impacts of ventilation and emission standards in the most populous U.S. state. Findings may inform other states and nations considering standards for residential mechanical ventilation.

2. Methods

2.1. Field Study Overview

Overview of Data Collection in Homes. The study was designed to assess how homes were meeting the mechanical ventilation requirements and how the installed ventilation equipment impacts indoor air quality. The study sought to characterize performance of installed equipment; quantify the use of mechanical ventilation, gas cooking appliances and equipment that can impact IAQ; measure key IAQ parameters over a weeklong monitoring period; and obtain data from building occupants on IAQ and comfort satisfaction and IAQ-relevant activities. A core goal was to evaluate IAQ in homes employing general (dwelling unit) mechanical ventilation but not natural ventilation because the previous studies showed that many California homes do not routinely open windows or doors for natural ventilation during one or more seasons of the year.

The study protocol was approved by the LBNL institutional review board. Methods are summarized in ensuing subsections and detailed protocols are available [8].

Each study home was visited three times. On the first visit, the field team obtained written consent, confirmed that code-required ventilation equipment was present and operable, and started to record house, appliance, and mechanical equipment characteristics. A utility service technician conducted a safety inspection of the gas appliances. In a few homes, the inspection identified a minor issue that the technician resolved on the spot or during a follow-up visit, and field measurements proceeded. During the second visit, the team completed equipment and house characterization, conducted ventilation diagnostics, installed air quality measurement equipment indoors and outdoors, and installed devices to track ventilation and gas cooking appliance use. The participant was provided with an activity log for each day of the study and asked to partake in normal household activities with the exception that windows and doors should not be used for routine ventilation. Most homes were monitored for seven days, five were sampled for 8 days and one for 6 days. On the third visit, all IAQ and mechanical equipment monitoring devices were removed, the survey and activity logs were collected and a $350 gift card to a home improvement store was provided to the participant.

Eligibility and Recruitment. The study was limited to owner-occupied, detached California houses, built 2011 or later, with gas appliances, mechanical ventilation, and no smoking allowed. Homes had to be customers of SoCalGas or PG&E. Homes with unusual filtration or ventilation systems were excluded. Code compliance records obtained for 23 homes verified they were certified to meet 2008 or more recent standards. The presence of compliant or close to compliant mechanical ventilation equipment was verified in all homes ultimately included in the study.

Most participants were recruited through postcards (see SI) mailed to addresses identified on a real estate website (Zillow.com), targeting single-family, detached homes built 2011 or later. Some participants learned of the study via referrals. Details about the number of respondents, early withdraws and non-qualifying homes is provided in the SI.

2.2. Field Data Collection Procedures

House and Equipment Characterization. The information collected about each home and its mechanical equipment is summarized in the SI.

Air Leakage. Air leakage of the building envelope and the forced air heating/cooling system were measured with the DeltaQ test (ASTM-E1554-2013, Method A) using a TEC Minneapolis Blower Door System with DG-700 digital manometer (energyconservatory.com). The test quantifies air leakage of the forced air system to outside of the living space under normal operating conditions. Testing was conducted with software that automatically operated the blower door fan through pressurization and depressurization, recorded airflow and pressure differences, calculated envelope and duct leakage, and assessed if the measured parameters were stable enough to provide both parameters. Air leakage was converted to air changes per hour at 50 Pa indoor-outdoor pressure difference (ACH50) using the estimated home volume.

Ventilation Airflows. Airflows of bath and laundry exhaust fans were measured using a TEC Exhaust Fan Flow Meter (energyconservatory.com). Range hood airflows were measured using a balanced-pressure flow hood method described by Walker and Wray[9]. A TEC Minneapolis Duct Blaster, which is a calibrated, pressure-controlled, variable-speed fan, was connected to either the exhaust inlet (preferred) or outlet. If connected at the inlet, a transition piece was adapted onsite to cover the entire underside of the range hood or over-the-range microwave exhaust fan (OTR). The flow through the Duct Blaster was adjusted to achieve neutral pressure between the surrounding environment and the range hood inlet (or outlet) and airflow was determined from the pre-calibrated fan speed versus airflow relationship. The measurement was repeated for the lowest and highest settings and at least one medium setting if available. OTRs were tested in a modified configuration: the top air inlet was covered with tape and the rate of air flowing into the OTR was measured only at the bottom inlet. Subsequent testing at LBNL revealed that this approach produces a biased measurement of total airflow occurring under the normal operating configuration. Correction factors for most of the OTRs seen in the field were determined by comparing the airflow into the bottom inlet when the top was taped to the total flow measured at the exhaust duct outlet in laboratory experiments. The correction factors were applied to the field measured airflows at each OTR setting.

Supply fan flow rates were not measured because the air inlets – usually on roofs or at the eave 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 attics. Supply airflows were inferred for two devices based on ratings.

Equipment Usage Monitoring. Operation of exhaust fans, range hoods, and clothes dryers were determined using one of the following: motor on/off sensor (Onset HOBO UX90-004), vane anemometer (Digisense WD-20250-22), or plug load logger (Onset HOBO UX120-018). The field team chose an appropriate sensor for each fan configuration. Range hoods or OTRs were monitored with anemometers and the velocity at each setting was determined at installation to enable tracking of airflows for AER calculations. State sensors (Onset HOBO UX90-001) were used to monitor the most often used exterior doors. Although participants were asked to keep doors and windows closed during monitoring, it was deemed valuable to check for any extended natural ventilation that could affect pollutant measurements and patio doors were assessed as most likely to be left open. Cooktop and oven use were monitored using Maxim iButton DS1922T temperature sensors. Burner use was inferred from analysis of the temperature signals.

Air Quality Measurements. Air quality parameters were measured outdoors on the premises and at several locations indoors, as summarized in Table 1. The central indoor site was generally in a large open room on the first floor that included the kitchen and/or living room, but monitors were not placed directly in the kitchen. Performance specifications of air quality measurement devices are provided in Table 1 with additional information in Table S1 of the SI. Table S2 provides a summary comparison of the methods used to collect air quality data in HENGH and the CNHS. At the HENGH central indoor site, equipment was mounted on a stacked crate system that allowed free airflow. The outdoor monitoring station was mounted on a tripod with air sampling at roughly 2 m height and the station placed at least 3 m from any exterior wall or pollutant source such as a grill. Outdoor formaldehyde and NO_X passive samplers were placed inside a 10 cm diameter PVC cap for rain protection. The ES-642 photometer is housed in a weatherproof enclosure that incorporates a sharp-cut cyclone to exclude particles larger than 2.5 μm aerodynamic diameter and an inlet heater to maintain a minimum relative humidity in the incoming sample stream; it also auto-zeroes each hour. Monitors used to collect time-resolved air quality data were purchased new at the start of the study and thus expected to perform according to manufacturer specifications. Performance checks during the study are summarized below and additional details are provided in the SI.

For the CO_2 monitors, an initial visual check was conducted by operating all units together in the warehouse used to prepare equipment for Northern California homes; but no formal calibration was conducted at that time. In most homes, CO_2 monitors were collocated during setup and confirmed to read within 100 ppm of each other before deployment. Extech CO_2 monitors were checked against a calibrated PP Systems EGM-4 monitor during two collocation events at LBNL, as described in the SI. Averaged over full spike-decay intervals, differences between individual Extech units and the EGM-4 ranged from -20 ppm to 84 ppm. No corrections were made to CO_2 data and the possibility of larger deviations in some homes cannot be ruled out.

The ES-642 and BT-645 are aerosol photometers that translate light scattering measurements to an estimated $PM_{2.5}$ concentration based on a device-specific laboratory calibration using a traceable reference of 0.6 μm diameter polystyrene latex spheres. Since photometer response varies with aerosol size distribution and optical properties, their accuracy for ambient (outdoor) or indoor $PM_{2.5}$ can vary substantially as the qualities of the aerosol vary[10-14]. The recommended practice is to conduct a collocated gravimetric $PM_{2.5}$ measurement and determine an environment specific adjustment factor. In this study, we sought to check both the calibration factor and the time-response of the Met One photometers by deploying Thermo pDR-1500 photometers with onboard filter sampling indoors and outdoors at 8 homes. Due to power interruptions, valid outdoor co-location data were obtained at only 5 homes and the results were too varied to provide study-wide adjustment factors. To fill this gap, we obtained data from up to three regulatory air quality monitoring stations closest to each house (Figure S1 of the SI) and calculated outdoor $PM_{2.5}$ for the study period at the house. As a second check on performance, at most homes the indoor and outdoor photometers were operated side by side (typically outdoors) for roughly an hour (Figure S2). Details about quality assurance for the air quality monitors are provided in the SI.

The standard software for the formaldehyde FM-801 monitor reports readings below 10 ppb as "<LOD". By special arrangement, GrayWolf provided modified software to enable us to access device readings below this nominal detection limit, which we used in 25 homes. Prior research indicates that the device may provide quantitative if more uncertain measurements below 10 ppb[15]. Some FM-801 formaldehyde was removed because of interference by high NO_2[16] from gas cooking burner use. Details about both adjustments are provided in the SI.

Duplicates and field blanks were collected to evaluate reliability for the passive samplers, and all available duplicate samples were averaged to improve precision. Four Ogawa samplers prepared according to manufacturer protocols were deployed at each home to measure NO_2 and NO_X: 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 home: one outdoors, two in the central indoor station (duplicates) and one in the bedroom. In most of the sampled homes, a fifth sampler was opened indoors as a field blank, then immediately packed and stored in a refrigerator during the monitoring week. The procedures used to analyze passive samplers are summarized in the SI. The sampling rates for NO_2 and NO_X samples were calculated based on measured average temperature and humidity according to Ogawa protocols. For UMEx samplers we used the sampling rate of 20.4 mL/min recommended by the manufacturer for air velocities <300 cm/min and 1 to 7 days of sampling. Offermann and Hodgson have shown that sampling rates for the UMEx and other passive monitors start to drop sharply when air velocity falls below about 75 cm/min[17]. Presenting measurements from six occupied houses and one unoccupied research house, Matthews et al.[18] reported that such low air velocities were infrequent. Since we did not measure velocities around the passive samplers and did not verify measured concentrations with pumped samples, it is possible that sampling rates could have been lower than the assumed standard values at some times in some homes.

Survey and Activity Log. Participants were asked to complete a survey about the household occupants and their general activities that impact ventilation and IAQ and also to complete an activity log for each day of monitoring. The survey was a condensed version of the online survey used to collect data about California detached homes built since 2002. Recruitment for the online survey was conducted primarily through emails sent by SoCalGas to customers who lived in homes that use natural gas and were thought to meet the requirement of being constructed in 2002 or later. A summary of findings from the survey is provided in the HENGH final project report[6]. The abridged survey tool used for the field study and the daily activity log are included in the SI to this paper.

Calculated Outdoor Air Exchange Rate (AER). The rate of outdoor air exchange – including both mechanical ventilation and air infiltration – was calculated minute-by-minute in each home following the Enhanced Model described in the 2017 ASHRAE Handbook– Fundamentals, as summarized in the SI. The calculation assumed that windows and doors were closed throughout the monitoring week (as required), so natural ventilation was negligible. The AER over the full monitoring period in each home was calculated as the harmonic mean of the minute-by-minute estimates. Measured AERs in CNHS houses[2] that did not have mechanical ventilation and did not open windows were analyzed to assess the accuracy of the infiltration portion of the AER calculation, as described in the SI.

3. Results and Discussion

3.1. Locations and Seasons of Home Visits

The field study collected data from 48 homes in the San Francisco Bay Area and Central Valley regions and 22 homes in Southern California, as shown in Figure 1. The breakdown by gas utility service territory, California climate zone, and city is provided in Table S3. Sampling occurred throughout the year, with slightly more homes visited in the months corresponding to summer seasonal conditions (June–September, n=27 homes) than each of the other seasons, in which 13 to 16 homes were studied (Table S4). None of the homes were within 300 m of a freeway, highway, or high-volume arterial road.

3.2. House and Household Characteristics

Characteristics of HENGH homes with selected comparisons to the CNHS and California data from the 2017 American Housing Study (AHS) are reported in SI Tables S5–S15 and Table 2. HENGH and CNHS samples had similar distributions of home size and occupant density; but HENGH homes were newer when tested and more commonly had gas cooking appliances (Table 2). HENGH included one 2.5-story, 42 two-story, and 27 one-story houses (Table S8) and all but one had an attached garage. HENGH homes mostly had three (n=20), four (n=28) or five (n=17) bedrooms and almost all had multiple bathrooms (Tables S9–S10). Thirty-two HENGH homes had vented gas fireplaces (Table S11).

HENGH households were similar in size to the AHS, with slightly more having 1-2 occupants (46% vs. 41%), fewer with 3-4 occupants (34% vs. 42%) and similar 5+ occupants (17% vs. 15%) (Table S12). HENGH households had similar age demographics as the AHS, with 40% of each having at least one resident under age 18 and 26-28% with at least one resident aged 65 or older (Table S13). Relative to the AHS, the HENGH sample was skewed in terms of income and education. In HENGH, 88% of the 66 participants who provided the information had a household income of $100,000 or greater; in the AHS sample, only 60% reported such income (Table S14). Of the 67 HENGH heads of household that reported education level, 88% had a college degree and 54% had a graduate or professional degree; in the AHS, 56% had someone with a college degree and 26% had someone with a graduate or professional degree (Table S15).

With the important caveat that the CNHS asked about medically diagnosed conditions and HENGH asked simply about the conditions, HENGH households more commonly reported someone with allergies (56% vs. 36%) or asthma (26% vs. 16%); CNHS also reported chemical sensitivity in 3.7% of homes (HENGH survey did not ask about this condition).

3.3. Envelope Air Tightness

The distribution of measured envelope air tightness, expressed as the air changes per hour at a 50 Pascal indoor-outdoor pressure difference (ACH50), are shown in Figure S3. The mean, median, and 10^{th}–90^{th} range of envelope air tightness from depressurization tests were 4.6, 4.4, and 3.4–6.0 ACH50. Measured air leakage under pressurization was higher than depressurization by 20% on average due to "valving" of some air leakage pathways, e.g., from exhaust fan backdraft dampers being pushed open during pressurization. Only four homes had envelope leakage less than 3 ACH50, the level required for compliance with the 2018 International Energy Conservation Code. Overall, HENGH homes had air leakage values similar to California homes built in the early 2000s, as reported in the online residential diagnostics database (resdb.lbl.gov)[19] and in the CNHS, which had a mean ACH50 of 4.8.

3.4. Ventilation and Filtration Equipment

All 70 HENGH homes had ventilation equipment that was mostly or completely compliant with the statewide standards. As summarized in Table S16, dwelling unit ventilation was provided by an exhaust system in 64 homes and by a supply system in 6 homes. Fifty-five of the exhaust systems used a continuous fan and 43 of those exhausted air from the laundry room; the others exhausted from a bathroom. Three of the exhaust systems had remote fans located in the attic and the others were upgraded laundry or bath exhaust fans. All supply systems were integrated into the central forced air heating and cooling system; four had inline fans and two relied on the central system fan operating on a timer to pull in outdoor air through a duct connecting the return to the outdoors. In all but two of the homes with measured airflow, the flow exceeded the code minimum requirement. The mean minimum requirement was 107 $m^3 h^{-1}$ and the mean installed flow was 163 $m^3 h^{-1}$, about 50% higher. In many homes, the "extra" airflow could be explained by use of a common fan size set to maximum capacity, i.e., not adjusted down to meet minimum requirements. Very importantly, the general ventilation equipment was running in only 26% of homes (18/70) when the field researcher(s) arrived for the initial visit. Systems with easily understandable signage at the power switch for the system were much more likely to be operating (see Table S17).

All of the homes had exhaust fans in the kitchen and in each bathroom, as required by the standards. Kitchen ventilation was provided by a range hood in 32 homes and an over the range (OTR) microwave in 38 homes. Twenty-two (69%) of the range hoods moved the required 50 L s^{-1} or 100 cfm on the lowest speed setting, seven met the standard on a medium setting, and three did so only at the highest setting. Of the 38 OTRs for which airflows were measured in homes, method correction factors were obtained and applied to 22 devices. For this group, the estimated airflow met the code requirement for 8 installed units (36%) on the lowest setting, 14 (64%) on a medium or higher setting, and 20 (91%) on high or boost setting. The setting needed to produce the required airflow is important because the code also requires that the fan operate at a sound level of 3 sone or less, with the rationale that kitchen exhaust may not be used as needed if it is too loud. Over 85% of the full bathrooms had exhaust fans that met the requirement of 25 L s^{-1} or 50 cfm, as shown in Figure S4. Exhaust fans in the toilet room or shower of the master bathroom suite are not required to meet the airflow standard if the main exhaust fan in the bathroom suite does so. These fans had lower measured airflows and only 60% met the 25 L s^{-1} benchmark. The median exhaust flows were 41, 37 and 31 L s^{-1} (87, 78 and 65 cfm) for master bath, other bathroom and toilet/shower compartments.

Of the 69 homes with a forced air thermal conditioning system, 22 had only one filter, 34 had two filters, 10 had three filters and 3 had four or more filters (with one filter per return duct). As shown in Table S18, 96% (107/111) of the filters for which a performance rating could be determined were MERV8 or better and 30% (33/111) were MERV11 or better. In the CNHS, filter ratings were determined in 97 of the 108 homes: 49% (48) had MERV8 or better and 32% (31) had MERV11 or better. In HENGH homes, we were able to determine the last date of change for 85 filters: 58% (49) had been changed within the last 6 months, 22% (19) had <u>not</u> been changed in the past year and 11 of those had never been changed (Table S19). Table S20 shows that 20 homes had filters that were clean or like new, 29 homes had filters that appeared used or somewhat loaded, and 18 homes had at least one very dirty filter. There were a few homes in which, at the owner's request, the research team replaced (n=2) or installed (n=1) air filters in the forced air systems during the first or second field visit, prior to monitoring.

3.5. Ventilation During the Week of Monitoring

Field teams set dwelling unit mechanical ventilation systems to operate during the monitoring period in each home. The two homes with supply ventilation powered by their central thermal conditioning system fans were ventilated during the study by running their laundry exhaust fans continuously. The average air exchange rate (AER) resulting from infiltration and mechanical equipment operating during the monitoring week was estimated for 63 homes, with results provided in Figure S5. AER was not estimated for four homes with supply ventilation fans because the system airflow could not be measured and for three homes that did not have a valid envelope air leakage measurement, which is needed to calculate infiltration. Five homes that had their dwelling unit exhaust fans stopped (presumably turned off by occupants) during the week had low calculated AERs: 0.07–0.15 h^{-1}. A sixth home, which had an intermittent exhaust fan that was not programmed to provide sufficient ventilation (by error of the field team), also had a low AER, of 0.06 h^{-1}. For the 57 homes that had measured airtightness and mechanical ventilation system airflows and their systems operated throughout the week of monitoring, the mean, median and 10^{th}–90^{th} percentiles of the estimated infiltration + mechanical AERs were 0.33, 0.30, and 0.20–0.46 h^{-1}. Mechanical ventilation provided substantially higher outdoor air exchange rates than would have occurred by infiltration only, as shown in Figure S6.

The AERs estimated for HENGH homes operating with code-compliant systems and windows presumed closed were marginally higher than in the CNHS (before ventilation was required), which reported sample median AERs of 0.26 h^{-1} for 107 homes measured during a single monitoring day and 0.24 h^{-1} for 21 homes measured over a 2-week period that included window use. Twenty-two CNHS homes had mechanical equipment to provide dwelling unit ventilation;

these included 8 with heat recovery ventilators (HRV) and 14 with ducts connecting the forced air heating/cooling system return duct to the outdoors. Of the 14 with outdoor air ducts, only 4 had controllers to operate the FAU for mechanical ventilation when no heating or cooling was needed. During the day of CNHS monitoring, all of the HRVs but only 34% of the outdoor-connected FAU systems met the ASHRAE 62.2-2004 standard applicable at the time.

In several of the HENGH study homes, the actual outdoor air exchange over the week was likely higher than the calculated values owing to use of natural ventilation. In six homes, the occupants reported opening the house-to-patio and/or garage door(s) for more than 3 h per day on average. The calculated AERs also could be roughly 20% higher based on the potential bias in infiltration calculation indicated by the analysis of CNHS data from homes without mechanical ventilation.

3.6. Sources of Air Pollutants Reported in the General Survey

Almost all HENGH homes reported being completely smoke free; one reported that smoking occurred a few times per year and one acknowledged informally that a family member smoked daily in a bedroom, with the window open. Occasional candle burning was fairly common, with 16 HENGH participants reporting candle use a few times per month, 11 using a few times per week, and 5 every day (Table S21). Thirty-four households had at least one furry pet and twelve reported two or more; 20 reported no pets and 16 did not respond to the pet question (Table S22).

3.7. Occupancy and Activities During the Week of Monitoring

Data from the HENGH daily activity logs are provided for occupancy (Tables S23–S24) and cooking (Tables S25–S27). Most of the homes had one to three occupants at home at any given time when occupied and 88% of those reporting were occupied during time intervals totaling 16 or more hours per day on average. Thirty-four of 68 homes with daily log data reported using the cooktop at least 7–14 times per week; oven use was less common. Cooktop use events were <30 min on average in most homes. Oven use was typically longer. Cooking and other activities reported in the CNHS homes are provided in Table S28.

3.8. Air Pollutant Concentrations: Formaldehyde

Multiple measurements of formaldehyde in each HENGH home indicated very good sampling precision and mostly similar concentrations in the master bedroom and central indoor sampling location. The average mass on field blanks corresponded to 0.6 ppb for a 7-day collection period and the 66 paired indoor samples agreed to within 1.0 ppb on average (median = 0.7 ppb). Sample-period averaged concentrations calculated from half-hourly resolved GrayWolf (Shinyei) multimode monitor data agreed well with the time-integrated sampler results as summarized in Table S29 of the SI. Figure 2 presents the formaldehyde concentrations measured in the master bedrooms and central indoor locations of each home by UMEx passive sampler. Among the 66 homes with valid samples in both locations, formaldehyde in the bedroom was >10% higher than in the living room in 20 homes and less than 90% in 7 homes. The median and 10^{th}–90^{th} ratios of bedroom to living room concentrations were 1.02 and 0.90–1.27. Period-averaged formaldehyde determined by the multimode monitor indicated a similar trend of the master bedroom having higher concentrations than the central area more frequently than the opposite. And the overnight concentration in the bedroom was even higher than the period-average at that location. (See SI for details). These findings suggest that for many people exposure to formaldehyde at home may be higher than indicated by average concentrations at a central indoor site.

Figure 3 shows that homes built in 2011–2017 and mostly operating with mechanical ventilation (HENGH) had formaldehyde concentrations substantially lower than those built in 2002-2005 and mostly not using mechanical ventilation (CNHS). Mean and median formaldehyde levels in HENGH homes were 44% and 38% lower than in CNHS (Table 3). Differences between the HENGH and CNHS indoor formaldehyde concentrations were found to be significant based on a two-tailed Student's t-test with equal variance comparing log-transformed concentrations (p-value = 3.4e-8) and the nonparametric Mann-Whitney test (p-value = 1.5e-7). The highest formaldehyde measured in any home in the current study was 44 ppb while 28% of the CNHS homes had a formaldehyde concentration over 44 ppb. Indoor emissions were the primary source in both studies; but based on median indoor and outdoor values, the fraction contributed by outdoor air increased from 6% in the mid-2000s to 15% more recently.

Formaldehyde levels in HENGH homes were all well below the World Health Organization (WHO) indoor air guideline of 80 ppb and also below non-U.S. national guideline levels as summarized by Salthammer [20]. However, all homes were still above the 7 ppb (9 $\mu g/m^3$) Chronic Reference Exposure Level set by the California Office of Environmental Health Hazard Assessment, which is the applicable target in California.

The substantial reduction in formaldehyde compared to the CNHS a decade earlier appears to result both from fewer homes being severely under-ventilated and from lower emissions. For 32 CNHS homes with measured air exchange rates below 0.2 h^{-1}, mean and median formaldehyde concentrations were 57 and 45 ppb. By contrast, in the HENGH dataset, only eight of the 63 homes for which overall AER was estimated had outdoor AERs below 0.2 h^{-1}; and the mean and median formaldehyde concentrations for these homes were 25 and 23 ppb.

Formaldehyde emission rates were calculated for 61 HENGH homes using the measured concentrations and estimated AERs. The median and mean emission rates were 5.8 and 6.1 $\mu g/m^3$-h compared to median and mean values of 11 and 13 $\mu g/m^3$-h calculated from 99 homes with the required component data in CNHS (Table 45 of Offermann et al., 2009). CNHS homes had more varied formaldehyde emission rates, with a 10^{th} to 90^{th} percentile range of 4.0 to 23 $\mu g/m^3$-h whereas the range for HENGH homes was 2.8 to 8.3 $\mu g/m^3$-h. For this comparison, it is important to note that the CNHS measured AERs with a PFT tracer gas whereas the HENGH AERs were estimated by combining the measured mechanical ventilation airflows and calculated air infiltration assuming no contributions from open windows or door. To the extent that actual AERs in HENGH homes were higher than calculated – e.g. from a possible ~20% bias in the calculated air exchange rates as discussed in the SI, or from use of windows and doors – the formaldehyde emission rates in HENGH homes would have been higher than stated above.

3.9. Air Pollutant Concentrations: Fine Particulate Matter ($PM_{2.5}$)

Time-resolved $PM_{2.5}$ concentrations reported by indoor photometers were adjusted based on comparison to gravimetric analysis of filter samples collected in 8 homes (Table S30). Indoor photometer measurements were adjusted by a multiplier of 1.23 for the BT-645, and 0.90 for the pDR-1500. Aside from the gravimetric adjustment, pDR-1500 also measured time-resolved $PM_{2.5}$ for comparison with BT-645. Hourly indoor readings from the 8 homes collected by the two photometers were highly correlated (R^2 = 0.96-0.99) and, after applying the respective multipliers, agreed to within ±1 $\mu g/m^3$ for 84% of the hourly readings, and ±2 $\mu g/m^3$ for 96% of the hourly readings.

Distributions of indoor $PM_{2.5}$ in HENGH and CNHS are shown in Figure 4. Mean and median indoor $PM_{2.5}$ concentrations in HENGH were 44% and 54% lower than in CNHS homes (Table 3). Even with uncertainty in the photometer adjustment factors, these data indicate substantially lower indoor $PM_{2.5}$ in the more recently constructed homes. The difference in log-transformed indoor $PM_{2.5}$ concentrations measured by the two studies are statistically significant using Student's t-test (p-value = 2e-6) and nonparametric Mann-Whitney test (p-value = 2e-5).

Since outdoor air is a major source of $PM_{2.5}$ inside U.S. homes[21-25], it is important to consider if the observed difference could be entirely attributed to lower $PM_{2.5}$ outdoors during HENGH. The CNHS reported 11 samples of outdoor $PM_{2.5}$; based on the clustering sampling approach used in that study, those measurements represent 28 homes. For the HENGH study, the 5 weeks of collocated outdoor photometer and gravimetric samples had such varied ratios (see Table S30 of SI) that they could not be used to adjust all of the outdoor photometer data. Data from regulatory ambient air monitoring stations nearby to HENGH homes provide a second set of estimates of areawide outdoor $PM_{2.5}$ during the study. Table S31 and Figure S7 of the SI show that outdoor $PM_{2.5}$ estimates from the air monitoring stations are higher than those from unadjusted outdoor photometer data. This is directionally consistent with outdoor photometer reading lower than the indoor photometer in side-by-side monitoring and suggests that the outdoor photometer may be understating the outdoor $PM_{2.5}$. Summary statistics of outdoor $PM_{2.5}$ from both data sets applied for the HENGH study are compared to CNHS data in Table 3. While limitations of both data sets make the comparison uncertain, the results in Table 3 do not indicate substantially lower $PM_{2.5}$ outside of HENGH versus CNHS homes. The lower $PM_{2.5}$ inside HENGH homes can therefore not be attributed to lower outdoor $PM_{2.5}$.

The lower indoor $PM_{2.5}$ in HENGH homes could result from reduced penetration of particles during air infiltration, lower indoor emissions (from cooking, candles, cleaning, etc.), more effective kitchen ventilation, and/or improved filtration. Reduced particle entry during air infiltration is not likely a major factor as the envelope air tightness was very similar in the two samples and the higher median outdoor air exchange rates in the HENGH study would tend to slightly increase indoor concentrations of outdoor particles as higher AERs bring in outdoor air more quickly and leave less time for particles to deposit onto indoor surfaces.

Assessing the impact of filtration overall requires consideration of filter quality, airflow and operating cycles of the central forced air system, and use of portable air filtration units. While the full analysis is beyond the scope of this paper, it was reported above that HENGH homes more commonly had at least a medium performance (MERV8) filter compared to CNHS homes. There also may have been more portable air cleaner use in HENGH homes. Of the 64 HENGH participants who answered the question, 14 (22%) reported using a standalone air cleaner. Air cleaner use was self-reported in 17% of CNHS homes and 15% of respondents to the statewide survey in 2002-4[1].

While it is difficult to compare the impact of all particle emitting activities – since emissions vary so widely even for a defined activity – we can at least compare the frequency of cooking and range hood use. In the CNHS study, during the day of IAQ monitoring, 87 homes (81%) reported at least one use of the cooktop or oven and 81 (75%) reported at least one cooking event involving frying, sautéing, baking or broiling. Despite this relatively high frequency of cooking that can emit substantial quantities of $PM_{2.5}$, only 22% of the CNHS occupant activity logs reported any range hood use during the day of IAQ measurements and 44% reported some range hood use during the prior week. Over the roughly one-week monitoring in HENGH homes, 34 of the 68 submitted activity logs (50%) reported cooking with the cooktop or oven at least 7 or more times during the week, i.e. once per day on average. The HENGH activity log did not ask about the type of cooking. In the general survey responses, 50% of HENGH participants reported using their range hood "most of the time" (4 of 5 times) or more and another 23% reported using the range hood "sometimes" (2–3 out of 5 times). Initial analysis of cooktop temperature and range hood/OTR use data indicate that kitchen ventilation was employed in some capacity during roughly 29% of cooktop uses and 22% of oven uses and actual use during the monitored week was much less than usage reported by survey. The range hood was operated for most or all of the duration of cooktop use during 8% of cooktop use events and 3% of oven use events.

3.10. Air Pollutant Concentrations: Nitrogen Dioxide and Nitric Oxide

Distributions of NO_2 concentrations inside HENGH and CNHS homes are presented in Figure 5 and summary statistics are provided in Table 3. The distributions were not significantly different based on the nonparametric Mann-Whitney test (p-value = 0.08) and the means of the log-transformed data were not statistically different using the Student's t-test (p-value = 0.15). This occurred despite all HENGH homes having natural gas cooktops (compared to just 2% of CNHS homes) and outdoor NO_2 being higher in HENGH. The higher median indoor NO_2 in HENGH may be misleading as the CNHS median was in the group of data set as half of the quantitation limit and the outdoor median for CNHS was lower (though uncertain for the sample as NO_2 was sampled outside of only a subset of homes). Differences in NO_2 between HENGH and CNHS homes were much smaller than those reported for homes with gas versus electric cooking in a recent study of mostly older and smaller California homes [5]. The highest weekly averaged NO_2 measured in a HENGH home was below the California annual average standard of 30 ppb and less than half of the U.S. annual air quality standard of 53 ppb. Figure S8 shows that for NO, indoor concentrations were almost always higher than outdoors, as indoor emissions added to the

NO coming from outdoors. For NO_2, deposition indoors resulted in indoor concentrations being lower than outdoors in many homes.

3.11. Air Pollutant Concentrations: Carbon Dioxide as Indicator of Adequate Ventilation

Overall, time-averaged CO_2 levels measured in HENGH and CNHS homes were similar, as presented in Table 3. The one substantive difference – at the 90th percentile – aligns with mechanical ventilation systems in HENGH homes more consistently providing outdoor air to dilute occupant emissions of CO_2.

Within HENGH homes, CO_2 concentrations varied spatially (Figure 6). The highest time-averaged concentrations were in the master bedroom and concentrations in other bedrooms were higher than in the main indoor living space.

CO_2 concentrations also varied in time, with the highest concentrations occurring overnight in bedrooms. Figure 7 shows the distributions of average CO_2 concentrations in each room, looking only at data from midnight to 5 am, and SI Figure S9 presents overnight CO_2 concentrations measured in the main indoor location and master bedrooms of the same houses. These results indicate that CO_2 in HENGH bedrooms did not reach the levels that have been reported to affect sleep or next day alertness[26, 27].

3.12. Satisfaction and Discomfort with Indoor Environmental Conditions

Sixty-eight of the 70 HENGH study participants provided responses to survey questions about their satisfaction with environmental conditions in the home. Responding to the question "To what extent are you satisfied or dissatisfied with the indoor air quality in your home?", 68% (n=46) selected one of four levels indicating positive satisfaction, 24% (n=16) selected neutral, and 9% (n=6) marked one of four levels indicating dissatisfaction. These results are very similar to those obtained from 2765 respondents to the online survey of people living in California homes built before ventilation standards were in place. That survey, conducted in 2014, was open to occupants of California homes built since 2002; yet almost all respondents lived in homes built before 2011 and located in the SoCalGas service territory of Southern California[6]. In the online survey, 69% indicated positive satisfaction, 21% were neutral, and 10% indicated dissatisfaction with their IAQ. Among 68 field study respondents, 51% were satisfied with the air quality *outside* of their homes, 17% were neutral and 32% were dissatisfied. These totals are also similar to the online survey, for which 47% were satisfied, 27% were neutral and 26% were dissatisfied with their outdoor air. When asked "How would rate you rate your home in protecting you from outdoor air pollution?" 62% of responding field study participants were satisfied, 31% were neutral and 7% were dissatisfied. The CNHS did not report results for IAQ satisfaction and the survey reported by Piazza asked about "acceptability" of indoor air quality, rather than "satisfaction", which is not directly translatable.

The survey of HENGH participants – both field study and online – also asked about the frequency of specific environmental discomforts, offering options of "never", "few times a year", "few times a month", "few times a week", and "every day". The CNHS study asked participants if they experienced discomfort during the preceding week. Table 4 shows that specific discomfort conditions were generally similar in the two studies, with the exception that 21% of HENGH participants reported not enough air movement compared to 12% of CNHS participants experiencing the air as "too stagnant" in the week prior. The robustness of that difference is unclear as 18% of the survey respondents from homes built around the same time as those in the CNHS also expressed frequent dissatisfaction with air movement.

Survey responses from the field study were analyzed to evaluate if environmental satisfaction differed in homes that had MV systems operating or not operating when the research team first arrived to study homes. Results provided in Tables S32 to S34 indicate no statistically significant associations with satisfaction for air quality, seasonal temperature, or other environmental conditions (air movement, dryness or dampness, musty odors).

3.13. Comparison to Other Studies of Ventilation and IAQ in Recent Construction Homes

There have been few large field studies examining the impact of mechanical ventilation on IAQ in recently constructed homes. The study that most directly addressed this topic examined 62 homes built in 2010-2012 to an Austrian efficiency standard that included general mechanical ventilation with heat recovery (MVHR) and 61 homes constructed during the same years using normal building standards without mechanical ventilation[28]. The study measured IAQ parameters roughly 3 months and 1 year after occupancy and used interviews to collect data about health symptoms and perceptions of IAQ and comfort[29]. The efficient homes with MVHR had lower concentrations of total volatile organic compounds (TVOC), formaldehyde, saturated acyclic aliphatic aldehydes, CO_2, and radon[28]. While there were not significant differences in self-reported overall health status or for most symptoms, occupants of the efficient, ventilated homes rated their environmental quality higher by more frequently noting positive attributes (pleasant, clean, fresh and fragrant) and less frequently perceiving negative attributes (stale, stuffy, stagnant, bad smelling or smoky)[29].

The effects of improving ventilation in existing airtight homes was reported by Lajoie et al.[30] in a study that added mechanical ventilation with heat or enthalpy recovery to 43 of 83 Quebec area homes of asthmatic children that were verified to be under-ventilated. IAQ parameters and the children's respiratory health were monitored over two years. The homes with added mechanical ventilation had several statistically significant and substantial (>25%) improvements including higher outdoor air exchange and lower CO_2, formaldehyde, styrene, limonene and mold spores; but also had higher indoor NO_2 and di(2-ethylhexyl) phthalate.

Several studies have reported on the installed performance of mechanical ventilation systems in modern homes. A study of mechanical ventilation systems in 299 Dutch homes completed in 2006-2009 conducted visual inspections, measured ventilation rates per room and equipment noise, and asked occupants their perceptions of their indoor air quality[31]. Issues identified in many homes included ventilation rates below and noise levels above building code requirements, blocked supply vents, and absence of required controls. Problems occurred during installations, maintenance and operations. A study in Belgium[32] conducted mechanical ventilation system diagnostics and measured carbon dioxide, temperature and humidity levels in 39 standard construction homes built in 2007-2008 with wet room exhaust ventilation and trickle vent supplies (and mean air leakage of 3 ACH50), 23 similarly tight (2 ACH50) low-energy homes with MVHR, and 16 passive houses (0.5 ACH50) with MVHR. Installed equipment in many of the homes did not achieve the required airflows at any setting and occupants generally operated the systems at lower settings, leading to large differences between actual and design airflows. Humidity and CO_2 measurements showed some differences between groups of homes but none indicated substantial problems. In a study of 29 homes in the U.S. state of Washington, which has required mechanical ventilation for many years, researchers reported that most had systems that were set, or that could be set to comply with the standard[33]. In many of the homes the MV systems were not operating according to design standards when researchers first arrived. A study of mechanical ventilation systems installed in 21 homes in the U.S. state of Florida[34], which did not require such systems at the time, found that only 12 were capable of operating and actual airflows generally were well below design targets. These two U.S. studies reported problems with installation (disconnected duct, blocked vent, poorly hung ducts, inoperable outdoor air exhaust duct damper, ERV/HRV system installed backward) and operations and maintenance (fan turned off, dirty filters, controller set to inadequate runtime fraction).

Among the air pollutants measured in HENGH, the most direct comparisons to prior U.S. studies can be made for formaldehyde. HENGH homes had substantially lower formaldehyde than a sample of homes constructed in the late 2000s with low-VOC flooring and paints along with mechanical ventilation; those homes had mean formaldehyde of 27 ppb (33 $\mu g\ m^{-3}$) at adjusted conditions of 23°C, 43% RH, and 2.25 years old[35]. In a study in the U.S. state of Arizona, apartments that were renovated in 2011 with low-VOC materials and mechanical ventilation had reported mean(SD) and median formaldehyde levels of 27(7) ppb and 26 ppb roughly 1 year after renovations[36]. These levels represented a decrease from pre-retrofit formaldehyde of 39(11) ppb and 38 ppb (ibid). The higher concentrations measured in these studies relative to HENGH could result from sampling occurring only during daytime hours in the summer season, a time at which emissions are expected to be higher than concentrations measured over full diurnal cycles and varied seasons[37]. The lower concentrations in HENGH homes could also result in part from lower emissions resulting from the California air toxic control measure.

3.14. Limitations

The samples of homes included in the HENGH and CNHS studies may not accurately represent the population of recently constructed homes in the state now or in the mid-2000s. Relative to the general population of new home owners, HENGH households were biased toward higher income and higher education and potentially also toward higher interest in IAQ (since they volunteered to participate in the study). The impact of these biases is not known.

Even within the homes studied, the air quality measured in both HENGH and CNHS may not accurately reflect average conditions. In the HENGH study, IAQ was measured while homes were operated without natural ventilation (i.e., with occupants agreeing to keep windows and doors closed) and with mechanical ventilation systems set to operate. This mode likely does not represent conditions in newer California homes throughout the year, especially since we found that general ventilation systems were not operating in 74% of the homes studied. This was not an issue for CNHS because occupants were asked to use natural ventilation as normal. For both studies, the act of participating could have changed occupant activities that impact indoor air quality. Since CNHS sampling occurred over a single 24 h period, occupant routines may have been impacted by modified schedules to accommodate sampling equipment installation, removal and diagnostics on subsequent days. The processes of completing surveys and activity logs and having monitoring equipment in the homes could have impacted behaviors in both studies. Between study differences in recruitment, sample design and measurement methods also may have impacted the relative results in HENGH and CNHS.

For the HENGH study, ventilation rates were not directly measured as they were in the CNHS. The ventilation estimated by combining calculated infiltration rates and measured mechanical airflows in the HENGH study would be biased low in any homes with sustained opening of doors and/or windows for natural ventilation.

4. Conclusions

Measurements were conducted in 70 single-family, detached homes constructed in 2011–2017 under California building standards that require mechanical ventilation and a separate regulation that limits formaldehyde emissions from composite wood products. All homes had mechanical ventilation equipment that was mostly or completely compliant with the requirements. With the general mechanical systems operating and most homes not using any natural ventilation, indoor air pollutant levels were generally lower than those measured in a prior study of otherwise similar California homes built before the ventilation and material emission standards took effect. The recently constructed homes had somewhat lower $PM_{2.5}$, much lower formaldehyde, and slightly higher NO_2 despite having gas cooking burners whereas homes in the prior study had electric cooking. IAQ satisfaction was also similar in the newer homes as compared to homes built in years prior. These results indicate the success of standards that limit formaldehyde emissions and require ventilation systems to maintain acceptable IAQ.

Table 1. Measured Air Quality Parameters[1]

Measurement Device	Para-meters	Accuracy[1]	Res.	Sampling Locations
Met One ES-642 Photometer Met One BT-645 Photometer	$PM_{2.5}$	± 5% traceable standard with 0.6 um PSL	1-min 1-min	Outdoor Indoor: central
Extech SD-800 Infrared	CO_2, T, RH	±40 ppm <1000; ±5% >1000ppm; [2] ±0.8°C ±4% below 70%; 4% of reading + 1% for 70–90% range	1-min	Indoor: central, master BR, other BR
Ogawa Passive Samplers	NO_2 and NO_X	Field validation[3]: 7 d rel. dev.: 3±2% NO_2 at 11-37 ppb; 4±3% NO_X at 16-85 ppb; 10±9% (NO_X-NO_2) at 4-56 ppb	1-week	Outdoor; Indoor: central
Aeroqual 500 Series Electrochemical	NO_2	± 0.02 ppm within 0 to 0.2 ppm range	1-min	Indoor: central
GrayWolf FM-801 (Shinyei Multimode)	HCHO	± 4 ppb <40 ppb, ± 10% of reading ≥40 ppb	30-min	Indoor: central, master BR
SKC UMEx-100 Passive	HCHO	± 25%, exceeds OSHA requirements	1-week	Outdoor; Indoor: central, master BR
Onset HOBO UX100-011 Onset HOBO U23 Pro v2	T, RH	±0.21°C from 0° to 50°C ±2.5% from 10% to 90%; up to ±3.5% at 25°C including hysteresis	1-min	Indoor: central (UX100-011); Outdoor (U23);

[1] Based on manufacturer specifications unless noted otherwise. Table S1 in Supporting Information provides some additional information. [2] Manufacturer indicates ± 40 ppm for CO2<1000 ppm; the cited value of ±50 ppm reflects our group's experience (unpublished) with the monitors. [3] Field validation in California reported by Singer et al.[38]

Table 2. Selected House and Occupancy Characteristics[1]

Parameter	HENGH	CNHS
Year Built[2]	2011-2017	2002-2005
Monitoring	07/2016–04/2018	08/2006–03/2007
Age at Testing[3]	91% ≤3 years	90% ≤4.3 years
Floor Area (m^2)[4]		
Mean	244	248
Median (10^{th}–90^{th})	243 (146–339)	251 (160–339)
Density (m^2/person)		
Mean	88	90
Median (10^{th}-90^{th})	77 (45–143)	80 (48–142)
Gas Cooking Burners		
Cooktop / Oven	100% / 43%	2% / 27%

[1]Additional information in SI Tables S5-S15. [2]Table S5. [3]Table S6. [4]Table S7. [5]Others had electric cooking.

Table 3. Time-averaged pollutant concentrations in California homes built 2011-2017 (HENGH, current study) and 2002-2005 (CNHS, Offermann, 2009).

Location	**HCHO**	**(ppb)**	**$PM_{2.5}$**	($\mu g/m^3$)	**NO_2**	**(ppb)**	**CO_2**	**(ppm)**
Statistic	**HENGH**	**CNHS[1]**	**HENGH**	**CNHS[1]**	**HENGH**	**CNHS[1]**	**HENGH**	**CNHS[2]**
Indoor	N=68	N=105	N=67	N=28	N=66	N=29	N=69	N=107
Mean	19.8	35.0	7.5	13.4	5.8	5.2	620	610
Median	18.2	29.3	4.8	10.5	4.5	1.6	608	564
10^{th}–90^{th}	13–28	11–70	1.6–16	6.0–31	1.1–12	1.4–12	481–770	405–890
Outdoor	N=66	N=39[4]	N=67[3]	N=11[4]	N=65	N=11[4]	No data	No data
Mean	2.2	1.8	9.3, 10.5	7.9	5.4	2.1		
Median	2.3	1.7	6.8, 9.7	8.7	3.6	1.5		
10^{th}–90^{th}	1.4–3.1	0.6–2.8	2.7–18.1, 5.3–16.7	5.0–10	0.1–11	1.4–1.7		

[1] From CNHS "all-home" sample frame dataset. [2] From Table 39 of Offermann (2009). [3] The first set of outdoor values are from unadjusted, on-site photometer measurements over the full monitoring period at each home; the second set are from air quality monitoring stations nearby to the homes and use only the 24-h data from complete days during each monitoring period. [4] The CNHS collected one outdoor sample per cluster of 2-3 homes in close proximity. Outdoor formaldehyde collected at clusters for all 108 homes. Outdoor samples for $PM_{2.5}$ and NO_2 collected for clusters that included 28 homes total.

Table 4. Discomfort rates reported by participants in California homes built with code-required mechanical ventilation (HENGH), recent online survey of homes mostly built before dwelling unit ventilation was required, and field study of homes built before ventilation was required (CNHS).

Parameter	HENGH field study (n=68)[1]	HENGH online survey (n=2271)[1]	CNHS[2]
Too hot	Winter: 14% Summer: 31%	Winter: 10% Summer: 41%	19%
Too cold	Winter: 29% Summer: 4%	Winter: 20% Summer: 9%	15%
Too dry	9%	11%	8%
Too damp (HENGH) / too humid (CNHS)	1%	2%	2%
Too much air movement (HENGH) / too drafty (CNHS)	1%	5%	0%
Too stagnant / not enough air movement	21%	18%	12%
Too dusty	Not asked	Not asked	11%
Musty odor	1%	3%	13% in bathroom 1-3% other locations

[1] When asked how often does the discomfort occurs, respondent selected “few times per week” or “daily”. [2] From Table 44 of Offermann (2009), respondents reporting that the discomfort occurred during 3 weeks prior. For musty odor, the CNHS asked if participants had “observed, seen or smelled mold” in the past week in various locations.

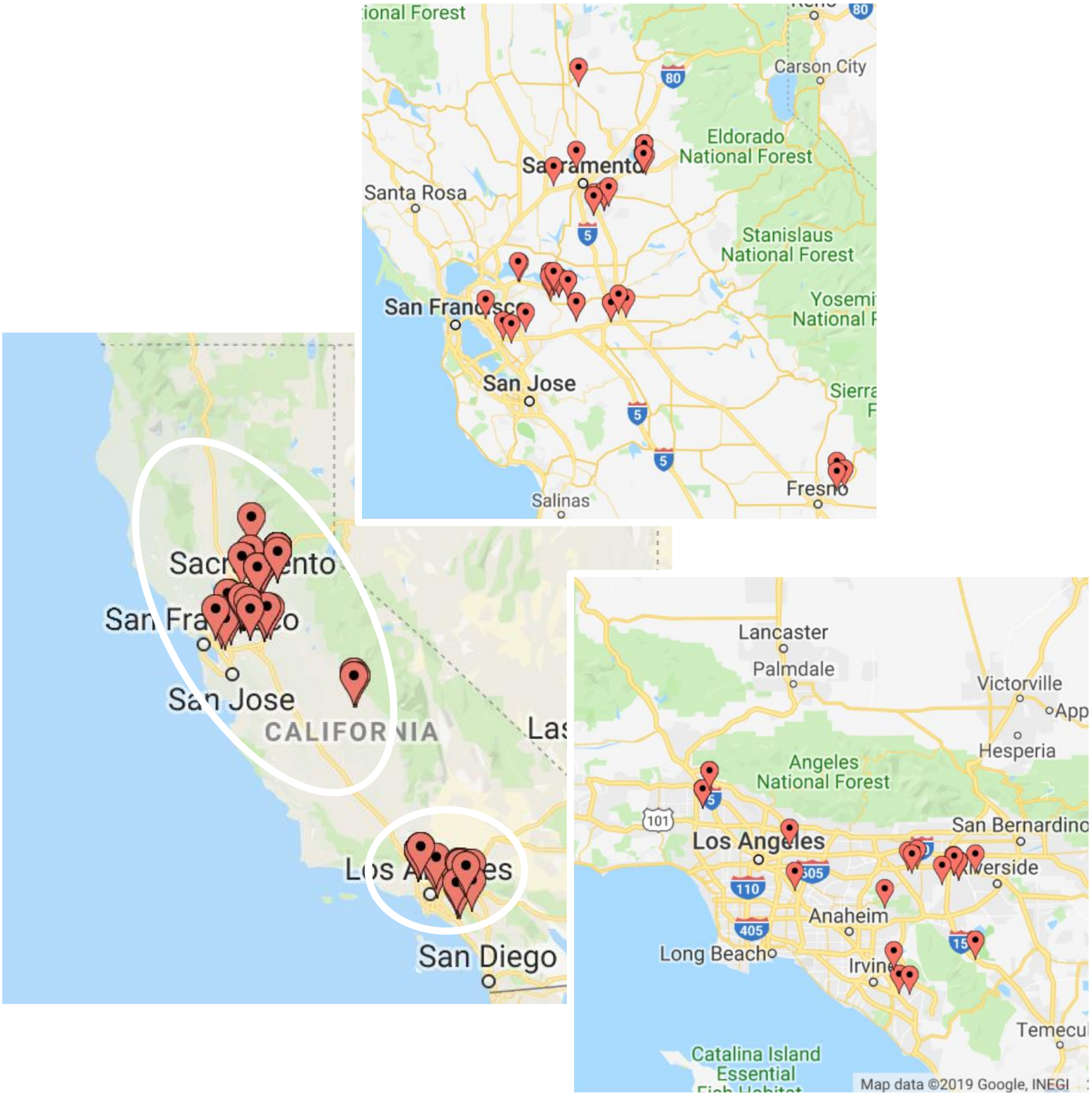

Figure 1. Locations of study homes.

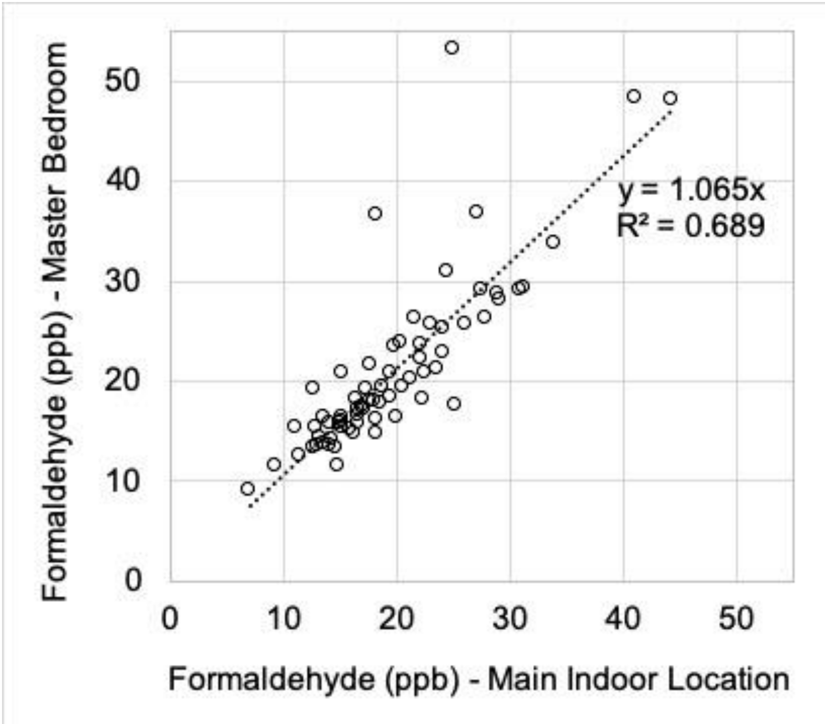

Figure 2: One-week integrated formaldehyde measured with passive samples: Comparison of concentrations in master bedroom and large, open common room (main) indoor locations

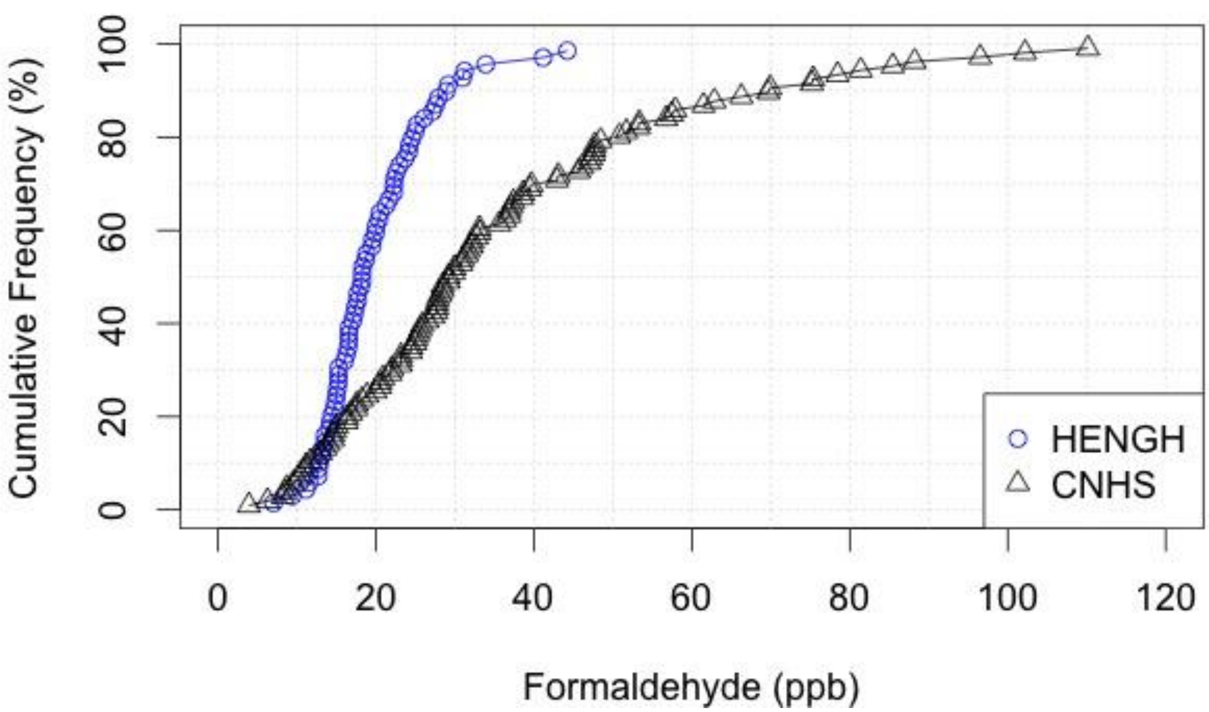

Figure 3: Time-Integrated formaldehyde concentrations measured in California homes built before (CNHS) and after (HENGH) mechanical ventilation was required.

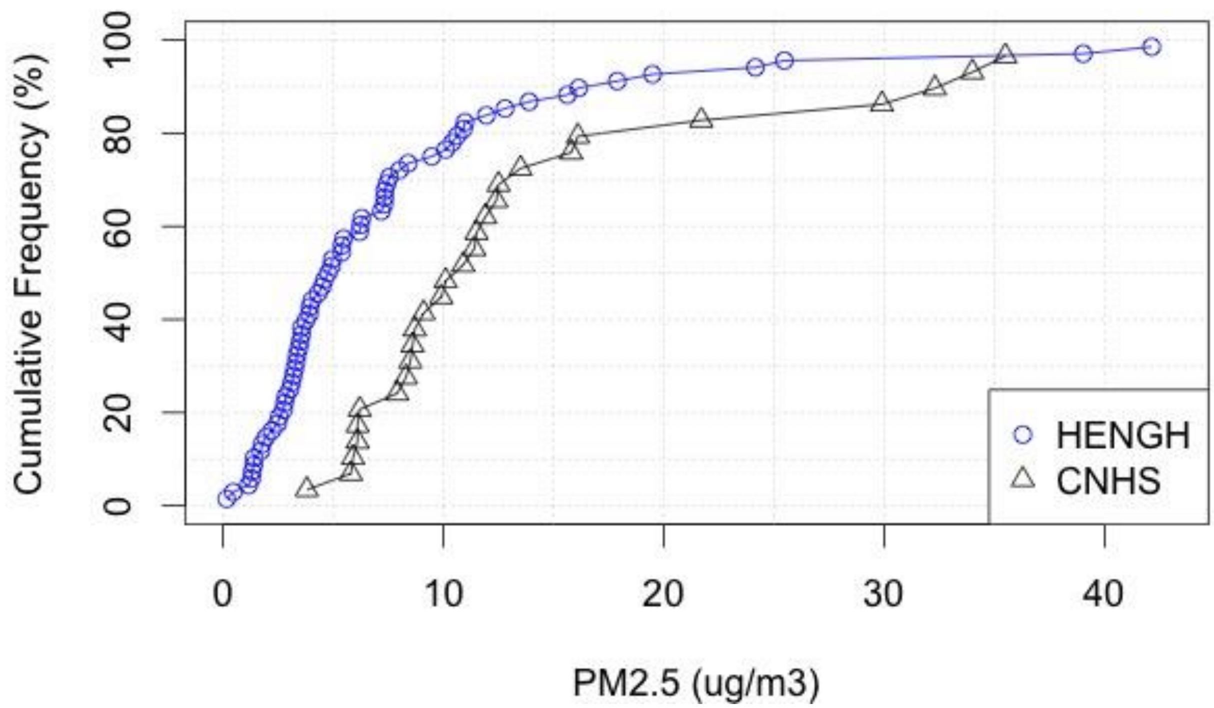

Figure 4: Time-averaged PM2.5 concentrations measured in California homes built before (CNHS) and after (HENGH) mechanical ventilation was required.

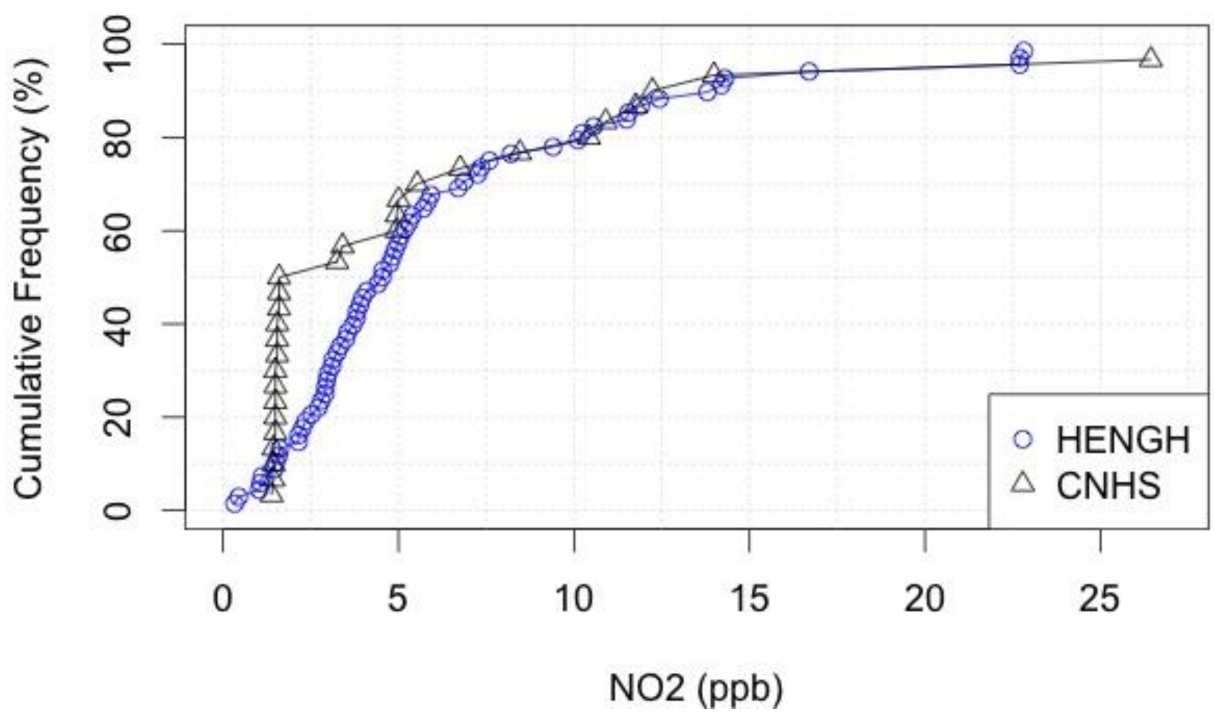

Figure 5: Time-integrated NO_2 concentrations measured in California homes built before (CNHS) and after (HENGH) mechanical ventilation was required. Most CNHS homes had electric cooking and all HENGH homes had gas cooking burners.

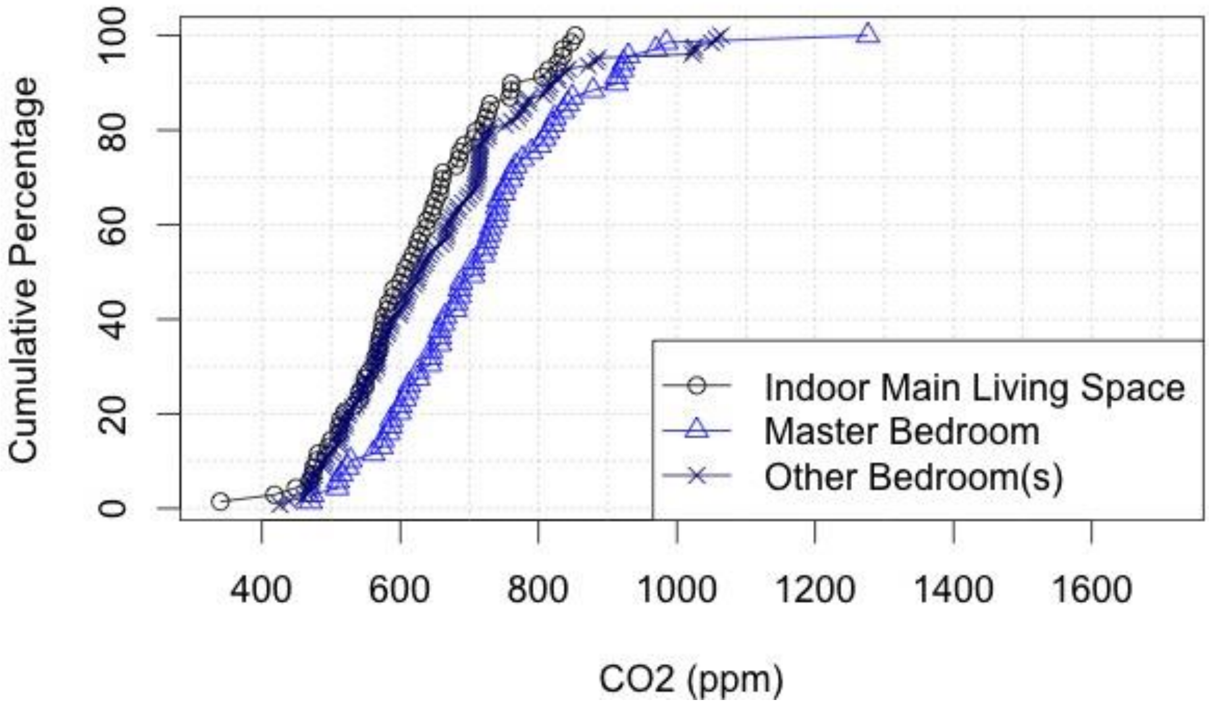

Figure 6: Time-average CO_2 concentrations in indoor main living space and bedrooms.

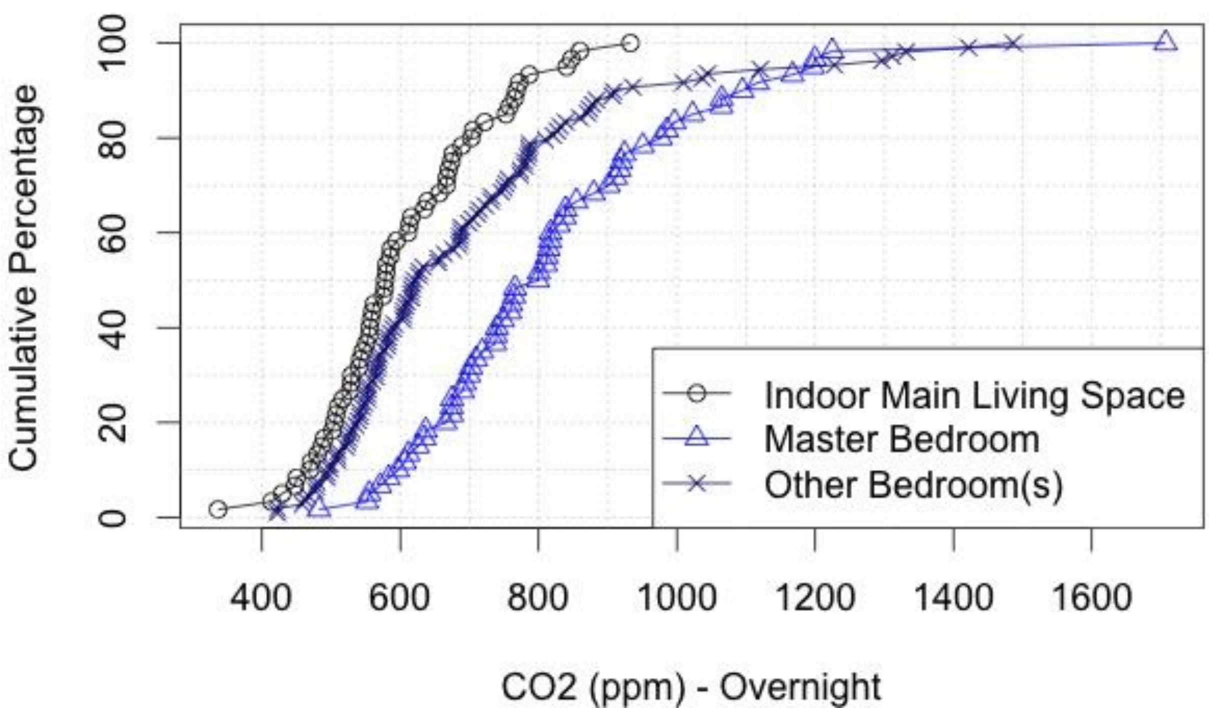

Figure 7: Nighttime (midnight-5am) CO_2 in indoor main living space and bedrooms

5. References

1. Piazza T, Lee R, Sherman M, Price P. *Study of Ventilation Practices and Household Characteristics in New California Homes. Final Report for Energy Commission Contract 500-02-023 and ARB Contract 03-026.* CEC-500-2007-033; Sacramento, CA: California Energy Commission and California Air Resources Board; June 2007, 2007.
2. Offermann FJ. *Ventilation and Indoor Air Quality in New Homes*. CEC-500-2009-085; Sacramento, CA: California Energy Commission and California Air Resources Board; 2009.
3. Lawrence Berkeley National Lab. LBNL. Ventilate Right: Ventilation Guide for New and Existing California Homes. https://homes.lbl.gov/ventilate-right/ashrae-standard-622 Last Accessed:05-Oct-2019-
4. Logue JM, Klepeis NE, Lobscheid AB, Singer BC. Pollutant Exposures from Natural Gas Cooking Burners: A Simulation-Based Assessment for Southern California. *Environ Health Perspect.* 2014;122:43-50.
5. Mullen NA, Li J, Russell ML, Spears M, Less BD, Singer BC. Results of the California Healthy Homes Indoor Air Quality Study of 2011-2013: impact of natural gas appliances on air pollutant concentrations. *Indoor Air.* 2016;26:231-45.
6. Chan WR, Kim Y-S, Less BD, Singer BC, Walker IS. *Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation*. LBNL-2001200; Berkeley CA: Lawrence Berkeley National Laboratory; 2019.
7. California Air Resources Board. CARB. Composite Wood Products Airborne Toxic Control Measure. www.arb.ca.gov/toxics/compwood/compwood.htm Last Accessed:05-Oct-2019-
8. Chan WR, Kim Y-S, Singer BC, Walker IS, Sherman MH. *Healthy Efficient New Gas Homes (HENGH) Field Study Protocol*. LBNL-1005819; Berkeley, CA: Lawrence Berkeley National Lab; 2016.
9. Walker IS, Wray CP, Dickerhoff DJ, Sherman MH. *Evaluation of flow hood measurements for residential register flows*. LBNL-47382; Berkeley CA: Lawrence Berkeley National Laboratory; 2001.
10. Dacunto PJ, Cheng KC, Acevedo-Bolton V, Jiang RT, Klepeis NE, Repace JL, Ott WR, Hildemann LM. Real-time particle monitor calibration factors and PM2.5 emission factors for multiple indoor sources. *Environmental Science-Processes & Impacts.* 2013;15:1511-1519.
11. Tryner J, Good N, Wilson A, Clark ML, Peel JL, Volckens J. Variation in gravimetric correction factors for nephelometer-derived estimates of personal exposure to PM2.5. *Environ Pollut.* 2019;250:251-261.
12. Singer BC, Delp WW. Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. *Indoor Air.* 2018;28:624-639.
13. Zhang J, Marto JP, Schwab JJ. Exploring the applicability and limitations of selected optical scattering instruments for PM mass measurement. *Atmos. Meas. Tech.* 2018;11:2995-3005.
14. Wang XL, Chancellor G, Evenstad J, Farnsworth JE, Hase A, Olson GM, Sreenath A, Agarwal JK. A Novel Optical Instrument for Estimating Size Segregated Aerosol Mass Concentration in Real Time. *Aerosol Sci Technol.* 2009;43:939-950.
15. Carter EM, Jackson MC, Katz LE, Speitel GE. A coupled sensor-spectrophotometric device for continuous measurement of formaldehyde in indoor environments. *J Exposure Sci Environ Epidemiol.* 2014;24:305-310.

16. Maruo YY, Yamada T, Nakamura J, Izumi K, Uchiyama M. Formaldehyde measurements in residential indoor air using a developed sensor element in the Kanto area of Japan. *Indoor Air.* 2010;20:486-493.

17. Offermann FJ, Hodgson AT. In *Accurancy of Three Types of Formaldehyde Passive Samplers*, Indoor Air 2018, Philadelphia PA, 2018; International Society of Indoor Air Quality Sciences: Philadelphia PA, 2018.

18. Matthews TG, Thompson CV, Wilson DL, Hawthorne AR, Mage D. Air velocities inside domestic environments: An important parameter in the study of indoor air quality and climate. *Environ Int.* 1989;15:545-550.

19. Chan WYR, Joh J, Sherman MH. Analysis of air leakage measurements of US houses. *Energ Buildings.* 2013;66:616-625.

20. Salthammer T, Mentese S, Marutzky R. Formaldehyde in the Indoor Environment. *Chem Rev.* 2010;110:2536-2572.

21. Allen RW, Adar SD, Avol E, Cohen M, Curl CL, Larson T, Liu LJS, Sheppard L, Kaufman JD. Modeling the Residential Infiltration of Outdoor PM2.5 in the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air). *Environ Health Perspect.* 2012;120:824-830.

22. Wallace LA, Mitchell H, O'Connor GT, Neas L, Lippmann M, Kattan M, Koenig J, Stout JW, Vaughn BJ, Wallace D, Walter M, Adams K, Liu LJS. Particle concentrations in inner-city homes of children with asthma: The effect of smoking, cooking, and outdoor pollution. *Environ Health Perspect.* 2003;111:1265-1272.

23. Allen R, Larson T, Sheppard L, Wallace L, Liu LJS. Use of real-time light scattering data to estimate the contribution of infiltrated and indoor-generated particles to indoor air. *Environ Sci Technol.* 2003;37:3484-3492.

24. Meng QY, Spector D, Colome S, Turpin B. Determinants of indoor and personal exposure to PM2.5 of indoor and outdoor origin during the RIOPA study. *Atmos Environ.* 2009;43:5750-5758.

25. Rodes CE, Lawless PA, Thornburg JW, Williams RW, Croghan CW. DEARS particulate matter relationships for personal, indoor, outdoor, and central site settings for a general population. *Atmos Environ.* 2010;44:1386-1399.

26. Mishra AK, van Ruitenbeek AM, Loomans M, Kort HSM. Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults. *Indoor Air.* 2018;28:339-351.

27. Strom-Tejsen P, Zukowska D, Wargocki P, Wyon DP. The effects of bedroom air quality on sleep and next-day performance. *Indoor Air.* 2016;26:679-686.

28. Wallner P, Munoz U, Tappler P, Wanka A, Kundi M, Shelton JF, Hutter HP. Indoor Environmental Quality in Mechanically Ventilated, Energy-Efficient Buildings vs. Conventional Buildings. *Int J Environ Res Public Health.* 2015;12:14132-14147.

29. Wallner P, Tappler P, Munoz U, Damberger B, Wanka A, Kundi M, Hutter HP. Health and Wellbeing of Occupants in Highly Energy Efficient Buildings: A Field Study. *Int J Environ Res Public Health.* 2017;14.

30. Lajoie P, Aubin D, Gingras V, Daigneault P, Ducharme F, Gauvin D, Fugler D, Leclerc JM, Won D, Courteau M, Gingras S, Heroux ME, Yang W, Schleibinger H. The IVAIRE project - a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. *Indoor Air.* 2015;25:582-597.

31. Balvers J, Bogers R, Jongeneel R, van Kamp I, Boerstra A, van Dijken F. Mechanical ventilation in recently built Dutch homes: technical shortcomings, possibilities for improvement, perceived indoor environment and health effects. *Architectural Science Review.* 2012;55:4-14.

32. Laverge J, Delghust M, Janssens A. Carbon Dioxide Concentrations and Humidity Levels Measured in Belgian Standard and Low Energy Dwellings with Common Ventilation Strategies. *International Journal of Ventilation.* 2015;14:165-180.

33. Eklund K, Kunkle R, Banks A, Hales D. *Pacific Northwest Residential Effectiveness Study - FINAL REPORT* NEEA Report #E15-015; Portland, OR: Prepared by Washington State University Energy Program; 2015.

34. Sonne JK, Withers C, Vieira RK. *Investigation of the effectiveness and failure rates of whole-house mechanical ventilation systems in Florida*. FSEC-CR-2002-15; Cocoa, FL: June 1, 2015, 2015.

35. Hult EL, Willem H, Price PN, Hotchi T, Russell ML, Singer BC. Formaldehyde and acetaldehyde exposure mitigation in US residences: in-home measurements of ventilation control and source control. *Indoor Air.* 2015;25:523-535.

36. Frey SE, Destaillats H, Cohn S, Ahrentzen S, Fraser MP. The effects of an energy efficiency retrofit on indoor air quality. *Indoor Air.* 2015;25:210-219.

37. Huangfu YB, Lima NM, O'Keeffe PT, Kirk WM, Lamb BK, Pressley SN, Lin BY, Cook DJ, Walden V, Jobson BT. Diel variation of formaldehyde levels and other VOCs in homes driven by temperature dependent infiltration and emission rates. *Build Environ.* 2019;159.

38. Singer BC, Hodgson AT, Hotchi T, Kim JJ. Passive measurement of nitrogen oxides to assess traffic-related pollutant exposure for the East Bay Children's Respiratory Health Study. *Atmos Environ.* 2004;38:393-403.