Title

Indoor air quality in new and renovated low-income apartments with mechanical ventilation and natural gas cooking in California

Permalink

https://escholarship.org/uc/item/55d7r5gp

Journal

Indoor Air, 31(3)

ISSN

0905-6947

Authors

Zhao, Haoran
Chan, Wanyu R
Cohn, Sebastian
et al.

Publication Date

2021-05-01

DOI

10.1111/ina.12764

Peer reviewed

Indoor Air Quality in New and Renovated Low-Income Apartments with Mechanical Ventilation and Natural Gas Cooking in California

Haoran Zhao[1], Wanyu R. Chan[1], Sebastian Cohn[2], William W. Delp[1], Iain S. Walker[1], Brett C. Singer[1*]

[1]Residential Building Systems Group and Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[2]Association for Energy Affordability, Emeryville, CA, USA

*Corresponding author:
Dr. Brett C. Singer
Lawrence Berkeley National Laboratory
1 Cyclotron Road Mail Stop 90R2121
Berkeley, CA, 94720
Phone: (510) 486-4779
Email: bcsinger@lbl.gov

Acknowledgements

This research was supported by the California Energy Commission via Contract PIR-16-012, the U.S. Department of Energy Building America Program via Contract DE-AC02-05CH11231, and the U.S. Environmental Protection Agency via Interagency Agreement DW-89-9232201-7. The authors thank our colleagues at LBNL their contributions: Toshifumi Hotchi prepared instrumentation and assisted with data collection at Sites 1-2; Marion Russell supervised preparation and analysis of passive samples; Yuhan Wang assisted with data analysis. We are also deeply appreciative of the building managers and participants.

Keywords

Multifamily; Nitrogen dioxide; Fine particulate matter; Formaldehyde; Range hood; Codes and standards

Abstract

This paper presents pollutant concentrations and performance data for code-required mechanical ventilation equipment in 23 low-income apartments at 4 properties constructed or renovated 2013-2017. All apartments had natural gas cooking burners. Occupants pledged to not use windows for ventilation during the study but several did. Measured airflows of range hoods and bathroom exhaust fans were lower than product specifications. Only eight apartments operationally met all ventilation code requirements. Pollutants measured over one week in each apartment included time-resolved fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), formaldehyde and carbon dioxide (CO_2) and time-integrated formaldehyde, NO_2 and nitrogen oxides (NO_X). Compared to a recent study of California houses with code-compliant ventilation, apartments were smaller, had fewer occupants, higher densities, and higher mechanical ventilation rates. Mean $PM_{2.5}$, formaldehyde, NO_2, and CO_2 were 7.7 $\mu g/m^3$, 14.1 ppb, 18.8 ppb, and 741 ppm in apartments; these are 4% lower, 25% lower, 165% higher, and 18% higher compared to houses with similar cooking frequency. Four apartments had weekly $PM_{2.5}$ above the California annual outdoor standard of 12 $\mu g/m^3$ and also discrete days above the World Health Organization 24-h guideline of 25 $\mu g/m^3$. Two apartments had weekly NO_2 above the California annual outdoor standard of 30 ppb.

Practical Implications

All 23 studied apartments had mechanical ventilation equipment with specifications that met state requirements, but measured airflows were substantially below those specification values and only 8 of 23 apartments had equipment that *operationally* met all code requirements; this suggests a need for improved on-site performance verification of ventilation equipment in new construction. The similarity of $PM_{2.5}$ concentrations in low-income apartments to those observed in larger and less densely occupied, single-detached homes of similar vintage and similar cooking frequency, and lower formaldehyde in the apartments are consistent with the apartments having higher mechanical ventilation airflows compared to houses. Higher NO_2 in apartments compared to houses with similar cooking frequencies indicates a higher risk from gas cooking burners in smaller spaces and a need for occupants to more effectively employ their venting range hoods.

Introduction

For many people throughout the world, home is the location of greatest intake of air pollution. This occurs largely because we spend so much of our time at home.[1, 2] In-home pollutants include those emitted from the buildings or activities inside and also outdoor air pollutants that enter with intentional ventilation and uncontrolled infiltration. Air pollutants are emitted from furnishings, finishes and structural materials; and various chemical and biological contaminants are generated by occupants and activities. In addition to recognized hazards such as smoking and irritants in concentrated cleaning products, activities that many consider innocuous emit air pollutants in quantities that yield concentrations in air that exceed health guidelines. Numerous studies have reported that cooking is an important source of fine particulate matter ($PM_{2.5}$)[3-9] and gas cooking burners emit nitrogen dioxide (NO_2) and other nitrogen oxides (NO_X) in amounts that can cause concentrations to exceed threshold values of health-based ambient air quality standards.[10-13]

High performance residential buildings have airtight envelopes to reduce uncontrolled outdoor airflow and mechanical ventilation equipment to help control contaminants from indoor sources. Standard 62.2 of the ASHRAE building performance society requires mechanical systems that provide continuous (or equivalent time varying) ventilation at minimum airflows tied to dwelling size and occupant capacity.[14, 15] The standard additionally requires an exhaust fan in each bathroom and a kitchen exhaust fan or range hood. Starting with the 2007 update to the statewide Title 24 Building Code – specifically in the Building Energy Efficiency Standards (BEES) that comprise Part 6 of the Code – California has required all newly constructed residences and major renovations to have mechanical ventilation equipment that is generally in line with the requirements of Standard 62.2.[16]

The recently completed Healthy, Efficient New Gas Homes (HENGH) study of 70 California single, detached houses built since 2011 found that almost all had mechanical ventilation equipment with airflows that met the BEES requirements.[17-19] Measurements made in the homes while the dwelling unit MV systems were operating found that both formaldehyde and $PM_{2.5}$ were substantially lower than reported in the California New Homes Study (CNHS) conducted a decade earlier in homes constructed in 2002-2005.[20] The lower formaldehyde concentrations resulted both from the operation of dwelling unit MV systems reducing the number of homes with very low ventilation and also from state and federal regulations that limit formaldehyde emissions from manufactured wood materials.[21, 22] The lower $PM_{2.5}$ in HENGH homes is thought to have resulted from a combination of lower indoor emissions and better filtration since outdoor $PM_{2.5}$ was higher in HENGH than in CNHS. Time-averaged NO_2 levels in HENGH homes were low overall and only marginally higher than in CNHS homes despite the HENGH homes all having natural gas cooktops as compared to only 2% of CNHS homes. IAQ satisfaction was high in both the HENGH and CNHS, and also in large surveys conducted by mail prior to the CNHS field study[23] and by email / internet prior to the HENGH field study.[24] An important caveat to these findings is that formaldehyde concentrations in almost all HENGH homes were still above California's chronic reference exposure limit of 9 $\mu g/m^3$ / 7 ppb (https://oehha.ca.gov/air). It is also important to note that the general MV fan was turned off in roughly three quarters of the HENGH homes when the field research teams first arrived (before being turned on for the study).

The HENGH study did not address whether California's mechanical ventilation standards are providing acceptable IAQ also for apartments, which generally are smaller and have higher occupant density. As one point of comparison, Noris et al. reported mean indoor $PM_{2.5}$ of 8, 42, and 23 μg/m^3 for groups of 6 apartments each that had energy efficiency retrofits with MV added at three separate properties in California.[25] Two of the sites had much higher indoor $PM_{2.5}$ than the HENGH houses, which had a mean of 9.7 μg/m^3. The high $PM_{2.5}$ occurred despite the retrofits including wall-mounted room air filtration devices. Other studies in new or retrofitted U.S. apartments with mechanical ventilation installed to meet ASHRAE 62.2 requirements reported mean $PM_{2.5}$ concentrations similar[26] or higher[27, 28] than those in HENGH. NO_2 also was lower for HENGH homes (indoor / outdoor means of 5.8 / 5.4 ppb) than apartments with gas cooking studied by Noris et al. (17 / 29 ppb and 17 / 16 ppb).[25]

In light of the evidence that (a) use of gas cooking burners can lead to short-term NO_2 concentrations that exceed health based outdoor standards, (b) cooking is a substantial source of $PM_{2.5}$ and (c) smaller homes with higher occupant densities may have higher air pollutant levels from occupant activities owing to more frequent emissions and less dilution, this study aimed to assess the adequacy of California's MV standards in apartments with regularly-used gas cooking equipment and with occupant densities substantially higher than those seen in the recent HENGH detached house study.

Methods and Materials

Apartment Characteristics

The study inclusion criteria were for apartment units to have mechanical ventilation (MV) equipment meeting the requirements of California's Title 24 residential building code and a natural gas cooking appliance. Required MV equipment included an exhaust fan in each bathroom, a kitchen exhaust fan or range hood, and equipment providing regular ventilation to the dwelling unit – each having specifications that met the code-minimum airflow requirements. It was an additional study aim to focus on apartments that were at least moderately airtight to the outside and to other areas of the building, with a target total air leakage <0.3 cfm per ft^2 (150 L/s per 100 m^2) of boundary area at 50 Pa pressure difference to the outdoors. This limit is specified in the 2019 version of ASHRAE 62.2 and is required in the 2019 version of California's BEES for apartments that use unbalanced ventilation. This criterion was relaxed to accommodate the inclusion of the low-income apartments at Sites 1 and 4 (0.43 and 0.51 cfm per ft^2, respectively).

Participation criteria included routine daily use of the gas cooking appliance, a prohibition on smoking in the apartment, and agreement to refrain from using windows or doors as a means of regular ventilation during the week of monitoring. These requirements were noted in flyers used to advertise in each site, communicated during the eligibility screening call, and listed in the participant consent forms. Despite these notices, there was substantial window or door opening in several apartments during monitoring and also indications of smoking in some apartments.

The study was approved by the institutional review board of LBNL. Details about the recruitment and screening procedures are provided in the Supporting Information (SI).

Overview of Data Collection

Each property was visited in advance of the week of monitoring to confirm the presence of compliant MV equipment; this was done by inspecting 2-4 unoccupied units per site. Since the first two sites were recent renovations of older buildings, blower door tests were conducted on the inspected units to assess airtightness. Recruitment commenced following this visit.

During the first visit, teams provided the participant with a paper version of the survey to obtain information about satisfaction with air quality and thermal conditions in the home and routine activities that impact ventilation and IAQ. Characteristics of mechanical ventilation equipment, cooking appliances, and thermal conditioning systems were documented and unit airtightness and ventilation equipment airflows were measured. Temperature, humidity, carbon dioxide and air pollutant concentrations were measured inside each apartment and air pollutant concentrations were measured outdoors on site. Sensors were installed to monitor use of gas cooking burners, ventilation equipment, and natural ventilation. Participants were asked to record occupancy and activities during each day of monitoring. Surveys and activity logs were collected and equipment was removed after one week of monitoring in each apartment. The incentive of a $300 gift card was provided for completion of all study elements.

Measurement Equipment and Procedures

Apartment Air Leakage

Air leakage of each apartment was measured using a TEC Minneapolis Blower Door System with DG-700 digital manometer (energyconservatory.com). At the first two sites, a single-point depressurization test was conducted at 50 Pa pressure difference. For the last two sites, data were recorded for 5 depressurization levels ranging from 10 to 60 Pa. In units 901 and 906 (Site 1), the blower door was placed in corridor-facing entry doors and the pressure connection between the corridor to outside was not checked; other tests were done in doorways directly to outdoors.

Exhaust Fan Airflows

Airflows of bath exhaust fans were measured using a TEC Exhaust Fan Flow Meter. Range hood airflows were measured using a balanced-pressure flow hood method described by Walker et al.[29] A pressure-controlled variable-speed fan (TEC Minneapolis Duct Blaster) was connected to the exhaust inlet of the range hood using a transition piece that was adapted onsite to cover the entire underside opening. The fan was controlled to match the flow of the range hood while maintaining neutral pressure with the room and the Duct Blaster flow meter used to determine the range hood flow.

Ventilation and Cooking Burner Monitoring

The operation of each mechanical system that contributed to ventilation was monitored. Most range hoods and bath exhaust fans were monitored with a logging vane anemometer (Digisense WD-20250-22). After an anemometer was installed, a range hood was operated at each available setting and the anemometer output for each speed setting was recorded. This enabled analysis of usage by speed setting. A motor on/off sensor (Onset HOBO UX90-004) was used to monitor the range hood in four homes, a bath exhaust fan in two homes and a venting clothes dryer in seven units. To check participants' adherence to keeping doors and windows closed, state sensors (Onset HOBO UX90-001) were used to monitor the most often used exterior doors and windows; details are in the SI.

Maxim iButton DS1922T temperature sensors were affixed to cooktops and ovens and use was inferred from analysis of the temperature signals. At Sites 3 and 4, toasters and toaster ovens found in 5 apartments were monitored with plug load loggers (Onset HOBO UX120-018).

Operation of the furnace or heat pump in each apartment was discerned from the log of a temperature sensor placed at the supply air register or on the wall furnace.

Measurements of Air Quality Indoors and Outdoors

Air pollutant concentrations and environmental parameters were measured at several locations inside each apartment and at up to two outdoor locations at each site. The instruments used and parameters measured at each location are shown in Table 1. The central indoor package was generally located in the large room that includes the kitchen, dining area, and living room; at this location, instruments and samplers were placed on a small, wire-mesh shelving unit as shown in Figure S1. For apartments with one or more bedrooms (BR), additional monitors were placed in the master bedroom, on a dresser or other horizontal surface typically between 0.5 and 2 m high. In the studios at Site 4, the “master BR” station was at a second location in the main room as far as feasible from the “central” monitors.

Table 1. Devices used for monitoring indoor air quality [a]

Measurement Device	Para-meters	Accuracy [b]	Data	Sampling Locations
GrayWolf FM-801 (Shinyei Multimode)	HCHO	± 4 ppb <40 ppb, ± 10% of reading ≥40 ppb	30 min	Central indoor Master BR
SKC UMEx-100 Passive	HCHO	± 25%, exceeds OSHA requirements [c]	1 week	Outdoor Central indoor Master BR
Ogawa Passive Samplers	NO_2 NO_X	(Based on published data [c]) 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 Central indoor
Clarity Node	NO_2, Optical PM_1, $PM_{2.5}$, PM_{10}	NO_2: ± 30 ppb at 0- 200 ppb; ± 15% of reading > 200 ppb PM: ± 10 µg/m^3 at 0-100 µg/m^3; within ± 10% of measured value > 100 µg/m^3	Indoor: 2-3 min; Outdoor: 17 min	Outdoor Central indoor
TSI DustTrak II- 8530 (DT)	Estimated $PM_{2.5}$	±0.1% of reading or 1 µg/m^3 [e]	2 min	Outdoor Central indoor
Thermo pDR-1500 (PDR)	Estimated $PM_{2.5}$	± 5% of reading	1 min	Central indoor
37-mm PTFE filter collected by DT or pDR	Gravimetric $PM_{2.5}$	± 15%, based on our co-location data	1 week	Outdoor Central indoor
IQAir Air Visual Pro Monitor (AVP)	CO_2, T, RH, Optical $PM_{2.5}$, PM_{10}	CO_2: ±50ppm or 2% of reading [e] PM: Within 10% in effective range: 0–1798 µg/m^3 [c]	10 s to 15 min [d]	Central indoor Master BR
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	Outdoor

[a] Some of the data listed are not presented in the current paper. [b] Based on manufacturer specifications unless noted otherwise. [c] Results of a field validation [30]. [d] Frequency of data storage changes when any parameter is changing quickly. [e] Performance also assessed by multi-instrument co-location in this study, as described in text and SI.

Outdoor monitors were deployed through all intervals of apartment monitoring at each site. Outdoor packages always included a TSI DustTrak (DT) real time photometer deployed in a TSI enclosure and model 801850 heated inlet system and passive NO_X, NO_2, and formaldehyde samplers. Starting with Site 2, two Clarity Nodes were also deployed outside, with at least one deployed close to other devices. The intent was to measure at an on-site location not impacted by local sources such as driveways or smoking areas. At Site 1, outdoor monitors were on a 2nd floor balcony in an interior courtyard. Since there was evidence of smoking on the balcony, residents of the unit were requested to refrain from smoking in that area during the monitoring week. (The area is supposed to be smoke-free by building rules). At Site 2, both primary and secondary packages were on interior courtyard patios outside of ground-floor study apartments. At Sites 3 and 4 all outdoor monitoring equipment was placed on the roof.

Quality assurance procedures for the air quality measurements are described in the SI.

Survey and Activity Log

A participant from each studied apartment completed a survey that asked questions about the household, their satisfaction with environmental conditions in their home, their use of ventilation equipment and other activities that impact IAQ. Each participant was also asked to complete a daily log to document occupancy and activities that impact IAQ through all days of on-site monitoring. The activity log sheet is provided at the end of the SI.

Adjustments for Indoor and Outdoor Time-Resolved $PM_{2.5}$ and NO_2

The DustTrak, AVP and Clarity use optical PM sensors that respond differently to varied aerosols sources.[31] Their time series data thus need to be adjusted to provide an accurate estimate of PM mass concentration. For this study, we used a pooled adjustment for indoor time-resolved $PM_{2.5}$. The first step was to use data from co-location measurements to assure accurate cross-calibration of the individual units of each model of device. Cross-calibrated, time-integrated responses from each unit were then compared to the filter-based estimate from the same apartments to fit a regression across all apartments. The fit from that regression was applied to the cross-calibrated time series in each apartment to estimate time-resolved mass concentration. The details of this process are described in the SI.

Time-resolved concentrations of outdoor $PM_{2.5}$ were obtained using the methods described below, with additional details in the SI. For Sites 1 and 4, we used hourly data from nearby regulatory air quality monitoring stations (AQS) to adjust the minute-by-minute data reported by the outdoor DT. For Site 2, data from the outdoor DT were determined to be invalid due to instrument failure and we used hourly data from an AQS station 1.6 km away. For Site 3, outdoor DT data was adjusted using the factor obtained for the first 5 days at Site 4 when ambient $PM_{2.5}$ was found to be representative of the regional air quality. Hourly NO_2 were obtained from the nearest AQS for all sites.

Data Analysis

Cooking Burner Events

Temperature data recorded by iButtons placed nearby to cooktop burners and oven vents were analyzed to identify individual burner use events, with specified start and end times. Burner events that overlapped in time, or consecutive events that ended and started within 3 min of one another were grouped into meal-based events. Each cooking burner event is defined by an overall start and stop time, by the burners used (cooktop only, oven only, both), by the total minutes of cooktop use (e.g. 2 cooktop burners used for 10 min each is 20 burner-min) and by the total minutes of all burner operation, including the estimated full duration of oven use not accounting for cycling of the oven burner.

NO_2 Emission Events

An algorithm was applied to set a baseline for indoor time-resolved NO_2 data reported by the Clarity monitors in this study and Aeroqual monitors in the HENGH study; rapid increases from the baselines were then identified as emission events. The algorithm searched the NO_2 time-series running average value over a trailing window of 12 h to identify the 3rd highest value, which was determined by visual reviews of the time series plots to be a robust estimate of concentrations not impacted by emission events. For each emission event, we calculated the highest 1 h mean, baseline-subtracted concentration.

Regressions and Testing for Statistical Significance

Time-integrated air pollutant concentrations measured in the apartments of this study are compared to those from a selected subset (N=40) of the single detached homes in the HENGH study such that the comparisons were made between groups of homes with similar cooking frequency during the monitoring week. Statistical significance of the potential differences in air pollutant concentrations in apartments and the subset of HENGH homes was determined by the nonparametric Mann-Whitney test. Analyses were conducted with the R statistical package.

Results and Discussion

Apartments and Household Information

Data collection occurred in 23 apartments at 4 sites that provided below market-rate rents to income-qualifying residents; subsequently described as “low-income” apartments. Two sites were in the San Francisco Bay Area of Northern California and two were in Southern California. Summary information about the sites is provide in Table S4 and information about individual units is provide in Table S5. The ranges of apartment size, occupancy and occupant density were similar for the first three sites; apartments evaluated at Site 4 were small studio or 1-bedroom units, each with 1 occupant. Summary characteristics of the studied apartments are compared to those from the recent HENGH study of California single detached houses in Table 2. The apartments had much smaller floor area, higher occupant density and much higher mechanical air exchange rates. Cumulative frequency plots of mechanical air exchanges rates in apartments and total air exchange rates in houses are shown in Figure S12. The low-income households in this study had much lower educational attainment and income than those in the recent HENGH study of market-rate, detached houses, as presented in Table S6. Sites 3 and 4 had underground garages and 69 of 70 houses from the HENGH had attached garages.

Table 2. Comparison of selected home characteristics between apartments and houses

	Apartments	Houses
Year built/renovated	Built or renovated 2013–2016	Built 2011–2017
Units studied	23 units at 4 sites	70 detached houses
Building heights	Sites 1–3: 1–3 stories Site 4: 5 stories	1–2.5 stories
Monitoring dates	02/2019–11/2019	07/2016–04/2018
Floor area (m^2)		
Mean	76	244
Median (10th–90th)	85 (35–106)	243 (146–339)
Density (m^2/occupant)		
Mean	38	88
Median (10th–90th)	33 (24–62)	77 (45–143)
ACH50[a]		
Mean	8.0	4.6
Median (10th–90th)	8.6 (2.0–14.3)	4.4 (3.4–6.0)
AER (hr^{-1})	Mech only[b]	Total[c]
Mean	0.55	0.33
Median (10th–90th)	0.54 (0.26–0.90)	0.30 (0.20–0.46)
Ventilation airflow (L/s)	Mech only[b]	Total[c]
Mean	26	56
Median (10th–90th)	20 (17–39)	55 (38–73)

[a] Air change rate at 50 Pascal pressure difference was measured by depressurizing each dwelling unit using a Minneapolis blower door system. For apartments, the leakage air comes from outdoor, corridors and other adjacent apartments. For single family houses, the leakage air comes from outdoors.

[b] Mechanical ventilation airflow and estimated mechanical AER were calculated from 21 out of 23 apartments, excluding one unit of which the ventilation airflows were not measured and one unit in which the continuous MV fan was not working.

[c] Total ventilation airflow and estimated total AER were calculated from 57 out of 70 detached houses, excluding 7 houses of which the ventilation airflows were not measured and 6 houses of which MV system were not properly operated.

Mechanical Ventilation Equipment

All of the studied apartments had kitchen and bath exhaust fans (listed in Table S7) that would comply with the mechanical ventilation airflow and sound requirements of the 2007 (through 2016) California BEES if the fans were operating and performing according to specifications. However, measured airflows met the 2007 code requirements for all mechanical equipment (bath exhaust, range hood and continuous MV) in only 8 apartments, as shown in Table S8. Three units lacked a complete set of operational equipment: one didn't have a functioning bath/central MV fan and two others didn't have working range hoods. Of the 21 apartments with airflow measurements for at least one continuous dwelling unit ventilation fan, 16 met the minimum required by the code that was applicable when they were built or renovated and 13 met the minimum requirement in the recently implemented 2019 code. Another four units were within 90% of the 2007 code requirements. Among the 63 houses in the HENGH study with measured whole-dwelling mechanical ventilation airflow, all but two had ventilation equipment that was mostly or completely compliant with the 2007 code.[17] Four apartments of 22 with measurements (18%) had at least one bath fan that did not meet the requirement of 20 cfm continuous airflow for bathrooms. Among the 65 HENGH homes with valid measurements from their two most commonly used bathrooms, 7 (11%) had at least one of two measured exhaust fans not meet the requirement of 25 L s^{-1} or 50 cfm intermittent airflow. The percentage of all bathroom exhaust fans measured in HENGH homes not meeting the requirement was 9% (19 out of 213). Including the two inoperable units, only seven of the 23 (30%) apartments had range hoods with installed airflows of at least 100 cfm at a setting that is rated to meet the requirement of $\leq$3 sone at 50 L s^{-1} (100 cfm) or higher airflow. Another five apartments had flows between 90 and 100 cfm. In the HENGH study, 34 houses (49%) had range hoods with installed airflows of at least 100 cfm at lowest setting, including 22 regular range hoods and 12 over-the-range microwaves with venting exhaust fans (OTRs). Another six houses had airflows between 90 and 100 cfm, including five OTRs and one regular range hood.

Sites 2 and 3 had mean values of measured apartment air leakage that met the limit specified in the 2019 state building code for apartments using unbalanced ventilation. While none of the sites were subject to this code when they were built or renovated, it is noteworthy that the target was met at Site 2, built in 1976 and renovated in 2016, and by Site 3, built in 2016, though not by Site 4, built in 2013.

All of the bath exhaust fans and range hoods installed in apartments had rated airflows certificated by the Home Ventilating Institute (hvi.org). Most of the installed airflows were much lower than values listed in product specifications and ratings certified by HVI, as presented in Table S7 and Table S8. The ratios of measured to rated bathroom fan and range hood airflows for each site are shown in Figure S13 and Figure S14. Across all apartments, mean and 10th–90th percentiles of the measured to rated airflow ratios were 54% and 21–90% for bath fans and 68% and 36–90% for range hoods. Decrements in installed performance were similar across sites for the bath fans whereas the range hoods at Sites 3 and 4 had airflows much closer to the rated values than did the range hoods at Sites 1 and 2. It is assumed that differences between rated and actual airflows result from higher duct static pressure as installed compared to the conditions used in the rating test. Across the 70 HENGH houses, 28 had range hoods certified by HVI, including four regular range hoods and 24 OTRs. The mean and 10th–90th percentiles of the ratios of installed to rated range hood and OTR airflows were 75% and 38-112% for the houses.

Twenty-two apartments had exhaust fans that were running to provide continuous ventilation when the research team first arrived at the apartment. This is in stark contrast to the finding in the HENGH detached house study in which ventilation fans were turned *off* in roughly three quarters of the homes when researchers arrived. The key difference is that the fans in the apartments were wired to operate continuously with no switch to turn them off.

When asked in the survey if “anyone in the household knows how to operate or adjust the mechanical ventilation system”, nine participants in apartments didn’t respond, five selected “I don’t know” (if anyone in the household knows), five said no, three said yes, and one correctly noted that “the system cannot be turned off or adjusted”. Only three of 14 who responded said that the mechanical ventilation system had been explained to them when they moved in.

Use of Windows and Doors

According to both activity log and sensor data, there was substantial window and door opening for ventilation in several apartments. In contrast to the HENGH houses, in which 47 (67%) reported no window use during monitoring, occupants from only three apartments (13%) reported that they fully complied with the expectation to keep windows closed during the test period. Additional details are provided in SI Tables S9–S10 and Figure S15.

Occupancy and Cooking Frequency

Occupancy log data obtained from 18 apartments indicate that they were occupied for more hours of the day, on average, than the HENGH detached houses. The mean fraction of occupied hours in apartments was 85% with 10th–90th range of 68–100%. Additional details are in the SI.

The recruiting and consent materials for the apartment study stated the expectation that participants should routinely use their cooking appliance “on a daily or almost daily basis” whereas the detached house study had no criterion related to cooking. Unsurprisingly, the frequency of cooktop and oven use was higher in the apartments as a group, as indicated in Figure 1. One apartment (903) that appears to have used the oven for overnight heating, was excluded in the cooking frequency duration analysis. The apartments had means of 2.2 burner events and 51 min of cooktop burner use, per day. The overall sample of single family detached houses (SFD-all in Figure 1) had means of 1.3 events and 31 cooktop burner min, per day. To provide comparisons of apartments and homes with similar levels of cooking, we selected the subset of 40 houses that did the most cooking; those houses (SFD-Top40) had means of 2.1 cooking burner events per day and 48 cooktop burner min/day.

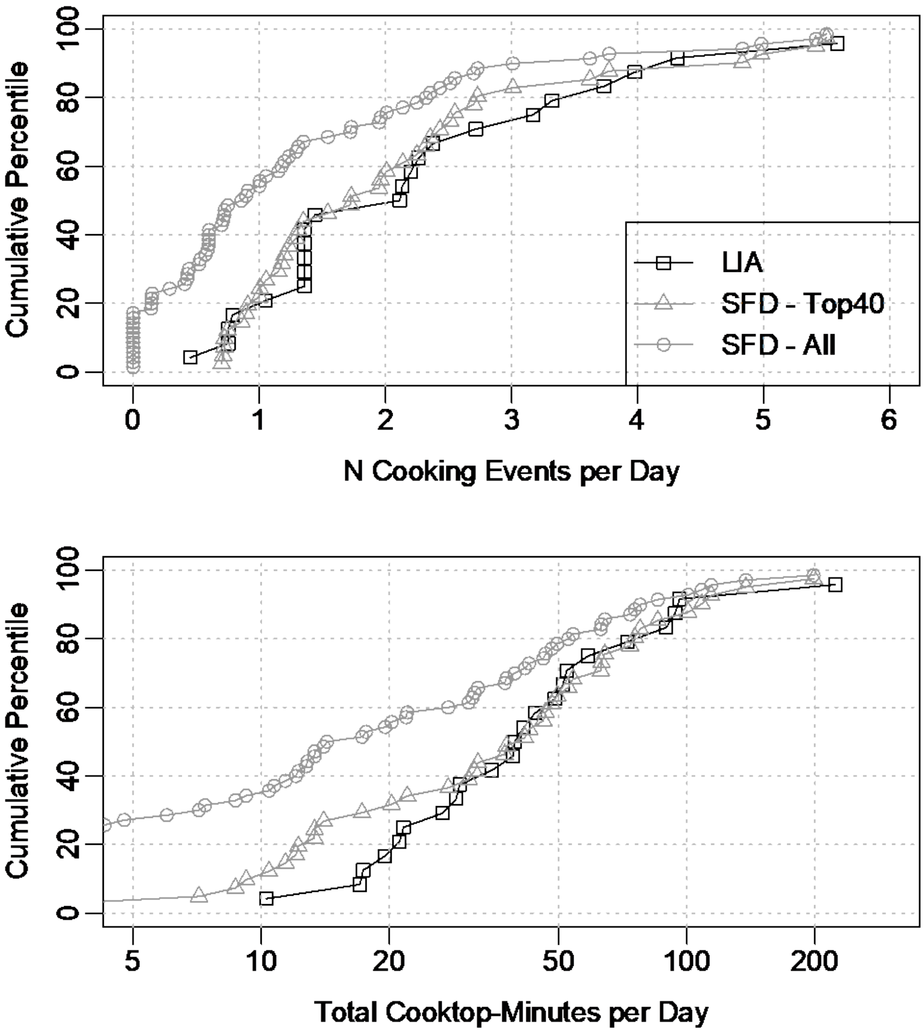


Figure 1. Cooking burner use in low-income apartments (LIA) and singe-detached homes of HENGH study (SFD-All). The SFD-Top40 are the 40 single, detached houses with the most cooking.

Measured Time-Integrated Air Pollutants

Table 3 presents summary statistics of the time-integrated air pollutant concentrations measured at the central indoor locations of the low-income apartments in this study and in the detached houses with frequent cooking of the HENGH study. The summary data for time-integrated air pollutant concentrations in each site are presented in Tables S11 to S14.

We applied the Mann-Whitney test to compare air pollutants concentrations measured in the 40 houses with more cooking to the full sample of 70 and found some differences as likely (e.g. p=0.12 for NO_2) but falling short of the threshold of $p<0.05$. Differences between the 40 high-cooking and 30 low-cooking houses were significant for NO_2 (p=0.002), but not for other pollutants. For consistency, Table 3 compares concentrations measured in the low-income apartments with the 40 high-cooking houses for all pollutants.

Table 3. Air pollutant concentrations over one week in apartments and houses with similar amounts of cooking with gas burners.

Measure	**HCHO**	**(ppb)**	**PM$_{2.5}$**	**(μg/m^3)**	**NO$_2$**	**(ppb)**	**CO$_2$**	**(ppm)**
Group	**Apts**	**Houses**	**Apts**	**Houses**	**Apts**	**Houses**	**Apts**	**Houses**
Indoor	N=21	N=40	N=21	N=40	N=22	N=38	N=23	N=40
Mean	14.1	18.7	7.7	8.0	18.8	7.1	741	628
Median	10.9	17.7	3.9	4.9	16.6	5.5	680	625
10th–90th	8.1–22.4	12.8–27.2	1.8–15.0	2.4–17.9	10.8–30	1.5–14.2	584–955	519-765
Outdoor	N=21	N=40	N=21	N=39	N=22	N=37	No data	No data
Mean	1.7	2.2	7.5	10.1	10.1	6.1		
Median	1.4	2.2	5.6	9.1	8.4	3.2		
10th–90th	0.8–2.8	1.5–2.9	4.8–14.2	5.3–16.4	4.5–20	0.1–13.4		

Formaldehyde was substantially lower in the apartments than in the detached houses with the difference statistically significant (p=0.005 based on Mann-Whitney test). This is an expected result since (a) the apartments were older than the houses and (b) because higher air change rates reduce formaldehyde.[32, 33] Building age is important because formaldehyde concentrations decrease substantially over the first few years after a building is constructed[34] and 48 of 70 houses in the HENGH study were measured when they were less than 3 years old. Formaldehyde was slightly lower outside of the apartments than outside of the houses, but the difference was small compared to the indoor difference. While formaldehyde in the apartments was lower than in the HENGH houses, concentrations still substantially exceeded the chronic and 8-h references exposure levels of the California Office of Environmental Health Hazard Assessment, set at 7 ppb for both time frames.

Mean indoor formaldehyde concentrations were 12.1, 16.1, 20.3 and 9.4 ppb at Sites 1 to 4, respectively, as summarized in Table S11. The low concentrations at Site 4 are expected from the substantially higher air exchange from mechanical ventilation (0.81 h^{-1}) compared to other sites (0.43-0.56 h^{-1}). Higher concentrations at Sites 2 and 3 are consistent with those being the newest construction or refurbishment, in 2016. The low concentration at Site 1, refurbished in 2015, is consistent with lower material emission rates from lower temperatures and lower solar insolation (which heats the building shell) as sampling at this site occurred in February.

Similar formaldehyde levels were reported in the Noris et al. study of 18 low-income apartments in California (Noris et al 2013) with mean indoor concentrations of 18.4, 13.9 and 12.8 ppb at the three sites. In another recent US study, mean indoor formaldehyde concentration of 7.5 ppb were reported for 18 small (~67 m^2) low-income apartments in a new green building with MV and electric cooking appliances.[26]

$PM_{2.5}$ concentrations inside the houses and apartments were not significantly different based on the Mann-Whitney test (p=0.73); but $PM_{2.5}$ was higher outside of the HENGH houses (p=0.02). The higher ratios of indoor to outdoor indicate more impact of indoor sources in the apartments. Mean indoor / outdoor $PM_{2.5}$ concentrations at the four sites were 8.1 / 5.0, 3.4 / 6.0, 4.7 / 4.9, and 14.9 / 13.6 μg/m^3. Time-integrated indoor PM$_{2.5}$ concentrations in this study were similar to Site 1 of the Noris et al. 2013 study (indoor / outdoor of 8.0 / 7.9 μg/m^3) but lower than the other two Sites after retrofits (42 / 6.7 and 23 / 3.9 μg/m^3). The indoor PM$_{2.5}$ concentrations in this study are also similar to the mean of 9 μg/m^3 reported for 18 low-income apartments with MV and electric stoves in Boston[26] but lower than the 27 / 18 μg/m^3 (in / out) reported post-retrofit in NY apartments with MV and gas stoves.[27]

In comparison to the annual average PM$_{2.5}$ of 12 μg/m^3 allowed in the California and U.S. EPA Ambient Air Quality Standards (AAQS), the adjusted DT data indicate four out of 20 apartments (20%) with weekly average indoor PM$_{2.5}$ above the threshold. Similarly, seven of 40 HENGH houses (18%) selected for comparison had weekly average PM$_{2.5}$ above 12 μg/m^3. Two of 21 apartments (11%) had 24-h PM$_{2.5}$ concentrations above the US EPA AAQS of 35 μg/m^3 based on the adjusted DT data, including unit 932 with a broken range hood and indications of smoking indoors. The other apartment (901) exceeding the 24h threshold also had one-week PM$_{2.5}$ above 12 μg/m^3 despite having MV that met the 2007 through 2016 code requirements. Seven of the 40 houses (18%) with PM$_{2.5}$ data from the HENGH sample had a 24-h concentration above 35 μg/m^3. More homes in both studies had instances of 24 h average concentrations exceeding the World Health Organization exposure guideline of 25 μg/m^3. Among the 20 apartments with adjusted DT data, four (20%) had at least one 24-h period with PM$_{2.5}$ above 25 μg/m^3. In the 40 comparison houses from the HENGH study, adjusted photometer data indicated nine (23%) with at least one 24-h period of PM$_{2.5}$ above 25 μg/m^3.

The adjusted AVP PM$_{2.5}$ data generally agrees well with DT, but time-integrated PM$_{2.5}$ concentrations measured by AVP overall were 5-10% lower. With adjusted AVP data from 22 apartments, weekly average $PM_{2.5}$ concentrations in three apartments were above 12 µg/m^3. One apartment (932) had a 24h average concentration adjusted AVP above 35 µg/m^3.

NO_2 concentrations were both substantially and significantly higher inside the apartments than inside the detached houses ($p<0.01$) and also higher outside of the apartments than outside of the houses ($p<0.01$). Mean indoor / outdoor NO_2 concentrations were 20.4 / 9.8 ppb at Site 1, 18.4 / 4.6 ppb at Site 2, 14.0 / 7.9 ppb at Site 3, and 22.0 / 19.7 ppb at Site 4. The effect of outdoor NO_2 is expected to be highest at Site 4 because that site had both the highest outdoor NO_2 concentration and also the highest air exchange rates. Indoor measurements of time-integrated NO_2 did not exceed the U.S. annual average AAQS of 53 ppb in any apartment or house, but three apartments (and no houses) had indoor NO_2 concentrations above the California AAQS of 30 ppb during the week of monitoring (Figure 3). The apartment that used the oven for overnight heating had the 3rd highest weekly-averaged indoor NO_2 (30.6 ppb) and the highest weekly-averaged NOx concentration (97.6 ppb). These measured NO_2 levels are consistent with the values reported for the two sites within the Noris et al. study that had gas cooking after retrofit, with in / out concentrations of 17.2 / 16.8 and 29.3 / 16.1 ppb. The results indicate much higher NO_2 in apartments than houses when all are equipped with mechanical ventilation equipment.

The higher indoor NO_2 in apartments is partly caused by higher outdoor concentrations but may also result from differences in emissions or emissions being less diluted by smaller volumes in apartments. To explore the magnitude of these factors, we estimated the indoor concentration resulting from indoor emissions in houses and selected apartments by material balance analysis, treating each housing unit as a well-mixed air volume with steady-state indoor and outdoor concentrations equal to the weekly averages and other influencing parameters. Details are provided in the SI. The analysis was conducted for 37 houses that had all required data and for 10 apartments which had outside entrance doors (not corridors) and window opening time less than one hour per day based on activity logs and monitored data. This analysis provided a mean indoor NO_2 concentration from indoor emission of 14.0 ppb and range of 4.8–32.4 ppb in the 10 selected apartments and mean of 4.8 ppb and range of 0–16.3 ppb in the 37 houses. Regarding emissions, we note the similar frequencies of cooking events with gas burners that occurred in the apartments and houses (Figure 1), with somewhat higher amounts of burner use at the lower end of the distribution for cooking events in apartments. Differences in emissions across the distribution of cooking events may have resulted from higher rates of range hood use in houses. Overall, range hoods were used in 36% of the cooking activities in houses and in 26% of the cooking activities in the study apartments. When using cooktop burners for more than 20 minutes, range hood use occurred 52% of the time in houses but only 31% in apartments. (Details of this analysis are included in a manuscript that is in preparation.)

Table 3 shows that CO_2 concentrations were generally higher in the apartments than in the detached houses of the HENGH study; but the differences in incremental CO_2 (above an assumed outdoor background of ~400 ppm) are not proportional to the more than 2x higher occupant densities in the apartments. The higher mechanical air exchange rates in the apartments – along with substantial natural ventilation in at least 5 apartments – resulted in a 90th percentile weekly mean CO_2 below 1000 ppm, a commonly used indicator of adequate ventilation. Mean indoor CO_2 concentrations were 643, 767, 828 and 725 ppm for the four sites. The weekly mean CO_2 was above 1000 ppm at the central location in two apartments; one of these (924) had the highest occupant density among apartments and the other (926) had the second lowest MV rate.

Spatial and Temporal Variations of Air Pollutant Concentrations

Several parameters were measured using the same device in both a central location and master bedroom in most apartments: time-integrated NO_2 and NO_X by Ogawa passive samplers and time-resolved CO_2 and $PM_{2.5}$ by AVP. Figure 2 compares NO_2 concentrations in bedrooms and central locations of 18 apartments (excluding the studios). NO_2 was more than 10% lower in the bedrooms in 12 apartments. The trend for NO_2 is consistent with findings of other recent studies[10, 35] and expected since the source is the gas burner in the kitchen. Similar comparison was also performed for total NOx concentrations, as shown in Figure S16. NO_X was more than 10% lower in 7 bedrooms. The other studies reported more pronounced differences between locations for total NO_X.

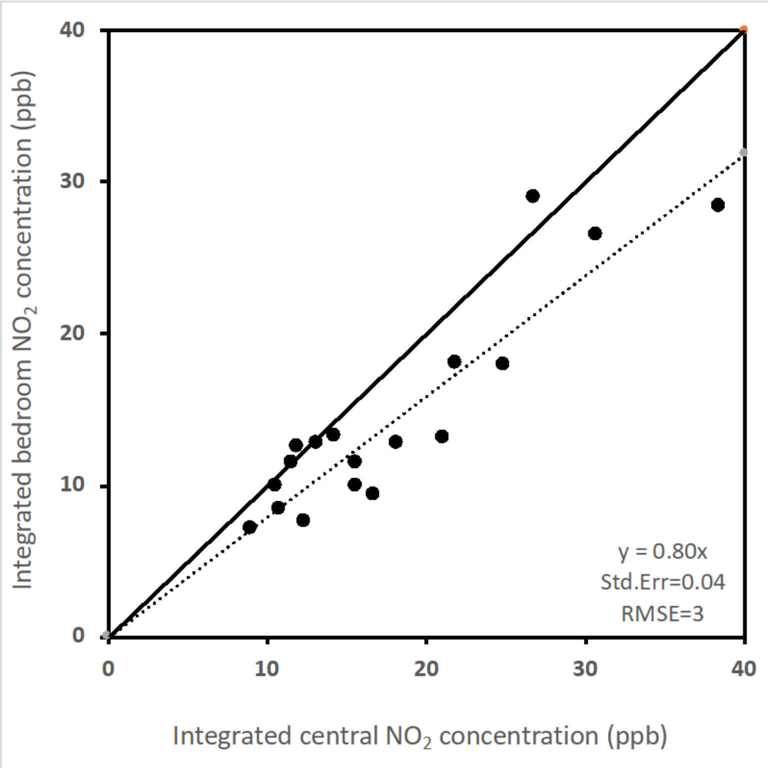


Figure 2. Comparison of NO_2 concentration measured in bedrooms and common (central) rooms of apartments. Dotted line shows robust linear regressions using Huber M-estimator.

A comparison of adjusted $PM_{2.5}$ concentrations by AVPs in bedrooms and central locations of 19 apartments are shown in Figure S17. Unlike NO_2, $PM_{2.5}$ concentrations were similar at central and bedroom locations.

Similar to the findings reported for the HENGH single detached houses, CO_2 concentrations in the master bedrooms were higher than in central locations in almost all of the apartments (Figure 3). Weekly average concentrations exceeded 1000 ppm in the master bedrooms of four apartments but at only two of the central measurement sites.

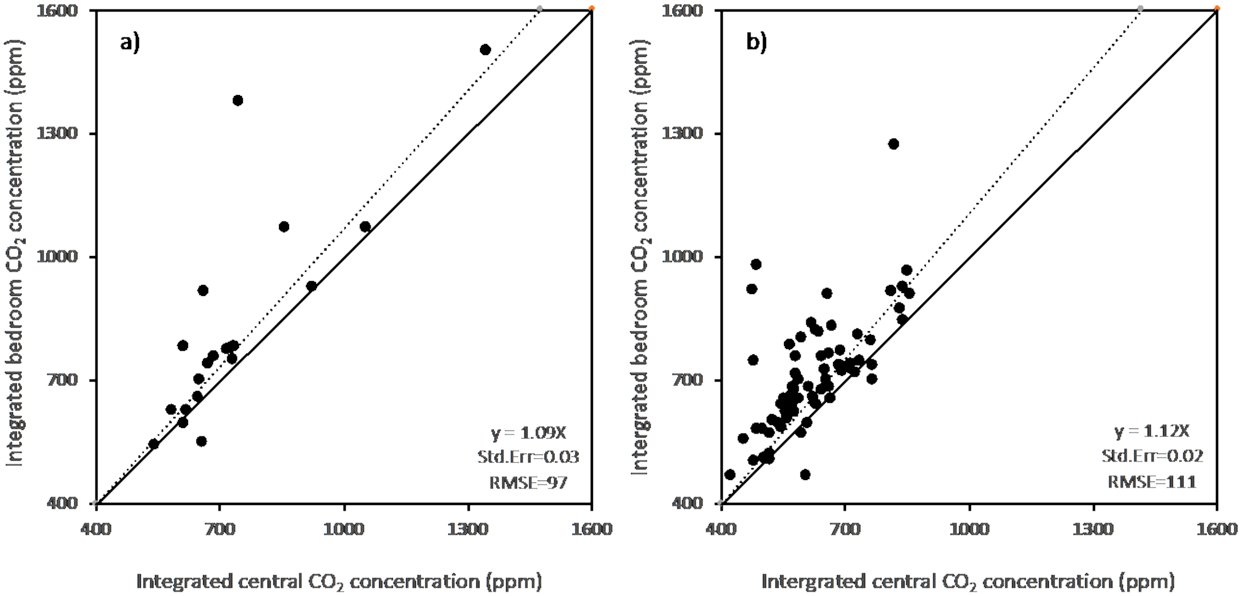


Figure 3. Comparison of CO_2 measured in bedrooms and common (central) rooms of (a) apartments and (b) houses. Dotted lines show robust linear regressions using Huber M-estimator.

Figure 4 shows the daily patterns of CO_2 in the bedroom and central measurement locations across the sample of apartments. The distributions at the two locations are similar from about midday through the evening, then diverge overnight when much higher concentrations occur in bedrooms. The higher bedroom concentrations persist into the mid-morning. Including the three studio apartments at Site 4, there were six apartments that had average bedroom CO_2 above 1000 ppm during the hours of midnight to 5 am. Analogous data from the detached houses are shown in Figure S18. In this houses, distributions of CO_2 at the two locations are similar from about midday through the evening, similar to apartments. But overnight differences between master bedroom and central CO_2 concentrations were much larger in the houses.

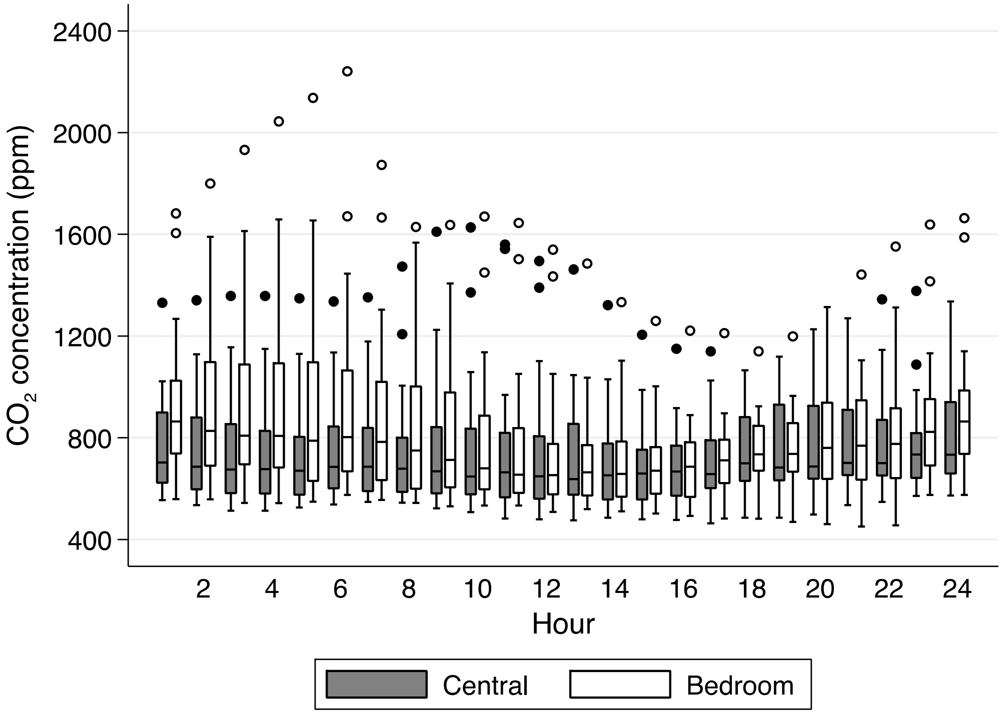


Figure 4. Distribution of mean CO_2 concentrations in each hour of the day across 23 apartments based on measurements made in 20 bedrooms and in 22 large common rooms containing the kitchen (central). Boxes show interquartile range (IQR), whiskers are limit values within 75th+1.5IQR) and 25th-1.5IQR and circles show all data outside of whiskers.

Acute Impacts of $PM_{2.5}$ and NO_2 Emission Events

We assessed the potential impact of indoor emission events on IAQ by examining hourly concentrations of mass-adjusted $PM_{2.5}$ and baseline-adjusted NO_2 in apartments and houses. This analysis considered the 3rd highest hourly concentration of each pollutant in each home, which is roughly the 98th percentile over the ~160 h of data available in most homes. While the subgroup of houses selected for frequent cooking had a higher median value of 3rd. highest $PM_{2.5}$

than the apartments, the ranges were similar. Short-term NO_2 was much higher in apartments. While different devices were used to measure time-resolved NO_2 in the two studies, and each has high uncertainty, the higher 1-h concentrations are consistent with the higher weekly-averages, as shown in Figure S19.

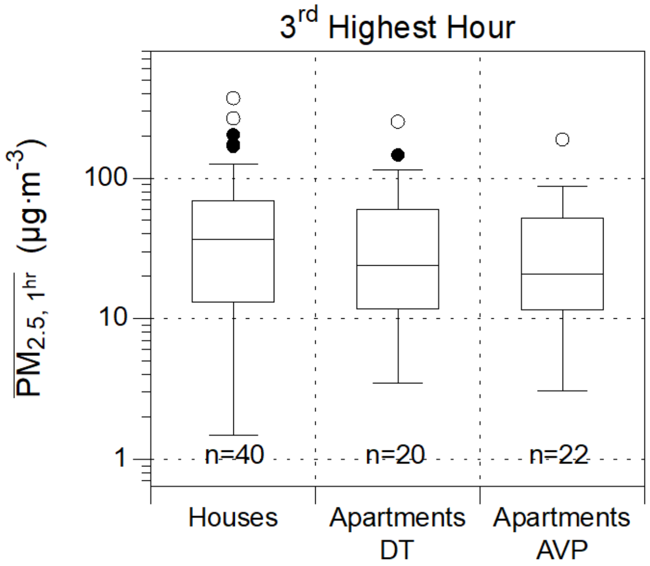


Figure 5. Comparison of 3rd highest hourly $PM_{2.5}$ concentrations in houses and apartments, using mass-adjusted photometer data.

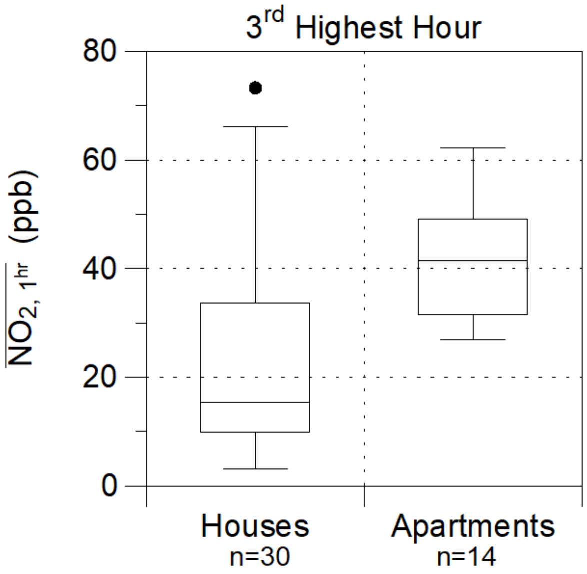


Figure 6. Comparison of 3rd highest hourly NO_2 concentrations in houses (HENGH) and apartments (this study) using Aeroqual and Clarity Node sensors, respectively.

Satisfaction with IAQ

Summary results of the frequencies of problematic discomfort with environmental conditions in the apartments of this study and the houses of the HENGH study are shown is Table S15 in the SI. The comparison is limited by the use of slightly different questions in the two studies and small samples sizes, but obvious differences were found for some comfort conditions. Eleven of 19 (58%) of apartments were problematically too cold in winter, compared with only 30% of houses being too cold a few times per week. In summer, too hot was a problem in 74% (14/19) of apartments but occurred a few times per week or more in only 30% of the houses. Not enough air movement was a problem in 32% of apartments and 22% of houses. The data suggest higher rates of IEQ discomfort in the apartments.

Limitations

This study had several substantial limitations. The most important is the unknown bias of a small and non-random sample. The working condition of ventilation equipment at the four sites and the measured indoor air quality parameters over a single week in 23 apartments cannot be assumed to represent conditions throughout the state, let alone the US; all results therefore must be regarded as exploratory and suggestive, rather than robust or certain.

Comparisons between measured IAQ parameters in houses and apartments may be influenced by multiple household and home characteristics.[36] We focused on cooking and gas burners as major indoor sources for nonsmoking households and selected a subgroup of houses with similar cooking levels to compare to apartments. Aside from the smaller volumes, higher densities and higher mechanical air exchange rates in apartments, IAQ also may have been impacted by more natural ventilation from window and door opening in at least 21% (5/23) of apartments compared to an estimated <10% of the houses. In addition to these differences, the request that residents not use windows and doors to provide natural ventilation during the week of monitoring may have impacted air pollutant concentrations relative to typical behavior in those homes. Air exchange rates were not measured previously in the houses or in the apartments in this study and it is not known how much of the mechanically-induced air exchange in the apartments came from outdoors and how much from other spaces within the building, via. internal leakage. For air pollutant comparisons, there were differences in instrumentation used by the two studies that could result in differences despite calibrations and quality assurance procedures. While outdoor concentrations of $PM_{2.5}$ and NO_2 are reported, their impact on indoor levels has not been formally quantified for apartments in the present study or for the prior study of houses; such an analysis would require a reliable estimate of overall outdoor air exchange and the pathway of air entry into apartments. Indoor pollutants concentrations were compared to thresholds used in outdoor standards, which may not directly translate to safe levels inside homes.

Conclusions

Notwithstanding the limitations noted above, several qualified conclusions may be drawn from the comparisons of mechanical ventilation equipment and indoor air quality measured in the current study and the same parameters reported in the recent study of detached houses subject to similar code requirements. While the apartments much more commonly had dwelling unit MV equipment operating, the airflows were generally much lower than equipment ratings compared to the houses. Measurements of $PM_{2.5}$ and NO_2 during a week of monitoring suggest that in a substantial minority of homes, concentrations may exceed health-based limits set by the US and California EPA for ambient air quality or by the WHO for personal exposure. Formaldehyde concentrations were lower in apartments than in houses; but still routinely above the chronic reference exposures levels set by the California EPA. Data collected in the apartments affirm prior research showing that use of gas cooking burners produces high short-term and time averaged NO_2. While concentrations of $PM_{2.5}$ were similar in apartments and houses with similar levels of cooking, NO_2 was much higher in the apartments.

Based on a very limited sample, the findings of this study suggest that mechanical ventilation systems in a substantial fraction of apartments may have operational deficiencies that impact their performance. These ventilation deficiencies likely translate to higher concentrations of air pollutants whose main source is indoor emission, compared to those that would occur with operation of ventilation meeting the state building code.

References

1. Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Exposure Anal Environ Epidemiol.* 2001;11:231-252.
2. Leech JA, Nelson WC, Burnett RT, Aaron S, Raizenne ME. It's about time: A comparison of Canadian and American time-activity patterns. *J Exposure Anal Environ Epidemiol.* 2002;12:427-432.
3. He CR, Morawska LD, Hitchins J, Gilbert D. Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmos Environ.* 2004;38:3405-3415.
4. 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.
5. Fortmann R, Kariher P, Clayton R. *Indoor air quality: Residential cooking exposures*. ARB Contract Number 97-330; Sacramento, CA: Prepared for California Air Resources Board; November 30, 2001, 2001.
6. Olson DA, Burke JM. Distributions of PM2.5 source strengths for cooking from the research triangle park particulate matter panel study. *Environ Sci Technol.* 2006;40:163-169.
7. Torkmahalleh MA, Gorjinezhad S, Unluevcek HS, Hopke PK. Review of factors impacting emission/concentration of cooking generated particulate matter. *Sci Total Environ.* 2017;586:1046-1056.
8. O'Leary C, Jones B, Dimitroulopoulou S, Hall IP. Setting the standard: The acceptability of kitchen ventilation for the English housing stock. *Build Environ.* 2019;166:106417.
9. Zhao YJ, Zhao B. Emissions of air pollutants from Chinese cooking: A literature review. *Building Simulation.* 2018;11:977-995.
10. Singer BC, Pass RZ, Delp WW, Lorenzetti DM, Maddalena RL. Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes. *Build Environ.* 2017;122:215-229.
11. Zhou S, Young CJ, VandenBoer TC, Kowal SF, Kahan TF. Time-Resolved Measurements of Nitric Oxide, Nitrogen Dioxide, and Nitrous Acid in an Occupied New York Home. *Environ Sci Technol.* 2018;52:8355-8364.
12. 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.
13. Fabian P, Adamkiewicz G, Levy JI. Simulating indoor concentrations of NO2 and PM2.5 in multifamily housing for use in health-based intervention modeling. *Indoor Air.* 2012;22:12-23.
14. ANSI/ASHRAE. Ventilation and Indoor Air Quality in Residential Buildings, Standard 62.2-2019. In ASHRAE: Atlanta GA, 2019.
15. Francisco PW, Jacobs DE, Targos L, Dixon SL, Breysse J, Rose W, Cali S. Ventilation, indoor air quality, and health in homes undergoing weatherization. *Indoor Air.* 2017;27:463-477.

16. California Energy Commission. 2008 Building Energy Efficiency Standards. In California Energy Commission: Sacramento, 2008.
17. Singer BC, Chan WR, Kim Y-S, Offermann FJ, Walker IS. Indoor Air Quality in California Homes with Code-Required Mechanical Ventilation. *Indoor Air.* 2020;Published online 18-Apr-2020.
18. Chan WR, Kim Y-S, Delp WW, Walker IS, Singer BC. Data from: Indoor air quality in California homes with code-required mechanical ventilation. In 2020.
19. 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-2001200R1; Berkeley CA: Lawrence Berkeley National Laboratory; 2019.
20. 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.
21. EPA US. Formaldehyde Emission Standards for Composite Wood Products. https://www.epa.gov/formaldehyde/formaldehyde-emission-standards-composite-wood-products Last Accessed:25-Apr-2020,
22. California Air Resources Board. Composite Wood Products Airborne Toxic Control Measure. https://ww2.arb.ca.gov/our-work/programs/composite-wood-products-program Last
23. Price PN, Sherman MH. *Ventilation Behavior and Household Characteristics in New California Houses*. LBNL-59620; Berkeley CA: Lawrence Berkeley National Laboratory; 2006.
24. Kim J-S, Singer BC, Chan WR, Walker IS. In *Investigation of quantitative relationships between occupant satisfaction and household IAQ-related characteristics in California homes.*, ASHRAE Winter Meeting 2020, Atlanta, GA, 2020; ASHRAE: Atlanta, GA, 2020.
25. Noris F, Adamkiewicz G, Delp WW, Hotchi T, Russell M, Singer BC, Spears M, Vermeer K, Fisk WJ. Indoor environmental quality benefits of apartment energy retrofits. *Build Environ.* 2013;68:170-178.
26. Colton MD, MacNaughton P, Vallarino J, Kane J, Bennett-Fripp M, Spengler JD, Adamkiewicz G. Indoor Air Quality in Green Vs Conventional Multifamily Low-Income Housing. *Environ Sci Technol.* 2014;48:7833-7841.
27. Patton AP, Calderon L, Xiong YY, Wang ZC, Senick J, Allacci MS, Plotnik D, Wener R, Andrews CJ, Krogmann U, Mainelis G. Airborne Particulate Matter in Two Multi-Family Green Buildings: Concentrations and Effect of Ventilation and Occupant Behavior. *Int J Environ Res Public Health.* 2016;13.
28. Jacobs DE, Breysse J, Dixon SL, Aceti S, Kawecki C, James M, Wilson J. Health and Housing Outcomes From Green Renovation of Low-Income Housing in Washington, DC. *Journal of Environmental Health.* 2014;76:8-16.
29. 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.
30. 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.

31. Wang Z, Delp WW, Singer BC. Performance of low-cost indoor air quality monitors for PM2.5 and PM10 from residential sources. *Build Environ.* 2020;171:106654.
32. 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.
33. 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.
34. Park JS, Ikeda K. Variations of formaldehyde and VOC levels during 3 years in new and older homes. *Indoor Air.* 2006;16:129-135.
35. 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.
36. Diaz Lozano Patino E, Siegel JA. Indoor environmental quality in social housing: A literature review. *Build Environ.* 2018;131:231-241.

Indoor Air Quality in New and Renovated Low-Income Apartments with Mechanical Ventilation and Natural Gas Cooking in California

Haoran Zhao[1], Wanyu R. Chan[1], Sebastian Cohn[2], William W. Delp[1], Iain S. Walker[1], Brett C. Singer[1*]

[1]Residential Building Systems Group and Indoor Environment Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

[2]Association for Energy Affordability, Emeryville, CA, USA

Supporting Information

Contents

Figures

Tables

Recruitment, Screening and Selection of Study Homes

Recruitment was carried out by the Association for Energy Affordability (AEA) starting in September 2018. AEA first searched its database of properties on which they had worked in the past, which identified Site 1. AEA then contacted building owners or operators with whom they had existing relationships to inquire about the suitability of their properties and their willingness to assist with the study. These were primarily low-income developers or owner groups that had participated in energy efficiency programs managed by AEA, or who had been involved in previous research with AEA. This led to Sites 2-4. With the intent to study apartments which are representative of near-future construction in California, recruitment targeted buildings constructed or remodeled in 2013 or later. When an owner or property manager suggested a candidate site, AEA checked that the cooking and mechanical equipment thought to be present met requirements. AEA reviewed available air leakage test results and in the absence of such results, considered the type and year of construction or renovation. After securing preliminary agreement of the building owner and operator, AEA visited the property to inspect 2-4 units. This visit was to confirm the presence of compliant ventilation equipment and, at the first two sites, to conduct blower door testing to measure compartment air leakage. Since the last two sites were built in the past 5 years, they were assumed to have compartment airtightness consistent with current construction. (As noted in Table S5, they actually did not meet the air tightness target).

Outreach to identify interested residents was accomplished with information sheets posted in hallways and left in front of entrance doors and building managers calling attention to the flyers. Flyers included basic information about the requirements of the study, what to expect, and the financial incentive. Interested residents were encouraged to contact AEA by telephone or email for more information. Most people who reached out to AEA with interest understood the requirements that participants should engage in regular cooking, prohibit smoking and keep windows closed for the week of monitoring. Interested residents were given additional details about the study protocols and confirmed they would be available during reasonable time periods for equipment installation and removal. Once a sufficient number of eligible volunteers were identified, AEA scheduled dates for equipment installation in each apartment.

Building and Apartment Characterization

The following equipment was identified and characterized, and photos were taken to document the details of the installation, as shown in the table below.

Table S1. Apartment and equipment characterization.

Equipment type	Characterization
Dwelling unit mechanical ventilation system	Basic design (exhaust, supply, or balanced); type of control; make, model, rated flow and sound; available settings.
Bath and kitchen exhaust fans.	Make, model, rated flow and sound; type of control for each fan; note if kitchen range hood is microwave or simple range hood
Heating and cooling system(s)	Type of system (all were forced air), make and model, capacity (in tons and Btuh). Any additional space heater? Dimensions and location of each return and locations of filter(s) if not at the return air grille. For each filter in forced air system, record make, model and MERV; visually assess condition; photo. Make and model of thermostat.
Gas-burning appliances	Make, model and firing rates of all burners and ovens; photo of nameplate.

Ventilation and Cooking Burner Monitoring

To check participants' adherence to keeping doors and windows closed, state sensors (Onset HOBO UX90-001) were installed to monitor open vs. closed status of the most frequently used window and doors in each unit, as summarized in Table S2. At Site 1 loggers were placed on front doors in all units and back deck doors in three units. At Site 2 loggers were placed on front doors in all units and back deck sliding doors in four units. At Site 3, loggers were placed on all the front doors and the most used window or door in each unit; but valid data were obtained for only three front doors, two back deck doors, and one bedroom window. At Site 4, logger data were obtained for three front doors, three bedroom windows, one back deck window and two kitchen patio windows.

Table S2. Windows and doors monitored in each home

Home	Front door	Back deck door	Bedroom window	Kitchen patio window
901	Y	Y		
902	Y			
903	Y			
904	Y			
905	Y	Y		
906	Y	Y		
911	Y			
912	Y	Y		
913	Y	Y		
914	Y			
915	Y	Y		
916	Y	Y		
921	Y			
922	Y			
923		Y		
924				
925				
926		Y	Y	
931	Y	Y	Y	
932				Y
933	Y			
934			Y	Y
935	Y		Y	

Measurement Equipment

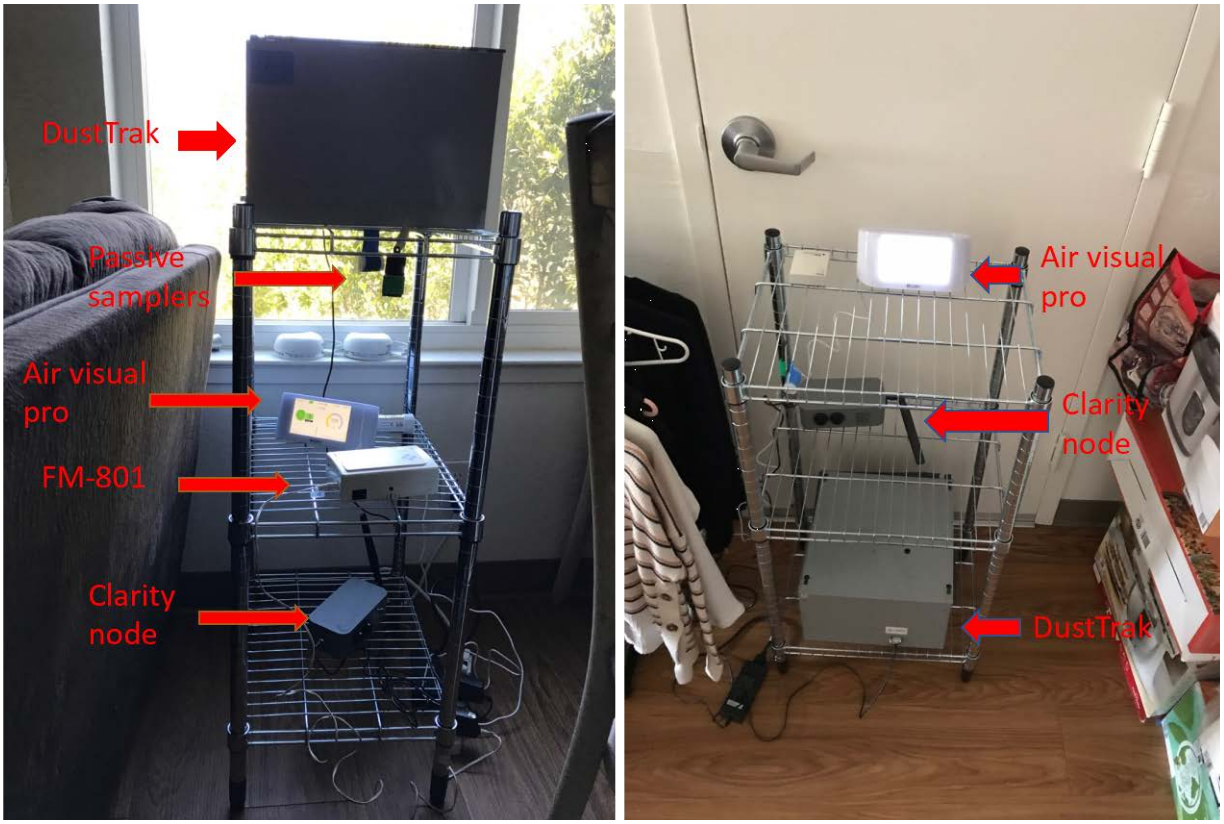


Figure S1. Examples of monitoring equipment at central indoor locations. At Sites 1 and 2, instruments were placed in varied configurations. At Sites 3 and 4, all were placed as shown.

Measurement Quality Assurance Procedures

Handling and analysis of passive NO_2, NO_X and formaldehyde 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 (one NO_X and one NO_2 pad per sampler), they were placed in sealed amber plastic bags (Ziploc) and refrigerated until deployment.

UMEx samplers and sampling cartridges for the Multimode formaldehyde monitor were transported in their original packaging and opened at the field sites. Each sampling cartridge was only used once for each test apartment.

At the end of the week of monitoring, collected NO_X/NO_2 samplers were placed in sealed amber plastic bags and stored at room temperature. UMEx formaldehyde passive samplers were closed and placed in the foil-lined envelopes provided by the manufacturer. Collected UMEx passive samples were refrigerated during any days required to complete visits to other apartments at the site, transported back to LBNL in coolers with ice packs, and refrigerated at LBNL until analysis.

In most apartments, Ogawa NO_X/NO_2 samplers were deployed at both the main indoor sampling location and also in the master bedroom (or a second location in the studios of Site 4). UMEx formaldehyde samplers were deployed at the main sites in all apartments and in seven master bedrooms. Two of each type of passive sampler were also deployed outdoors at each site. The intent was to have one start on the first day of monitoring and sample for seven days, and have the other start seven days before the end of monitoring. This occurred at Site 3 and something close occurred at Site 4, with the first sampler going for 8 rather than 7 days. At Site 1 there was only a single outdoor sampler of each type, deployed over the full 13 days. At Site 2, one outdoor sampler was deployed for the first 10 days and the other for the last 7 days. There was at least one field blank for each type of sampler at each site. Field blanks were opened either at the indoor or an outdoor measurement location, then packaged and stored in a refrigerator for the monitoring week. At the completion of monitoring at each apartment, Ogawa and UMEx passive samplers were stored cold (refrigerator then packed in a cooler with ice) for transport to LBNL and stored cold until they were analyzed at LBNL.

Since the same materials, procedures and laboratory equipment were used to analyze the passive samples used in this study and the HENGH study, we assumed the same precision and consistency reported previously. In the HENGH study, analysis of 64-paired duplicates of indoor Ogawa samplers found that agreement in NO_2 concentrations was within 0.6 ppb on average (median = 0.3 ppb). The mass determined for field blanks corresponded to 0.9 ppb of NO_2 and 1.3 ppb of NOx for a 7-day collection period. The average sample mass on the field blanks was subtracted from the mass determined for samplers before calculating concentrations. In the current study, two duplicates of indoor Ogawa samplers were deployed in homes 932 and 934. The differences between duplicates at the two homes were 2.3 and 2.9 ppb for NO_2 and 0 and 1.8 ppb for NO_x. The NO_2 blanks corresponded to 0, 0, 0.2, and 0.2 ppb for Sites 1-4 and NOx blanks corresponded to 0.3, 0, 0.5 and 0.3 ppb for Sites 1-4. Concentrations reported for each site have these values subtracted.

In the HENGH study, the mean mass determined from all available field blanks for formaldehyde corresponded to 0.6 ppb for a 7-day collection period. In the current study, the UMEx blanks corresponded to 0.5, 0.8, 0.9 and 0.5 ppb for Sites 1-4; concentrations reported for each site have these values subtracted. There were no co-located UMEx samplers in the current study. In the HENGH study, sixty-six pairs of indoor formaldehyde samples agreed to within 1.0 ppb on average (median = 0.7 ppb). A sampling rate of 20.4 ml/min was used to calculate the sampling rate for UMEx samplers, following manufacturer instructions for extended sampling in environments with air velocities under 300 cm/min.

Co-location check of temperature and relative humidity sensors

In February 2019, before the first field deployment, 15 Onset HOBO temperature and relative humidity sensors (including model U23 and model U012-13) were co-located at a warehouse for about 18 hours. Temperatures ranged from 10 to 20 °C and relative humidity varied from 50 to 70%. Most of the sensors operated well within the range of uncertainty stated for each of the sensors (±0.4 °C for temperature, ±2.5% for relative humidity). The battery level of each temperature and relative humidity logger was checked prior to each field visit. We also conducted on-site check by visually examining the initial readings of each temperature and RH sensor when deploying on the field.

Quality Assurance Procedures for Air Pollutant Monitors

Co-location checks and mass calibrations of PM2.5 photometers

Time-resolved concentrations of $PM_{2.5}$ were estimated using four monitors with optical sensors that detect particles by light scattering: TSI DustTrak II-8530 (DT), Thermo-Scientific pDR-1500 (PDR), Clarity Node, and Air Visual Pro (AVP). All of the Clarity Node monitors and almost all of the AVP monitors used to collect data in apartments were purchased new at the start of the study. Four of the eight DT units (111714, 111801, 113221 and 172816) that were used in the study were calibrated by the manufacturer (TSI) during February 27th to March 17th 2019 between deployments at Sites 1 and 2. A fifth (113220) was calibrated on August 16th 2019 about one month before deployment at Site 3.

Basic instrument functionality checks occurred before or at the time of deployment. These included checking battery life, power and data logger connections, alignment of instrument clocks, and sample airflows of DustTrak and pDR monitors. During each on-site sampling, initial zero checks were conducted using inlet zero HEPA filters and all the DustTrak units were operated with autozero modules (TSI 801690) which periodically set the inlet flow passing through a zeroing filter for two minutes every one hour to adjust the baseline of subsequent measures in next hour. AVP duplicates were also deployed in three studios on Site 4, including home 932, 933 and 934.

Groups of PM monitors were co-located for cross-calibration and/or comparison to reference monitors on several occasions before and between site visits. This included deploying DustTrak, pDR-1500, AVP, and/or Clarity Node monitors in a 50 m^3 ventilated experimental room at LBNL. Particles were generated by burning incense or candles for a short time or stir-frying vegetables in oil on an electric hot plate. The generation was followed by multiple days of introducing ambient air by using a fan system that brought unfiltered air into the room. Peak concentrations during sources exceeded those in most apartments. Many of the monitors also were deployed together in an occupied house to cross-compare measurements of $PM_{2.5}$ and NO_2 from typical residential sources along with CO_2 from intermittent occupancy. Events are described in Table S4.

Filters for gravimetric analysis were collected inside each apartment and outdoors at each site. The filters used 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 % RH and 19.5±0.5 °C). The filters were passed over a deionizing source to remove any static charges and each filter was weighed twice using a Sartorius SE2-F balance. After pre-weighing, filters were stored in cassettes then loaded into the pDR-1500 and DustTrak photometers on site when deploying. Filters were returned to LBNL with the photometers. The filters were again preconditioned and weighed as noted above. The collected mass was determined as the difference in mass, post-sampling versus pre-sampling. The sample air volume was calculated as the product of the sampling time and flow rate, and concentration was calculated as collected mass / air volume.

Table S3. Summary of details of co-location events

Dates	Location	Instruments	Procedure
Feb 4-5	LBNL 50 m^3 test room.	7 DustTrak, 2 pDR Grimm mini-wide range aerosol spectrometer	Co-location for about 1 day; Burn incense and stir-fry beans in the chamber to generate particles
Feb 6 -20: Site 1, Hayward			
Mar 1-4	LBNL 50 m^3 test room.	4 DustTrak 2 pDR	Co-location for about 3 days; Burn incense and candle in the chamber to generate particles
April 7-17: Site 2, San Francisco			
Apr 20 to May 7	Living room of occupied house with gas stove	2 Clarity	2-week co-location with daily household activities including cooking and cleaning
Aug 8-12	LBNL 50 m^3 test room.	6 DustTrak 2 pDR 5 AVP	Burn incense and candle, and introduce outdoor air
Sep 9-13	LBNL 50 m^3 test room.	5 DustTrak 2 pDR	Co-location for about 3 days; Burn incense and introduce outdoor air
Sep 17-21	LBNL 50 m^3 test room.	4 DustTrak (one recently calibrated) 8 Clarity	Co-location for about 3 day; Burn incense and introduce outdoor air
Oct 2-11: Site 3, San Diego			
Nov 1-8	LBNL 50 m^3 test room.	7 DustTrak 13 AVP 12 Clarity	Co-location for about 7 days; Burn incense and introduce outdoor air
Nov 11-22: Site 4, Los Angeles			
Dec 12-19, 2019	Dining room of occupied house with gas stove	7 DustTrak 2 pDR 4 AVP 12 Clarity	One-week co-location with daily household activities including cooking and cleaning

Data from five colocation events were selected to perform cross-calibration for the DustTrak. Colocation events were labeled in relation to time proximate field sties. The colocation during Feb 4-5 was marked as before Hayward. The colocation during Mar 1-4 was marked as after Hayward. The colocation during Sep 9-13 was marked as before SD. The colocation during Nov 1-8 was marked as before LA. And the colocation during Dec 12-19 was marked as after LA. Time resolved PM concentrations for co-located DTs for the five events are shown in Figure S2.

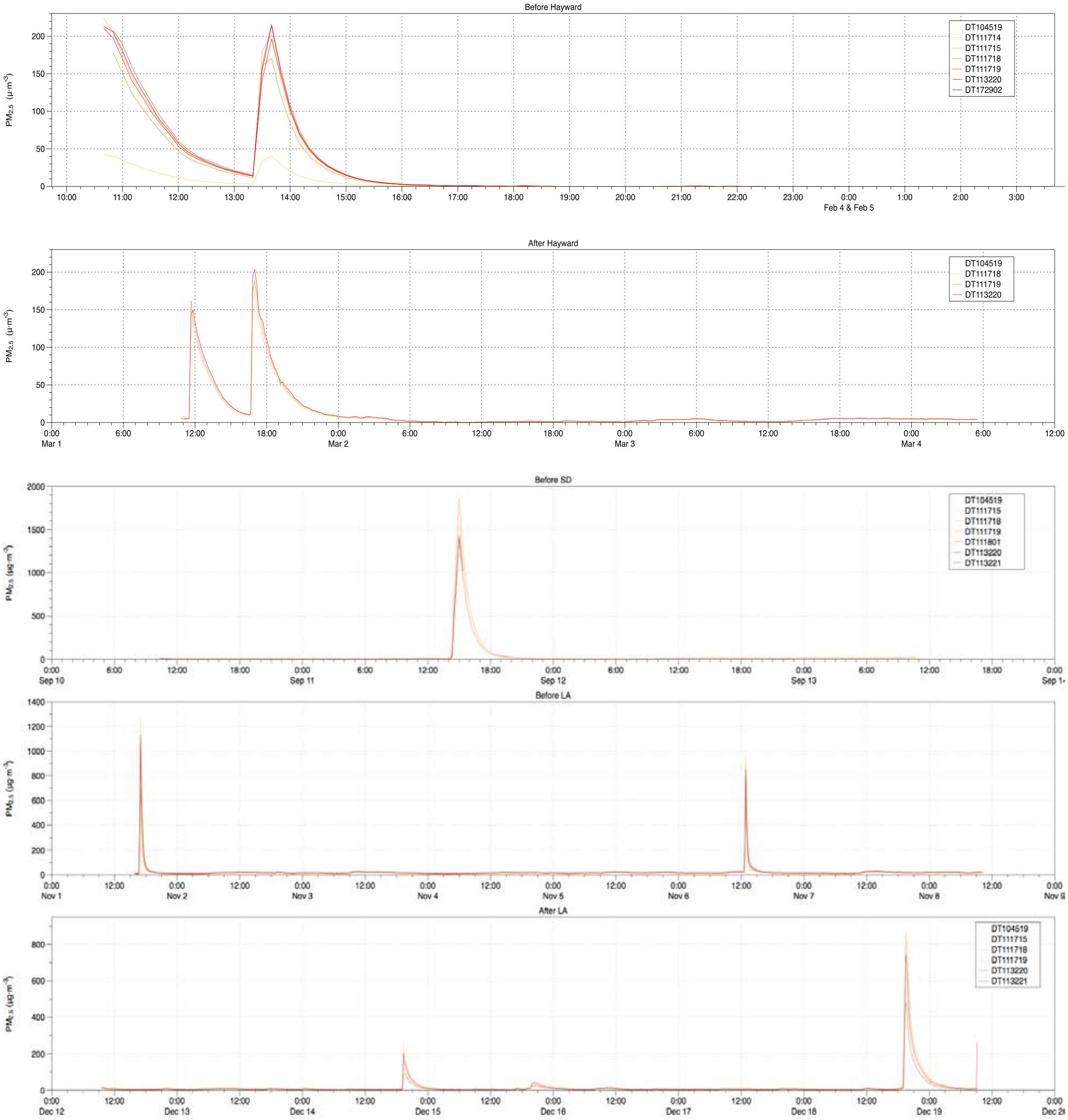


Figure S2. Time-resolved DustTrak co-location data before and after site visits

The DustTrak, AVP and Clarity all use optical sensor units that are based on light scattering and respond differently to varied aerosols that are present and emitted in homes (Wang et al., 2020). Thus, the calibration factors of these instruments would change over time. Without knowing the specific mix of PM sources, it is only feasible to make overall adjustments. That can be done with the filter-based gravimetric concentration determined independently for each apartment or by assuming that the mix of sources is broadly similar and pooling data across apartments. For this study, we used a pooled adjustment. The first step was to use the co-location data to cross-calibrate the individual units of each device (DustTraks, AVPs, etc.). To compensate for this the instruments were cross checked with each other using the data from colocation before each deployment. All data was downloaded from the instruments and averaged to a 10-min basis. There were two instruments (DT111719 and DT111519) involved in all of the tests that had little-to-no instrument-to-instrument variation over the course of the study. These two instruments were used as an arbitrary reference to cross calibrate all of the other instruments together. For each cross-check, other DustTrak units were calibrated against the average of the two reference units using all of the 10-min averaged data over the period. This resulted in a set of linear calibration parameters (slope and intercept) for each instrument for each period. Results are shown in Figure S3. The R^2 for each fit was typically greater than 0.99, and the intercepts were between -0.2 and 0.8. This provided an equal footing for the DustTrak units across the study.

Then the cross-calibrated, time-integrated responses of each unit were compared to the filter-based estimate from the same apartments to fit a regression across all apartments (Figure S4). The fit from that regression was applied to the cross-calibrated time series in each apartment to estimate the time-resolved mass concentration. This process was applied to data from indoor DustTraks and AVP monitors, using Equation S1:

$$Estimated\ PM_{2.5} = (Device\ PM_{2.5}) * Scalar + Offset \tag{S1}$$

Since DustTraks had hourly autozero and a fit with similar R^2 was obtained with zero or non-zero intercept, we used a no-offset adjustment with scalar of 0.232.

Figure S3. Cross-calibration plots for 5 co-location events (Separate File)

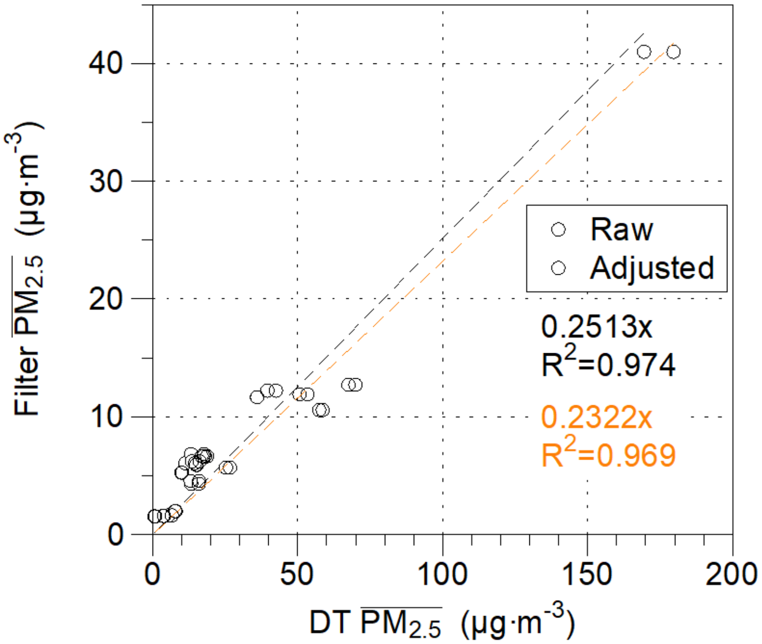


Figure S4. Time-integrated raw and cross-calibrated PM concentration measured by DustTrak compared to filter mass

The cross-calibration of AVP monitors utilized similar procedure as DustTrak. The data were achieved from three co-location events: colocation during Sep 17-21 at LBL, colocation during Nov 1-8 at LBL and colocation during Dec 12-19 at a house. The AVP monitors were observed to co-locate with each other very well and did not have obvious change over time. Thus, there was no cross-calibration adjustment of AVP data. The time-integrated AVP data were then regressed with the filter samples obtained from each apartment. The AVP data were fit to all the filter data using the non-zero intercept, as shown in Figure S6.

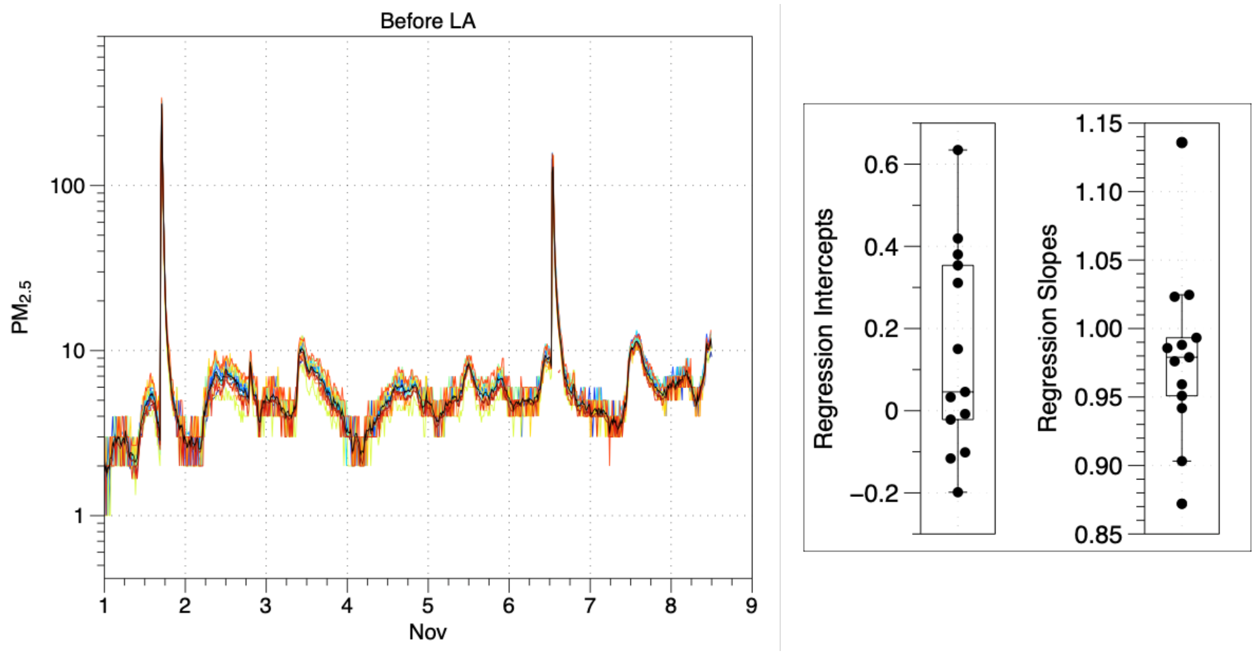


Figure S5. Co-location for 13 Air Visual Pros on time-resolved $PM_{2.5}$ measurements

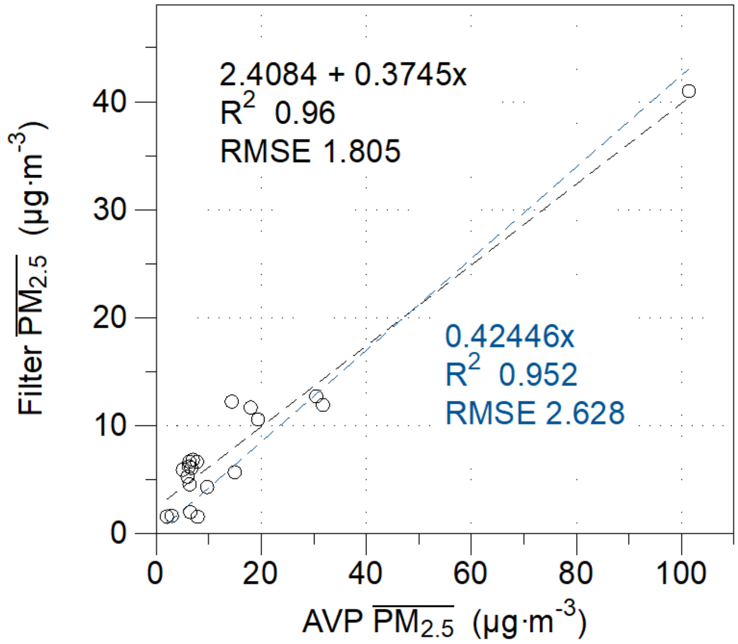


Figure S6. Time-integrated cross-calibrated PM concentration measured by AVP compared to filters

Calibrations checks for time-resolved CO_2, NO_2 and formaldehyde monitors

The accuracy of AVP monitors for CO_2 was checked between deployments at Sites 3 and 4 by placing all twelve units in the ventilated 50 m^3 room at LBNL and injecting pure CO_2 to achieve a peak of roughly 2000 ppm followed by decay to the baseline of roughly 400 ppm. CO_2

concentrations were measured concurrently using an EGM-4 gas analyzer (PP systems, Amesbury, MA, USA) calibrated with CO_2 standards over the range of 0–2500 ppm. CO_2 concentrations measured by the AVP were compared minute by minute against the EGM-4 data. The EGM4 readings were regressed to the corresponding data for each of the AVP monitors. Fitted slopes had a mean and range of 1.045 and 0.997–1.064. Offsets had a mean of –31.0 ppm and a range of –53.2 to –3.9 ppm. The CO_2 sensor used by the AVP has an automatic baseline correction that considers the lowest stable reading over each 4 h period during the preceding 7.5 days as a baseline. Prior to each deployment, AVP monitors were placed and run in the ventilated chamber described above for roughly a week to set the baseline.

Time-resolved NO_2 concentrations were measured by the Clarity Nodes. Several approaches were applied for quality assurance. All 12 Clarity Nodes for about 7 days at an occupied house with regular cooking activities that resulted in elevated NO_2 level for co-location after deployment of Site 4. Results show that the Clarity nodes roughly correlated with each other well. Issues with indoor NO_2 numbers were assumed to be entirely baseline drift. Baselines were estimated by taking the 5th quantile values (of a 12hr rolling window) of the running 1hr averages. This was subtracted from the raw numbers to yield baseline adjusted values.

Output of the FM-801 formaldehyde monitor is subject to a negative artefact or bias when high concentrations of NO_2 are present (Maruo et al., 2010). The bias is observed as a sharp drop in FM-801 data when there is substantial gas cooking burner use and corresponding increases in NO_2. FM-801 data that could be subject to this bias were identified by visual review, considering both the time-resolved NO_2 data from the Clarity Node and the cooktop and oven temperature sensors, and flagged. A modified series of FM-801 data were created by removing any data points that were clearly biased low from this effect (indicated by a sharp drop corresponding to the burner use or NO_2 and rebounding after). We did not remove all FM-801 data during burner use because formaldehyde was observed to increase sometimes during cooking, presumably from cooking-related emissions. These data were likely biased low but removing data from periods of elevated concentrations would increase the bias. Special software provided by GrayWolf enabled us to record estimated concentrations below the instrument limit of detection of 10 ppb and these were used in the calculation of weekly mean values.

Use of different devices to measure the same or similar parameters at either the central indoor site or at the two indoor sites provided another form of quality assurance. Formaldehyde was measured with the FM-801 multimode monitor in the master BR of all apartments while UMEx samplers were used at the central locations in all apartments and in 7 master BRs. $PM_{2.5}$ was measured at the central indoor location using the optically-based DustTrak, AVP, Clarity Node and sometimes pDR; and the DustTrak or pDR collected a filter sample for gravimetric analysis.

The time-series data from each apartment was visually reviewed to check for anomalies and physically rational temporal alignments, e.g. NO_2 and some (but not all) PM peaks aligning with cooking burner use, higher CO_2 overnight in bedrooms, etc.

Outdoor Air Quality Data

Time-resolved concentrations of outdoor $PM_{2.5}$ were obtained using the methods described below. The measured outdoor $PM_{2.5}$ concentrations by DustTrak were compared to hourly data from the closest regulatory air monitoring stations (AQS) with hourly $PM_{2.5}$ data. The results are shown in Figure S7, Figure S8, Figure S9 and Figure S10. For Site 1 at Hayward, we used hourly data from nearby regulatory AQS to adjust the minutely data reported by the DustTrak monitor outdoors. The stations were 10.7 km away at similar distance as the apartment sites from large freeways in the area, and having roughly similar surrounding land use. The measured outdoor PM by DustTrak were consistently correlated with AQS station data with a scalar of 0.38, as shown in Figure S7. So, the adjustment was a scalar of 0.38 with zero intercept. For Site 2, the on-site outdoor DustTrak readings followed a similar trend to the AQS but were much lower for reasons that could not be determined. The data from the outdoor DustTrak were determined to be invalid and this was confirmed by two checking process: 1) we checked two other AQS stations located in SF area and similarity of $PM_{2.5}$ were found; 2) we found an apartment (912) that had an 18-h overnight window opening period during sampling and indoor concentration measured by DustTrak at window opening period were consistently 5-7 times higher than the outdoor DustTrak measures. Given the indoor concentrations are expected to be very close to outdoors during long-term window opening period and the indoor and outdoor DustTrak units were co-located well before deployment (slope=1.06). Thus, outdoor $PM_{2.5}$ concentrations at Site 2 were assumed to be equal to the data from the closest AQS monitor located 1.6 km away. At Site 3 the closest AQS with $PM_{2.5}$ data (15.4 km away) was deemed not to be representative as it was substantially farther inland and closer to the border with Mexico, with greater impacts from cross-border traffic. Outdoor DT data at Site 3 was adjusted using the scalar of 0.365 from the first 5 days of Site 4. An interval of 33 hours of outdoor DT data at Site 3 was flagged as invalid because concentrations dropped to zero or near zero for approximately 24 h then slowly rose back to values consistent with coincident indoor data at the site and at the AQS station. For Site 4, the comparison between outdoor DustTrak and AQS monitors shown the adjustment factor changed over time. We used a scalar of 0.365 for the first 5 days and a slope of 0.464 and intercept of 4.43 for the last 5 days.

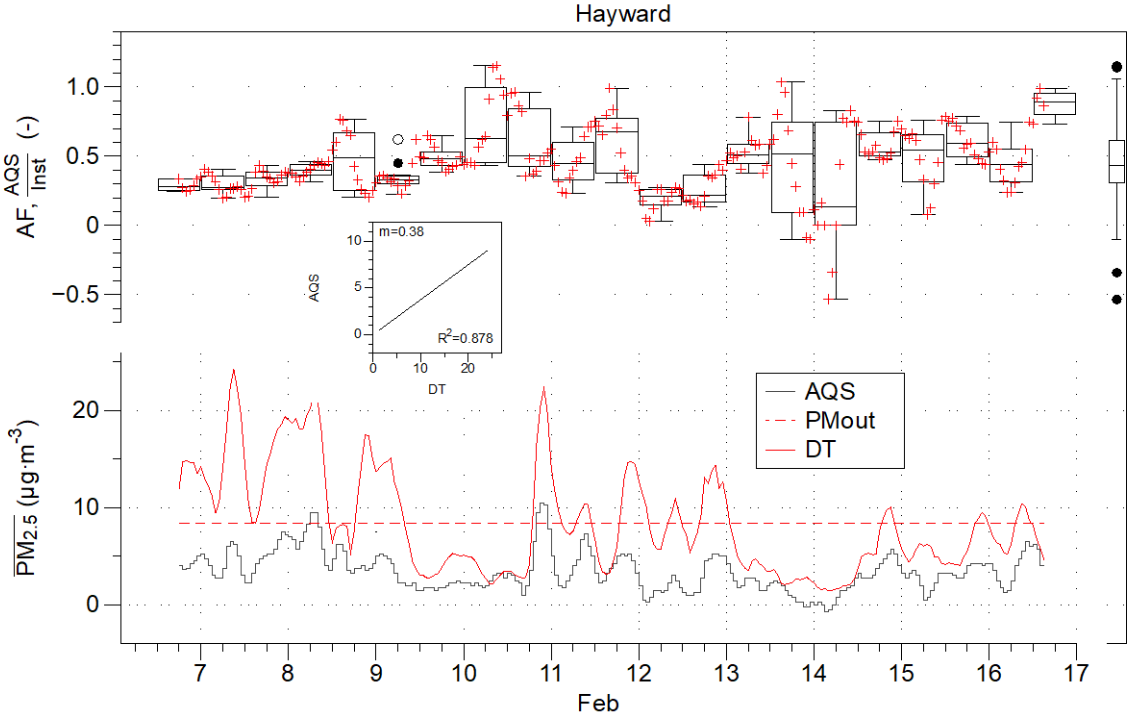


Figure S7. Comparison of outdoor $PM_{2.5}$ measured on-site in Hayward and at nearby AQS station.

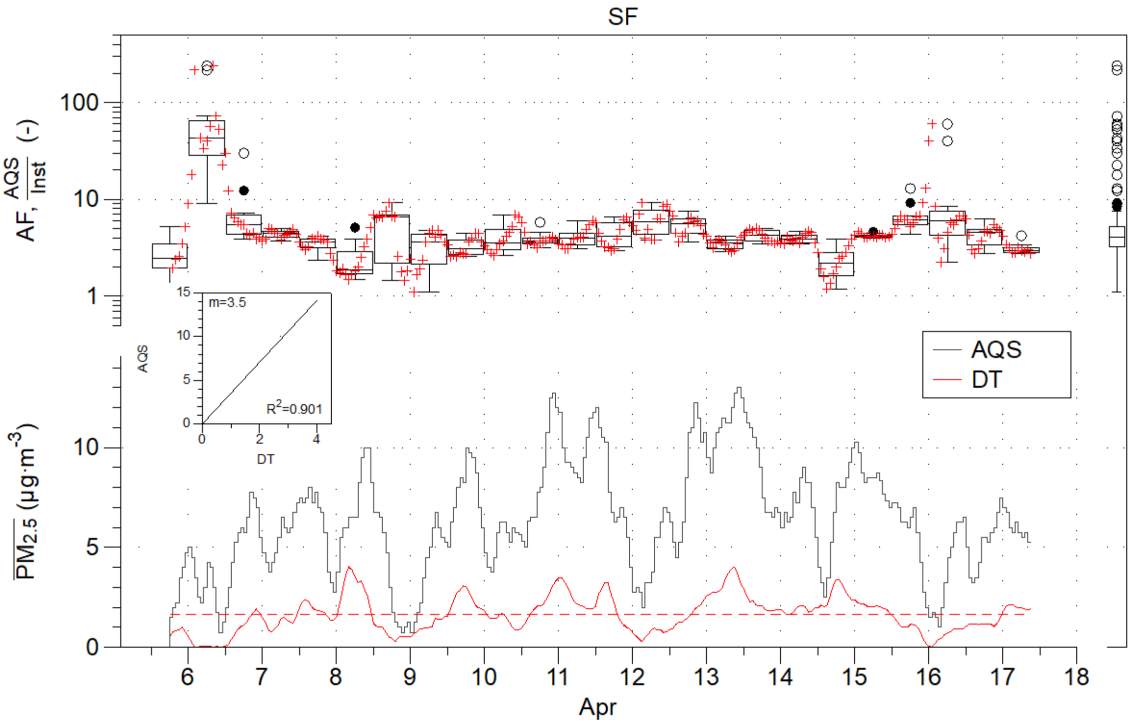


Figure S8. Comparison of outdoor $PM_{2.5}$ measured on-site in SF and at nearby AQS station.

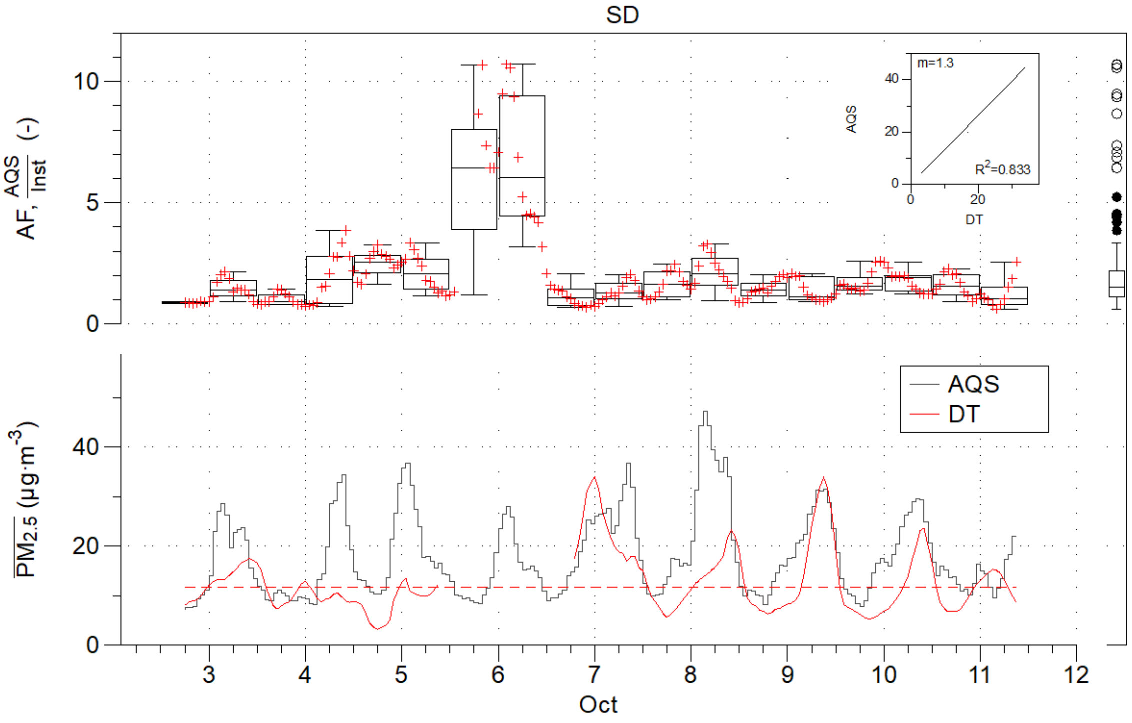


Figure S9. Comparison of outdoor $PM_{2.5}$ measured on-site in SD and at nearby AQS station.

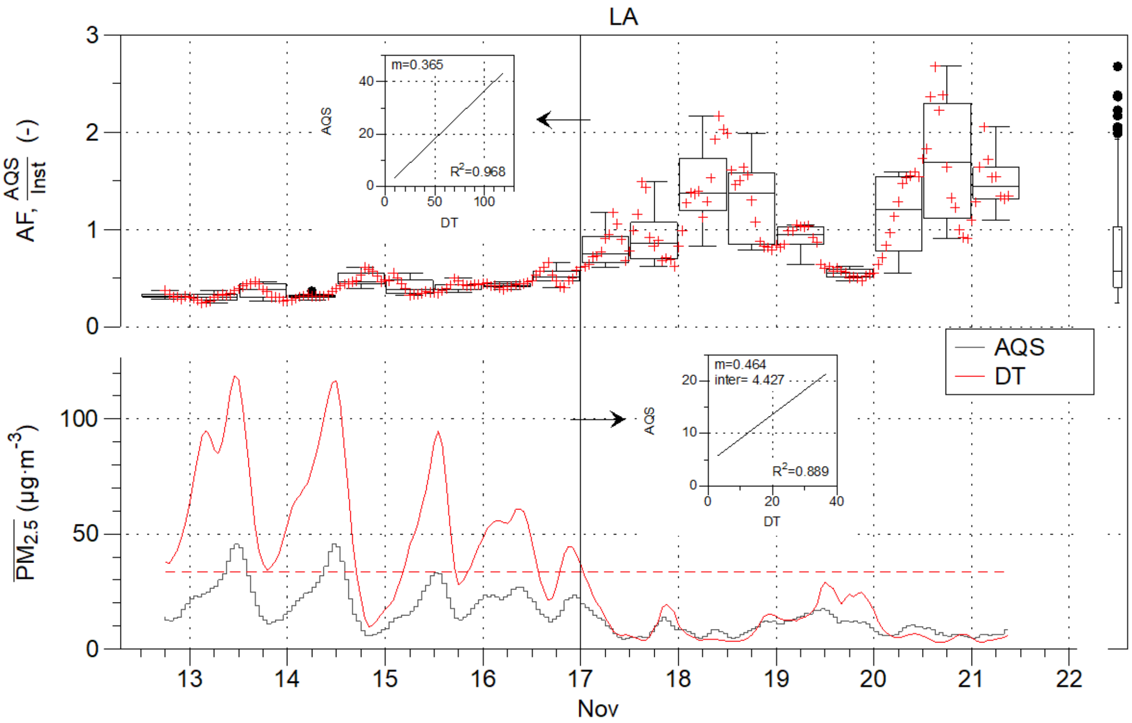


Figure S10. Comparison of outdoor PM$_{2.5}$ measured on-site in LA and at nearby AQS station.

Apartments and Household Information

Table S4. Characteristics of sites and specific apartment units included in the study.

	Site 1	Site 2	Site 3	Site 4
Dates (2019)	Feb 6–20	Apr 7–17	Oct 2–11	Nov 11-22
City	Hayward	San Francisco	San Diego	Los Angeles
Year built, renovated	Built 1993, renovated 2015	Built 1976, renovated 2016	Built 2016	Built 2013
Site units & buildings	37 units in 3 buildings	50 units in 5 buildings	33 units in 1 building	45 units in 1 building
Units studied	6 units	6 units	6 units	5 units
Building heights	2 and 3 stories	2 and 3 stories	3 stories	5 stories
Unit area, m^2	54–108	64–96	64–100	33–47
Bedrooms(n)	1BR (1), 2BR (1), 3BR (4)	2BR (2), 3BR (4)	1BR (2), 2BR (2), 3BR (2)	Studio (3), 1BR (2)
Bathrooms(n)	1Ba (2), 2Ba (4)	1Ba (2), 1.5Ba (4)	1Ba (2), 2Ba (6)	1Ba (5)
Residents	1-4	1-4	1-7	1
Density, m^2/occupant	24-54 (mean=41)	21-64 (mean=32)	14-64 (mean=41)	33-47 (mean=38)
Thermal conditioning	Forced air gas furnace. No AC.	Gas wall furnace in 2BR; forced air gas-furnace in 3BR. No AC.	Forced air hydronic heating. No AC.	Forced air ducted heat pump.
HVAC filters	Not measured	Unidentifiable low-MERV filters in 3BR units; No filter in 2BR units	MERV 8	Unidentifiable low-MERV filters

Table S5. Characteristics of studied apartment units.

ID	Bldg total floors	Floors in Bldg	Location in Bldg	Entrance	Area (m^2)	BR	BA	Occupants	Density (m^2/occ)	ACH50	MV airflow (L/s)	ACH Mech	L/s per 100m2
901	2	2	Middle	Corridor	54	1	1	1	54	11.4[1,2]	18.9[3]	0.52	243
902	3	2-3	Middle	Exterior	105	3	2	3	35	NM	55.7[3,4]	0.78	NM
903	3	2-3	Middle	Exterior	107	3	2	2	53	9.5	39.2[3]	0.54	183
904	3	2-3	Middle	Exterior	106	3	2	2	53	10.7	21.2[3]	0.30	205
905	3	1	End	Exterior	108	3	2	4	27	10.0[1]	18.9[3]	0.26	230
906	2	1	End	Corridor	72	2	1	3	24	12.3[2]	44.7[3,4]	0.98	260
911	3	3	Middle	Exterior	64	2	1	3	16	2.3	27.4[3]	0.63	45
912	3	2-3	Middle	Exterior	96	3	1.5	4	32	3.1	NA	NA	62
913	3	2-3	End	Exterior	96	3	1.5	3	32	3.2	NM	NM	65
914	3	3	End	Exterior	64	2	1	1	64	1.4	26.0[3]	0.60	28
915	3	2-3	Middle	Exterior	96	3	1.5	4	24	10.2	17.5	0.27	205
916	3	2-3	Middle	Exterior	96	3	1.5	4	24	2.5	14.6	0.22	50
921	3	2	Middle	Exterior	85	2	2	2	42	1.5	17.5	0.27	37
922	3	2	Middle	Exterior	85	2	2	3	28	2.0	33.0	0.51	48
923	3	2	End	Exterior	64	1	1	1	64	7.0	38.7	0.79	159
924	3	3	Middle	Exterior	100	3	2	7[5]	25	5.6	23.1	0.30	136
925	3	1	End	Exterior	64	1	1	1	64	8.4	17.5	0.36	190
926	3	2	Middle	Exterior	100	3	2	3	33	5.8	17.5	0.23	141
931	5	5	End	Exterior	47	1	1	1	47	15.6	17.9	0.57	308
932	5	5	End	Exterior	33	0	1	1	33	18.1	17.9	0.81	330
933	5	3	Middle	Exterior	33	0	1	1	33	14.5	17.5	0.79	265
934	5	4	End	Exterior	33	0	1	1	33	12.4	19.8	0.90	225
935	5	3	Middle	Exterior	47	1	1	1	47	8.8	30.7	0.97	173
Mean					76	2.0	1.4	2.4	38	8.0	25.6	0.55	163
Median					85	2.0	1.5	2.0	33	8.6	19.8	0.54	178

[1] ACH50 also measured at pre-visit, with same result.

[2] ACH50 measured with blower door connected to corridor; pressure connection to outside not checked.

[3] MV airflows were inferred by first fitting estimating a system curve from measured airflow and fan curve at high speed, then locating the corresponding airflow on the low-speed fan curve.

[4] MV airflows were provided by bath fans and range hood continuously.

[5] Survey response indicated 4 occupants; but occupancy log reported 7 people overnight.

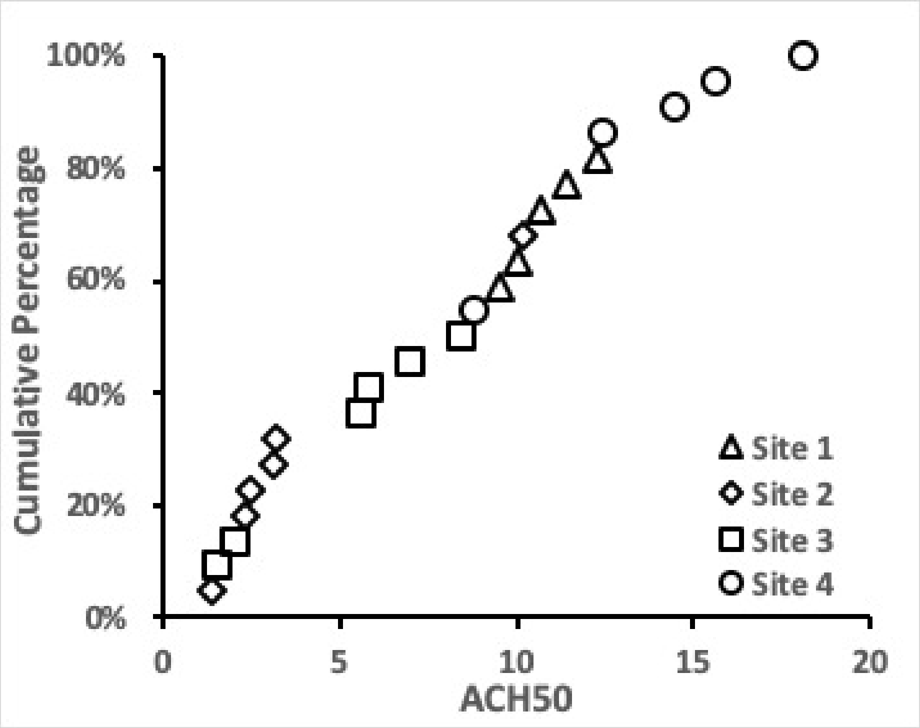


Figure S11. Distribution of apartment unit air tightness by depressurization test.

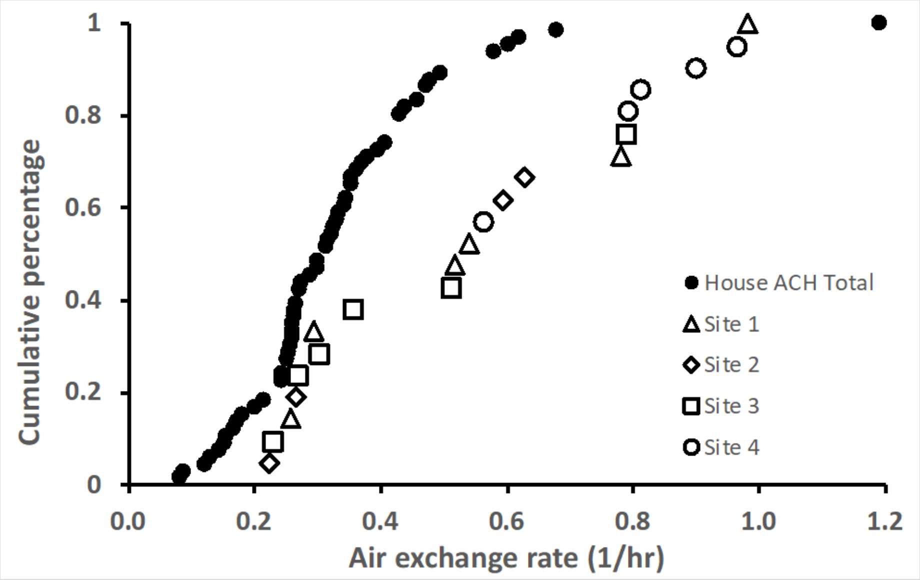


Figure S12. Comparison of mechanical ACH in apartments with total ACH in houses

The household demographics of participants in this study were very different from those in the recent HENGH study of market-rate single detached houses, as presented in Table S6. In the houses, 88% had at least one college graduate and more than half had someone with an advanced degree; only 15% of the 20 apartment study participants that answered the survey question had a college graduate. Household incomes were also very different: in the houses: 88% earned over $100,000 per year compared to none of the apartment study households. And household income was less than $35,000 per year in 68% of the apartments.

Table S6. Highest education of any household member and household income in current study of low-income apartments and recent HENGH study of market-rate, single-detached homes.

Parameter	B1	B2	B3	B4	Total (Apts)	HENGH (houses)
Highest education in household						
Completed high school	1	3	1	1	30%	1%
Some college	5	0	3	3	55%	10%
College degree	0	1	2	0	15%	34%
Graduate or professional	-	-	-	-	0%	54%
No response	0	2	0	1	--	--
Annual household income						
Less than $35,000	2	2	5	4	68%	
$35,000–$49,999	1	1	1	0	15%	2%
$50,000–$74,999	1	0	0	1	11%	3%
$75,000–$99,999	0	1	0	0	5%	8%
$100,000–$150,000	-	-	-	-	0%	44%
Greater than $150,000	-	-	-	-	0%	44%
No response	2	2	0	0	--	

Mechanical Ventilation Equipment

Table S7. Mechanical ventilation equipment at sites visited in this study.

	Site 1	**Site 2**	**Site 3**	**Site 4**
MV fan location	Bath1+Bath2: 3 units Bath1+Bath2+RH: 1 unit Bath1: 1 unit Bath1+RH: 1 unit	Bath1	Bath1+Bath2: 4 units Bath1: 2 units	Bath1
Bath/MV fan control type	BA fan: continuous low; motion sensor to high. Fan in Bath2 of unit 905 off with light switch; flow of this fan not msd. Range hoods in 902 and 906 operated continuously at low speed[d].	Continuous low; wall switch to high. Units 911 and 913 always in boost mode.	Continuous	Continuous
Bath fan model	DELTA SIG80MLED	Delta SIG110DL	Air King ESB130DG	Broan QTR 081
Bath rated flow (high, low) [cfm]	80, 50	110, 60[a]	113[b]	80
Range hood (RH) model	Airking ECQ303	Airking ESDQ1308	GE JVE40DT1BB	GE JVE40DT1WW
RH rated airflow [cfm] [c]	HS: 270 WS: 180	HS: 270 WS:150	HS: 210 WS: 110	HS: 210 WS: 110
RH rated sound [sone] [c]	HS: 5 WS: 1.5	HS: 4 WS: 1.5	HS: 6 WS: 1.3	HS: 6 WS: 1.3

[a] Continuous low speed setting is adjustable with options of 30, 60 or 80 cfm. Field team did not remove cover to check setting. Measurements of low-setting in two apartments found airflow consistent with a setting of 60 cfm, based on measured airflows at high and low settings and checking of fan curve rom manufacturer.

[b] Device has two configurations. Can be set to (a) operate continuously at 50 cfm with boost to 130 cfm by motion sensor or (b) to operate continuously at 113 cfm. The units were set to the second mode.

[c] HS = high speed; WS = working speed, i.e. lowest setting.

[d] Range hoods were installed to operated continuously at one of the low speed settings: 30, 50, 70 or 90 cfm

Table S8. Measured performance of ventilation equipment and airtightness of each apartment in relation to the requirements of California Title 24 standards. Airflows that are <90% of code requirements and air leakage >110% of code limits are shown in bold.

Apt ID	Cont. airflow in 2007 code[1] [cfm]	Cont. airflow in 2019 code[1] [cfm]	Range hood airflow: low, high[2] [cfm]	Bath1 airflow: cont., on demand[3] [cfm]	Bath2 airflow: cont., on demand[3] [cfm]	Unit air leakage[4] [cfm50/sf]	Ratio actual to 2007 code	Ratio actual to 2019 code	To code: 2007/ 2019
901	21	32	122/175	40/42	-	**0.48**	1.92	1.24	Y/N
902	41	64	**86**/98, 30[9]	43/51	45/59	NM	2.86	1.84	N/N
903	41	64	111/130	35/35	48/76	**0.36**	2.00	1.29	Y/N
904	41	64	**0**/156[5]	22/22	23/23	**0.40**	1.09	**0.70**	N/N
905	42	65	121/155	40/48	NM[7]	**0.45**	0.96[8]	**0.62[8]**	Y/N
906	30	46	**57**/65, 65[9]	36/36	-	**0.51**	3.34	2.21	N/N
911	29	43	**80**/91	58/106	-	0.09	1.97	1.34	N/N
912	40	61	107/128	Inoperable	-	0.12	**0**	**0**	N/N
913	40	61	Inoperable[6]	NM	-	0.13	NM	NM	N/N
914	29	43	**159**/159 [7]	55/85	-	0.05	1.87	1.27	N/N
915	40	61	111/150	37/63	-	**0.40**	0.92	**0.61**	Y/N
916	40	61	**72**/80	31/48	-	0.10	**0.77**	**0.51**	N/N
921	32	50	102/190	21	**16**	0.07	1.17	**0.74**	N/N
922	32	50	**81**/165	46	24	0.09	2.21	1.40	N/N
923	22	36	95/187	82	-	0.31	3.74	2.29	Y/Y
924	41	62	**61**/131	**11**	38	0.27	1.20	**0.79**	N/N
925	22	36	94/178	37	-	**0.37**	1.69	1.04	Y/N
926	41	62	99/200	25	**12**	0.28	0.91	**0.59**	N/N
931	40	30	97/172	38	-	**0.61**	0.94	1.26	Y/N
932	31	18	Inoperable	38	-	**0.65**	1.23	1.49	N/N
933	31	18	**89**/177	37	-	**0.52**	1.19	1.45	N/N
934	31	18	**88**/164	42	-	**0.44**	1.35	1.65	N/N
935	40	30	94/181	65	-	**0.34**	1.62	2.16	Y/N

[1] For low-rise multifamily (901-926), the 2008 California Building Energy Efficiency Standards (BEES) required [cfm] = 0.01*(Area, ft^2)+7.5*(BR+1). The airflows listed for units 931-935 are those required under the high-rise residential mechanical ventilation option (natural ventilation was also allowed), [cfm] = 0.06*(Area, ft^2)+5*(BR+1). Studios treated as 1 BR. The 2019 BEES required [cfm] = 0.03*(Area, ft^2)+7.5*(BR+1) for any residential unit.

[2] The first listed airflow is at the setting that is rated at 3 sone, and thus needs to be at least 100 cfm.

[3] Each bath fan must exhaust 50 cfm on-demand or 20 cfm continuously; several fans were not measured on continuous setting because fan speed boosted from motion sensor when researcher entered room.

[4] When ventilation provided by unbalanced system, California code requires mean unit air tightness of 0.3 cfm/sf; relevant since all apartments had continuous fans, the 2019.

[5] Low-speed setting not operational (broken).

[6] Had non-working range hood during the first visit. Building manger install a new one during sampling but not monitored.

[7] Device incorrectly wired to always operate on high speed.

[8] Assumed no contribution from Bath2 fan which was connected to the light on/off switch and thus did not operate continuously.

[9] Range hoods were installed to operate at settings to provide continuous exhaust ventilation airflows.

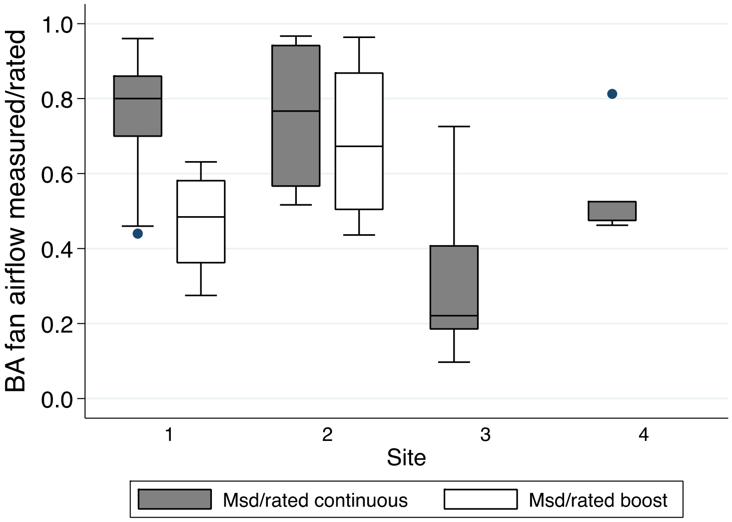


Figure S13. Ratio of measured and rated airflows of bathroom fan airflows for each site.

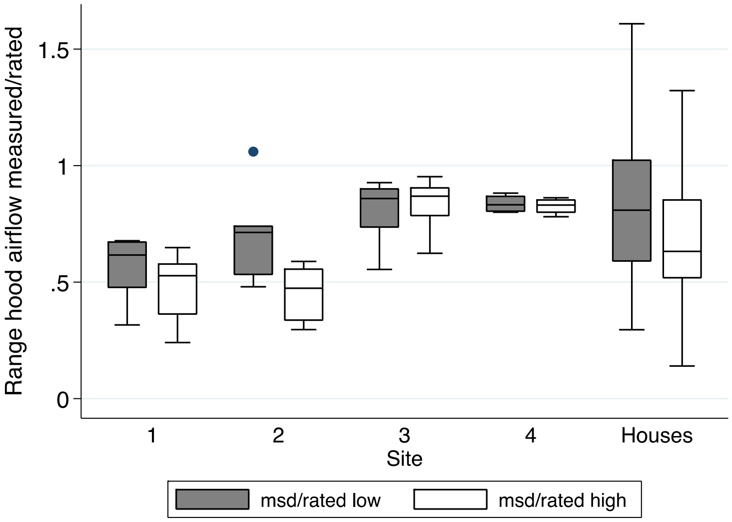


Figure S14. Ratio of measured over rated airflows of range of hood for each site.

Use of windows and doors

The self-reported window and door use frequency and total length of time during monitoring period are shown in Table S9 and Table S10. Only three apartments reported no window or exterior door use whereas seven reported opening a window and door to the outside more than 30 times during the sampling period. Eleven apartments reported opening windows and any door to outside for less three hours during the week while three apartments reported to open windows more than 21 hour during the sampling period. In single family houses, 63 reported opening windows for less than three hours and none had more than 21 hours of window opening during the week.

The sensor monitored data for door and window opening for the apartments are summarized in Figure S15. There were five apartments with a window or door open for at least 10 min on average during more than half the hours each day. Findings from both self-reported and monitored window opening results indicate the potential for substantially higher total outdoor air exchange rates than calculated from mechanical airflows in apartments.

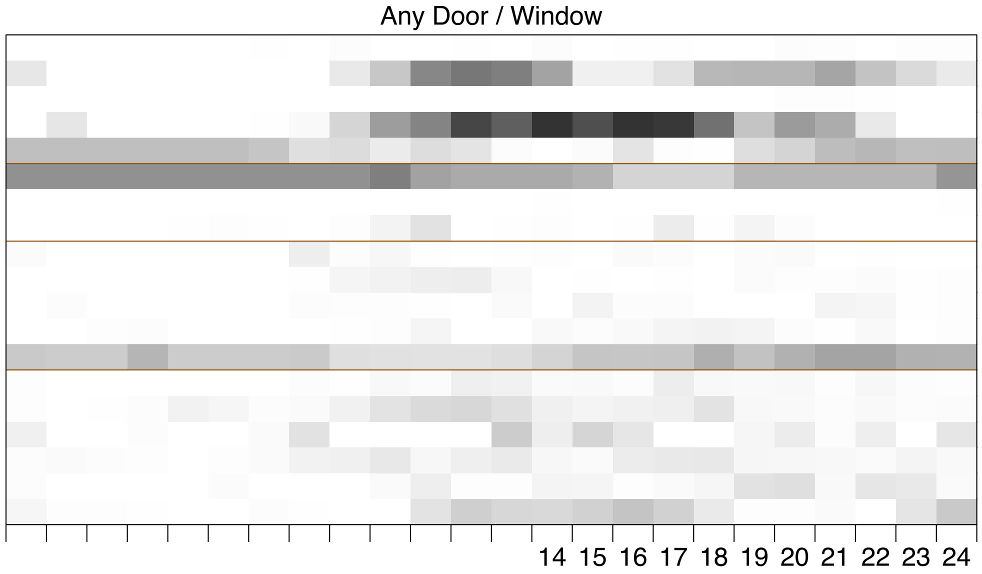


Figure S15. Mean fraction of each hour that window and/or door opening was recorded by sensors in each apartment.

Table S9. Self-reported window and door to outside use (number of times) during one-week monitoring period

Number of times	Apartments (window and door to outside use)	Houses (window and patio door use)
0	3	47
1–10	4	18
10–20	4	2
20–30	3	1
>30	7	0
No response	2	2
Total	23	70

Table S10. Self-reported window and door to outside use (total length of time) during one-week monitoring period

Number of times	Apartments (window and door to outside use)	Houses (window and patio door use)
0	3	47
<1 hour	4	10
1 to 3 hours	4	5
3 to 7 hours	4	5
7 to 21 hours	3	1
>21 hours	3	0
No response	2	2
Total	23	70

Occupancy and Cooking Frequency

Occupancy log data were successfully obtained from 18 homes. The mean fraction of occupied hours was 85% with 10th–90th range of 68–100%. The daily activity log used in the study of detached houses resolved occupancy to multi-hour blocks rather than hourly. To compare between studies, the apartment log data were analyzed at the same resolution. Of the 18 households that provided occupancy data for apartments, 17 (94%) were occupied during periods totaling at least 16 hours per day on average, and 15 (88%) were occupied during periods that totaled 20 hours per day. For the 68 single houses that provided occupancy data, 60 (88%) were occupied during periods totaling at least 16 hours per day on average, and 43 (63%) were occupied during periods that totaled 20 hours per day.

Measured Time-Integrated Air Pollutants

Table S11. Time integrated formaldehyde concentration in each site and in single family houses

	Site 1	Site 2	Site 3	Site 4	House (all)
Mean	12.1	16.1	20.3	9.4	19.8
Median	9.9	17.1	21.8	10.8	18.2
Range	8.1 – 23.7 (Min–Max)	10.8 – 20.8 (Min–Max)	7.5 – 30.0 (Min–Max)	5.0– 11.8 (Min–Max)	13.0 – 28.2 (10th – 90th)
Year Built	2015 (Refurbished)	2016 (Refurbished)	2016	2013	2013 – 2016 (New)
AER (hr^{-1})	0.56 (Mech only)	0.43 (Mech only)	0.41 (Mech only)	0.81 (Mech only)	0.33 (Total)
Indoor Temperature (°C) /RH	19.2/47% (Mean)	22.9/52% (Mean)	28.1/50% (Mean)	22.2/50% (Mean)	22.8/45% (Mean)
Outdoor Temperature (°C) /RH	9.3/73% (Mean)	13.6/71% (Mean)	20.7/65% (Mean)	18.5/62% (Mean)	16.7/64% (Mean)

Table S12. Time integrated NO_2 concentration in each site and in single family houses

	Site 1	Site 2	Site 3	Site 4	House (top 40)
Mean	20.4	18.4	14	22.0	7.1
Median	19.1	13.9	11.8	18.1	5.5
Range	13.0 – 30.6 (Min–Max)	8.9 – 38.3 (Min–Max)	10.4 –21 (Min–Max)	16.5– 36.6 (Min–Max)	1.5 – 14.2 (10th – 90th)
Outdoor mean	9.8	4.6	7.9	19.7	6.1

The higher indoor NO_2 in apartments is partly caused by higher outdoor concentrations but may also result from higher indoor emissions and higher concentrations resulting from smaller volumes in apartments. To explore the magnitude of these factors, we estimated the indoor concentration resulting from indoor emissions in houses and selected apartments by material balance analysis, treating each housing unit as a well-mixed air volume with steady-state indoor and outdoor concentrations equal to the weekly averages and other influencing parameters. The mass balance is described in Equation S2, with the following parameters:

- $C_{in,\,emission}$ is the estimated indoor NO_2 concentration from indoor emissions;
- $C_{\text{in, msd}}$ is the measured indoor NO_2 concentration;
- C_{out} is the measured outdoor NO_2 concentration;
- P is the penetration factor, assumed to be 1;
- k is the indoor loss rate, assumed to be 0.75 as in Chan et al. 2020, citing Zhou et al. 2018, Francisco, Gordon, and Rose 2010 and Gordon, Francisco, and Rose 2008;
- AER is the weekly averaged air exchange rate, equivalent to the mechanical air exchange rates in apartments and total air exchange rates in houses.

The last set of terms represents the estimated indoor NO_2 from outdoor air. The analysis was conducted for 37 houses that had all required data and for 10 apartments which had outside entrance doors (not corridors) and window opening time less than one hour per day based on activity logs and monitored data.

$$C_{in,emission} = C_{in,msd} - \left(\frac{P * AER}{AER + k}\right) C_{out,msd} \qquad \text{S1}$$

This analysis provided a mean indoor NO_2 concentration from indoor emission of 14.0 ppb and range of 4.8–32.4 ppb in the 10 selected apartments and mean of 4.8 ppb and range of 0–16.3 ppb in the 37 houses.

Table S13. Time integrated $PM_{2.5}$ concentration in each site and in single family houses

	Site 1	Site 2	Site 3	Site 4	House (top 40)
Mean	8.1	3.4	4.7	14.9	8.0
Median	5.8	1.7	1.8	8.7	4.9
Range	0.9 – 15.7 (Min–Max)	1.8 – 6.2 (Min–Max)	3.7 –8.4 (Min–Max)	2.5– 41.7 (Min–Max)	2.4 – 17.9 (10th – 90th)
Outdoor mean	5.0	7.0	4.9	13.6	10.1

Table S14. Time integrated CO_2 concentration in each site and in single family houses

	Site 1	Site 2	Site 3	Site 4	House (all)
Mean	643	767	828	725	620
Median	635	734	698	642	608
Range	578 – 722 (Min–Max)	653 – 920 (Min–Max)	537–1340 (Min–Max)	538 – 964 (Min–Max)	480 – 770 (10th – 90th)
Density (m^2/person)	41	32	41	38	88
AER (hr^{-1})	0.56 (Mech only)	0.43 (Mech only)	0.41 (Mech only)	0.81 (Mech only)	0.33 (Total)

Spatial and Temporal Variations of Air Pollutant Concentrations

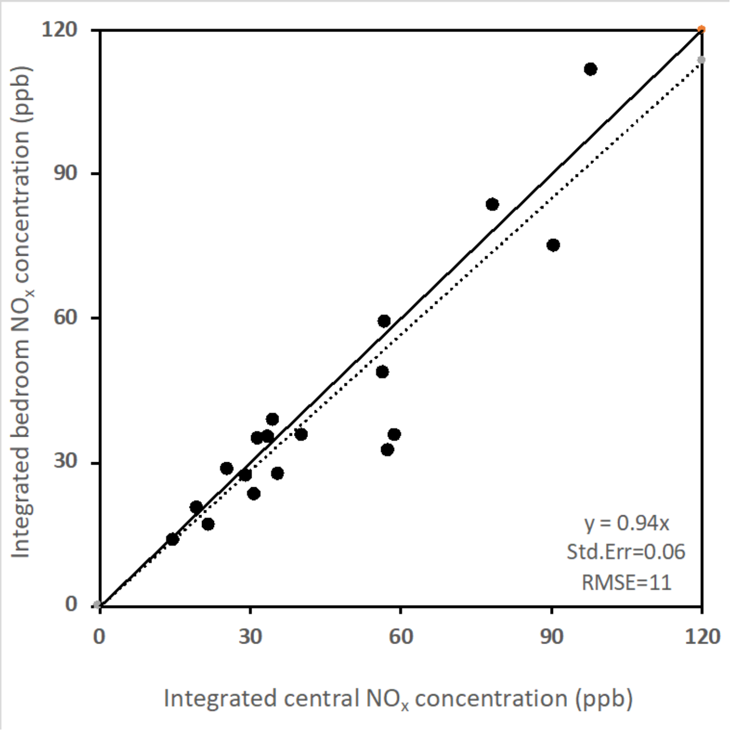


Figure S16. Comparison of NO_x concentration measured at central station and bedroom.

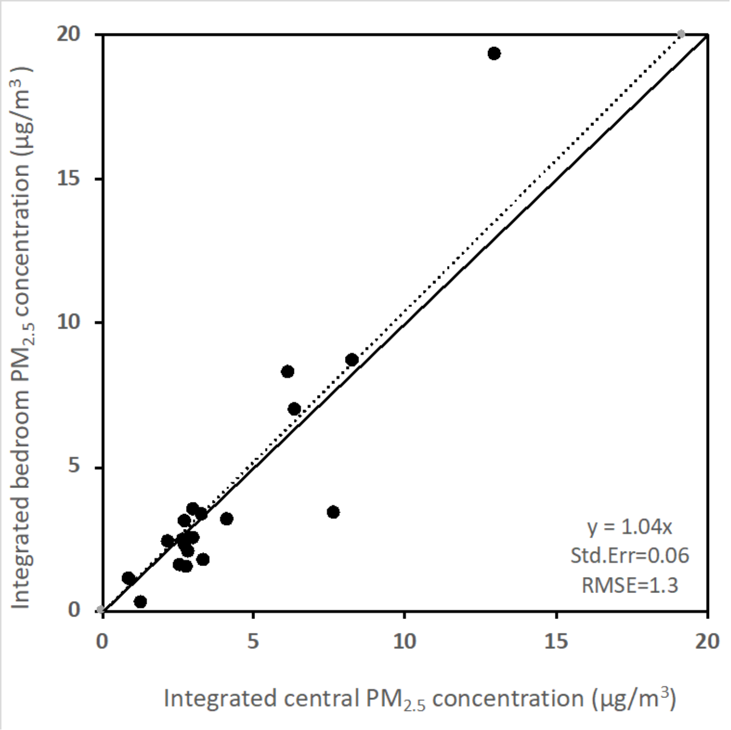


Figure S17. Comparison of adjusted $PM_{2.5}$ concentration measured by AVPs at central station and bedroom.

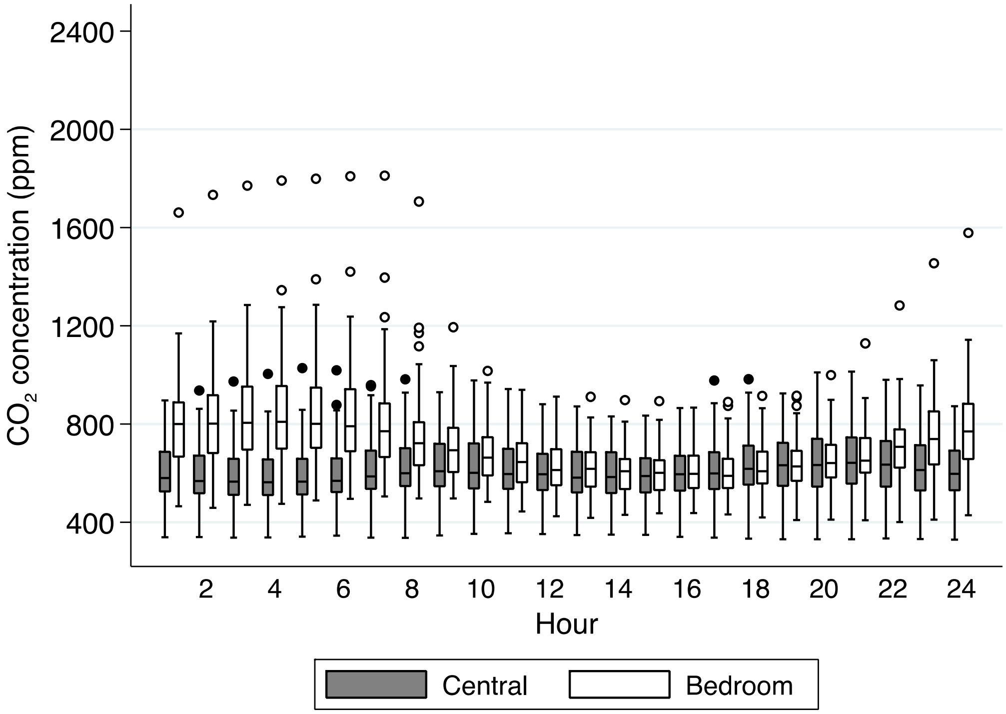


Figure S18. Distribution of mean hourly CO₂ across 70 houses based on measurements made in 69 master bedrooms and in 69 large common rooms containing the kitchen (central). Boxes show interquartile range, whiskers are 1.5 times the differences between 25th and 75th percentiles (IQR) and circles show all measurements outside of 1.5*IQR.

Acute Impacts of $PM_{2.5}$ and NO_2 Emission Events

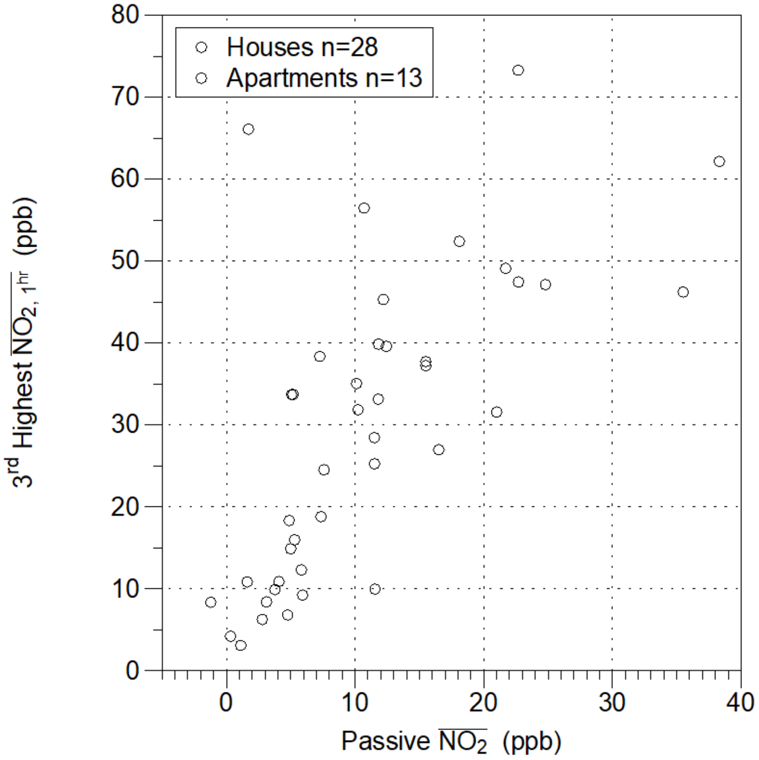


Figure S19. Comparison of high short-term NO_2 concentrations in houses (HENGH) and apartments (this study) using Aeroqual and Clarity Node sensors, respectively.

IEQ Satisfaction

Table S15. Complaint rates about environmental conditions in apartments and recent study of single detached house (Chan et al., 2019) based on survey responses of participants.

Parameter	Apartments (n=19)[1]	Houses (n=68)[2]
Too cold any season (Apts) Too cold in winter (Houses)	Total winter: 58% Other seasons also: 32% All: 21%; Fall: 11%; Spring: 11% Not a problem: 42%	≥ few times per week: 30% ≤ few times per month: 70%
Too warm in winter	0%	≥ few times per week: 16% ≤ few times per month: 84%
Too warm by season (Apts) Too hot in summer (Houses)	Total summer or fall: 74% Other seasons also: 11% Not a problem: 26%	≥ few times per week: 32% ≤ few times per month: 68%
Too dry	Year-round: 16% Any season: 21% Winter: 5%; Summer: 16%; Fall: 5% Not a problem: 63%	≥ few times per week: 9% ≤ few times per month: 91%
Too humid (Apts) Indoor air too damp (Houses)	Year-round: 5% Summer: 16% Not a problem: 79%	≥ few times per week: 1% ≤ few times per month: 99%
Too much air movement	Year-round: 11% Not a problem: 89%	≥ few times per week: 1% ≤ few times per month: 99%
Not enough air movement	Year-round: 32% Winter: 5.5%; Summer: 5.5% Not a problem: 58%	≥ few times per week: 22% ≤ few times per month: 78%
Air smells musty	Spring: 5% Summer: 16% Not a problem: 79%	≥ few times per week: 2% ≤ few times per month: 98%
Unpleasant odors from other units in building	Year-round: 16% Summer: 5% Not a problem: 79%	Not asked.

[1] Based on 19 completed surveys. Question asked if each source of discomfort was a **problem** (bold in question) in the home during each season or year-round ("all" seasons). Results are for discomfort in season or year-round.

[2] Based on 68 surveys; responses to individual questions varied from 63 to 68. Percentages relate to number of total responses for specific question. Discomfort considered a problem if respondent said it occurred few times per week or few times per day. Not a problem if only a few times per month or less often.

[3] Includes one participant that reported too warm only in fall.

Daily Activity Log: See Second SI File

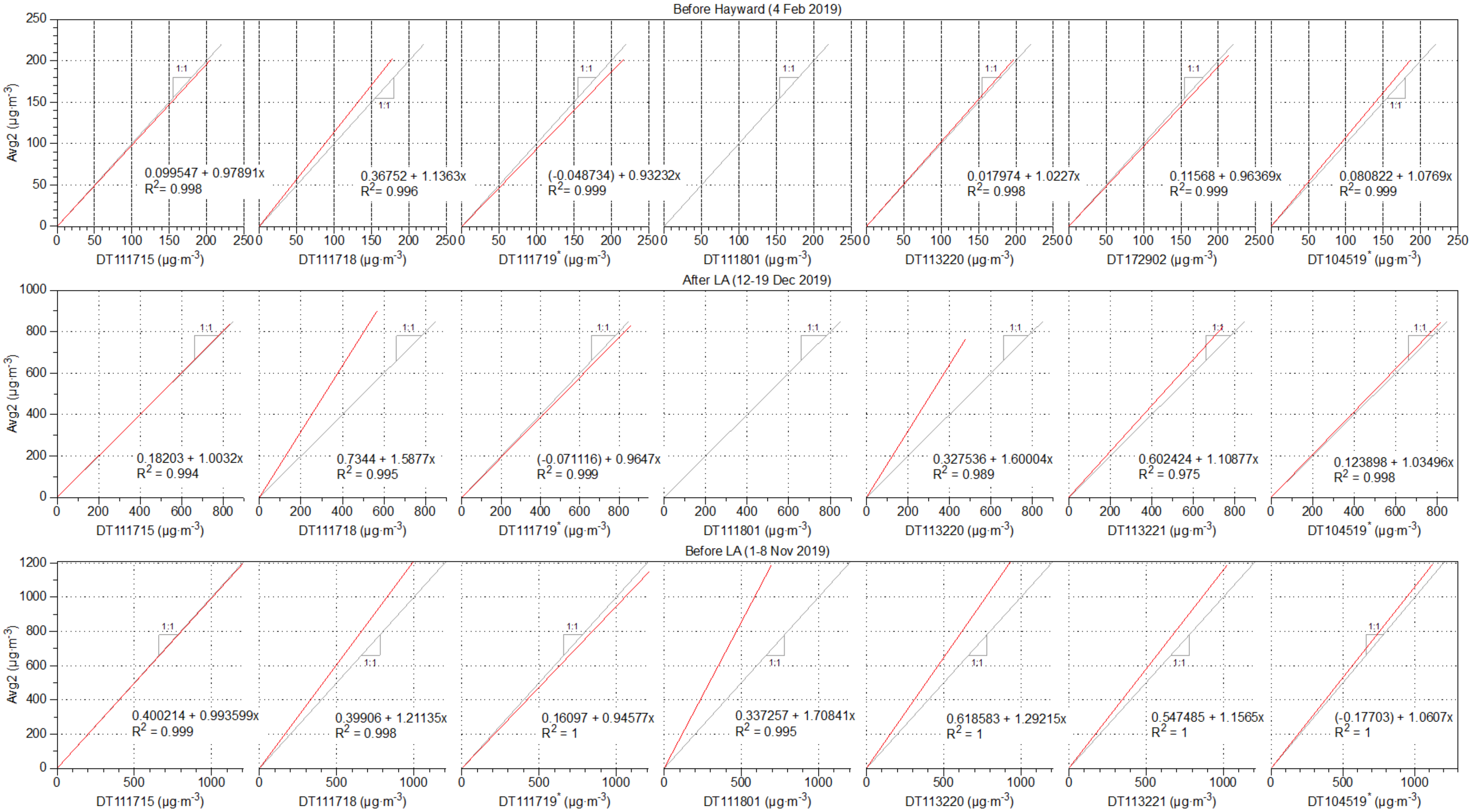
References

Chan, W. R., S. Kumar, A. L. Johnson, and B. C. Singer. 2020. "Simulations of Short-Term Exposure to NO2 and PM2.5 to Inform Capture Efficiency Standards." LBNL-2001332. Berkeley California: Lawrence Berkeley National Lab.

Francisco, P. W., J. R. Gordon, and B. Rose. 2010. "Measured Concentrations of Combustion Gases from the Use of Unvented Gas Fireplaces." *Indoor Air* 20 (5): 370–79. https://doi.org/10.1111/j.1600-0668.2010.00659.x.

Gordon, J. R., P. W. Francisco, and W. B. Rose. 2008. "Combustion Product Concentrations of Unvented Gas Fireplaces." Final Report to the Department of Housing and Urban Devlopment for Grant ILLHH0125-04.

Zhou, S., C. J. Young, T. C. VandenBoer, S. F. Kowal, and T. F. Kahan. 2018. "Time-Resolved Measurements of Nitric Oxide, Nitrogen Dioxide, and Nitrous Acid in an Occupied New York Home." *Environmental Science & Technology* 52 (15): 8355–64. https://doi.org/10.1021/acs.est.8b01792.


Before Hayward (4 Feb 2019)
Avg2 (μg·m-3)
0.099547 + 0.97891x
R2= 0.998
0.36752 + 1.1363x
R2= 0.996
(-0.048734) + 0.93232x
R2= 0.999
0.017974 + 1.0227x
R2= 0.998
0.11568 + 0.96369x
R2= 0.999
0.080822 + 1.0769x
R2= 0.999
1:1
DT111715 (μg·m-3)
DT111718 (μg·m-3)
DT111719* (μg·m-3)
DT111801 (μg·m-3)
DT113220 (μg·m-3)
DT172902 (μg·m-3)
DT104519* (μg·m-3)
After LA (12-19 Dec 2019)
Avg2 (μg·m-3)
0.18203 + 1.0032x
R2 = 0.994
0.7344 + 1.5877x
R2 = 0.995
(-0.071116) + 0.9647x
R2 = 0.999
0.327536 + 1.60004x
R2 = 0.989
0.602424 + 1.10877x
R2 = 0.975
0.123898 + 1.03496x
R2 = 0.998
DT111715 (μg·m-3)
DT111718 (μg·m-3)
DT111719* (μg·m-3)
DT111801 (μg·m-3)
DT113220 (μg·m-3)
DT113221 (μg·m-3)
DT104519* (μg·m-3)
Before LA (1-8 Nov 2019)
Avg2 (μg·m-3)
0.400214 + 0.993599x
R2 = 0.999
0.39906 + 1.21135x
R2 = 0.998
0.16097 + 0.94577x
R2 = 1
0.337257 + 1.70841x
R2 = 0.995
0.618583 + 1.29215x
R2 = 1
0.547485 + 1.1565x
R2 = 1
(-0.17703) + 1.0607x
R2 = 1
DT111715 (μg·m-3)
DT111718 (μg·m-3)
DT111719* (μg·m-3)
DT111801 (μg·m-3)
DT113220 (μg·m-3)
DT113221 (μg·m-3)
DT104519* (μg·m-3)

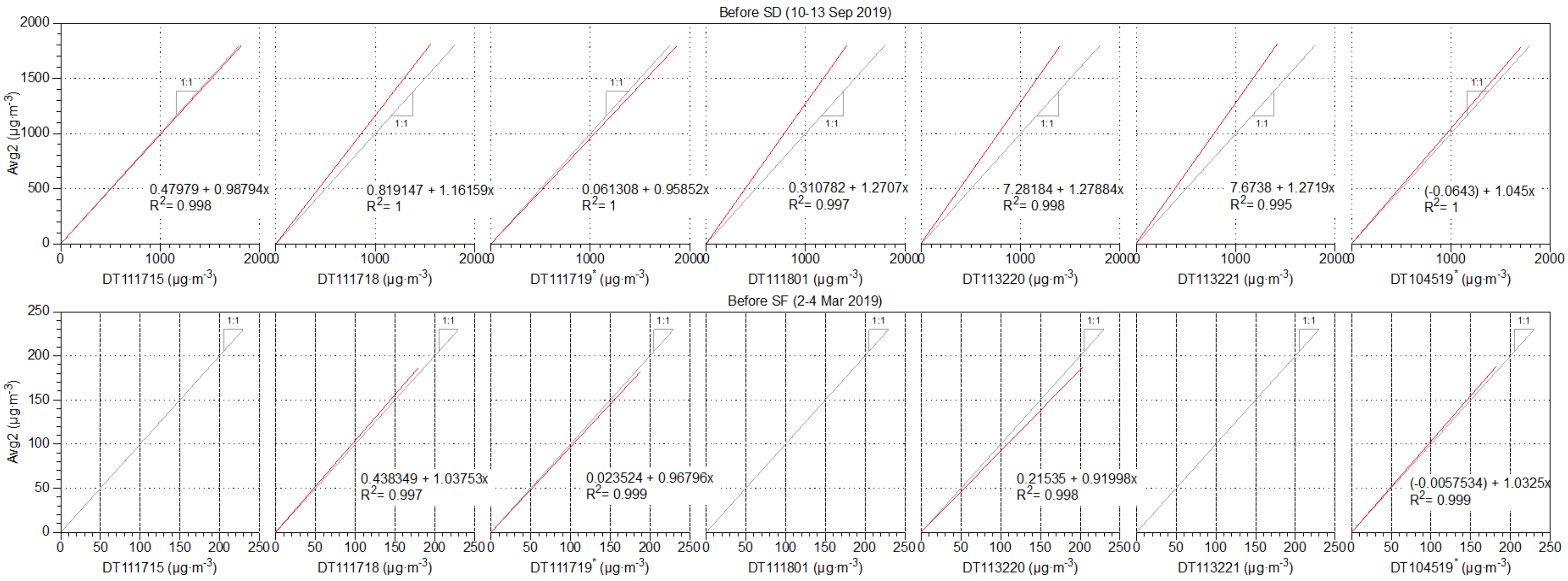


Figure S3. Cross-calibration plots for 5 co-location events (Separate File)

Date ______/______/______ Mon Tue Wed Thu Fri Sat Sun Date completed ________________

Instructions: Please fill out this daily activity log each day. If you are unsure, please provide your best guess. *Do not list the names of any people.*

	Night						Morning						Afternoon						Evening					
	Midnight	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
# people in home																								

For Activities Enter Number of Minutes per Hour

	Midnight	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Cooktop - Frying																								
Cooktop - Other																								
Main oven use																								
Toaster oven or electric grill																								
BBQ/outdoor grill																								
Vacuuming																								
Open window/ door-to-outside																								
Other events - Minutes																								
Other events – code*																								

*Other notable event codes:
(Please put the first letter of the word in the table)

Air freshener
Candle
Dehumidifier
Fireplace
Humidifier
Incense
Portable air cleaner
Smoking
X for bad outdoor air (e.g., wood smoke, wildfire)

For events not listed above, describe the event below and write the letter in the table:

V: __________________________________ W: __________________________________ Y: ______________________________