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INDOOR ENVIRONMENTAL QUALITY BENEFITS OF APARTMENT ENERGY RETROFITS

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ABSTRACT

Sixteen apartments serving low-income populations in three buildings were retrofit with the goal of simultaneously reducing energy consumption and improving indoor environmental quality (IEQ). Retrofit measures varied among apartments and included, among others, envelope sealing, installation of continuous mechanical ventilation systems, upgrading bathroom fans and range hoods, attic insulation, replacement of heating and cooling systems, and adding wall-mounted particle air cleaners. IEQ parameters were measured, generally for two one-week periods before and after the retrofits. The measurements indicate an overall improvement in IEQ conditions after the retrofits. Comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, volatile organic compounds, and particles generally improved. Formaldehyde and nitrogen dioxide levels decreased in the building with the highest concentrations, were unchanged in a second building, and increased in a third building. IEQ parameters other than particles improved more in apartments with continuous mechanical ventilation systems installed. In general, but not consistently, larger percent increases in air exchange rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources.

Keywords: apartments, energy, indoor environmental quality, retrofit, selection

1.0 INTRODUCTION

Approximately 20 percent of all U.S. households live in multifamily buildings [1]. Older apartments serving low-income populations are often poorly maintained, with deficiencies in indoor environmental quality (IEQ) such as poorly controlled thermal comfort conditions and high levels of pollutants [2, 3]. The U.S. is implementing many energy retrofits in homes with the goal of reducing building energy consumption and carbon dioxide emissions, as well as improving national energy security. Several protocols and tools exist to help with the selection and implementation of housing energy retrofit measures [4]. These protocols are typically based on energy models, engineering judgment and cost-benefit analysis, rarely considering potential effects on IEQ. Features of IEQ that may be affected by retrofits include thermal comfort conditions, indoor air pollutant concentrations, and acoustic and lighting conditions [5-7]. Although retrofit efforts provide an opportunity to simultaneously save energy and improve occupant's health and comfort, potential IEQ improvement opportunities are often not considered during selection of retrofits measures. If IEQ is neglected when retrofits are selected and implemented, the retrofits have the potential to degrade IEQ. In particular, sealing leaks in building envelopes, a very common practice, will reduce outdoor air ventilation and lead to increases in indoor air concentrations of indoor-generated air pollutants.

Improvements of IEQ have been demonstrated in a few home retrofit studies. Studies from New Zealand reported improved comfort, indoor air quality (IAQ), and health symptoms resulting from upgrading insulation and replacing ineffective heating systems or heating systems that vent combustion gases to indoors [8, 9]. Because pre-retrofit indoor air temperatures were lower than typical temperatures in U.S. homes and because many of the New Zealand homes had heating systems that vented combustion gases indoors, the results of this study are not generally applicable to U.S. homes. Some retrofit studies have focused on a specific IAQ challenge in multifamily buildings -- the inter-apartment transport of pollutants. Bohac, Hewett [10] reported reduced transfer of secondhand tobacco smoke between apartments resulting from apartment air sealing and increased ventilation. However, to the best of our knowledge, no study has empirically investigated the potential for simultaneous energy and IEQ benefits when broad packages of retrofits are implemented in apartments.

The current paper describes the changes in IEQ conditions (air quality and thermal comfort conditions) from the implementation of energy and IEQ retrofits in a total of 16 apartments serving low-income populations within three buildings in different California climates and seasons. Energy savings data are still being collected and will be described in a future paper. The retrofits were selected using a protocol [4] that estimates the value of energy, comfort, and IEQ benefits of retrofit measures for the purpose of optimizing retrofit packages to achieve these three goals.

2.0 METHODS

2.1 Apartments and Retrofits

Buildings and apartments were selected and retrofit specifically for this project. Selection criteria included low-income residents (subsidized housing), heating and cooling systems that serve individual apartments (not shared among apartments), and locations in multiple California climate zones. Also, building owners, management companies, and individual residents had to agree to participate. For more information on the buildings and the selection process see [4]. Buildings 1, 2, and 3 (B1, B2, B3) were located in Sacramento, Richmond, and Fresno, CA and were constructed in 1967, 1973, and 1975, respectively. Fresno has the poorest outdoor air quality of the three cities and Richmond has the mildest climate. Apartments had two to four bedrooms and floor areas that ranged from 70 m^2 to 139 m^2. Seven apartments had a single floor, nine had two floors and resembled townhouses. Five apartments were retrofit in B1, five in B2 (plus a sixth that did not complete post retrofit measurements) and six apartments were retrofit in B3. The number of apartments included in the study was constrained by the project budget. Only apartments whose residents reported that no smoking was allowed inside the unit were included in the project. The retrofits implemented are listed in Table 1. Some retrofit measures, such as refrigerator and light bulb replacement, were expected to have no significant impact on the measured IEQ parameters. Envelope air sealing performed in B2 and B3 apartments was expected to reduce inter-apartment air leakage (a potential source of pollutants) but to also decrease infiltration of outdoor air that helps control indoor concentrations of indoor-generated air pollutants. Envelope sealing will also reduce entry rates of some outdoor air pollutants. The intent was to provide continuous mechanical ventilation at 1.5 times the rate specified in ASHRAE Standard 62.2 [11]. Mechanical ventilation was provided using balanced energy recovery ventilators (ERVs) in B1 and in three of the apartments in B3. Continuously operating bathroom exhaust fans were installed in B2 and in three apartments in B3. The reason for targeting 1.5 times the amount specified in the standard is that only a fraction of the infiltration is provided with outdoor “fresh” air, while the remaining air comes from surrounding internal spaces (e.g., other apartments, common areas). This is particularly true when exhaust fans are used to provide the mechanical ventilation and is reflected by the increased mechanical ventilation rates in the recently released Addendum J to the ASHRAE Standard [11]. Contrary to plans, continuous bathroom fan operation was not implemented until after post-retrofit

IEQ measurements were completed in B2 and B3[1]. Thus, this paper is based on data from eight apartments in which continuous mechanical with was added with ERVs, and from eight apartments without addition of continuous mechanical ventilation. Kitchen range hoods vented to outdoors were installed or replaced in all apartments. These range hoods can help prevent cooking-related pollutants and combustion gases from entering the occupied spaces. The existing range hoods did not vent to outdoors or had flow rates substantially lower than required by ASHRAE Standard 62.2 [4]. The opportunity for IEQ improvement was increased in B1 because the apartments had gas stoves with pilot lights that were a continuous source of particles and nitrogen oxides, and that waste energy. The range hoods in these apartments also did not vent to outdoors. The stoves in B1 were replaced with electronic-ignition models. In B2 and B3, wall-mounted HEPA filter units (RabbitAir MinusA2 Ultra Quiet HEPA Air Purifier) with maximum airflow rates of 88 L/s were installed in living rooms. We suggested that occupants operate these filtration systems in "auto" mode that has a continuous low airflow rate that increases when a high level of particles are detected. Addition of thermal insulation in B2 and B3, replacement of some single-pane windows in B3, and replacement of some sliding glass doors in B2 were expected to improve comfort conditions. The average retrofit cost per apartment was $12,700 in B1, $7,700 in B2, and $9,000 in B3. Apartments in B1, B2, and B3 were retrofit in August 2011, January 2012, and March 2012, respectively. More information about the buildings, the apartments, the retrofit selection, the retrofit implementation and the diagnostic measurements is available from [4].

2.2 IEQ parameters

To evaluate the impacts of the retrofits on the apartment IEQ, measurements were performed before and after retrofit implementation in the retrofitted apartments as well as outdoors. The pre- and post-retrofit measurements and the retrofits were all conducted during the same season, the cooling season for B1 and the heating season for B2 and B3, although post retrofit outdoor air temperatures at B3 were considerably higher than the pre-retrofit temperatures. We conducted the pre- and post-retrofit measurements during the same season to minimize the potential for changes in occupancy and/or occupants' activity patterns that could impact IEQ and potentially mask the effects of retrofits. Measurements were performed continuously during two one-week consecutive periods before retrofits started and during two one-week periods at least two weeks after retrofits were completed.

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[1] During the second week of post-retrofit measurements in B3, bathroom fans operated continuously; however, we have not used data from this period because summer-like outdoor air temperatures likely prompted considerable window use.

Table 1. Number of retrofit measures implemented in each building.

Retrofit	B1	B2[a]	B3
Air sealing	-[b]	5	6
Install energy recovery ventilator (ERV)	5	-	3
Replace intermittent bath exhaust fan	5	-	3
Add continuous bath exhaust fan	-	5[c]	3[c]
Replace intermittent kitchen range hood	5	5	6
HVAC system filter upgrade	5	5	6
Add water heater jacket and insulation	-	3	-
Replace natural draft water heater with forced combustion condensing water heater	5	-	-
Weather strip water heater closet door	-	2	-
Provide portable fan	5	5	6
Install carbon monoxide (CO) detector	5	5	-
Clean minor mold damage in bathroom	3	-	-
Replace incandescent light bulbs with compact fluorescent lights	5	5	6
Replace gas cook stove with standing pilot with electronic ignition stove	5	-	-
Replace refrigerator with energy-efficient refrigerator	5	5	6
Replace heating and cooling rooftop packaged unit with a more efficient unit	5	-	-
Add attic insulation (cellulose R-38)	-	4	4
Replace HVAC ductwork & seal return plenum	-	5	3
Install stand-alone wall-mounted HEPA filter	-	5	6
Replace single pane sliding door with double pane door	-	1	-
Replace single pane window with double pane window	-	-	3

[a] Some recommended measured not implemented in one apartment to accommodate tenant preferences
[b] Entry doors were weather-stripped
[c] Intent was to have continuous operating bathroom fans installed; however, continuous operation was not implemented until after the post-retrofit IEQ measurements were completed.

The IEQ parameters selected for measurement at indoor and outdoor locations include the following: temperature (T); relative humidity (RH); and concentrations of carbon dioxide (CO_2), carbon monoxide (CO), particle matter less than 2.5 micrometers (PM2.5), nitrogen dioxide (NO_2), acetaldehyde, formaldehyde, and a suite of volatile organic compounds (VOCs). The measurements were conducted using time-resolved and time-integrated methods. The parameters monitored with time-resolved instruments included carbon dioxide (CO_2) and carbon monoxide (CO) measured using Langan Model L76v (Langan Products, Inc., San Francisco, CA, USA). This instrument incorporates a GE Telaire 7001 (GE Measurement & Control Solutions, Billerica, MA, USA) for CO_2 quantification, while the CO was assessed with a built in electrochemical passive sensor (Langan Model T15n). TSI Dust Trak instruments (TSI Inc., Shoreview, MN, USA) were used to measure particle matter (PM) mass less than 2.5 micrometers in diameter. T and RH were measured with Onset HOBO U12 sensors (Onset Corp., Bourne, MA, USA), while to monitor RH in bathrooms with showers we used Onset HOBO U23 sensors capable of withstanding the greater humidity levels encountered in bathrooms. Time-integrated sampling methods were employed to measure nitrogen dioxide (NO_2), formaldehyde, acetaldehyde, and volatile organic compounds (VOCs). These methods employ diffusive sample collection (no pumping required) and subsequent analysis of the samples in the laboratory. NO_2 was collected using Ogawa samplers and sampling media (Ogawa & Co. USA, Inc., Pompano Beach, FL, USA), and quantified through ion chromatography (IC). A validation of the NO_2 measurement methods is provided by [12]. Formaldehyde and acetaldehyde were sampled using Waters cartridges (Waters Corporation, Milford, MA, USA) containing 2,4-dinitrophenylhydrazine (DNPH) coated with silica and then quantified by high-performance liquid chromatography (HPLC). Side by side active and passive sampling with these cartridges have been reported in two studies [13] and [14]. When calculating aldehyde concentrations, we applied the more recent, and lower passive sampling rates of validation experiments [14] because the sampling duration, concentration range, and environments were better matched to the conditions of this study. Volatile organic compounds were passively sampled using an adsorbent (stainless steel tube filled with Tenax®-TA, Supelco P/N 28271-U), subsequently thermally desorbed for analysis by gas chromatography-mass spectroscopy (GC-MS) The VOC methods are described in [15]. A set of approximately 30 VOCs was quantified. The overall apartment ventilation flow rate over each monitoring period was assessed using the perfluorocarbon tracer (PFT) method. To measure this time-integrated parameter, we installed two to three continuous passive emitters of hexafluorobenzene. This tracer was then sampled and analyzed using the passive Tenax tubes and GC-MS methodology employed for VOCs [16]. Hexafluorobenzene sources were placed in different locations within the apartments away from operable windows and doors. The measured apartment ventilation rate represents the total airflow through the apartment, without distinguishing between the airflow coming from outdoors or from other parts of the building.

All the instruments and samplers for the IEQ indoor measurements were placed in a protective enclosure and located in a central location inside the apartment (away from windows and doors) about 2 m above the floor. The indoor Tenax tubes were located outside the indoor enclosure to avoid possible contamination caused by pollutants emitted by the enclosure. T and RH were also measured in any bathroom with a shower and in the main bedroom. Additional NO_2 passive samplers were located in the main bedrooms of each apartment. The outdoor instrumentation was placed at approximately 1.5 m of height inside a locker located in a central location within the apartment complex.

A summary of the methodologies employed for the IEQ measurements is presented in Table 2. The CO and CO_2 instruments were calibrated with gas standards before and after measurements in each building. The PM instruments were initially checked by comparison of their output to PM mass determined from the weight changes and air flow rates through filters [17], and were subsequently inter-compared before and after measurements in each building. To minimize device-induced variability in the measurements, the same real time instruments for CO, CO_2, PM2.5, temperature, and relative humidity were utilized for the pre- and post-retrofit measurements in the same apartment. Consequently, the uncertainties in changes in these parameters between the pre- and post-retrofit measurement periods will be less than the uncertainties indicated in Table 2. For the passive methods, field blank and duplicates tubes were analyzed. Laboratory blanks and field blanks were used for quality control, while duplicates were utilized to determine relative precision. Calibration checks and calibration standards were also performed for each set of field samples to assure performance of the laboratory instruments and techniques.

Table 2. Description of parameters, locations, techniques and instruments used for indoor and outdoor measurements.

Parameter	Locations	Resolution	Sampler	Instrument	Uncertainty Estimate	Uncertainty Sources
Temperature (T) and Relative Humidity (RH)	Indoor & outdoor enclosures, bedroom, bathroom	Time resolved	-	Onset HOBO U12 or U23 in bathroom	±0.35 °C ±3.5%	Product Literature
Carbon dioxide (CO_2)	Indoor & outdoor enclosures	Time resolved	-	Langan Model L76v – GE Telaire Model 7100	90 ppm (7%) at 1260 ppm avg. concentration	Analysis of repeated instrument calibrations
Carbon monoxide (CO)	Indoor & outdoor enclosures	Time resolved	-	Langan Model L76v – Model T15n	0.7 ppm at 2 ppm avg. concentration	Analysis of repeated instrument calibrations
Particle matter (PM) mass	Indoor & outdoor enclosures	Time resolved	-	TSI Dust Trak	0.8 μg/m^3 precision	[17]
Nitrogen dioxide (NO_2)	Indoor & outdoor enclosures, main bedroom	Time integrated	Ogawa badge	Ion Chromotography	~8%	[12]
Acetaldehyde Formaldehyde	Indoor & outdoor enclosures	Time integrated	Waters DNPH tube	High Performance Liquid Chromotography	Less than 1.2 μg/m^3 or 10% Less than 1.8 μg/m^3 or 12%	Analysis of replicates
Volatile organic compounds (VOCs)	Outdoor enclosure & indoor living room, main bedroom	Time integrated	Tenax tube	Gas Chromotography Mass Spectrometry	10% coefficient of variation of replicate measurements	[15]
Ventilation rate (VR)	Living room, main bedroom	Time integrated	Tenax tube	Gas Chromotography Mass Spectrometry	20%[a]	Analysis of replicates

[a] accounts for uncertainty in measurement of tracer gas concentration based on replicate data, does not account for errors due to imperfect mixing of tracer in indoor air

2.3 Resident satisfaction surveys

At least one resident on each of the study apartments participated in the occupant surveys. They were composed of three sections: baseline, pre-retrofit and post-retrofit. The surveys included questions about apartment conditions, occupant behaviors, and satisfaction with air quality and the implemented retrofits. The surveys and other study protocols were approved by the Lawrence Berkeley National Laboratory's Institutional Review Board.

2.4 Metrics of IEQ Change

To indicate how the retrofits affected thermal comfort conditions, for each apartment the percent of time with the indoor air temperatures at the central measurement location exceeding or falling below the applicable ASHRAE Thermal Comfort zones [18] were calculated for pre-retrofit and post-retrofit periods. For B1, retrofit in summer, the percent of time with an indoor air temperature above 27.4 °C was calculated. For apartments in B2 and B3, retrofit in winter, the percent of time with indoor air temperatures below 20.5 °C was calculated. The boundaries of ASHRAE's thermal comfort zone vary somewhat with humidity and values of 27.4 °C and 20.5 °C were based on typical indoor values of humidity. Also, the thermal comfort boundaries only apply when air speeds are less than 0.2 m s^{-1}.

We also calculated the percent time with overcooling in B1 (studied in summer) and overheating in B2 and B3 (studied in winter) relative to ASHRAE's summer and winter thermal comfort zones. It is not clear if the resulting data indicate the extent of thermal discomfort or if the data indicate tenant willingness to pay for energy to be a slightly cooler in summer and warmer and winter.

The measured values of apartment relative humidity (RH) were almost always between 35% and 55%, never indicating a humidity problem. There were periods of elevated RH in the main bathroom, potentially contributing to mold growth, thus, the percent time with bathroom RH greater than 75% was used as a metric of performance.

For carbon dioxide, formaldehyde and acetaldehyde the average pre-retrofit and post- indoor and outdoor concentrations were calculated, and then the indoor minus outdoor differences were calculated. These calculations are based on two weeks of data before and after the retrofits. To characterize the effects of the retrofits, percent improvements in these average concentration differences were then calculated.

In many cases, large changes in outdoor air concentrations of NO_2 and PM2.5 made changes in the indoor, or indoor minus outdoor, concentration differences of NO_2 and PM2.5 invalid as indicators of the effect of the retrofits on indoor air quality. Consequently, adjusted pre-retrofit indoor air concentrations of NO_2 and PM2.5 were calculated. The adjustments, based on mass balance models, yielded estimates of what the pre-retrofit indoor air concentrations would have been if the outdoor air concentration during the pre-retrofit period had been the same as the post-retrofit outdoor air concentration.

For NO_2, a change in outdoor air concentration of ΔC_0 will change the indoor air NO_2 concentration ΔC_i by less than ΔC_0 because of indoor NO_2 depositional losses. From a steady state mass balance

$$\Delta C_i = \Delta C_o \, \lambda_v \, / (\lambda_v + K_d) \qquad (1)$$

where λ_v is the air exchange rate (h^{-1}) and K_d is the NO_2 deposition loss constant (h^{-1}). This equation assumes negligible NO_2 depositional losses as NO_2 laden outdoor air enters the building. Nazaroff, Gadgil [19] provide data on from a review of literature that indicate values of K_d from 0.2 to 1.2 h^{-1}. Yang, Lee [20] assumed that $K_d = 1.0$ h^{-1} based on studies in Korean houses. Equation 1 was used to calculate values of K_d based on measured indoor and outdoor NO_2 concentrations and ventilation rates from five apartments in B3 with no indication of indoor NO_2 sources. The average pre- and post-retrofit values of K_d were 0.44 and 0.25 h^{-1}, respectively. Consequently, the average K_d of 0.34 h^{-1} was used in all subsequent NO_2 calculations. Adjusted pre-retrofit indoor NO_2 concentrations were calculated as the measured indoor concentrations plus ΔC_i, using the pre-retrofit value of λ_v in equation 1.

For PM2.5, a change in outdoor air concentration of ΔC_0 will change the indoor air PM2.5 concentration ΔC_i by less than ΔC_0 because of indoor PM2.5 depositional losses and removal by the particle filter in the forced air heating and cooling system. From a steady state mass balance

$$\Delta C_i = \Delta C_o \, \lambda_v \, / (\lambda_v + K_d + K_f) \qquad (2)$$

where K_f is a constant indicating the rate of PM2.5 removal by filtration. For PM2.5, we assumed K_d =0.09 (Riley et al 2002) and used this value in all PM2.5 calculations. The time average rate of particle removal by the filter was calculated from equation 3

$$K_f = \lambda_f F \, \varepsilon \qquad (3)$$

where λ_f is the volume normalized rate of airflow through the heating and cooling system. Values of λ_f were calculated for each apartment based on the air flow rates in the product literature for the heating and cooling systems and the apartment volumes and ranged from 4.9 to 9.3 h^{-1}. The parameter F is the fraction of time when the heating or cooling system operated, and ε is the particle removal efficiency of the filter. Values of F were estimated for each apartment from measured temperatures in the supply airstream of forced air heating and cooling systems, averaged 0.19 and ranged from 0.05 to 0.72. A value of 0.19, applicable to a low efficiency furnace filter, was assumed for ε [21]. The resulting values of K_f ranged from 0.06 to 1.0, with a mean value of 0.27. Adjusted pre-retrofit indoor PM2.5 concentrations were calculated as the measured indoor concentrations plus ΔC_i. A limitation of this analysis is that it does not correct for changes in F that area consequence of differences between pre-retrofit and post-retrofit weather conditions.

Other than formaldehyde and acetaldehyde, no individual VOCs had concentrations near guidelines or standards, thus, we summed the concentrations of all VOCs that had concentrations above detection limits. In general, the sums included approximately 30 quantified VOCs. These VOCs are listed in Table S1 in the supplemental information. The percent improvements in the summed concentrations were used as a general indicator of the effects of the retrofits on indoor VOCs, recognizing that health risks are not proportional to the summed VOC concentration because the toxicity of VOCs varies widely. Outdoor air concentrations of VOCs were often below detection limits, thus, outdoor air concentrations were not subtracted from indoor air concentrations.

3.0 RESULTS

Tables S2 – S4 in the supplemental information provide the main IEQ measurement results from periods before and after the retrofits for apartments in buildings B1 through B3, respectively. These tables provide for each apartment, for both pre-retrofit and post-retrofit periods, values of the IEQ parameters described in the methods section. When applicable, outdoor air values of parameters are also provided. Carbon monoxide concentrations were consistently below guidelines and near to the level of measurement uncertainty, thus, these data are not included. Because the large amount of tabulated data in S2 – S4 does not facilitate easy communication of study findings, the findings are illustrated in the subsequent figures.

Figure 1 shows the measured air exchange rates. In this figure and in Figures 2-9, solid columns represent data from apartments without continuous mechanical ventilation and patterned columns represent data from apartments with continuous mechanical provided by energy recovery ventilators (ERVs) in the post retrofit data collection periods. Air exchange rates increased by 180% in B1 (with ERVs installed), by 11% in B2 without ERVs (not a significant change given measurement uncertainty), and by 68% in B3 which had ERVs installed in A2, A3, and A4. Only one of three B3 apartments without an ERV installed (B3A5) had a notable increase in air exchange rate.

The retrofits that may have affected thermal comfort include envelope sealing, attic insulation, replacement of windows and sliding glass doors, duct sealing or replacement, and replacement of heating and cooling systems. The calculated values of the metrics relevant to thermal discomfort are plotted in Figure 2. In B1 and B3, after the retrofits there was substantially less time with temperatures above (in B1) or below (in B3) the boundaries of ASHRAE thermal comfort zone. Thus, the retrofits appear to have improved comfort in these buildings. In B2 there was a modest increase in time with temperatures outside of the comfort zone, indicating discomfort. These findings remained after considering only daytime (07:00 – 23:00) temperature data (results not shown). Results from B3 should be viewed with caution, because the average outdoor air temperature was 14.6 ^{o}C after the retrofits compared to 8.1 ^{o}C before retrofits.

We also examined the hours of overcooling in B1 (studied in summer) and overheating in B2 and B3 (studied in winter), relative to the boundaries of ASHRAE's summer and winter thermal comfort zones, at 50% relative humidity. In B1, temperatures were below 21 ^{o}C, the approximate lower boundary of ASHRAE's summer thermal comfort zone, 1% of the time before the retrofits and 4% of time after the retrofits. In B2, temperatures exceeded 25.5 ^{o}C, the approximate upper boundary of ASHRAE's winter comfort zone, 17% of the time before the retrofits and 13% of time after the retrofits. In B3 the percent time with indoor temperatures above 25.5 ^{o}C increased from 4.3% to 9.4%. In all cases, the changes were small.

In most apartments, bathroom RH exceeded 75% only a few percent of the time (Figure 3). In B1 and B2, the percent of time with bathroom RH greater than 75% was generally less after the retrofits, potentially indicating the beneficial effect of the bathroom fans that came on automatically when bathroom RH was high (B1) or when an occupant was detected (B2). In B3, the periods of high RH were small, and, on average, increased slightly after the retrofits possibly because the moisture content in outdoor air was 75% higher after the retrofit (0.0065 versus 0.0037 gram water per gram dry air). Before the retrofits, in three B2 apartments the bathroom RH exceeded 75% more than 20% of the time. In each of these cases, the periods of high RH were much reduced after the retrofits.

Carbon dioxide concentrations are higher indoors because CO_2 is released by occupants and cooking. Figure 4 shows that the difference between indoor and outdoor CO_2 concentration decreased in most apartments. The average decreases were 33%, 24%, and 35% in B1, B2, and B3, respectively. At these concentrations, CO_2 is not believed to directly pose any health risks; however, it is a proxy for unmeasured indoor-generated pollutants with emission rates linked to occupancy. In many cases, indoor minus outdoor concentrations exceeded 600 ppm. Many practitioners assume ventilation rates are insufficient when indoor CO_2 concentrations exceed 1000 ppm, corresponding to indoor-outdoor concentration differences exceeding 600 ppm.

Formaldehyde is emitted from a range of indoor sources with manufactured wood products as a major source. Formaldehyde has been declared a human carcinogen by the International Agency for Research on Cancer. As shown in Figure 5, in B1, the average indoor minus outdoor formaldehyde concentration decreased by 48% from 45 $\mu g\ m^{-3}$ before the retrofits to24 $\mu g\ m^{-3}$ ppb after the retrofits. In B2, the average pre- and post-retrofit indoor minus outdoor formaldehyde concentrations, 19.5 and 20.0 μg m^{-3}, were no different considering measurement uncertainty. In B3, the average indoor minus outdoor formaldehyde concentration increased 64% from 11 to 18 μg m^{-3}. Indoor concentrations exceeded California EPA's acute reference exposure level (REL) of 9 μg m^{-3} in all but one apartment, always exceeded the California EPA's chronic REL of 3 μg m^{-3}, and in one apartment exceeded the World Health Organization's short and long-term guideline of 100 μg m^{-3}. Changes in ventilation rates, temperatures and humidity may partially explain the changes in indoor formaldehyde concentrations.

Acetaldehyde sources include cooking and outdoor air. The U.S. EPA classifies acetaldehyde as a probable human carcinogen. Acetaldehyde concentrations (Figure 6) were consistently well below California EPA's chronic reference exposure level of 140 μg m^{-3} but, in all except one apartment, exceeded the U.S. EPA's reference concentration for inhalation exposures of 9 μg m^{-3} based on respiratory toxicity. On average, the indoor minus outdoor concentration difference decreased 49%, 12%, and 35% in B1 through B3, respectively. The retrofits that may have decreased acetaldehyde concentrations include the range hood replacements and installation of continuous mechanical ventilation systems in apartments in B1 and in apartments 2, 3, and 4 in B3.

Figure 7 shows the summed indoor VOC concentrations, excluding formaldehyde and acetaldehyde. The average concentration decreased 62% in B1, increased 10% in B2, and decreased 28% in B3. Concentrations of individual VOCs were well below applicable guidelines; thus, the implications of these VOCs for health are not well understood. Health risks from additive or synergistic effects of multiple VOCs are a possibility. The retrofits that may have affected the summed VOC concentration are the same as listed above for acetaldehyde. In addition, education of tenants about the importance of cleaning products and air fresheners as a source of VOCs might have affected indoor concentrations.

Higher levels of NO_2 are linked to respiratory health effects, particularly in children. California's outdoor air standard is 30 ppb as an annual average. Indoor air concentrations in most apartments were below this standard, but two apartments had pre-retrofit indoor air concentrations, before the adjustments for changes in outdoor air concentrations, above 50 ppb. The results of the NO_2 measurements, after the above-mentioned adjustments, are shown in Figure 8. NO_2 sources include outdoor air and indoor combustion. The importance of the indoor sources, raising indoor concentrations above those outdoors, was most evident in B1 which had gas stoves. In the pre-retrofit period the stoves had standing pilot lights. The average indoor concentration decreased 58% after the retrofit, presumably because of replacement of the stove to eliminate the pilot lights, addition of range hoods that vented to outdoors, and increases in apartment ventilation rates. Apartments in B2 had gas stoves without pilot lights and apartments in B3 had electric stoves. NO_2 concentrations increased 11% in B2, an insignificant increase given measurement uncertainties. In B3, the average concentration increased 169%, from 2.5 to 6.8 ppb; however, at these low concentrations the measurement uncertainty is very high.

PM2.5 in outdoor air is linked to a broad range of adverse respiratory and cardiovascular health effects. Key sources of indoor PM2.5 include outdoor air, indoor combustion, and cooking. Vacuum cleaning and resuspension from surfaces can also be particle sources. The outdoor air standard for PM2.5 in California is 12 μg m^{-3}. In B1, indoor concentrations of PM2.5 (unadjusted) were generally well below this standard, while in B2 and B3 concentrations were usually well above the standard and as high as 160 μg m^{-3}. After the adjustments for changing outdoor air concentrations, average indoor PM2.5 concentrations decreased 2% (insignificant given measurement uncertainty), 44%, and 51% in B1 through B3 respectively. The retrofits that may have contributed to changes in indoor PM2.5 include replacement of range hoods, upgrading of filters in forced air heating and cooling systems, addition of continuous mechanical ventilation in apartments in B1 and in apartments 2, 3, and 4 in B3, installation of wall mounted air cleaners in B2 and B3, and education of tenants about particle emission from burning incense.

The relationships of changes in pollutant concentration with change in air exchange rate is shown in Figure 10 for CO_2, formaldehyde, acetaldehyde, and the sum of 30 VOC. An overall trend is evident with a larger percent increase in air exchange rate associated with a larger decrease in indoor (or indoor minus outdoor) pollutant concentration. In almost all cases with more than a 50% increase in air exchange rate, these IEQ parameters improved. However, data from individual buildings do not always show the same trends with air exchange rate, potentially because indoor pollutant emission rates were not constant. Occupancy, tenant behaviors, and temperature and humidity are factors that influence emission rates of these pollutants. Also, one should keep in mind the fact that the measured air exchange rates included air from outdoors and from surrounding apartments.

Figure 11 shows overall percent change of IEQ metrics for each building, for all apartments with ERVs providing continuous mechanical ventilation (ERV apartments), and for all apartments that had intermittent bathroom exhaust ventilation fans but no continuous mechanical ventilation (Ex.Vent apartments). The changes in the comfort and humidity metrics in B3 should be viewed with particular caution because of the substantially higher outdoor air temperature and outdoor air moisture content in the post-retrofit monitoring period. Overall, there are far more improvements than degradations in IEQ metrics. However, results for nitrogen dioxide and formaldehyde are mixed, with some decreases and some increases in indoor concentrations. For pollutants other than PM2.5, apartments with ERVs had better results than apartments without continuous mechanical ventilation. Apartments with ERVs had a smaller improvement in PM2.5 (after adjustments). There are two possible explanations. First, outdoor air is a major source of indoor PM2.5 and the mechanical ventilation in ERV apartments brought in more outdoor air. The ERVs did include particle filters with a MERV 6 rating – these filters when new would be expected to remove less than 35% of the PM2.5 from the incoming outdoor air [22]. Second, all Ex.Vent homes had wall mounted particle air cleaners installed but these air cleaners were installed in only three of eight homes with ERVs.

There were 17 complete sets of surveys from the 16 apartments. Twelve of the 17 subjects reported some improvement in overall air quality, with five subjects reporting no change. Three of the five subjects reporting no change were from B3 and one each was from B1 and B2. Because of the very small numbers of subjects, and because the subjects were not blinded, the surveys provide only a suggestion of an overall improvement in perceived air quality.

4.0 DISCUSSION

This study was based on the hypothesis that a set of practical retrofits could simultaneously save energy and improve IEQ conditions in apartments. Because energy data are still being collected, the validity of this hypothesis cannot yet be assessed. The findings presented in this paper do indicate an overall improvement in IEQ conditions. In general, the measurements indicate improvements in comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, VOCs, and PM2.5. However, not all IEQ parameters were improved after the retrofits. Formaldehyde levels decreased in B1, which had the highest concentrations, were essentially unchanged in B2, and increased in B3. The average NO_2 concentration (after adjustment) was essentially unchanged in B2. In B3, NO_2 concentrations were very low and the measurements indicate a large percentage increase in the average concentration after the retrofits, but this finding is uncertain because of the estimated measurement uncertainty at low concentrations. For IEQ parameters other than PM2.5, IEQ improved more in apartments with continuous balanced mechanical ventilation systems installed compared to apartments without continuous mechanical ventilation. In general, larger percent increases in ventilation rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources.

The substantial increase in average formaldehyde concentrations in B3 were unexpected given that the average air exchange rate increased by 60%. Also, formaldehyde concentrations increased marginally in some B2 apartments. The increases could not be linked to any retrofit. Emission rates of formaldehyde from manufactured wood products increase with temperature and humidity. Changes in indoor temperature and humidity were modest and do not appear to explain the increases in indoor formaldehyde levels. Outdoor temperature and humidity were significantly higher after the retrofits in B3 and might have influenced emission rates from formaldehyde sources in walls and attics. Solar heating of wall cavities and attics could have affected formaldehyde emission rates. We cannot rule out introduction of new formaldehyde sources such as new furniture by the occupants between the pre- and post-retrofit measurement periods, but this seems unlikely in multiple apartments.

To the best of our knowledge, no other study has evaluated broad packages of retrofits designed to both save energy and improve IEQ conditions, thus, we cannot compare our findings to prior findings. Strengths of this study include incorporation of a broad set of high quality IEQ measurements and the reliance on pre- and post-retrofit measurements within apartments, as opposed to use of a cross sectional study design. Study limitations include the moderate number of apartments retrofit. Also, measurements occurred for only two weeks before and after retrofits, and given these limited periods, changes in occupant activities likely affected study results. The study methods cannot control perfectly for changes in outdoor air weather conditions and air pollutant levels. The effects of climate, season, outdoor air quality, and building features cannot be separately determined because of the small number of study buildings.

The generally positive IEQ results reported in this paper should not be assumed to be applicable to the usual energy efficiency retrofits of apartments or single-family homes. In most energy retrofits, there is little or no consideration of IEQ effects when the retrofits are selected. The study results do indicate the potential to improve IEQ during energy efficiency retrofits if retrofit selection protocols are revised so that both energy savings and IEQ are considered.

5.0 CONCLUSIONS

The results of this study indicate the potential for overall improvements in IEQ when a package of retrofit measures is implemented in apartments to both save energy and improve IEQ. There was a general improvement in comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, VOCs, and PM2.5. However, not all findings were positive. Formaldehyde levels decreased in B1, which had the highest concentrations, were unchanged in B2 and increased in B3. Also, NO_2 levels decreased in B1, which had the highest concentrations, were unchanged in B2, and increased in B3 which had the lowest concentrations.

For IEQ parameters other than PM2.5, IEQ improved more in apartments with continuous mechanical ventilation systems installed compared to apartments without continuous mechanical ventilation.

In general, but not consistently, larger percent increases in air exchange rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources.

6.0 ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1. Air exchange rates.

Figure 2. Percentages of times with temperatures above (B1) or below (B2 and B3) the temperature boundaries of the ASHRAE thermal comfort zone.

Figure 3. Percentages of times with bathroom relative humidity greater than 75%.

Figure 4. Carbon dioxide concentrations.

Figure 5. Formaldehyde concentrations.

Figure 6. Acetaldehyde concentrations.

Figure 7. Summed VOC concentrations.

Figure 8. Nitrogen dioxide concentrations.

Figure 9. PM2.5 concentrations.

Figure 10. Relationships of pollutant concentrations with air exchange rates.

Figure 11. Summary results.

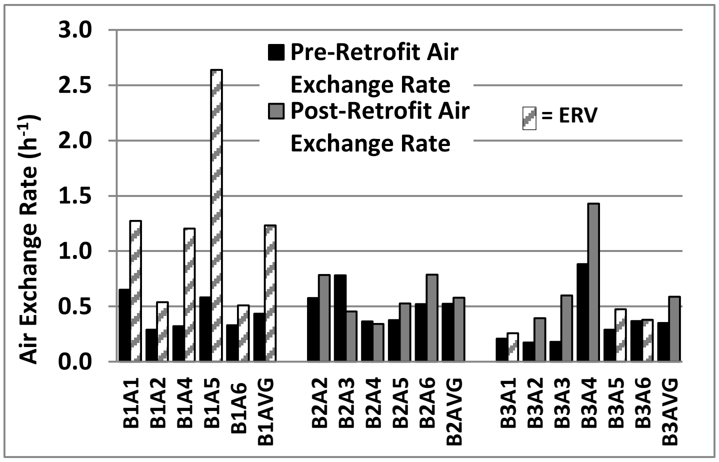

Figure 1. Air exchange rates

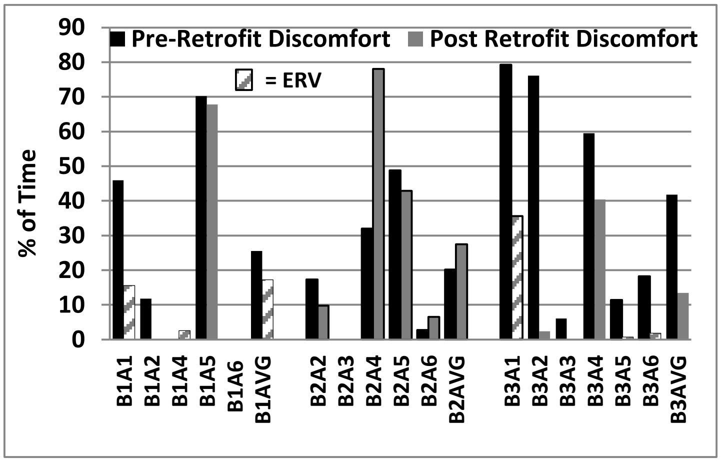

Figure 2. Percentages of times with temperatures above (B1) or below (B2 and B3) the temperature boundaries of the ASHRAE thermal comfort zone

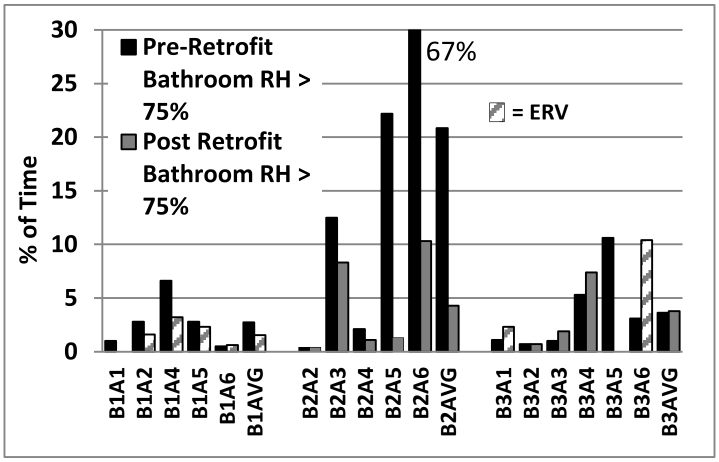

Figure 3. Percentages of times with bathroom relative humidity greater than 75%

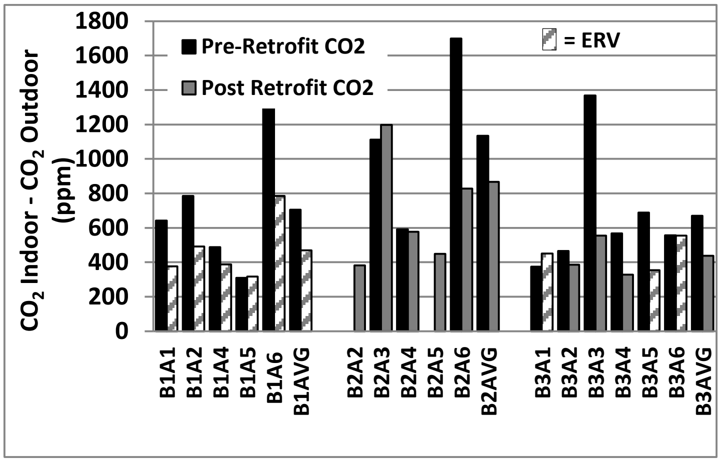

Figure 4. Carbon dioxide concentrations

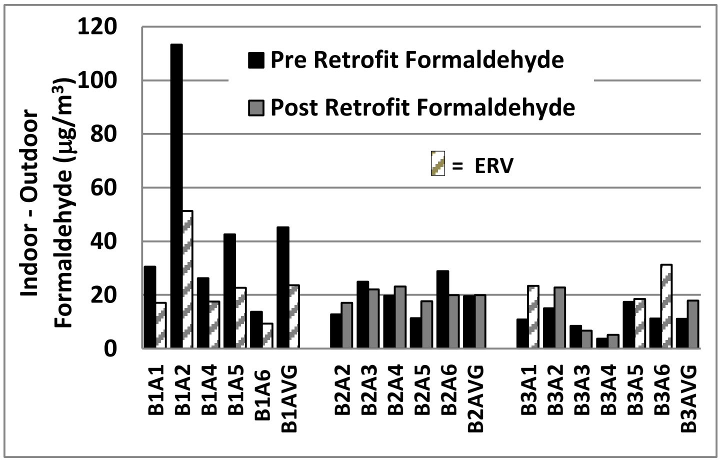

Figure 5. Formaldehyde concentrations

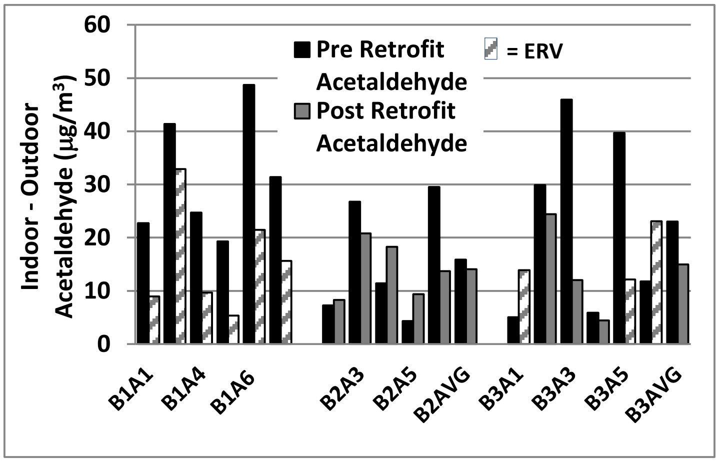

Figure 6. Acetaldehyde concentrations

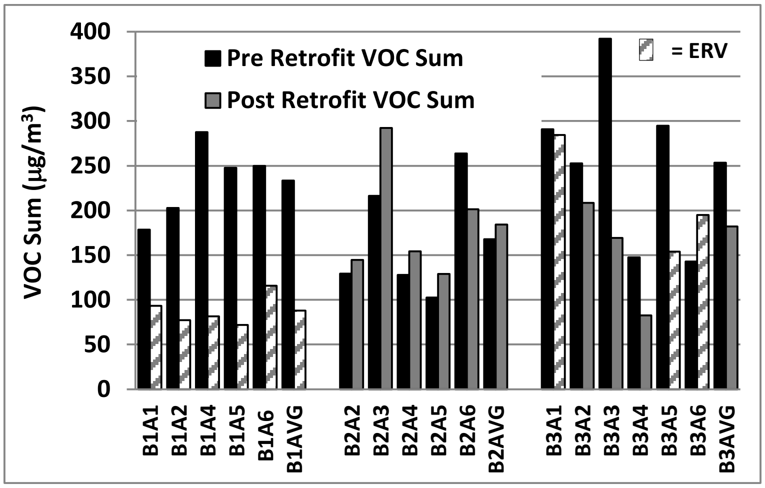

Figure 7. Summed VOC concentrations

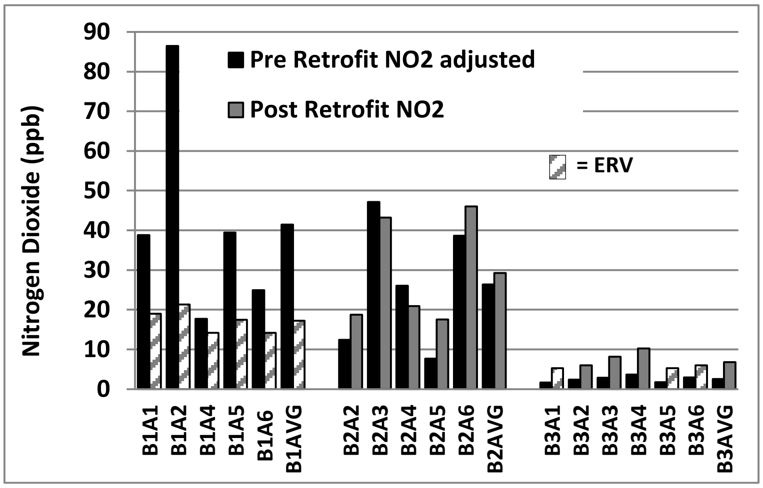

Figure 8. Nitrogen dioxide concentrations

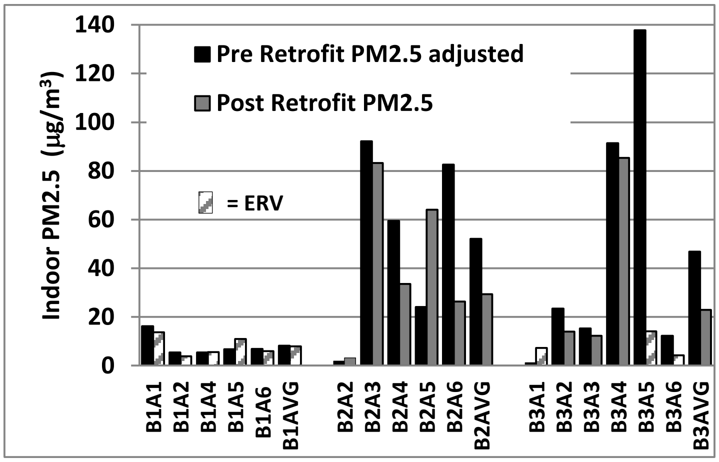

Figure 9. PM2.5 concentrations

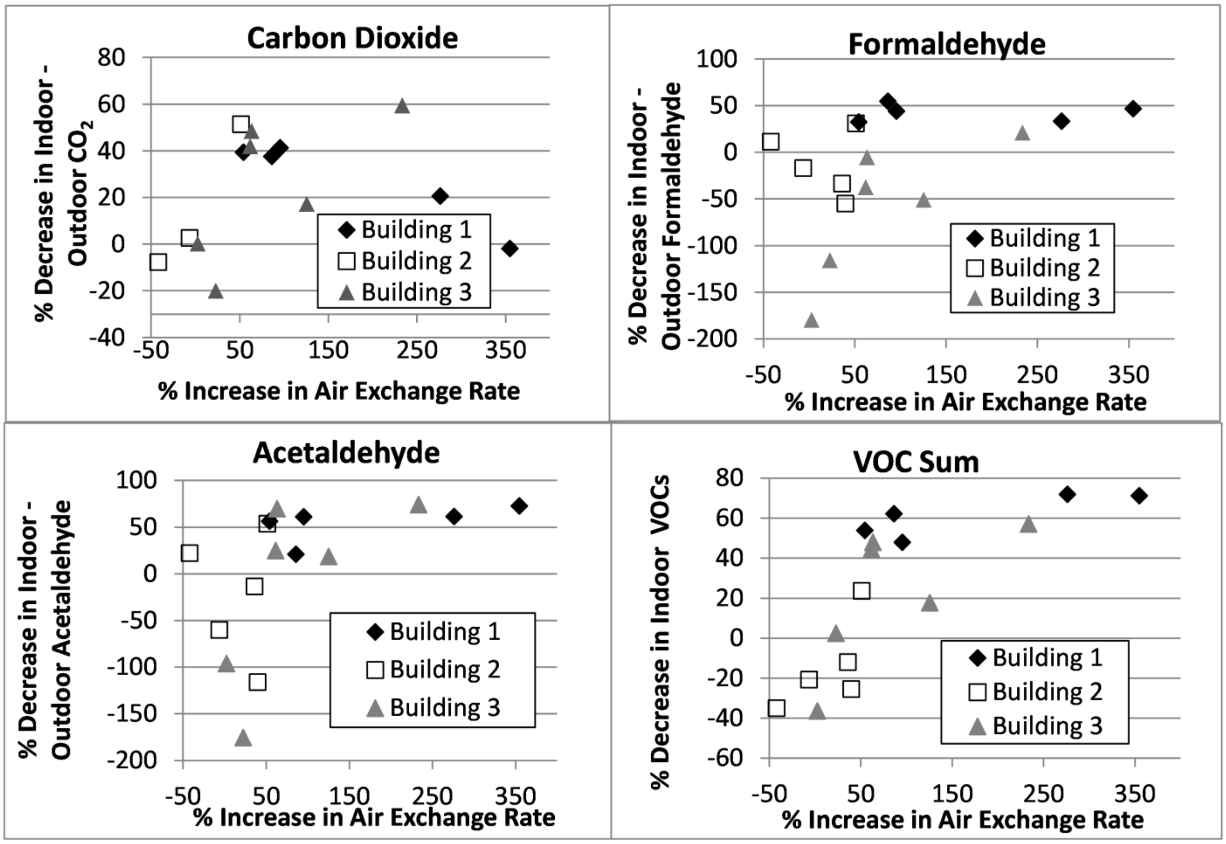

Figure 10. Relationships of pollutant concentrations with air exchange rates

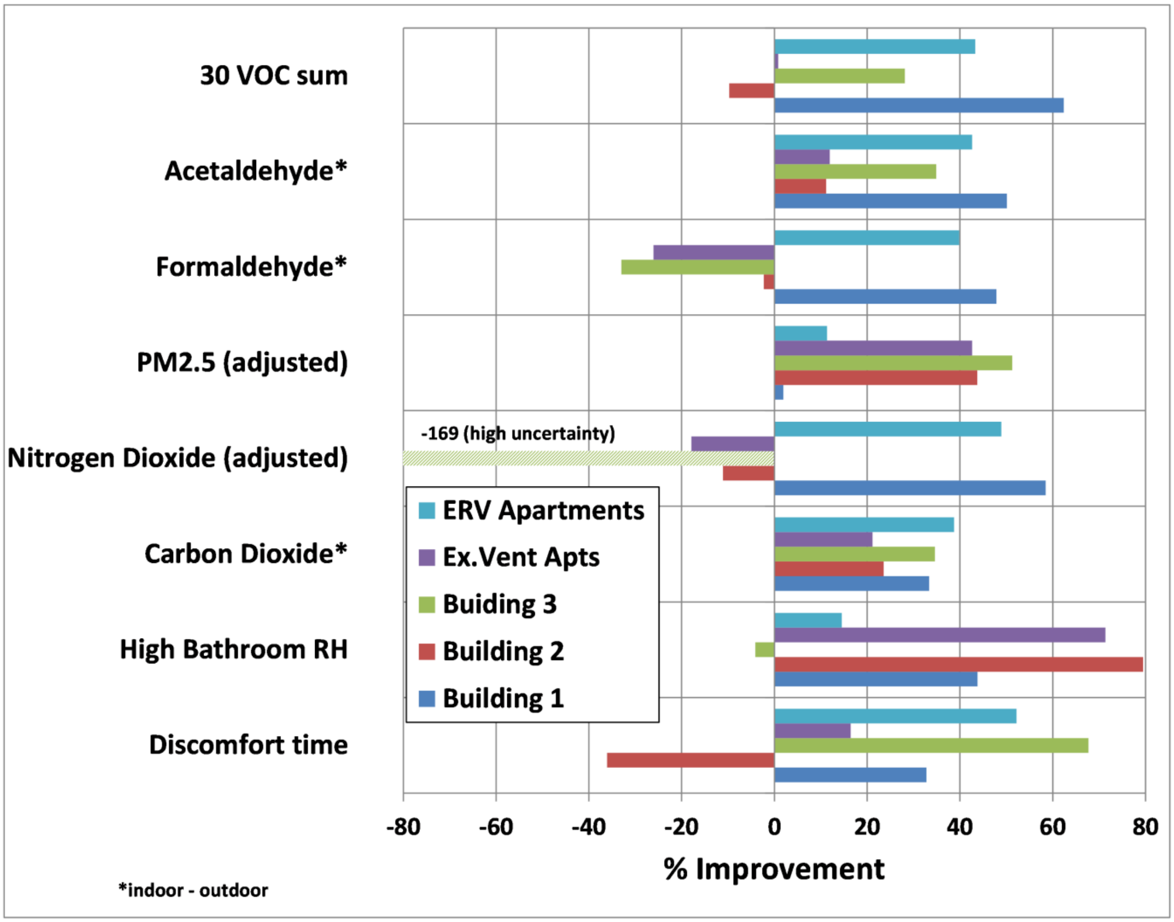

Figure 11. Summary results

SUPPLEMENTAL INFORMATION

Table S1. List of VOCs included in the summed VOC Concentration

Building 1	Building 2	Building 3
Butanal	Hexane	Hexane
Heptane	Benzene, hexafluoro-	Benzene, hexafluoro-
Benzene	Butanal	Butanal
Octane	Heptane	Heptane
Toluene	Benzene	Benzene
Hexanal	Octane	Octane
Ethylbenzene	Toluene	Toluene
m/p-Xylene	Hexanal	Tetrachloroethylene
a-Pinene	Ethylbenzene	Hexanal
o-Xylene	m/p-Xylene	Ethylbenzene
Hexanal	o-Xylene	m/p-Xylene
Ethylbenzene	Heptanal	o-Xylene
Heptanal	Decane	a-Pinene
Decane	2-Butoxyethanol	Heptanal
2-Butoxyethanol	3-Carene	Decane
3-Carene	Benzene, 1,2,4-trimethyl-	2-Butoxyethanol
1,2,4-Trimethylbenzene	D-Limonene	3-Carene
d-Limonene	Benzaldehyde	Benzene, 1,2,4-trimethyl-
g-Terpinene	Octanal	D-Limonene
Benzaldehyde	Undecane	Benzene, 1,2,3-trimethyl-
Octanal	1-Hexanol, 2-ethyl-	g-Terpinene
Undecane	Nonanal	Benzaldehyde
2-Ethyl-1-hexanol	Dodecane	Octanal
Nonanal	Decanal	Undecane
Dodecane	a-Terpineol	1-Hexanol, 2-ethyl-
Decanal	Tetradecane	Nonanal
a-Terpineol	TXIB (mono-isomer)	Dodecane
Tetradecane	Hexadecane	Decanal
TXIB (mono-isomer)	TXIB (di-isomer)	a-Terpineol
Hexadecane	Diethyl phthalate	Tetradecane
Dimethyl phthalate		TXIB (mono-isomer)
TXIB (di-isomer)		Hexadecane
Diethyl phthalate		Dimethyl phthalate
		TXIB (di-isomer)
		Diethyl phthalate

Table S2. Key IEQ results from B1.

Ventilation System Type			**ERV**	**ERV**	**ERV**	**ERV**	**ERV**	**ERV**		**ERV**	**ERV**	**ERV**	**ERV**	**ERV**	**ERV**	
Pre- or Post-Retrofit		**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Post**	**Post**	**Post**	**Post**	**Post**	**Post**	**Post**	**% Improve-ment**
Apartment		**Out-door**	**1**	**2**	**4**	**5**	**6**	**Aver-age**	**Out-door**	**1**	**2**	**4**	**5**	**6**	**Aver-age**	**All**
Air Exchange Rate	h^{-1}		0.65	0.29	0.32	0.58	0.33	0.43		1.27	0.54	1.20	2.64	0.51	1.23	184
Temperature	^{o}C	22.6	27.2	26.0	23.8	28.2	22.8	25.6	23.5	26.2	22.8	23.8	28.3	22.6	24.7	
Relative Humidity	%	43	40	48	44	41	38	42	48	41	53	47	40	40	44	
Discomfort (time T > 27.4 ^{o}C)	% of time		45.9	11.8	0	70.2	0	25.6		15.6	0	2.6	67.8	0	17.2	33
Bathroom RH (time > 75%)	% of time		1.0	2.8	6.6	2.8	0.5	2.7		0	1.6	3.2	2.3	0.6	1.5	44
CO$_2$	ppm	400 - 590	1232	1376	1078	900	1696	1256	416-426	803	907	814	742	1212	896	29
CO$_2$ (indoor - outdoor)	ppm		642	786	488	310	1296	704		377	491	388	316	786	470	33
PM2.5	mg/m^3	5	15	4	5	5	6	7	7.4-8.3	14	4	6	11	6	8	
PM2.5 (adjusted)	mg/m^3		16	6	6	7	7	8		14	4	6	11	6	8	2
NO$_2$	ppb	9	34	83	14	35	21	37	16 - 17	19	21	14	17	14	17	
NO$_2$ adjusted	ppb	9	39	86	18	39	25	41		19	21	14	17	14	17	58
Formaldehyde	μg/m^3	7	38	120	33	50	21	7	8	25	59	25	30	17	31	40
Formaldehyde (indoor-outdoor)	μg/m3		31	113	26	43	14	45		17	51	18	23	9	24	48
Acetaldehyde	μg/m^3	10	33	52	35	30	59	42	9	18	42	19	15	31	25	40
Acetaldehyde (indoor-outdoor)	μg/m^3		23	41	25	19	49	31		9	33	10	5	21	16	49
30 VOC sum	μg/m^3		178	203	288	248	250	233		93	77	82	72	116	88	62
K HVAC filtration PM2.5	h^{-1}		0.5	0.1	0.4	0.1	1.0	0.4								

Abbreviations: ERV = energy recovery ventilator operating continuously plus intermittent bathroom exhaust fan, Ex-Vent = intermittent bathroom exhaust fan

Table S3. Key IEQ results from B2.

Ventilation System Type			Ex-Vent	Ex-Vent	Ex-Vent	Ex-Vent	Ex-Vent	Ex-Vent		Ex-Vent	Ex-Vent	Ex-Vent	Ex-Vent	Ex-Vent	Ex-Vent	%
Pre- or Post-Retrofit		**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Post**	**Post**	**Post**	**Post**	**Post**	**Post**	**Post**	**Improve-ment**
Apartment		**Out-door**	**2**	**3**	**4**	**5**	**6**	**Aver-age**	**Out-door**	**2**	**3**	**4**	**5**	**6**	**Aver-age**	**All**
Air Exchange Rate	h^{-1}		0.58	0.78	0.36	0.38	0.52	0.52		0.78	0.45	0.34	0.53	0.79	0.58	11
Temperature	^{o}C	9.4	21.0	24.8	22.1	20.9	23.6	22.5	10.9	24.2	24.6	19.3	21.9	22.4	45	
Relative Humidity	%	58	41	41	38	46	50	43	58	39	46	51	43	48	27	
Discomfort (time T > 27.4 ^{o}C)	% of time		17.3	0	32	48.8	2.8	20.2		9.8	0	78.1	42.9	6.5	27.5	-36
Bathroom RH (time > 75%)	% of time		0.4	12.5	2.1	22.2	67	20.8		0.4	8.3	1.1	1.3	10.3	4.3	79
CO_2	ppm	375-393		1487	972		2092	1517	410-413	792	1610	987	861	1238	1278[a]	16
CO_2 (indoor - outdoor)	ppm			1112	592		1699	1134.3		382	1198	577	448	827	867[a]	24
PM2.5	$\mu g/m^3$	24-27	14	106	73	35	97	65	6.1-7.8	3	83	34	64	26	42	
PM2.5 (adjusted)	$\mu g/m^3$		2	92	59	24	82	52		3	83	34	64	26	29	44
NO_2	ppb	24	17	52	30	12	43	31	16	19	43	21	18	46	29	
NO_2 (adjusted)	ppb		12	47	26	8	39	26		19	43	21	18	46	29	-11
Formaldehyde	$\mu g/m^3$	4	17	29	24	16	33	24	4	21	26	27	21	24	24	2
Formaldehyde (indoor-outdoor)	$\mu g/m^3$		13	25	20	11	29	20		17	22	23	18	20	20	-2
Acetaldehyde	$\mu g/m^3$	4	12	31	16	9	34	20	4	12	25	22	13	18	18	10
Acetaldehyde (indoor-outdoor)	$\mu g/m^3$		7	27	11	4	30	16		8	21	18	9	14	14	12
30 VOC sum	$\mu g/m^3$		129	216	128	103	264	168		145	292	154	129	201	184	-10
K HVAC filtrationPM2.5	h^{-1}		0.2	0.2	0.06	0.2	0.1	0.2								

[a]average for apartments 3, 4,and 6

Table S4. Key IEQ results from B3. (part 1)

Ventilation System Type			**ExVent**	**ERV**	**ERV**	**ERV**	**ExVent**	**ExVent**		**ExVent**	**ERV**	**ERV**	**ERV**	**ExVent**	**ExVent**
Pre- or Post Retrofit		**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Pre**	**Post**	**Post**	**Post**	**Post**	**Post**	**Post**	**Post**
Apartment		**Out-door**	**1**	**2**	**3**	**4**	**5**	**6**	**Out-door**	**1**	**2**	**3**	**4**	**5**	**6**
Air Exchange Rate	h^{-1}		0.21	0.17	0.18	0.88	0.29	0.37		0.26	0.39	0.60	1.43	0.47	0.38
Temperature	^{o}C	8.1	19.0	19.6	22.7	20.0	21.5	23.8	14.6	20.9	24.2	24.1	21.5	22.0	23.3
Relative Humidity	%	55	40	42	43	37	45	34	63	50	43	41	45	46	49
Discomfort (time T > 27.4 ^{o}C)	% of time		79.3	76.1	6.1	59.5	11.4	18.3		35.6	2.4	0.1	40.4	0.7	1.8
Bathroom RH (time > 75%)	% of time		1.1	0.7	1.0	5.3	10.6	3.1		2.3	0.7	1.9	7.4	0	10.4
CO_2	ppm	383-499	874	901.0	1751	1046	1144	998	407-414	864	798.0	963	738	762	969
CO_2 (indoor - outdoor)	ppm		375	466	1368	567	689	556		450	386	555	329	355	555
PM2.5	$\mu g/m^3$	51-55	20	44	34	130	160	34	2-5	7	14	12	85	14	4
PM2.5 (adjusted)	$\mu g/m^3$		1	23	15	91	138	12		7	14	12	85	14	4
NO_2	ppb	29	9	9	10	17	11	13	10	5	6	8	10	5	6
NO_2 (adjusted)	ppb		2	2	3	4	2	3		5	6	8	10	5	6
Formaldehyde	$\mu g/m^3$	5	16	20	14	9	22	16	4	27	26	10	9	22	35
Formaldehyde (indoor-outdoor)	$\mu g/m^3$		11	15	8	4	18	11		23	23	7	5	18	31
Acetaldehyde	$\mu g/m^3$	6	11	36	52	12	46	18	6	20	31	18	11	18	29
Acetaldehyde (indoor-outdoor)	$\mu g/m^3$		5	30	46	6	40	12		14	24	12	4	12	23
30 VOC sum	$\mu g/m^3$		291	253	392	147	295	143		284	208	169	82	154	195
K HVAC filtration PM2.5	h^{-1}		0.2	0.2	0.2	0.2	0.3	0.4							

Table S4. Key IEQ results from B3. (part 2)

Ventilation System Type		**All**	**ExVent**	**ERV**	**All**	**ExVent**	**ERV**	**%**	**%**	**%**
Pre- or Post Retrofit		**Pre**	**Pre**	**Pre**	**Post**	**Post**	**Post**	**Improvement**	**Improvement**	**Improvement**
Apartment		**Average**	**Average**	**Average**	**Average**	**Average**	**Average**	**All**	**ExVent**	**ERV**
Air Exchange Rate	h^{-1}	0.35	0.29	0.41	0.59	0.37	0.81	68	28	96
Temperature	^{o}C	21.1	21.4	20.8	22.7	22.1	23.3			
Relative Humidity	%	40	40	40	46	49	43			
Discomfort (time T > 27.4 ^{o}C)	% of time	41.8	36.3	47.2	13.5	12.7	14.3	68	65	70
Bathroom RH (time > 75%)	% of time	3.6	4.9	2.3	3.8	4.2	3.3	-4	14	-43
CO$_2$	ppm	1119	1005	1233	849	865	833	24	14	32
CO$_2$ (indoor - outdoor)	ppm	670	540	800	438	453	423	35	16	47
PM2.5	µg/m^3	70	71	70	23	9	37			
PM2.5 (adjusted)	µg/m^3	47	50	43	23	9	37	51	83	14
NO$_2$	ppb	11	11	12	7	5	8			
NO$_2$ (adjusted)	ppb	3	2	3	7	5	8	-169	-162	-175
Formaldehyde	µg/m^3	16	18	14	21	28	15	-33	-53	-7
Formaldehyde (indoor-outdoor)	µg/m^3	11	13	9	18	24	12	-61	-85	-27
Acetaldehyde	µg/m^3	29	25	33	21	23	20	27	10	41
Acetaldehyde (indoor-outdoor)	µg/m^3	23	19	27	15	16	14	35	13	50
30 VOC sum	µg/m^3	253	243	264	182	211	153	28	13	42