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Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an unoccupied modern California house

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ABSTRACT

This study evaluated nine ventilation and filtration systems in an unoccupied 2006 house located 250m downwind of the I-80 freeway in Sacramento, California. Systems were evaluated for reducing indoor concentrations of outdoor particles in summer and fall/winter, ozone in summer, and particles from stir-fry cooking. Air exchange rate was measured continuously. Energy use was estimated for year-round operation in California. Exhaust ventilation without enhanced filtration produced indoor $PM_{2.5}$ that was 70% lower than outdoors. Supply ventilation with MERV13 filtration provided slightly less protection whereas supply MERV16 filtration reduced $PM_{2.5}$ by 97-98% relative to outdoors. Supply filtration systems used little energy but provided no benefits for indoor-generated particles. Systems with MERV13-16 filters in the recirculating heating and cooling unit (FAU) operating continuously or 20 min/h reduced $PM_{2.5}$ by 93-98%. Across all systems, removal percentages were higher for ultrafine particles and lower for black carbon, relative to $PM_{2.5}$. Indoor ozone was 3-4% of outdoors for all systems except an electronic air cleaner that produced ozone. Filtration via the FAU or portable filtration units lowered $PM_{2.5}$ by 25-75% when operated over the hour following cooking. The energy for year-round operation of FAU filtration with an efficient blower motor was estimated at 600 kWh/year.

KEYWORDS

Residential filtration, $PM_{2.5}$, Ultrafine particles, Black carbon, Residential ventilation

PRACTICAL IMPLICATIONS

This study quantitatively demonstrates the potential for advanced filtration to reduce in-home exposures to outdoor air pollutants through engineered systems. It also demonstrates that high quality filtration is required on supply ventilation systems to achieve the same reductions of outdoor particles as exhaust ventilation in a moderately airtight home. Results from this work should help inform the setting of filtration requirements for high performance home standards and building codes.

INTRODUCTION

Extensive research links outdoor $PM_{2.5}$ (US EPA, 2009) and ozone (US EPA, 2013) to increased risk of adverse human health outcomes. Black carbon (BC) is an indicator of diesel particulate matter (DPM), which has been associated with adverse health outcomes independently of $PM_{2.5}$ mass (Cassee et al., 2013; Ristovski et al., 2012). Many studies have reported associations between ultrafine particles (UFP, smaller than 100 nm diameter) and health impacts (Beko et al., 2015; Wolf et al., 2015). While a recent expert review found the available evidence on the health effects of ultrafine particles UFP to be inconclusive (HEI Review Panel on Ultrafine Particles, 2013), significant concerns remain about UFP (Terzano et al., 2010)

Outdoor air pollutants are carried into homes with ventilation air entering through open windows, infiltrating through the building shell, and moving through supply ventilation fans. Mechanical systems that extract air from homes – including exhaust fans and venting

combustion appliances – increase outdoor air and pollutant entry. Particles (Chen and Zhao, 2011) and ozone (Stephens et al., 2012) may be removed as outdoor air infiltrates through the building shell. Particles are removed from indoor air through deposition (Nazaroff, 2004) and ozone is lost through reactions with surfaces (Weschler, 2000), further reducing indoor concentrations relative to those in outdoor air. The net result of these processes yields an infiltration factor (Allen et al., 2003; Bennett and Koutrakis, 2006; Chen and Zhao, 2011) that relates indoor to outdoor concentrations of outdoor pollutants.

In-home exposures to outdoor particles and ozone are reduced when homes are air-sealed to reduce uncontrolled infiltration as an energy efficiency measure. Indoor concentrations are reduced because entry is slowed in relation to indoor deposition. There is also evidence that removal rates during infiltration increase as air leakage is reduced (Stephens and Siegel, 2012b).

Traditionally, air infiltration provided substantial dilution of indoor-generated pollutants even when windows were closed. Concerns about increasing exposures to indoor-generated pollutants as homes were air-sealed led to the development of the ASHRAE 62.2 residential ventilation standard (Persily, 2015) and the adoption of mechanical ventilation requirements in building codes in California and some other U.S. states.

Air cleaning and filtration can be integrated into mechanical systems to reduce pollutant concentrations in residences (Siegel, 2016). A high performance filter in the forced air heating and cooling (HAC) system will remove particles when the system operates for thermal control and can be operated on a timer when no conditioning is needed. Filtration effectiveness has been investigated through measurement studies in homes (Batterman et al., 2012; Du et al., 2011; MacNeill et al., 2012; Noris et al., 2013; Spilak et al., 2014; Stephens and Siegel, 2013) and also via simulation studies that tend to focus on population-scale benefits (Azimi et al., 2014; MacIntosh et al., 2010; Zhao et al., 2015).

In this paper, filters are characterized by the Minimum Efficiency Reporting Value (MERV), determined by the ASHRAE Standard 52.2 test procedure (ASHRAE, 1999), The standard measures removal in 12 particle size bins then aggregates results in bins of 0.3–1, 1–3, and 3–10 μm diameter particles. Higher MERV filters remove higher percentages of particles. The lowest MERV designation that considers removal of 0.3–1 μm particles is MERV13. The ASHRAE 62.2 standard requires a MERV6 filter for recirculating forced air systems (ASHRAE, 2013). Stephens and Siegel have reported filter performance results for particles below the size range of the ASHRAE 52.2 test (Stephens and Siegel, 2012a; Stephens and Siegel, 2013). Installed filter performance can vary over time, depending on the media and type of charging (if any), the characteristics of the aerosol, the amount of loading, bypass, and other factors (Hanley et al., 1994; Hanley and Owen, 2003; Lehtimaki and Saamanen, 2005; Owen et al., 2013).

This study aimed to measure the performance of various ventilation and filtration system designs in an uninhabited house with a relatively airtight shell and a central forced air heating/cooling system as representative of modern construction. Systems were operated over multiday periods in two California seasons: very warm to hot conditions in summer and locally cool to cold in fall/winter. This paper focuses on performance of the systems for outdoor $PM_{2.5}$, UFP, BC, and ozone, and for indoor-generated particles from a scripted cooking procedure. Performance results for VOCs and additional analyses are included in the final project report (Singer et al., 2016).

MATERIALS AND METHODS

Overview

Systems of ventilation and filtration components were evaluated for pollutant removal and energy performance in an unoccupied house in Sacramento, California. The systems included variations in ventilation approach, filtration location, and filtration quality. Two sets of air pollutant analyzers were configured to continuously measure size-resolved indoor and outdoor concentrations of particles from 6 nm to 2.5 μm diameter, black carbon, and ozone. $PM_{2.5}$ mass was estimated from size-resolved particle number concentrations. Data from the two monitoring apparatuses were analyzed to obtain continuous time series of indoor and outdoor concentrations, from which 24h and 1h running means were calculated. Indoor/outdoor (IO) ratios and percent reductions of indoors relative to outdoors were calculated. Systems were evaluated for indoor particle removal using a scripted cooking event. Energy impacts were estimated from measurements and rated power consumption of components and estimates of system run time.

Test House and Mechanical Systems

Experiments were conducted in a 2006-built, 106.7 m^2 (1148 ft^2), detached house that was leased for the study from September 2013 to February 2015. A schematic is provided in Figure 1 and the house exterior is shown in Figure S.1 of the Supporting Information (SI). The house is typical for its vintage in California: single-story, concrete slab foundation, stucco exterior, and tile roofing. Ceiling heights were 2.75 m (9 ft) except for the great room, which had a sloped ceiling rising from 2.75 m at the back wall to 4 m (13 ft) in the center of the house. Envelope air leakage was measured as 438 L/s (928 cfm) at a 50 Pa indoor-outdoor pressure difference (ASTM E1827-11, 2011), equivalent to 5.0 ACH50 at the calculated volume of 316 m^3 (11,154 ft^3). Heating and cooling were provided by a ducted forced air unit (FAU) with gas furnace and split air conditioner. The house is 250 m from Interstate 80, in the predominantly downwind direction.

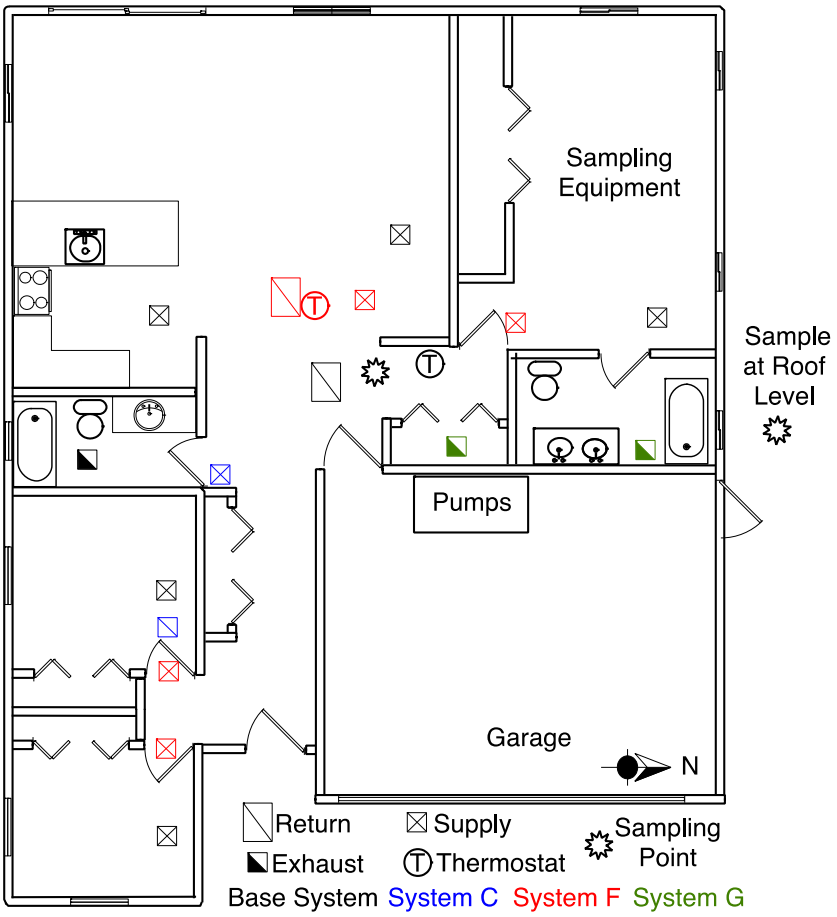

Figure 1.Schematic plan view of test house, drawn to scale.

Nine systems combining mechanical ventilation and air cleaning components were installed for evaluation. They are described in Table 1 and schematics are provided in Figure 2. The system selection process and details about system components are provided in the SI. Selected systems included variations for each major component: (a) exhaust, supply and balanced ventilation; (b) enhanced particle removal using MERV8, MERV13, MERV16, or HEPA filters or an electrostatic precipitator (ESP); (c) VOC removal using activated carbon, a chemisorbent, and a catalyst technology; (d) supply and balanced ventilation provided via the FAU or separate ductwork. A system with continuous exhaust ventilation and no enhanced filtration was designated as the Reference owing to its common use in California.

Table 1. Summary descriptions of system designs selected for testing.

System ID	Ventilation system description	Runtime control[1]	HAC return filtration	Filtration of ventilation air	VOC removal
Ref.	Exhaust, continuous	No	MERV4[2]	Building envelope[3]	None
E	Exhaust, continuous	Yes	MERV13 (2.5 cm) at return grille	Building envelope[3]	None
F	Exhaust, continuous	Yes[7]	MERV13 at return of mini-split	Building envelope[3]	None
Port-ables (+Ref)	Exhaust, continuous	No	MERV4 on FAU[2] + 2 portable filtration units	Building envelope[3]	None
A	Supply, continuous; distributed by FAU ducts or exiting at return grille	No	MERV4[2]	MERV13	None
B	Supply, continuous; distributed by FAU ducts or exiting at return grille	No	Electrostatic precipitator (ESP)[4]	MERV13	None
C	Supply, continuous; separately ducted and blended	No	MERV4[2]	MERV16	Catalyst[5]
D	Supply, on timer[1]; distributed by FAU ducts	Yes	Deep pleated MERV16 at FAU, on timer[6]	MERV8 on supply, MERV16 on FAU	Chemi-sorbent[6]
G	HRV, on timer[1], supplying into FAU	Yes	HEPA on bypass timed w/HRV + MERV4 on FAU	MERV8 on HRV + HEPA bypass	Activated Carbon

[1]The runtime controller operates the forced air unit (FAU) for at least 20 min each hour. [2]Installed as minimal protection for the furnace and coiling coils; not intended for removal of health relevant particles. [3]Envelope can remove particles as air infiltrates to replace air being removed by the exhaust ventilation system; particle removal rates in building envelopes vary. [4]Product marketed as an "electronic air cleaner". [5]Manganese oxide catalyst that oxidizes formaldehyde and other VOCs at room temperature (Sidheswaran et al., 2011). [6]Purafil PuraGrid with IAQ Media Blend (PG20252-IAQ). [7]The mini-split fan ran continuously on low speed to provide low pressure drop filtration and operated at higher speeds as needed for thermal conditioning.

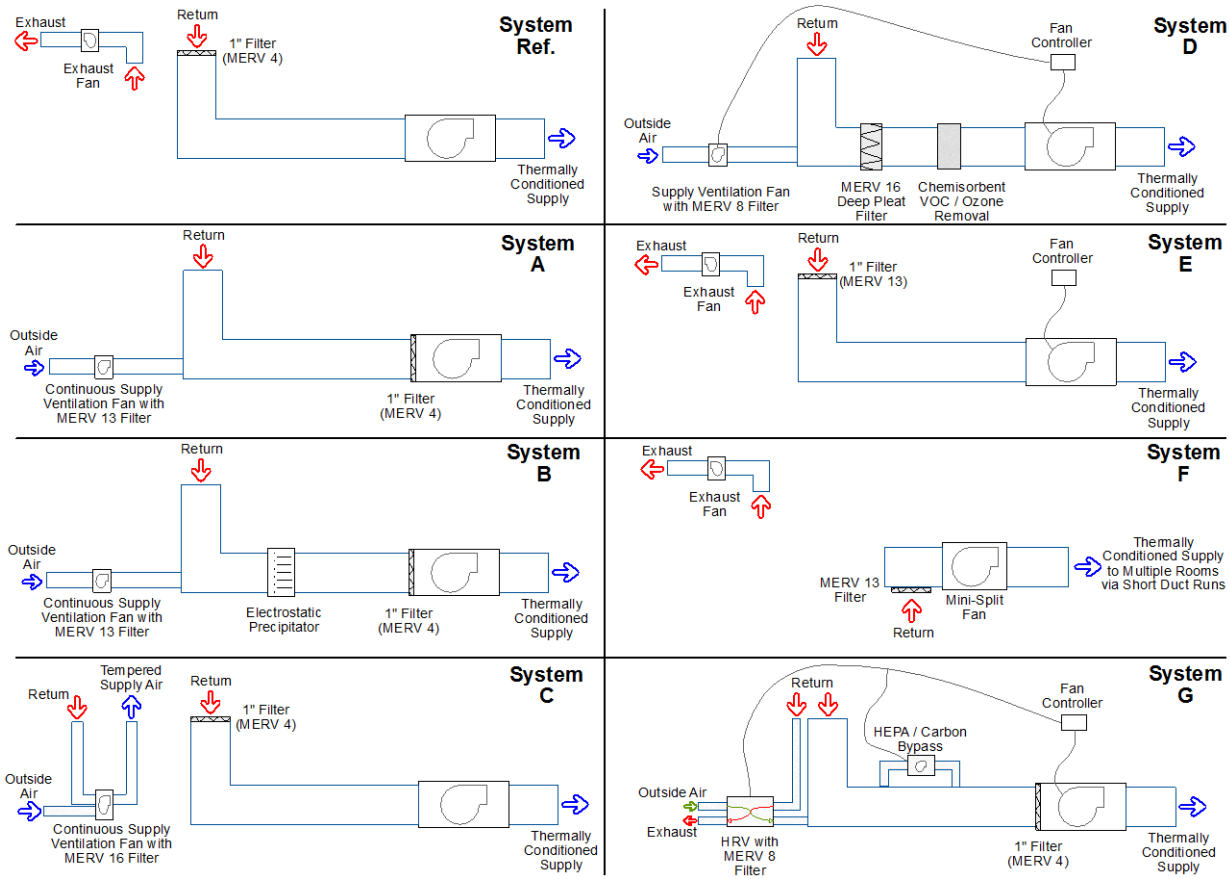

Figure 2. System schematics.

Systems were installed to enable quick switching for sequential operation during each season. The existing forced air heating and cooling system (FAU) was retained and ducting was modified to incorporate all system architectures. High-quality dampers established the flow paths show in Figure 2. Testing confirmed low leakage rates. Supply and return register locations are shown in Figure 1. Most of the equipment was in the attic. The blending unit for System C was installed in the central hall closet and the HRV was installed in the garage. Supply ventilation air intakes were connected to a gable vent below the outdoor particle inlet (Figure S.1 of SI).

An Ecobee Smart SI Thermostat was installed to provide remote access and set with the schedule assumed in the Title 24-2013 Residential Alternative Calculation Method (SI Section S.1.4).

Airflow and power consumption were measured for each air-moving component and power consumption was measured for the ESP of System B. Methods and results of these measurements are provided in the SI.

Since pollutants inside the house were measured at only one location, the air was mixed to reduce spatial variations. Portable fans (AirKing Model 9102, rated at 439 L/s or 930 cfm) were installed by the front door, on the kitchen counter, and in the hallway near the return grille and operated continuously. In May, an additional mixing fan (FanTech FR-100) with ducting was installed to move air at 52 L/s (110 cfm) from the master bedroom to the great room. This also

moved heat generated by the instruments to other parts of the house. The effect of mixing fans on particle removal rates in the home was not determined. During all monitoring periods, blinds in all the windows and doors were angled to minimize incoming sunlight.

Environmental, air pollutant, and equipment monitoring

Wind speed and direction were measured with an anemometer (containing Met One 010C and 020C sensors) mounted above the roofline, adjacent to the air intakes for supply ventilation and outdoor particles, as shown in Figure S.1. Outdoor T and RH were measured and logged every 5 min using an Onset HOBO U23-001 placed on the north end of the house approximately 1 m above the ground. Precipitation and fog data were obtained from measurements at McClellan air force base, located approximately 5 km from the test house. Data were downloaded from www.weatherunderground.com.

Temperature and humidity inside the home were measured and logged every 5 min using ONSET HOBO loggers (model U12-012) and every 15 min by the ECOBEE thermostat. HOBOs were placed at 1 m height in the front bedroom and master bedroom, in the supply register in the master bedroom, in the return plenum, and in the garage.

The measurement system was designed for continuous, unattended monitoring of indoor and outdoor concentrations of particles from 6 nm to 2.5 μm, black carbon, and ozone. Instrument specifications are provided in Table S.3. Particle concentrations were resolved to the following size bins (in μm): 0.06–0.1, 0.1–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.7, 0.7–1.0, and 1.0–2.5. The first bin was calculated as the difference between CPC 3787 (0.06–2.5 μm) and CPC 3781 (0.1–2.5 μm) measurements. The second bin was obtained as the difference between CPC 3781 data and the summed total of particle counts from the OPC channels between 0.3 and 2.5 μm. The other bins are those of the OPC.

Pairs of real-time monitoring instruments simultaneously measured indoor and outdoor air with functionally identical isokinetic sampling lines and manifold systems. Valves synchronously switched indoor and outdoor sample inlets between the two manifolds. This configuration was intended (1) to minimize errors in comparisons of indoor and outdoor particle levels that would result from drifts in instrument response, and (2) to reduce data loss by ensuring that at least a semi-continuous signal would be obtained for each location in the event of instrument failure. Ozone monitors were dedicated to indoor and outdoor air without switching. More details about the pollutant monitoring system are provided in the SI.

The air exchange rate was measured by continuous release and time-resolved measurement of sulfur hexafluoride (SF_6). Details are provided in the SI.

Monitoring Periods

Initial system operation and performance measurements occurred in January and February 2014, providing valid winter data for the Reference and System C (Table S.4). Instruments were powered down on March 19 and serviced as needed. Systems were restarted in May and operated through August to determine performance for outdoor particles and ozone during summer conditions and also for cooking particles (see below). Equipment was shut down August 6 for servicing then restarted in early October and operated through December 2014 to evaluate performance for outdoor particles during locally relevant fall and winter conditions. Table S.5 of the SI presents the monitoring dates for each system in each season.

Experiments to determine performance for indoor-generated particles

Performance for indoor-generated particles was assessed using a scripted cooking activity that generated particles from the ultrafine mode (<100 nm) to >1 μm. The activity involved stir-frying of string beans with oil, in a wok, over high heat for about 5 min (Lunden et al., 2014).

Cooking was synchronized with the start of a 20/60 operating cycle for Systems A, B, D, E, and G. This provided roughly 40 min for particles to mix throughout the house and be removed by ventilation and deposition before enhanced filtration operated for 20 min. Systems A and B operated through one hour-long cycle and Systems D, E, and G operated through two cycles. Continuous systems (C, F, Reference) were tracked for 80-90 min after cooking started. SF_6 was injected just before cooking to track outdoor air exchange during each experiment.

Following completion of each cooking experiment, a standalone 566 L/s (1200 cfm) fan (Dayton model 7M7T1) with HEPA filter unit (AirHandler model 2EJY3) and the two portable air cleaners were operated on high speed for 30-60 min. The supplemental fan-filter unit was in the great room at the back of the house. The intent was to remove particles that remained from cooking prior to starting an evaluation period for outdoor particles.

Data processing and analysis

Size resolved particle concentrations were used to estimate mass concentrations following the approach of (Sioutas et al., 1999), which was applied in field studies in Pittsburgh (Khlystov et al., 2004) and Los Angeles (Shen et al., 2002). Our application used the following assumptions: (1) all particles were spherical; (2) the mass mean diameter within each size bin was the midpoint diameter of the bin, and (3) all particles had the same seasonally-dependent density. Based on the first assumption, the volume of an individual particle was taken as $V_p=4/3\pi(d/2)^3$ where d is particle diameter. Based on the second assumption, the total volume of the n_i particles within bin *i*, was calculated as $V_{bin}=n_i*V_{p,i}$. Volume estimates were converted to mass using the seasonally-dependent densities of 2.16 g cm^{-3} for winter and 1.43 g cm^{-3} for summer, as reported in Table 2 of (Hasheminassab et al., 2014).

Data from the two sets of instruments on the switching manifolds were processed to obtain continuous indoor and outdoor time series, as described in Section S.1.12 of the SI. These data were used to calculate running means for time windows of 1, 8 and 24 h. Since the home was unoccupied, system effectiveness for outdoor pollutants is indicated by the indoor to outdoor (IO) concentration ratio and as the percent reduction of indoor relative to coincident outdoor concentrations, calculated as 1–IO. Summary statistics were calculated for each diurnal interval and each monitoring period. Diurnal intervals were set to begin and end in the troughs of the outdoor particle profiles. Effectiveness for outdoor peaks was calculated by first identifying the highest 1h outdoor concentration each day, then finding the highest 1h indoor peak within the next 4 h and taking the IO ratio.

Performance for indoor-generated particles is presented as the reduction in time-integrated concentration when a system operated compared to the concentration with no system operation. To calculate this parameter, we used first order decay rates determined for each particle size bin over 15-min intervals after each cooking event because the decay rates in many cases changed over time. For intervals interrupted by a change of state (e.g. FAU turned on), shorter sections of data were used. The “as-tested” performance for each system was calculated as the reduction in

time-integrated concentration over the first hour following the peak from cooking. To account for variability in emissions from the scripted cooking event (Lunden et al., 2015), we calculated the reduction using the fitted decay rates for each system state of operation along with the actual operating schedule. The time-integrated concentration for the reference condition was based on the observed decay with no FAU operation. Potential reductions were calculated for each system assuming continuous operation and applying the fitted decay rates over a full hour of operation.

Estimation of Annual Energy Use

There is an energy cost to operating mechanical systems for ventilation and pollutant removal. We estimated the fan and air cleaner energy requirements for system to be deployed in California, including (1) extra hours of FAU operation for filtration and/or supply ventilation (but not the energy required for thermal conditioning), (2) changes in fan power as airflow resistance increases, and (3) operation of air cleaning devices including the ESP of System B and the HEPA + Activated Carbon unit of System G. We calculated incremental energy as the product of run time and power draw for each system component. Details are provided in the SI.

RESULTS AND DISCUSSION

Performance for Outdoor Particles

Tables S.7–S.8 in the SI provide summary statistics for outdoor conditions during each of the assessment periods for outdoor particles. $PM_{2.5}$ levels generally were higher in fall/winter than summer, though there was substantial variability in each season.

Examples of the processed data analyzed to assess performance for outdoor particles are presented in Figures 3–4. These plots show outdoor and indoor time series of $PM_{2.5}$ estimated from size-resolved particle counts, as described above. During both periods, outdoor concentrations varied by an order of magnitude with a diurnal pattern of peaks around midnight. Indoor concentrations followed outdoors with a delay of several hours and at substantially lower levels owing to particle losses during infiltration and from indoor deposition. There were large differences between the systems, with 24h indoor/outdoor (IO) ratios of 0.3–0.5 for System A and 0.04–0.06 for System F. Plots for all particle size bins during all assessment periods are included in appendices to the final project report at www.arb.ca.gov/research.

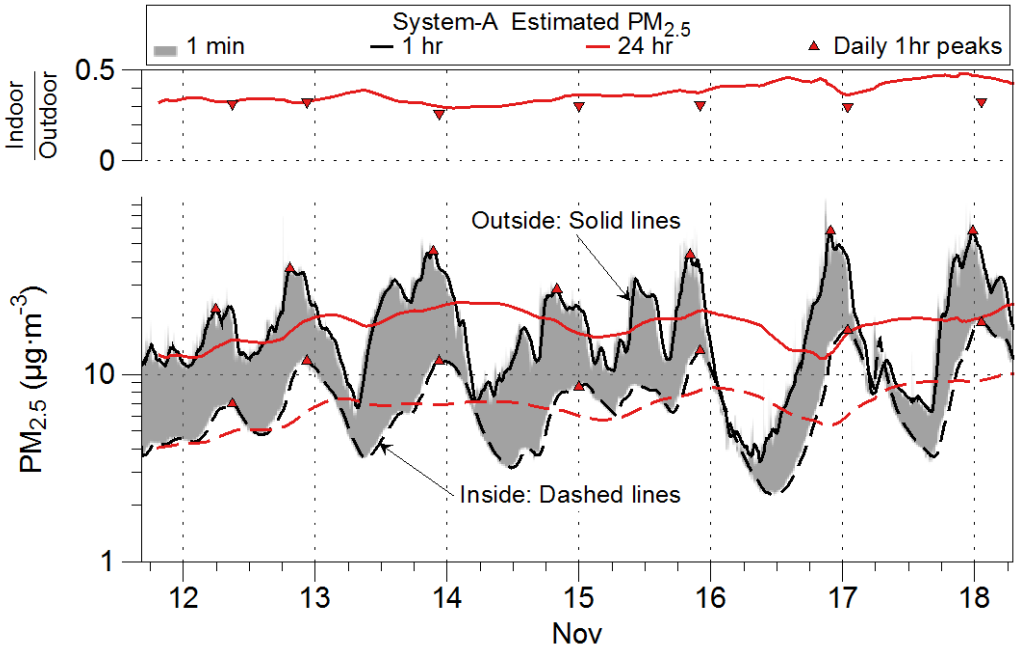

Figure 3. **Estimated $PM_{2.5}$ mass calculated from size-resolved particle number concentrations during operation of System A (continuous supply ventilation with MERV13 filtration), Nov 11-17, 2014.** The top and bottom of the grey band are 1-minute outdoor and indoor concentrations. Black lines are running 1h averages and red lines are running 24h averages. Red triangles show the indoor highest 1h average during each day and the corresponding highest 1h average outdoors. The top section shows indoor / outdoor ratios.

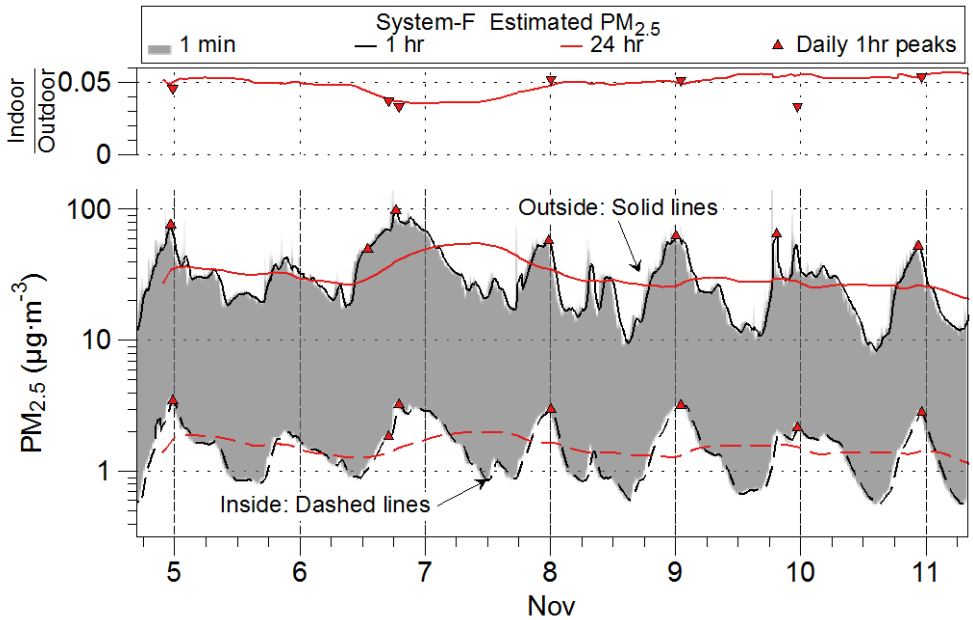

Figure 4. Estimated $PM_{2.5}$ concentration calculated from size-resolved particle number concentrations during operation of System F (exhaust ventilation and MERV13 filtration on a mini-split heat pump operating continuously at low speed), Nov 4-10, 2014. See caption of Figure 3 for description of data plotted.

Effectiveness at reducing in-home concentrations of outdoor particles is indicated by the 24h average IO ratios for estimated $PM_{2.5}$, UFP, and BC, shown in Figure 5. The boxes present the interquartile range of all the IOs calculated for all minutes of each assessment period and whiskers show 1.5x the interquartile range. All systems performed better (lower IO) for UFP and worse (higher IO) for BC relative to $PM_{2.5}$. BC results for Systems C and D in both summer (SU) and fall/winter (FW) are biased toward lower performance as indoor concentrations were often below quantitation limits (QL) and set to half the QL when that occurred. The second (right) result for Systems A and E in FW is for monitoring that occurred with filter edges taped to minimize bypass. Consistency of these results with standard operation (left bars) suggests that bypass was not a factor. During the period when the portable air filters were set to “Auto” they mostly remained on low speed; hence the use of “low” to identify this period.

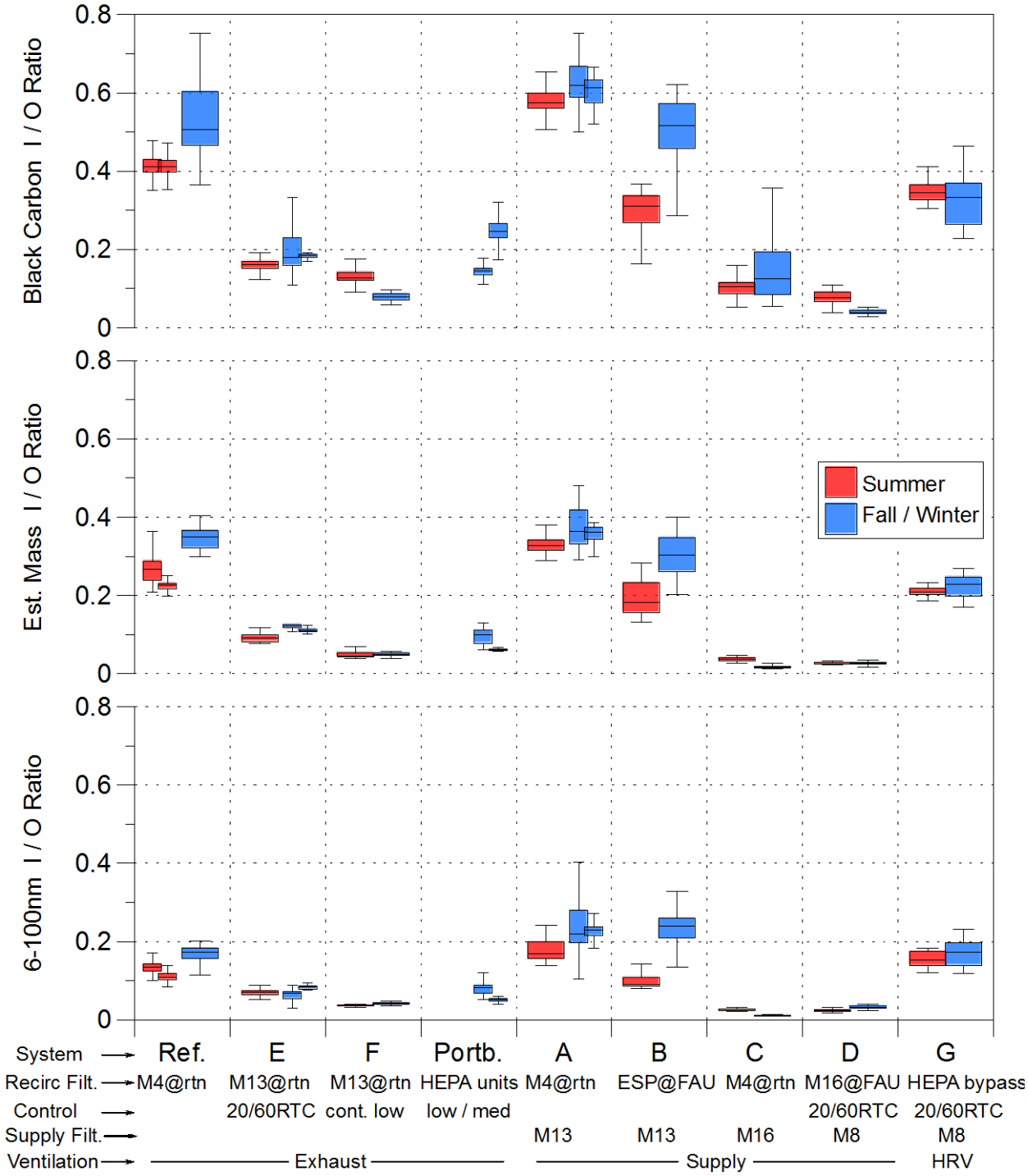

Figure 5. Running 24h mean indoor/outdoor ratios for black carbon, estimated $PM_{2.5}$, and ultrafine particles (6-100 nm) for systems operating over multi-day periods in fall/winter (FW) and summer (SU). The Reference was assessed over two distinct periods in SU. For Systems E and A, the right bar in FW presents results for operation with tape around the filter to ensure no bypass and the left bar represents the standard weeklong assessment period. Bars present the interquartile range (IQ) and whiskers are 1.5x the IQ. SI Table S.10 provides the days of data for each system and season.

Though we did not conduct a systematic analysis of this relationship, a visual review of the data suggests that $PM_{2.5}$ IO ratios were relatively insensitive to outdoor concentrations. As an example, the first and third diurnal intervals for System A in FW (Figure 3) had outdoor $PM_{2.5}$ of 14 and 24 μg m^{-3}, respectively, and the IO ratios were 0.33 and 0.30 on these days.

Table 2 presents the percent reductions of indoor 24h mean concentrations relative to coincident outdoor 24h means. Results in this table are the mean and standard deviation across daily intervals set according to the diurnal pollutant pattern.

Table 2. Percent reduction in 24h mean indoor $PM_{2.5}$ mass, ultrafine particles (UFP) and black carbon (BC), relative to outdoors for each evaluation period, presented as mean (SD) across distinct diurnal periods [days].[1] Mean of daily air exchange rates (AER) also shown.

System Description	N [days]		$PM_{2.5}$		UFP		BC		AER [h^{-1}]	
(M=MERV)	SU	FW	SU	FW	SU	FW	SU	FW	SU	FW
Exhaust Ventilation										
Ref: M4@rtn	13	7	75 (3)	65 (3)	87 (2)	84 (3)	57 (6)	47 (8)	0.29	0.22
E: M13@rtn	6	3-7[3]	93 (2)	88 (1)	93 (2)	95[3] (3)	91 (3)	81 (6)	0.27	0.35
E: w/o bypass	nd[2]	4	nd[2]	88 (1)	nd[2]	91 (1)	nd[2]	81 (2)	nd[2]	0.27
F: M13 on mini-split	4	7	95 (1)	95 (1)	96 (0)	96 (0)	87 (2)	92 (1)	0.31	0.30
Portables on Auto / Low	nd[2]	4	nd[2]	90 (2)	nd[2]	92 (1)	nd[2]	85 (3)	0.31	0.31
Portables on Medium	nd[2]	3-4[4]	nd[2]	94 (0)	nd[2]	95 (1)	nd[2]	79[4] (5)	nd[2]	0.35
Supply Ventilation										
A: M13@Supply	4-5[5]	7	67 (2)	63 (5)	82 (3)	77 (8)	45[5] (3)	39 (6)	0.29	0.28
A: w/o bypass	nd[2]	4	nd[2]	64 (2)	nd[2]	77 (2)	nd[2]	39 (4)	nd[2]	0.31
B: M13@Supply/ESP@FAU	7	7	82 (7)	69 (5)	90 (4)	76 (5)	75 (9)	50 (9)	0.21	0.28
C: M16@Supply	7	7	96 (1)	97 (3)	97 (1)	99 (0)	91 (3)	84 (10)	0.23	0.22
D: M8@Supply/M16@FAU	7	7	97 (0)	97 (1)	98 (0)	97 (1)	93 (2)	96 (1)	0.25	0.34
Balanced Ventilation										
G: M8@Sup/HEPA bypass	5	6	79 (1)	78 (3)	84 (2)	83 (3)	66 (2)	68 (5)	0.27	0.35

[1]Diurnal periods did not start at the same time as monitoring. Some days have <24h of data; but no day has <10h of data. [2]No data. [3]UFP based on 3d of data; both CPC-3787 instruments failed during other days. [4]BC based on 3 days of data; 4th day was outlier (>3σ from mean). [4]BC based on 4 days of data; 5th day was outlier (>3σ from mean).

Despite having no enhanced pollutant removal technology beyond a modestly tight shell to limit infiltration with windows and doors closed, the Reference system had indoor concentrations much lower than outdoors. System A, with MERV13 filtration on continuous supply ventilation, performed a bit worse than the Reference for all three parameters. System B, which had the same ventilation system as System A along with an ESP on the FAU, performed similarly and perhaps slightly better than System A in fall/winter. In summer, the ESP operated several hours per day as the FAU provided cooling and the performance of System B was clearly better. The systems that provided the best protection for outdoor particles were C, D, and F. These systems – which included two with MERV16 filtration on supply ventilation (C and D) and one with MERV13 filtration on a continuous recirculating flow through the mini-split fan unit (F) – yielded reductions in indoor concentrations, relative to outdoors, by 95-97% for $PM_{2.5}$, 96-99% for UFP, and at least 84-96% for BC across SU and FW seasons. The next-best system was E, with

MERV13 filtration through the FAU operating intermittently with a fan timer. System G, with supply ventilation and a HEPA bypass on the FAU return operating intermittently with timer, performed similarly to the Reference for UFP, but showed moderate improvements for $PM_{2.5}$ and BC. During limited testing in FW, the two portable HEPA air filtration units lowered UFP and $PM_{2.5}$ similarly to System F when the portables operated continuously on medium setting. When operated on automatic setting, performance was similar to System E for UFP, $PM_{2.5}$ and BC.

Table 2 also presents the measured AERs for the outdoor particle mitigation evaluation periods. There were variations in AER, even for systems that used the same ventilation equipment (e.g. Ref, E, and F) caused by variations in temperature and wind driving forces impacting the infiltration component of outdoor air exchange. Higher AER tends to increase IO ratios when other parameters are unchanged. It is thus notable that systems D, E, F, and the Portable HEPA units achieved low IO ratios despite having higher AERs relative to the Reference in fall/winter. Higher AERs may have contributed to the slightly worse performance of Systems A and B relative to Reference in winter.

Performance for Indoor-Generated (Cooking) Particles

Example data from a cooking experiment are provided in Figures S.10–S.11 of the SI.

Summary results for cooking particle removal are provided in Figure 6, which presents the reduction in time-integrated $PM_{2.5}$ relative to the baseline condition of no FAU operation. An analogous plot of UFP results is provided in the SI. The “As Tested” performance of System A is expected to be the same as the Reference (within experimental error) because it has no recirculation filtration. And the recirculation flow through System C (for tempering) is too small to provide noticeable benefit. Systems D, E, and G all provide moderate improvements over the Reference system. A much larger benefit was observed for System F and for the Portables, which operated continuously for the hour after cooking. As Tested results represent a minimum benefit because intermittent systems operated only at the end of the hour. For the first 40 min, intermittent systems were identical to the Reference.

Figure 6 also presents calculated reductions for systems operating over the entire hour (Always On). For intermittent systems (B, D, E, and G) the reduction was estimated by calculating the concentration over the hour assuming the first order removal rate observed during intermittent system operation. For the Reference and System A, reductions for Always On are assumed to result from deposition of large particles in the FAU and ductwork. When operated continuously, Systems B, D, E, and G provide large reductions for the indoor-generated particles.

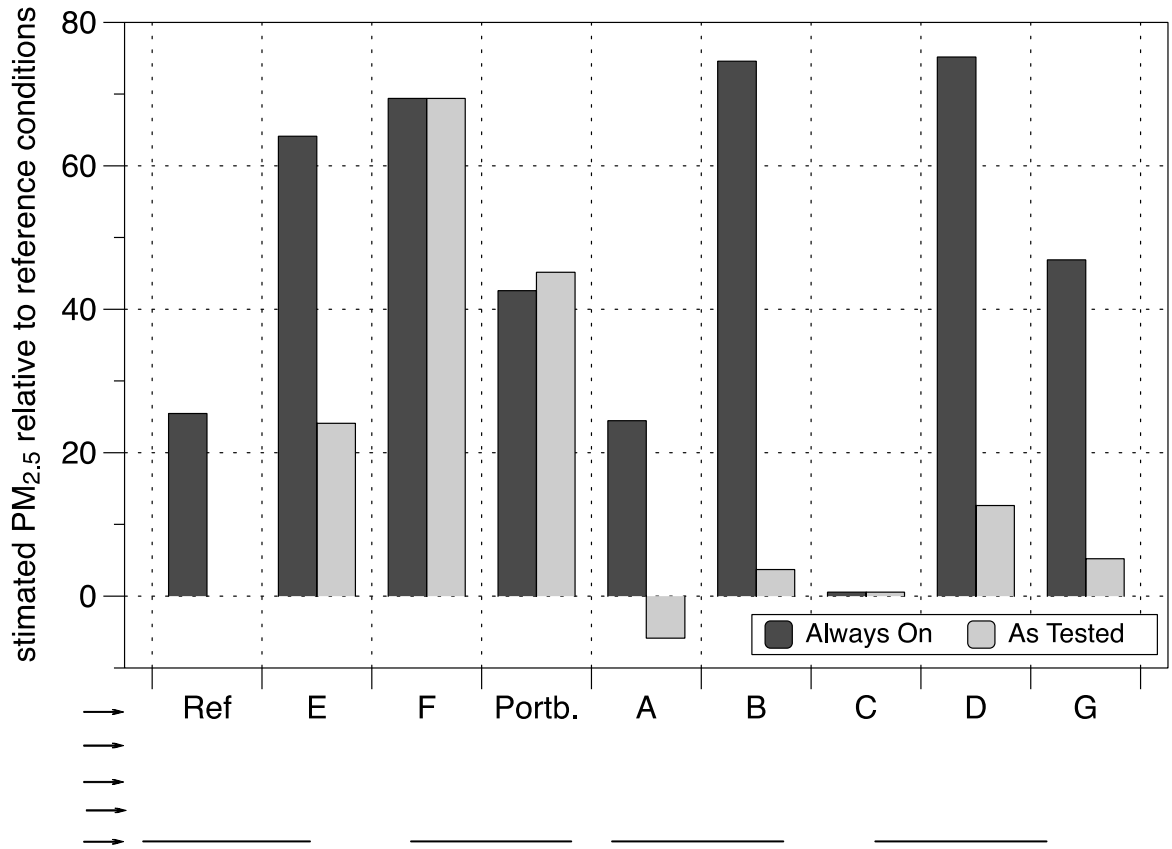

Figure 6. Reductions in estimated $PM_{2.5}$ concentrations over 1h following an indoor cooking event, relative to Reference system. For systems with intermittent FAU operation, cooking occurred at the start of the 40 min interval between FAU operating periods. "Always on" is the estimated reduction with the recirculating filtration system operating continuously for the hour.

Performance for Ozone

Example ozone data are provided in SI Figure S.13. Summary results for measured concentrations and system performance for ozone during summer are presented in Table 3. Performance was similar for all systems other than System B, which had substantially higher IO ratios and thus a lower protection factor. The IO ratios of 0.03–0.04 for the highest daily 8h and 1h concentrations for the Reference and Systems C and D are calculated using mean indoor concentrations below the nominal single measurement quantitation limit. Only System B had indoor daily high concentrations mostly above the QL. The higher IO ratios for System B result from ozone production in the ESP, as shown in Figure S.14 of the SI. Ozone production by an ESP has been reported previously (Poppendieck et al., 2014).

Table 3. Summary results for ozone.[1]

System[2] (start)	Days	Highest 8h Outdoor		Highest 8h Indoor		High 1h Outdoor		Highest 1h Indoor		**I/O ratio of highest 8h**		**I/O ratio of highest 1h**	
		Mn	SD	Mn	SD	Mn	SD	Mn	SD	**Mn**	SD	**Mn**	SD
Ref (7/2)	7	60	10	1.9	0.2	72	9	2.0	0.2	**0.03**	0.00	**0.03**	0.00
Ref (7/16)	6	37	6	1.6	0.1	44	8	1.6	0.1	**0.04**	0.01	**0.04**	0.01
B	7	50	12	5.9	1.3	59	16	7.4	1.5	**0.12**	0.02	**0.13**	0.03
C	7	55	12	1.7	0.2	64	17	1.9	0.3	**0.03**	0.00	**0.03**	0.01
D	7	53	11	1.5	0.1	64	19	1.7	0.3	**0.03**	0.01	**0.03**	0.00
G	3	59	11	2.5	0.6	68	15	2.5	0.6	**0.04**	0.00	**0.04**	0.01

[1] Data unavailable for Systems E and F because of instrument problems. [2] Ref = Reference, exhaust ventilation with no enhanced filtration. B has supply ventilation with MERV13 filtration and electrostatic precipitator on FAU return controlled by thermostat. C has MERV16 filtration on a blended supply ventilation system. D has supply ventilation with MERV8 filter and MERV16 filtration on the FAU operating on a 20/60 cycle. G has an HRV with MERV8 filter on the supply and a bypass with HEPA filtration on the FAU.

Power and Energy Use

Annual energy use estimates, presented in Figure 7, are for systems installed in mid-2000s, code-compliant homes in California. Actual incremental energy use would vary somewhat by climate zone, specific characteristics of the home, and thermostat settings, which impact both the baseline operating schedule of the forced air system and extra operation for air cleaning. The left panel of Figure 7 is for a conventional permanent split capacitor (PSC) FAU motor, as found in the test house. The panel at right is for a brushless permanent magnet (BPM) fan motor. These results demonstrate the increased energy required when the FAU is operated year-round for filtration (e.g., for D, E, and G). Systems with filtration only on supply fans (A-C) have much smaller energy requirements. The Portable HEPA filtration units, which reduce exposure to both indoor and outdoor particles, require only a modest increase in energy use. The right panel shows that an efficient blower motor reduces energy use for all systems, with the largest impact on systems that use the FAU for ventilation and/or filtration.

We do not provide a quantitative estimate the incremental energy requirement of System F because the mini-spilt heat pump cannot be assumed to have the same base operation schedule as the conventional FAU. Since mini-splits operate at varying capacity over many more hours in both heating and cooling seasons, there would be less operation expressly for the purpose of filtration. Since these devices are also more efficient at part-load, the incremental energy required for System F is likely to be much less than for D and E, i.e. <600 kWh/y.

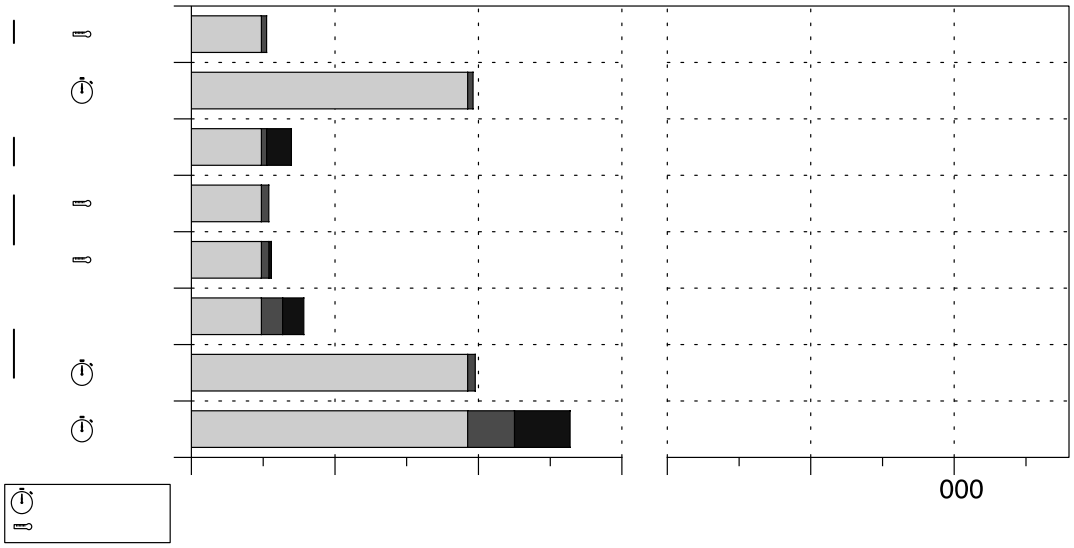

Figure 7. Estimated fan energy use for ventilation and air recirculation for filtration.
Results for the Reference system include the FAU fan energy required for thermal conditioning of the extra outdoor air brought in by the mechanical ventilation system along with energy to power the ventilation fan. The energy required to thermally condition the ventilation air is not included. Results for other systems include FAU fan energy for heating and cooling distribution plus any additional operation for enhanced pollutant removal. The panel at right presents estimates for a system with an efficient, variable speed brushless permanent magnet motor.

The higher MERV filters tested in this study had small impacts on airflow and power. The deep-pleated MERV16 filter of System D reduced FAU flow by 2.7% and power consumption by 2%. The 1” MERV13 filter of System E reduced FAU flow and power by roughly the same amount, 5%. Details are provided in SI Section S.2.5.

Considerations for Low Energy Homes

Many new homes in California and elsewhere are tighter than the test house (Chan et al., 2013), and high performance home standards require even tighter construction. With less air entering via infiltration, ventilation design (exhaust vs. supply/balanced) and the quality of supply filtration will have a larger impact on indoor concentrations of outdoor particles. There is evidence that tighter homes have lower penetration rates for submicron particles (Stephens and Siegel, 2012b). Results for System A in this study suggests that a MERV13 or better filter is needed on supply ventilation to avoid increasing in-home levels of outdoor particles relative to exhaust ventilation for a moderately airtight home.

Changes to heating and cooling (HAC) equipment designs and operation in energy efficient homes will impact the costs and benefits of central FAU filtration. An increase in the availability and use of multistage, variable output HAC equipment that also has sophisticated controls could lead to more opportunities to modulate and manage filtration airflow for lower energy operation.

Caveats and Other Considerations

There are several important caveats to the results presented in this paper. The first is that all filters were installed and used without preconditioning or preloading. Even accounting for the higher loading rate associated with 20/60 or continuous operation, filters were used over short durations relative to recommended service lifetimes in residences. Except for the filter on the mini-split unit (System F), all filters were replaced at the start of each season. Results thus reflect performance of filters that were used for less than 3 weeks total run time. There were no obvious indications – such as dramatic shifts in IO ratios – that any of the filters saw sharp performance degradations that can occur as charged media filters load or performance enhancements that can occur as fiberglass media filters load (Hanley et al., 1994; Hanley and Owen, 2003; Lehtimaki and Saamanen, 2005; Owen et al., 2013).

The second caveat is that there is variability in the performance of filters with any given MERV designation. It is therefore possible that different filters with the same MERV designations would have produced different results for one or more of the systems.

Conditions in the test house differed from occupied homes in ways that could bias particle deposition and affect IO ratios. The lack of furnishings and much lower surface to volume ratios in the test house reduced particle deposition rates relative to an inhabited home, while the higher air velocities from the mixing fans pushed deposition rates higher (Thatcher et al., 2002).

As with all experimental studies, results of this study are based on a limited set of conditions. The test house FAU and the local outdoor air pollution are relevant to many homes throughout California. Assessment during both summer and fall/winter provides results for outdoor pollutant mixes with distinctly different characteristics and patterns. Scripted cooking experiments were included to raise the issue that filtration can be used to protect occupants from indoor-generated particles in addition to those from outdoors; however, effectiveness for the cooking particles should not be construed as predictive of performance for all indoor aerosols.

$PM_{2.5}$ estimated from size resolved particle concentrations may differ from gravimetric measurements. The estimate will be biased if the midpoint bin sizes are very different from the mass mean diameters by bin, or if the effective density differs substantially from assumed values. If selective removal of particles changes either of these parameters between outdoors and indoors, the IO ratio analysis would be impacted. Use of density values from Los Angeles (Hasheminassab et al., 2014) is reasonable as Sacramento has a similar mix of ambient pollutant sources and similar climate, but the lack of coincident density data is a potential source of error.

CONCLUSIONS

Results indicate that houses with moderately airtight shells and continuous exhaust ventilation provide substantial protection from outdoor $PM_{2.5}$, UFP, BC, and ozone, even without enhanced filtration. To achieve a roughly similar level of protection with supply ventilation requires MERV13 filtration or better. In-home concentrations of outdoor particles can be reduced to <10% of outdoors using MERV13 filtration on a timer-controlled FAU and exhaust ventilation, and to <4% using MERV16 filtration either inline with supply ventilation or on the FAU with timer if using exhaust ventilation. Supply filtration is an energy efficient approach to addressing outdoor pollutants but does nothing for indoor-generated pollutants. The lowest energy solution for reducing in-home exposures to both outdoor- and indoor-origin particles is MERV13 (or

better) filtration on an FAU with efficient fan motor or efficient portable air cleaners, with exhaust ventilation.

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Measured Performance of Filtration and Ventilation Systems for Fine and Ultrafine Particles and Ozone in an Unoccupied Modern California House – SUPPORTING INFORMATION

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S.1 Methods and Materials

S.1.1 Test House

Figure S.8. Weather station and air intakes for supply ventilation and outdoor particle sampling. The meteorology tower is visible above the roofline. Just above the apex of the roof is the outdoor aerosol sample inlet. Outdoor air inlets for supply ventilation systems were connected to the gable end vent. The sample inlet for outdoor ozone was just outside the master bathroom window.

S.1.2 System Selection Considerations

The first stage of mechanical system selection involved specification of seventeen candidate systems followed by a semi-quantitative evaluation of each system on the eleven criteria noted in Table S.4 below. The systems included various combinations of ventilation approaches (exhaust, supply, balanced), particle filtration locations (as part of supply ventilation, as part of forced air heating and cooling system, standalone), particle filtration quality (MERV8 through HEPA), VOC removal technologies (physical sorbents, chemisorbents, photocatylitic oxidation, etc.), and operational approaches (continuous, minimum of 20 min of every 60, only when heating or cooling required, etc.). The categorical scoring approach was designed primarily to elucidate strengths and weaknesses of the systems rather than to provide a firm priority order for testing.

Table S.4. Assessment criteria for system selection.

Evaluation Criterion	Weight	Considerations
Outdoor-generated particle removal efficiency	10	Filter rating and configuration. Building shell filtration with exhaust ventilation assumed to be equivalent to MERV8.
Outdoor VOC/ozone removal effectiveness	8	Available product information (limited)
Energy Performance	8	Based on residential energy model simulations, power ratings from manufacturer specs, and engineering estimates
Indoor-generated particle removal efficiency	7	Filter efficiency rating and configuration
Noise	5	Home Ventilating Institute (HVI) product database and contractor input
Suitability for California climate and construction practices	5	Contractor input and researcher assessment
Maintenance requirements	4	Manufacturer's recommended maintenance schedules and contractor input
Component availability	3	Contractor input and product searches on internet
Durability (including. performance with imperfect maintenance)	3	Assessment based on system complexity, how long technology available; contractor input
Initial cost of equipment and installation	3	Contractor estimated costs
Annual operating costs in addition to energy	2	Maintenance kit costs as provided by on-line vendors

S.1.3 Selection of Components to Meet Design Objectives

(a) Ventilation. There were 4 systems with supply ventilation specified, including three (A-C) with continuous supply fans and one that operated intermittently with a run-time controller (D). All provided enhanced filtration on the supply air, with MERV13 on the supply duct of A and B; MERV16 on C, and the timer-coordinated supply ventilation and AHU with MERV16 filter for D. The airtight envelope was thought to provide something akin to supply filtration but the effectiveness was unknown. System G used an HRV linked to the central system air handler, with enhanced filtration provided by the HEPA bypass that was designed to operate whenever the HRV was operating.

(b) Particle removal. For the Reference system having no enhanced filtration, we specified a low-efficiency filter of the type that has been used historically to reduce dust accumulation on cooling coils. This corresponds to MERV4. This filter was used in the return of several other systems that featured enhanced filtration at another location. System A had enhanced particle filtration only for ventilation supply air. System B had additional filtration with an ESP in the FA system, but that was designed to operate only when heating or cooling was needed. System C was primarily a supply filtration design but also provided filtration to the indoor air that was blended into the supply for tempering (the blending air was roughly twice the mechanical ventilation air flow rate). System G had a MERV8 filter on the supply, with higher performance HEPA bypass filtration at the central system return. The bypass unit directs a portion of the air moving through the FAU ductwork through the HEPA filter assembly; the remainder of the air moving through the AHU passes through the low efficiency filter only. The other three systems featured high performance filters on a central forced air system return: MERV16 for D, MERV13 for E and F. Systems D-G were designed to provide regular filtration for particles

already in the house owing to programmed operation of the system for at least 20 min of each hour with the runtime controller (D-E) and continuous, lower speed/flow operation of System F. Any system with enhanced filtration on a recirculation loop (B, D-G) could be operated on demand when indoor particle sources are known to be present.

(c) VOC removal. We selected three technologies for VOC removal. For System C, we specified inclusion of a recently developed (by LBNL) manganese oxide catalyst that oxidizes formaldehyde and other VOCs at room temperature (Sidheswaran at al., 2011). For System D, the intent was to use a chemisorbent that removes formaldehyde (and potentially also nitrogen dioxide) in addition to other VOCs. For System G, we specified activated carbon, which is the most common of the technologies available for VOC removal in residential HVAC systems and is known to remove some VOCs, such as the BTEX compounds, but is not very effective for removal of formaldehyde.

(d) Design of supply ventilation. There were two systems (D and G) in which outdoor air was supplied via the central forced air ducting system with intermittent operation of the AHU. There were three supply systems (A-C) featuring continuous supply ventilation that did not rely on the central blower. These designs were selected in place of the more common intermittent supply using the AHU to avoid the energy costs of running the typically much larger, and higher power consumption AHU blower. To avoid pushing supply air back through the central system filter that is used to protect equipment, the system protection filter was moved from the return grille to a slot just before the AHU for systems A and B.

(e) Systems that are low-cost. Systems A, B, E, and F are all relatively simple and should be relatively low initial cost (with the exception of the ESP on system B).

(f) System for low-load homes. System F explores a technology combination – ducted mini-split heat pump with a custom, low pressure drop MERV13 filter compartment – that is applicable to low-load homes including homes that have undergone energy efficiency retrofits to achieve very low loads.

(g) Low-energy pollutant removal. Systems A and F should incur relatively low energy costs as they use low resistance filtration with efficient fans. System C may also be low energy provided a low resistance MERV16 filter is available.

S.1.4 Thermal Conditioning Schedule and Equipment

Title 24 has two pathways for compliance, prescriptive or performance. The performance pathway is model based, and the prescribed model inputs are covered in the Alternative Calculation Methods (ACM) manual. The schedules are shown in Figure S.9 below.

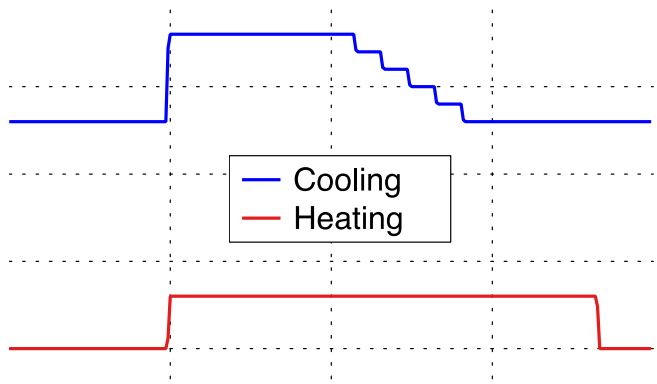

Figure S.9. Thermostat daily schedule based on California Title 24 design standard.

The thermal conditioning system for the home included a single-stage 75,000 Btu/h, 80% AFUE furnace; a 2.5 ton, an air conditioning unit with seasonal energy efficiency rating (SEER) of 13; and a blower with a nominal 600 W permanent split capacitor (PSC) motor. The return duct was located in the ceiling of the central hallway, at 2.75 m (9 ft) height and insulated flex duct distributed conditioned air to registers located in each room. Measurements of airflows at all heating/cooling supply registers were used to determine the total system airflow of 566 L/s (1200 cfm).

For System F, heating and cooling were provided by a mini-split heat pump (Daikin SkyAir 18 kbtu Minisplit with ducts & control) with the fan-coil unit mounted on scaffolding that was installed in the large common room for the duration of all experimental periods. A manifold at the outlet of the fan-coil unit fed smooth, sheet metal (for low pressure drop) duct runs to each of the three bedrooms. The mini-split was rated at 20 kbtuh for heating and (HSPF 10.6), 18 kbtuh for cooling (SEER 17.5). The instrument's native control system was programmed to operate on the Title 24 schedule described above.

S.1.5 Specifications of Installed Ventilation Systems

Specifications for ventilation system components are provided in Table S.5.

The exhaust fan used in Systems Ref, E and F (Panasonic model FV-08VKS3) was a "double-duty" fan installed in the bathroom. The double-duty refers to the fan providing continuous exhaust ventilation at the rate required to meet Title 24 / ASHRAE 62.2-2010, 17.5 L/s (37cfm) while having a higher speed of 41.5 L/s (88cfm) that can be manually initiated when needed for bathroom humidity or odor control.

All of the systems that provided ventilation through a dedicated supply fan (including A, B, C, D, and G) pulled outdoor air from the same location (the gable end vent on the north end of the house), which was nearby to the sampling point for outdoor air.

The same supply fan was used for Systems A, B, and D (Fantech model FR125). For System D the fan speed was set to provide a flow rate of 51.4 L/s (109 cfm) to meet the Title 24 / ASHRAE 62.2-2010 airflow requirement when operated for 20 min of each hour. A balancing damper just downstream of the fan was used to reduce the airflow rate for continuous operation

for Systems A and B. The damper position that provided the desired continuous airflow (the same flow as that used for the exhaust fan) was determined and marked prior to the start of multi-day experiments and the damper was set to this position when System A or B was tested. The actual flows achieved with the damper were not precisely 1/3 of the intermittent rate.

The blended supply ventilation for System C was provided by a commercially available product (American Aldes Model BV120). This product blended 16.5 L/s (35 cfm) indoor air drawn from the one of the small bedrooms and 28.3 L/s (60 cfm) of outdoor air drawn from the same location as the other supply fans, and supplied this mixture to the hallway in front of the main bathroom. The blending unit was mounted on the ceiling in the hallway closet.

The heat recovery ventilator (Fantech model FLEX 100H) used in System G was installed in the garage. It pulled outdoor air from the common intake used for all supply systems and provided that ventilation air to the return side of the FAU after heat exchange. The exhaust side of the HRV pulled indoor air from the laundry and master bathrooms, and exhausted that airstream to under an eave on the side of the house. Active flow-capture measurements using an Energy Conservatory Duct Blaster confirmed the supply and exhaust airflows were balanced at 52.9 L/s (112 cfm).

Airflow and power consumption were measured for each air-moving component and power consumption was measured for the ESP of System B. FAU airflow was measured as the sum of all supply register flows, after the distribution system was balanced according to industry standard Manual J HAC load calculations. Airflows were measured using the Energy Conservatory DuctBlaster™ and the active flow method outlined in the product manual. The nominal accuracy for this measurement is ±3%. For components with plugs, spot power measurements were made using a plug-through power meter (WattsUp PRO, www.wattsupmeters.com), with nominal accuracy ±1.5%. For components without plugs, power consumption was measured with WattNode model WNB-3Y-208P current transducers (www.onsetcomp.com), with nominal accuracy of ±0.5%. Performance measurements of installed system components are summarized in Table S.2.

Energy use and operating patterns of mechanical systems were monitored using WattNode current transducers (model WNB-3Y-208P) connected to a PointSix wireless data logging system. The following systems were monitored: FAU; exhaust fan used by Systems Ref, E, F; Supply fan used by Systems A, B, D; the mini-split unit of System F; the HRV of System G; and the HEPA bypass of System G. The ECOBEE thermostat system logged set points and system operation at 15 min resolution.

Table S.5. Airflows and power consumption of system components.

Component, Setting	Airflow[2] [L/s]	Measured Power[3] [W]	Catalog Power [W]	Notes
Exhaust fan for Systems E, F, Ref. (continuous)	17.5	4.2	3.7	Catalog power for 18.9 L/s @ 25 Pa
Supply fan, continuous setting for Systems A-B	17.5	17.7	18	Flow set with balancing damper. May have varied each time System A or B was set up.
Supply fan, intermittent setting for System D	51.4	18.0	18	
Blending supply fan for System C	44.8	33.8	43	Flow from outdoors = 17.4 L/s Flow from indoors = 27.4 L/s
HRV for System G, during intermittent operation	52.9	111.3	102	Catalog power for 46.7 L/s
HRV for System G, standby mode	No flow	10.1	N/A[1]	
AHU, high speed w/MERV4	566	660	N/A[1]	Cooling mode, sum of flows measured at supply registers
AHU, high speed w/MERV13	NM[1]	627	N/A[1]	System E; flow not measured in this configuration
AHU, high speed w/ESP	NM[1]	659	N/A[1]	System B; flow not measured in this configuration
AHU, high speed w/MERV16 + VOC	NM[1]	605	N/A[1]	System D; flow not measured in this configuration
AHU, medium high speed w/MERV4	500	N/A	N/A[1]	Heating mode, sum of flows measured at supply registers
AHU, standby mode	No flow	7.6	N/A	
System F mini-split, continuous setting for filtration	282	106.5	N/A[1]	Power measured by WattNode.
Electronic air cleaner (ESP) for System B	NR[1]	23.8	36	Catalog lists 36W as the maximum power
HEPA bypass for System G	85	121.1	125	Flow from manufacturer spec sheet.
Portable air filtration devices (n=2), Auto setting (~99% Low)	55	8.2	N/A[1]	Flow from manufacturer spec sheet (Low speed). Power measured over operating period
Portable air filtration devices (n=2), Medium setting	106	19.7	N/A[1]	Flow from manufacturer spec sheet (Medium speed). Power measured over operating period

[1] NM = Not measured in this configuration; N/A = not available; NR = not relevant to equipment. [2] Unless otherwise noted in the last column, all airflows measured with Ductblaster method noted in the text. The nominal accuracy of this measurement is ±3%. [3] The nominal accuracy of power measurements is ±0.5% to ±1.5%.

S.1.6 Specifications of Particle Removal Technologies

Specifications for particle removal technology components are provided in Table S.5.

The Reference system featured a nominal 1-inch (2.5 cm) thick, 50 x 76 cm (20 x 30 in.) filter (Purolator F312) installed at the return grille. The design intent was to use a low-efficiency (i.e., low MERV) filter that protects the heating and cooling equipment from dust but does not provide any benefit of enhanced particle removal. The decision to use the F312, which is rated as MERV4, instead of a MERV6 filter as specified by ASHRAE62.2, was based on input from HVAC and home performance contractors who conveyed to us that the lower quality filter is much more widely available and more commonly used. The same filter was installed at the return grille for System C and an appropriately sized 51 x 63 cm (20 x 25 in.) version of this product was installed at the AHU for System A, B and G.

Systems A and B both included a nominal 2-inch (5cm) thick, 41 x 34 cm (16 x 14 in.) MERV13 filter installed at the junction of the supply ventilation duct and the return air duct. Since this was not a commonly available size, the local filter vendor (Air Filter Supply in Sacramento, CA) fabricated these filters from media that met the MERV13 specification (Airguard DP-g13een). System B additionally incorporated an ESP, marketed as an Electronic Air Cleaner (Honeywell model F300A2025/U), installed between the supply air junction and the central heating and cooling equipment. The ESP only operated when the central FAU was operating for thermal control.

System C utilized the same MERV4 filter at the FAU return grill as the Reference system, but also included a MERV16 filter on the blended air system. The MERV16 filter was a specially modified IQAir model HyperHEPA cartridge. The filter was downstream of the blending, and the fan was always on.

System D included a nominal 1-inch (5cm) thick, 41 x 36 cm (16 by 14 in.) MERV8 filter installed at the junction of the supply ventilation duct and the return air duct. As with the supply filter for Systems A and B, this filter was fabricated as a special order by Air Filter Supply in Sacramento CA using media that met the MERV8 specification (AirGuard DP-Max). System D also included a nominal 5-inch (13 cm) thick, 51 x 63 cm (20 x 25 in.) MERV16 filter (Lennox model X8313). Both the ventilation fan and the FAU were controlled by an AirCycler controller (model g2) serving as a runtime controller to ensure that the FAU with this filter in-line operated for at least 20 min of each hour, irrespective of cooling or heating demand.

System E provided the simplest filtration upgrade, relative to the Reference, with a nominal 1-inch (2.5 cm) thick, 50 x 76 cm (20 x 30 in.) MERV13 filter (FiltersFast model FFM1361) installed at the return air grille and the AirCycler controller (model g2) serving as a runtime controller to ensure that the FAU with this filter in-line operated for at least 20 min of each hour, irrespective of cooling or heating demand.

System F incorporated a nominal 1-inch (2.5 cm) thick, 81x 63 cm (32 x 25 in.) MERV13 filter (FiltersFast model FFM1361) into a custom-built sheet-metal box that was attached to the return side of the mini-split evaporator and fan unit. The purpose of the custom box was to enable use of a high quality filter with low enough pressure drop to meet the mini-split's pressure tolerance limits. The outlet of the mini-split was directed through smooth, low-pressure drop ductwork to deliver filtered and conditioned (when needed) air to the living space and three bedrooms.

System G had the previously described MERV4 filter installed at the AHU. It also included a HEPA bypass unit (Lennox model HEPA-20 with optional 94X98 carbon canister). The bypass unit drew 85 L/s (180 cfm) from the return plenum downstream of where the HRV airstream

entered, and discharged the filtered air just upstream of the FAU. The AirCycler controller (model g2) served as a runtime controller to ensure that the FAU with the bypass filter and HRV operated for at least 20 min of each hour, irrespective of cooling or heating demand.

The portable air filters were RabbitAir model SPA-780A (A2-minus) with a HEPA main filter and the "pet / allergy" pre-filter. One was set up in the living room and the other was in the front hallway by the entry door. For one of the two test periods the units were operated in an AUTO mode where the speed of the fan increases if the unit senses high particle concentrations. The other week had the units running at a fixed medium speed. Both weeks had the air ionizer turned off but main filter and pre-filters in place.

S.1.7 Measurements of Envelope and Duct Air-tightness Between Summer and Fall Monitoring.

Prior to the start of the fall monitoring campaign, we again measured the envelope air tightness and also measured air leakage in the FAU ductwork configured for the Reference system. The envelope air leakage was 5.0 ± 0.2 air changes per hour at 50 Pascal indoor-outdoor pressure difference. Duct leakage was determined by a "Delta-Q" test (Walker et al., 2001) to be 4.2 ± 0.5 % of system flow on the return side and 3.8 ± 0.5 % on the supply side of the FAU. Here the uncertainty reflects the precision of the measured value. Measurements of air exchange rates in the house with and without the FAU operating during the cooking experiments suggest lower duct leakage than implied by these measurements. This is possible because the relative accuracy of the Delta-Q test decreases as duct leakage airflows become small relative to envelope leakage airflows.

S.1.8 Supplemental Cooling for Manifold Pumps (Summer Only)

The two large diaphragm pumps that pulled air through the instrument manifolds were located in the garage to reduce heat gain to the house interior. This appeared to be sufficient during the winter operation period; but we observed when restarting the systems in May that heating of the garage by the pumps would have a substantial impact on cooling demand and AHU operation for cooling.

To solve this problem, we constructed a chamber to house the pumps and provided supplemental mechanical cooling to this chamber. The chamber, situated in the garage, close to the common wall with the house, was constructed of wood and measured 1.2 m high by 2.4 m wide by 0.8 m deep. Cooling was provided by a 2.7 kW (9300 Btu/h) portable air conditioner (Friedrich model P09B) located in the garage with the hose for venting the condenser heat connected to the outdoors through the side door of the garage.

S.1.9 Details of Time-Resolved Pollutant Monitoring Systems

Sample air was drawn at 0.28 L/s (0.59 cfm) through each sample line using vacuum pumps in the garage. The outdoor air inlet for particles was 0.5 m above the apex of the roof just above the supply air inlet and the indoor air inlet was in the central hallway at 1.5 m height. The aerosol inlet assembly (BGI, Inc.) on each sampling line comprised a PM_{10} inlet with rain shield coupled with a sharp cut 2.5 μm cyclone. Sample lines connected to indoor and outdoor inlets had identical lengths of conductive tubing and similar bends to arrive at a set of switching valves that connected the two air streams to manifolds from which aerosol instruments sampled. The main

sampling lines – from inlet assemblies to switching system leading into instrument manifolds – were 7 m long. The lines used for winter 2014 monitoring had internal diameters (ID) of 11.1 mm (0.436 in.). Prior to the start of summer monitoring, we changed sample inlet tubing for both indoor and outdoor inlets, using larger diameter samples lines. The sample lines used in summer and fall 2014 had ID of 14.1 mm (0.555 in.). The larger diameter sampling lines were expected to yield lower particle deposition losses with negligible impact on the analysis of system performance since indoor and outdoor sampling lines were identical both before and after the switch.

Valves synchronously switched indoor and outdoor sample inlets between the two manifolds. The switching interval was 10 min during monitoring in Jan-Feb 2014 that included fall/winter evaluation of the Reference system and System C. The switching interval was changed to 15 min on March 6, 2014 and this interval was used for all subsequent measurement periods. This change was made to reduce the fraction of samples that had to be removed because they straddled a switch and thus reflected a combination of both indoor and outdoor air.

Table S.6 lists the instrumentation used to measure each pollutant parameter. All instruments other than the aethalometer were set to calculate and record 1-min average values. The Aethalometers were initially set to record 1-min average values then reset on March 6, 2014 to record 3-min running averages. The longer sample time provided a lower minimum quantitation limit and improved resolution for systems with high efficiency filters.

Air pollutant monitoring instruments and switching valves were located in the master bedroom. The layout of the instruments is shown in Figure S.10. Aerosol and ozone analyzers were sent for manufacturer calibration prior to first deployment.

Ozone monitors were dedicated to indoor and outdoor air without switching. The outdoor sample was drawn from 2.5 m below the outdoor aerosol inlet and 0.5 m from the exterior wall. The indoor sample location was at the indoor aerosol inlet. Air was pulled from these locations through 5 m lengths of 3.2 mm ID Teflon tubing to ozone instruments in the master bedroom. Ozone instruments were installed prior to the start of hot weather monitoring in June 2015.

Table S.6. Measured air pollutant parameters and monitoring equipment.

Parameter	Device	Quantitation limit (QL)	Calibration and nominal accuracy.
Number conc. of particles ≥6 nm	TSI Condensation Particle Counter (CPC) Model 3781	Max. QL 500,000 particles cm^{-3}	Manufacturer calibrated before deployment.
Number conc. of particles ≥100 nm	TSI CPC Model 3787 with TSI particle size selector	Max. QL 500,000 particles cm^{-3}	Manufacturer calibrated before deployment.
Number conc. of particles in 6 bins from >0.3μm to >2.5μm[1]	MetOne Optical Particle Counter (OPC) Model BT-637S	Max. QL 10^7 particles cm^{-3}	Manufacturer calibrated before deployment. Accuracy: ±10% to calibration aerosol.
$PM_{2.5}$ mass estimated by forward light scattering	TSI DustTrak II 8530	Min. QL 4 μg m^{-3} for 1h avg[2]	Manufacturer calibrated before deployment.
Mass concentration of black carbon aerosol (BC)	Magee Scientific Aethalometer AE22	Min. QL 30 ng m^{-3} for 3 min sample[3]	Manufacturer calibrated before deployment.
Ozone (O_3)	2BTech Model 202 UV-absorbance analyzer	Min. QL 4.5 ppb[4]	Manufacturer calibrated before deployment. Nominal accuracy: larger of 1.5 ppb or 2% of reading;

[1]Bins defined by lower size cut, e.g. >0.3, >0.4, >0.5, >0.7, >1.0, >2.5μm. [2]Reported by (Wallace et al., 2011). [3]Estimated based on visual review of data. Estimated min. QL of 90 ng m^{-3} for 1-min sample duration. [4] Based on manufacturer precision (1σ) of 1.5 ppb.

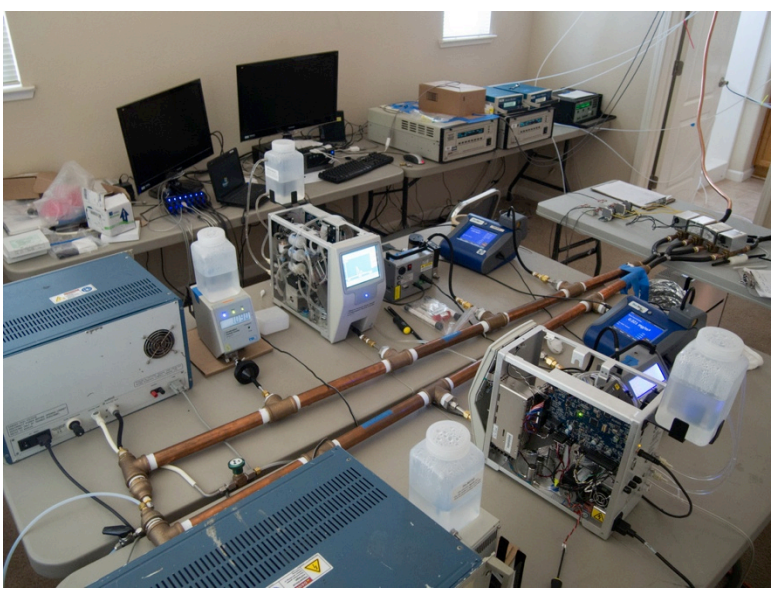

Figure S.10. Layout of instrumentation in master bedroom.

The photo shows the two manifolds with identical particle instrumentation. Aethalometers are the large blue boxes at the bottom left of the photo. Moving up and to the right, there are CPC 3781s with water bottles on top, CPC 3787s without covers, MetOne OPCs, and DustTraks (small, dark blue cases). Switching valves are visible at the inlet of the manifold, toward the right edge of the photo. In the back corner are two 2BTech ozone analyzers sitting atop an API NO_X analyzer (not discussed in this paper), and the B&K instrument used to monitor SF_6 (far corner).

S.1.10 Details of SF_6 Release and Measurement

SF_6 was released at the kitchen peninsula counter and at 1 m height in the nook just outside of the two smaller bedrooms. At each location the tracer was released using a peristaltic pump connected to a Tedlar bag containing pure SF_6 and a 30 cm axial fan was positioned to blow the tracer outward for mixing. Concentrations of SF_6 were measured with ~1 min resolution in the central hallway, near the FAU return, at a height of 2 m using a Bruel & Kjaer (now Innova) 1312 photoacoustic infrared analyzer. The instrument was zero-checked between most monitoring intervals and a span calibration was conducted at the start of each seasonal campaign. The time-resolved air exchange rate was calculated by the constant injection method in ASTM Standard E741-11.

S.1.11 Experimental Schedule

We started with a series of "shakedown" and pilot experiments conducted from mid-January through the first few weeks of February 2014, as summarized in Table S.7. These mostly used the Reference system. One objective was to confirm performance of the switching, parallel manifold systems and all instrumentation for unattended monitoring periods lasting approximately one week. Another objective was to develop and test algorithms for a remote, daily review of data to affirm proper operation and to generate data that was used to develop processing and analysis algorithms for assessing enhanced particle removal. During two of these early monitoring periods we obtained data sets that were complete enough to use for the analysis of system performance under winter conditions. All systems and instruments were powered down on March 19 and instruments were serviced as needed.

Table S.7. Winter 2014 "Shakedown" and pilot experiments to identify and resolve challenges related to weeklong, unattended monitoring.

Dates	System	Data Notes
1/15–1/22	Reference	Monitoring systems operating in parallel, no switching. Outdoor 3781 and Aeths offline for repairs. DustTraks off manifolds.
1/23–1/29	Reference	Outdoor 3781 offline for repairs. Switching started. AER 2x design b/c bath fan set too high. DustTraks off manifolds.
1/29–2/6	Reference	Outdoor 3781 offline for repairs. AER still 2x design. DustTraks off manifolds.
2/6–2/12	C: Blended Supply, MERV16	Outdoor 3781 offline for repairs. DustTraks off manifolds. Indoor DustTrak and BC below QL much of week.
2/12–2/19	Reference	No data from 3781s starting 2/13; pump failure. Indoor BC below QL for much of week. Response shift of 3781s on 2/16.
2/20–2/27	Reference[1]	DustTraks on manifolds; curious data 2/20-2/22. Increase Aeth flow to 4 L/min. Other instruments and systems operating as designed.
2/27–3/6	C: Blended Supply, MERV16[1]	No AER data from 2/28; B&K problem. Other instruments and systems operating as designed.
3/6–3/12	A: Cont. Supply w/MERV13.	One 3781 not operating; take offline to repair. Computer down 3/7-3/8.
3/13–3/19	E: MERV13 on return	Lost power to one manifold on 3/16. Various other problems.
3/19	Shutdown	Power down all equipment for service.

[1]Data collected in this period used for system performance analysis.

Table S.8. Monitoring periods to assess system performance for outdoor particles in fall/winter and outdoor particles and ozone in summer.

Fall/Winter Performance		Summer Performance	
Dates (2014)	**System**	**Dates (2014)**	**System**
2/21–2/27	Ref: Continuous exhaust ventilation; no enhanced filtration	6/6–6/12	E: Continuous exhaust ventilation; MERV13 on FAU, 20/60 fan timer
2/27–3/6	C: Continuous blended supply w/MERV16	6/12–6/17	A: Continuous supply w/MERV13
10/28–11/4	E: Continuous exhaust ventilation; MERV13 on FAU, 20/60 fan timer	6/18–6/22	F: Continuous exhaust ventilation; Cont. MERV13 on mini-split fan unit
11/4–11/10	F: Continuous exhaust ventilation; Cont. MERV13 on mini-split fan unit	6/25–7/2	G: Supply ventilation + HEPA bypass on FAU, 20/60 fan timer
11/11–11/17	A: Continuous supply w/MERV13	7/2–7/9	Ref: Continuous exhaust ventilation; no enhanced filtration
11/18–11/25	B: Continuous supply w/MERV13; ESP on FAU, thermostat control.	7/9–7/16	D: Supply ventilation + MERV16 on FAU, 20/60 fan timer
11/25–12/2	D: Supply ventilation + MERV16 on FAU, 20/60 fan timer	7/16–7/23	Ref: Continuous exhaust ventilation; no enhanced filtration
12/2–12/8	G: Supply ventilation + HEPA bypass on FAU, 20/60 fan timer	7/23–7/30	C: Continuous blended supply w/MERV16
12/8–12/12	Portable air filtration unit set to Auto operation mode	7/30–8/6	B: Continuous supply w/MERV13; ESP on FAU, thermostat control.
12/12–12/15	Portable air filtration unit set to Medium speed operation mode		
12/16–12/19	E: Continuous exhaust ventilation; MERV13 on FAU, 20/60 fan timer		
12/19–12/23	A: Continuous supply w/MERV13		

S.1.12 Data Processing and Analysis

S.1.12.1 Processing to produce time series of indoor and outdoor concentrations

The first step of pollutant data analysis was to filter/remove data points from the measurements that were recorded just after the two manifolds synchronously switched between indoor and outdoor inlets. During the first two months of sampling in Jan-Feb, 2014, the manifolds switched on 10 min intervals. On March 6, the switching interval was changed to 15 min. Measurements just after switching reflect a combination of air from indoors and outdoors, and are thus not valid as indicators of concentrations in either location. For the instruments that were on the manifolds and that recorded measurements at 1 min intervals, i.e. CPCs, Optical particle counters (OPCs), and DustTraks, it was typically the case that only the first data point after the switch was invalid as a measurement of either indoor or outdoor air. However, in a non-

negligible number of cases, the first data point was so close in time to the switch that a second measurement was impacted. For consistent and efficient data handling, two data points were filtered from the time series from these instruments following each synchronous manifold switch. Starting on March 6, only one point was filtered from aethalometer time series data because that instrument was configured to switch every 3 minutes. Prior to March 6, the aethalometers sampled every 1 min; so two aethalometer measurements were removed following manifold switching for data collected prior to March 6.

An example of after-switching data filtering is shown in the two figures below. Figure S.11 displays particle number concentration time series that include all of the measurements output by the two CPCs; data from one instrument are shown in blue, the other in red. The instruments sampled from manifolds that switched every 15 min between indoor and outdoor inlets. At many of the manifold switches, there are two blue and two red data points that reflect a combined indoor and outdoor air sample. The time series with these points removed are shown in Figure S.12.

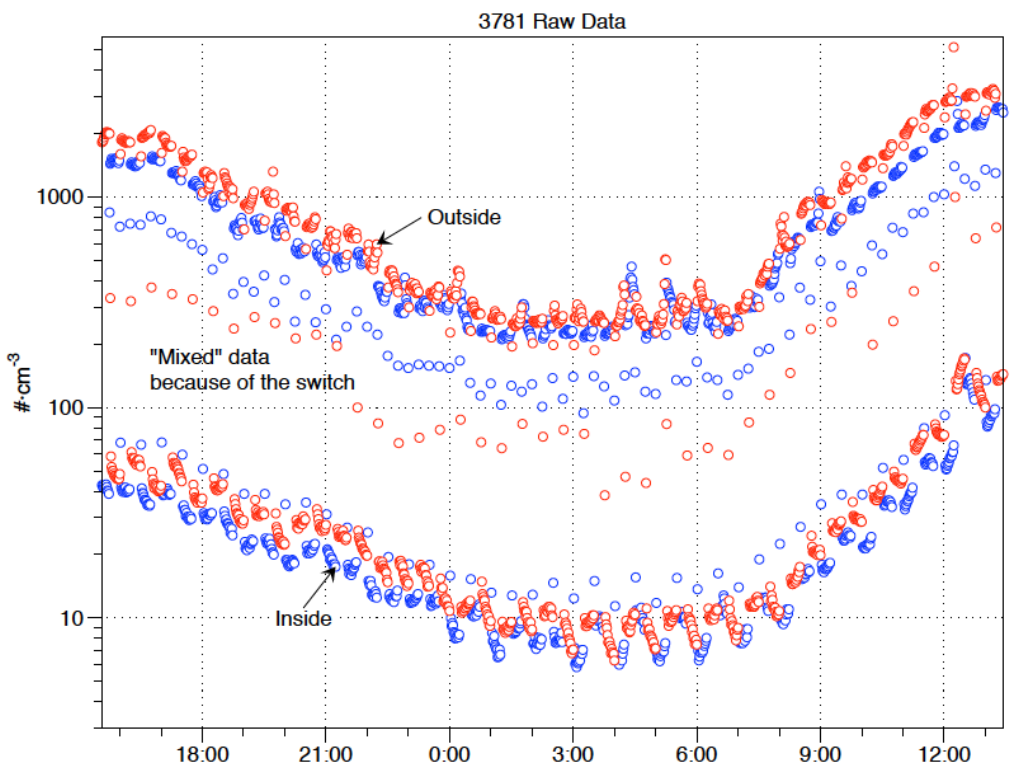

Figure S.11. Time series of measurements from two CPC3781 units (shown as red and blue circles) switching synchronously, on a 15-min interval, between indoor and outdoor sample inlets.
Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm diameter particles. Concentrations at top are outside and at bottom are indoors. Points between the outdoor and indoor series occur just after the switch and reflect measurements in air samples drawn partly from each location.

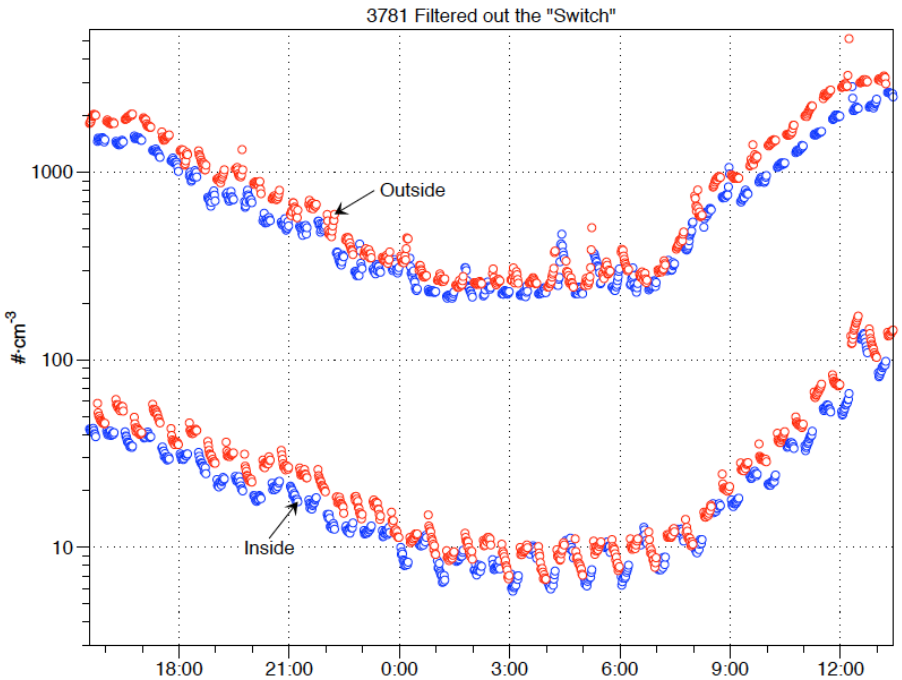

Figure S.12. Time series data shown in Figure S.11 with post-switching points removed.
Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm.

The next step in the analysis was to align the indoor and outdoor data from the two instruments to create nearly continuous data series for indoor and outdoor sampling locations. To accomplish this alignment, we compared the indoor time series of the two instruments as a form of cross-calibration; then used the relative responses to adjust both indoor and outdoor data. The cross-calibration and adjustment is needed because instrument responses drift apart over time and field calibration of particle instrumentation is not practical. Alignment was accomplished as follows. We first applied a locally weighted scatterplot-smoothing algorithm to the available indoor data for each instrument. The available data excluded the post-switching data points and any missing data. We used an open source python implementation[1] of the LOESS[2] algorithm that is based on methods first proposed by Cleveland (1979) and further developed in Cleveland (1981) and Cleveland and Devlin (1988). A good description of the method is available via Wikipedia[3]. Briefly, the algorithm uses near-neighbor data points, weighted by proximity, to develop a low order polynomial fit to the data around each point. When applied across a time series, the algorithm produces a smoothed series with 1-min time resolution. At each time

[1]http://statsmodels.sourceforge.net/devel/generated/statsmodels.nonparametric.smoothers_lowess.lowess.html.

[2]LOESS, in capital letters, is a particular form of the smoothing algorithm. It is not an acronym.

[3]As of Oct 2015, a good description of method is presented on Wikipedia:

http://en.wikipedia.org/wiki/Local_regression

interval, the two LOESS-smoothed indoor time series were compared to the mean of the two series to determine a scaling factor to align the time series from each instrument to the mean of the two instruments. This provides a one-min resolution time-series of a scaling factor that was applied to the data from both instruments to create merged indoor and outdoor time series. The following three figures demonstrate this procedure. Linear interpolation was used to impute concentrations for the two-min period following each switching event.

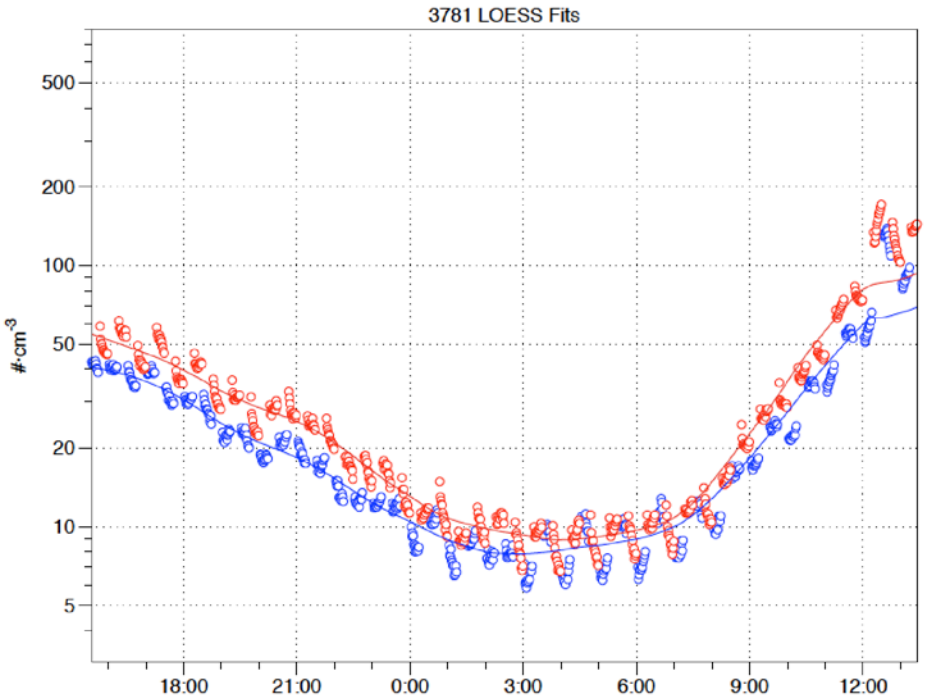

Figure S.13. Smoothed time series of indoor measurements from each of two CPCs obtained by applying a python implementation of the LOESS algorithm to data series of each CPC.
Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 μm.

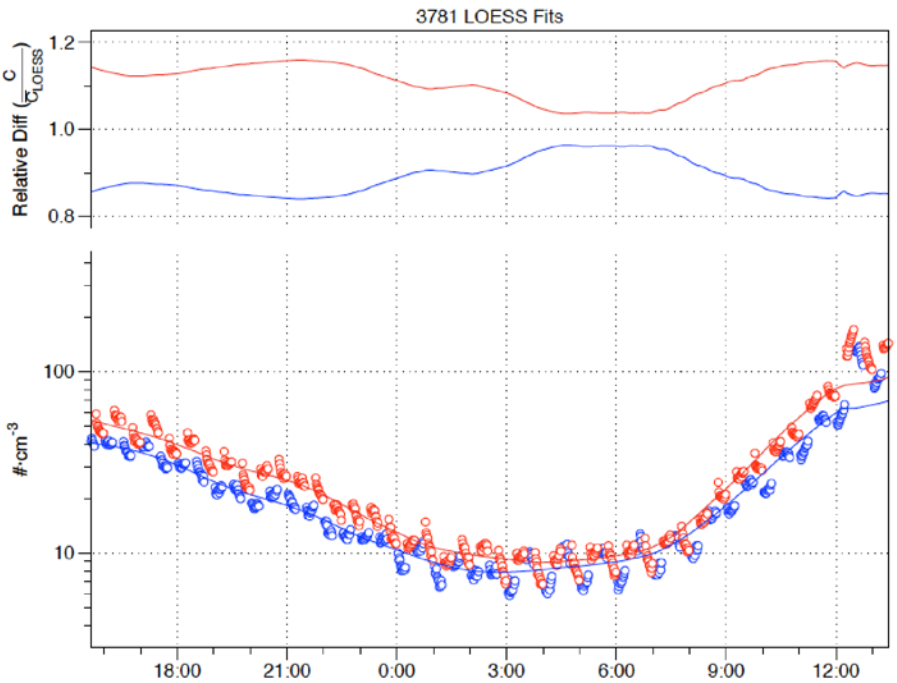

Figure S.14. Relative difference (top) of smoothed indoor time series (bottom) for each CPC 3781 relative to the mean of the two time instruments.

The time-resolved relative difference functions are used to align the indoor and outdoor time series for the two instruments. Units of y-axis on bottom panel are particles cm^{-3} for size range of 100 nm to 2.5 µm.

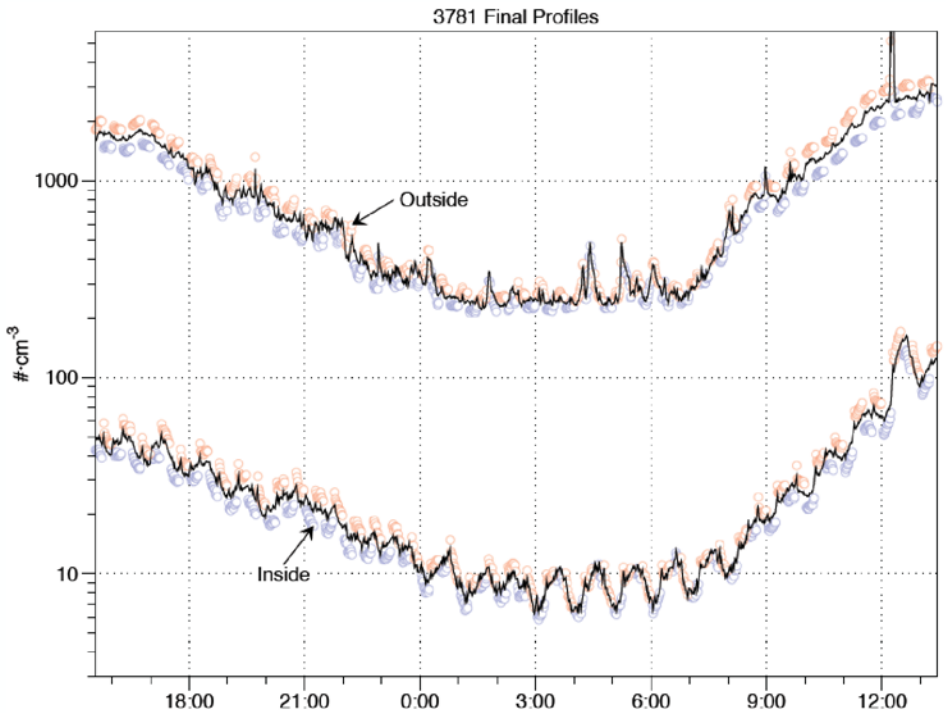

Figure S.15. Indoor and outdoor time series constructed by aligning data from two instruments alternately measuring indoors and outdoors at 15 min intervals via synchronously switching.
Raw data show as partially opaque red and blue open circles. Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm. The saw tooth pattern indoors (e.g. during the hours of 3:00 to 8:00) results from intermittent operation of a filtration system.

For UFP, we first developed continuous time series for total particles 6nm–2.5um and for 100nm–2.5um, using data from the two pairs of instruments. We then subtracted the latter from the former to obtain the number concentration of 6–100nm particles.

S.1.12.2 Screening of data impacted by activities inside the home

For multi-day monitoring periods, a screen was applied to the start of the time series data to avoid any biases from field technician impacts on indoor particle levels, typically this was 3-4 h after the field technician exited the test house. A varying delay was applied to the start of the running 24h averages, with the delay determined from a visual review of data. For each week of monitoring, we applied the same initial delay to all pollutant parameters. This screening was not applied to the highest daily 1h outdoor and indoor values because the short-term running averages were not as impacted by earlier activity in the homes.

Additional masking of 24h running average time series data was done on monitoring days when the house was accessed by a field technician. These included set-up of VOC samples and a system check by the HVAC contractor on 19-Jun. Additional details are provided in the Appendix results for each system in the final project report (Singer et al., 2016).

S.1.12.3 Calculation of 24h, 8h and 1h running averages

After screening the data as described in the preceding sub-section, we calculated running statistics (mean, median, standard deviation) from the 1-min data for each of the measured

parameters (and 3 min data for BC). Running statistics were calculated for time windows of 1, 8, and 24 hours. When calculating summary statistics for a monitoring period, we did not use running 8h and 24h mean values until a sufficient amount of time had elapsed that these means were representative. This initial delay varied from a few hours to nearly 24h.

S.1.12.4 Selection of dividing time for statistics by day

Distinct 24h diurnal periods ("days") within a monitoring period were set by selecting a daily dividing time, with the intent that this would be at a time of low outdoor concentrations. The diurnal patterns varied seasonally, across weeks within a season and sometimes even across days within a monitoring period. A daily dividing time was selected for each multi-day monitoring period by visual review of the time series for all measured parameters. Summary statistics were then calculated for all data available during each specified day during the monitoring period. The dividing time for each period is specified at the front of the appendix that presents data from the period in the final project report.

S.1.13 Estimation of Annual Energy Use

Incremental fan energy requirements for each system, relative to the Reference, were calculated for deployment across California using equipment runtime estimates and component power consumption. Actual energy consumption during the limited monitoring periods in the test house is not reported because they are not representative of annualized impacts.

Incremental fan energy requirements result from the following: (1) extra hours of FAU operation for filtration and/or supply ventilation; (2) increased or decreased fan power as airflow resistance increases, (3) operation of air cleaning devices including the ESP of System B and the HEPA + Activated Carbon unit of System G.

To calculate the energy for extra central air handler operation, we used baseline heating and cooling system runtimes developed for studying the impacts of ventilation requirements in California's Title 24 building code (Walker and Sherman, 2006). That analysis used a heat transfer, airflow, and moisture simulation model to determine FAU operating times attributed to heating, cooling and ventilating. Simulations were conducted for Title 24 prototype homes, including a 1761 ft^2 home, under various ventilation configurations in several California climate zones. Although the simulated house is larger than the test house, FAU runtimes should be similar since heating and cooling systems are sized to demand. The simulated home had a typical efficiency (2 cfm/W) air handler and fan power varied by climate zone according to industry standards for equipment sizing. Simulations assessed the effect of the supply fan and central blower fan heat on heating and cooling loads. Simulations were conducted for California climate zones 3, 10, 13, 15 and 16. California's climate zones are shown in Figure S.16. For this assessment, we analyzed simulations for a Central Fan Integrated Supply (CFIS) system that operates for a minimum of 20 min each hour (20/60).

Climate Zone	City
1	Arcata
2	Santa Rosa
3	Oakland
4	Sunnyvale
5	Santa Maria
6	Los Angeles
7	San Diego
8	El Toro
9	Pasadena
10	Riverside
11	Red Bluff
12	Sacramento
13	Fresno
14	China Lake
15	El Centro
16	Mt. Shasta

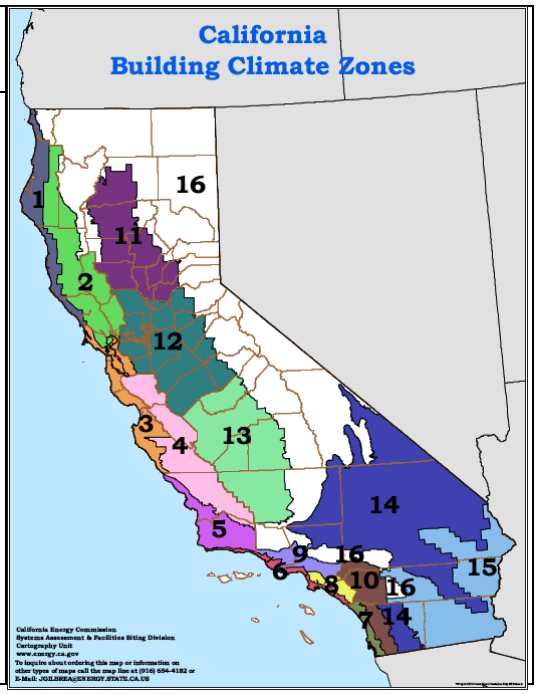

Figure S.16. California climate zone map.

To estimate incremental runtime for 20/60 operation, we start with the Reference system operating hours for heating and cooling only. We compare this to the total hours of FAU operation for the CFIS system, which includes additional runtime to thermally condition the extra airflow for ventilation, and all hours of 20/60 operation. Table S.9 breaks out these components. Despite large variations in Reference system runtimes for heating and cooling, the relative variation of incremental runtime is small across climate zones. From this analysis, we used an incremental runtime of 2400 hours per year for the FAU to run on a 20/60 cycle to provide enhanced filtration or supply ventilation.

Operating the FAU continuously for pollutant removal requires an additional 7949 hours of operation (8760 total – 811 for heating + cooling).

Table S.9. Simulation based estimates of annual operating hours for central forced air system in typical new California homes in various California climate zones.[1]

Climate Zone	City	Reference heating + cooling hours	Total CFIS runtime, hours	CFIS heating + cooling hours	CFIS ventilation, hours	**Incremental runtime of CFIS, hours**
3	Oakland	606	3056	616	2440	**2450**
10	Riverside	709	3191	752	2439	**2482**
13	Fresno	882	3278	928	2351	**2397**
15	El Centro	988	3332	1046	2287	**2345**
16	Mt. Shasta	870	3187	887	2300	**2318**
Mean		**811**	**3209**	**846**	**2363**	**2398**

[1] From Walker and Sherman (2006).

The energy for additional FAU fan operation was calculated as the product of the incremental run time and 600 W, the actual power consumption of the test house FAU (Table S.5); this

corresponds to 0.5 W/cfm, a typical efficacy for a permanent split capacitor (PSC) motor. Incremental power needs were also calculated for an efficient, brushless permanent magnet (BPM) FAU motor. These fans operate more efficiently in low speed continuous mode – as used in the System F mini-split F – than intermittently at higher speed. For the FAU with BPM, we assumed that the schedule and airflow did not change from the Reference system and assumed an efficacy of 0.375 W/cfm, corresponding to 450 W for all HAC operation. For an FAU operating continuously at low speed, we assumed airflow of 188 L/s (400 cfm) and an efficacy of 0.175 W/cfm as measured for the mini-split in System F. For this situation, a power draw of 70 W was assumed to occur 7949 hours per year. For System G, we assumed the BPM motor operating at the higher flow rate on a fan cycler to keep energy use estimates consistent with pollutant removal performance. If the System G bypass were operated continuously it would have higher energy consumption but also better pollutant removal.

The fan power to overcome airflow resistance of higher performance filters was treated as follows. For the PSC motor, we assumed no change in power. In fact, there may be a small decrease in power as the higher resistance leads to lower airflows. For the BPM motor, we estimated a power increase proportional to those reported by Lutz et al. (2006). For the MERV16 filter of System D, we assumed an 8W increase (11.4% increase) and for the MERV13 filter of System E, we assumed a 4W increase (5.7%) increase.

We accounted for filtration energy costs on the supply ventilation systems by assuming that, in the absence of enhanced filtration, the fan efficacy would be the same as for exhaust fans: 0.11 W/cfm. For the supply systems with MERV13 filtration, the incremental energy attributed to filtration was 2.2 W (0.17 - 0.11 = 0.06 W/cfm * 17 cfm) for continuous operation and 6.7 W for intermittent operation. We used the supply fan efficacy measured for System D because the lower flow for Systems A and B was obtained by partially closing a damper to increase duct pressure. The energy cost for MERV16 filtration on the blended (higher airflow) System C was 22.8W (0.35 - 0.11 = 0.24 W/cfm * 95 cfm).

The energy costs of operating the ESP and HEPA bypass were calculated from the component power consumption data presented in Table S.5.

S.2 Results

S.2.1 Assessment Periods for Outdoor Particles

Table S.10. Outdoor conditions during fall/winter monitoring periods assessing performance for outdoor particles

Dates (2014)	System	Period mean $PM_{2.5}$ mass (g/m	Period mean dry-bulb temp. (°C)	Mean daily low/high temp. (°C)
2/21–2/27	Ref: Continuous exhaust ventilation; no filtration	21	11.7	5.7 / 19.3
2/27–3/6	C: Continuous blended supply w/MERV16	12	13.8	10.4 / 17.2
10/28–11/4	E: Cont. exhaust ventilation; MERV13 on FAU, 20/60 timer	15	14.4	9.1 / 21.0
11/4–11/10	F: Cont. exhaust vent.; Cont. MERV13 on mini-split fan unit	31	14.9	9.0 / 21.9
11/11–11/17	A: Continuous supply w/MERV13	19	12.3	8.1 / 17.3
11/18–11/25	B: Cont. supply w/MERV13; ESP on FAU, t-stat control.	22	10.9	7.0 / 15.3
11/25–12/2	D: Supply ventilation + MERV16 on FAU, 20/60 fan timer	25	11.6	8.1 / 17.3
12/2–12/8	G: Supply ventilation + HEPA bypass on FAU, 20/60 fan timer	12	14.6	11.8 / 17.7
12/8–12/12	Portable air filtration unit set to Auto operation mode	18	12.6	10.3 / 15.5
12/12–12/15	Portable air filtration unit set to Medium speed operation mode	12	9.8	8.3 / 13.1
12/16–12/19	E: Cont. exhaust ventilation; MERV13 on FAU, 20/60 timer; tape around edges of filter to ensure no bypass.	8.3	11.5	9.6 / 14.3
12/19–12/23	A: Continuous supply w/MERV13; tape around edges of filter to ensure no bypass.	8.1	13.0	10.5 / 15.9

Table S.11. Outdoor conditions during summer monitoring periods assessing performance for outdoor particles

Dates (2014)	System	Period mean $PM_{2.5}$ mass (μg/m^3)	Period mean dry-bulb temp. (°C)	Mean daily low/high temp. (°C)
6/6–6/12	E: Cont. exhaust ventilation; MERV13 on FAU, 20/60 timer	15	27.0	16.5 / 40.5
6/12–6/17	A: Continuous supply w/MERV13	12	22.2	14.2 / 33.0
6/18–6/22	F: Cont. exhaust vent.; Cont. MERV13 on mini-split fan unit	12	24.9	15.5 / 39.1
6/25–7/2	G: Supply ventilation + HEPA bypass on FAU, 20/60 fan timer	10	26.7	17.6 / 40.2
7/2–7/9	Ref: Continuous exhaust ventilation; no enhanced filtration	16	27.5	17.9 / 41.2
7/9–7/16	D: Supply ventilation + MERV16 on FAU, 20/60 fan timer	9.4	26.6	18.5 / 38.1
7/16–7/23	Ref: Continuous exhaust ventilation; no enhanced filtration	6.3	23.8	17.7 / 34.8
7/23–7/30	C: Continuous blended supply w/MERV16	12	28.3	19.7 / 40.6
7/30–8/6	B: Cont. supply w/MERV13; ESP on FAU, t-stat control.	12	25.8	19.3 / 34.3

Table S.12. Median and mean of continuous air exchange rate measurements during each assessment period for outdoor particles.

Summer			Fall/Winter		
Sys	Median	Mean	Sys	Median	Mean
Ref	0.278	0.290	Ref	0.218	0.218
Ref	0.283	0.292			
A	0.208	0.218	A	0.268	0.275
			A taped	0.267	0.267
B	0.213	0.226	B	0.274	0.277
C	0.232	0.250	C	0.217	0.219
D	0.262	0.276	D	0.337	0.339
E	0.292	0.306	E	0.347	0.347
			E taped	0.352	0.352
F	0.265	0.268	F	0.303	0.303
G	0.298	0.313	G	0.352	0.353
			Port auto/low	0.302	0.312
			Port medium	0.304	0.307

S.2.2 Performance for Outdoor Particles

Table S.13 presents the days of monitoring data and the days of 1-minute resolved running 24h mean indoor/outdoor ratios (IOs) presented in Figure 5 in the main paper.

Table S.13. Days of data presented in Figure 5 in main paper.[1]

System Description	Days of monitoring data		Days of 1-minute resolved running 24h mean IOs in Figure 5	
(M=MERV)	SU	FW	SU	FW
Exhaust Ventilation				
Ref: M4@rtn	6.7, 6.7	6.5	6.3, 6.4	5.5
E: M13@rtn	6.0	7.0	5.7	2.4
E: w/o bypass	nd[2]	2.7	nd[2]	2.3
F: M13 on mini-split	4.5	6.8	4.0	6.4
Portables on Auto / Low	nd[2]	3.7	nd[2]	3.4
Portables on Medium	nd[2]	3.8	nd[2]	3.4
Supply Ventilation				
A: M13@Supply	5.2	6.7	4.3	6.5
A: w/o bypass	nd[2]	4.0	nd[2]	3.8
B: M13@Supply/ESP@FAU	6.7	6.7	5.7	6.4
C: M16@Supply	6.8	6.8	5.7	5.6
D: M8@Supply/M16@FAU	6.7	6.7	6.5	6.4
Balanced Ventilation				
G: M8@Sup/HEPA bypass	5.0	5.7	4.7	5.2

[1]Each data point is an IO ratio calculated from minute-by-minute running 24h mean indoor and outdoor concentrations. The running 24h concentrations start 5-24h after the start of the monitoring period in almost all cases. [2]No data collected

To address system performance for reducing the highest short-term exposures, Table S.11 presents the protection factors for the highest 1h outdoor-origin $PM_{2.5}$ mass and UFP. Hourly results are not presented for BC because those data are not as well resolved for short time duration analysis. The IO ratios for the highest daily 1h concentrations were lower than the 24h IO ratios for almost all systems and parameters. For the Reference system, the highest indoor hourly $PM_{2.5}$ concentrations were lower than the highest outdoor hourly $PM_{2.5}$ concentrations by 77-78% on average for each season. The supply ventilation & filtration of System A had somewhat higher 1h IO ratios compared to the Reference, corresponding to a 70% reduction. System B had lower 1h IO ratios in SU than FW, corresponding to 85% and 71% reductions of outdoor $PM_{2.5}$. The better performance in summer resulted from the ESP operating with the FAU for cooling. As with the longer time-averaged performance, the best systems for reducing short-term indoor concentrations of outdoor particles were C, D, and F, followed by System E and the portables.

Table S.14. Percent reduction in highest daily 1 h indoor concentrations compared to corresponding highest daily 1h outdoor concentration of outdoor-origin $PM_{2.5}$ mass and ultrafine particles (UFP) over each evaluation period; mean and standard deviation across distinct 24h diurnal periods of analysis within each period.

System	$PM_{2.5}$				UFP			
	SU		FW		SU		FW	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ref	78	3	77	5	89	2	90	2
A	70	7	70	2	86	3	81	6
B	85	10	71	5	86	4	84	3
C	95	2	98	1	98	1	99	1
D	97	1	98	0	98	0	97	1
E	92	1	89	1	94	2	92	8
F	95	0	96	1	97	1	96	1
G	81	3	81	3	85	0	86	3
Port	nd[1]	nd[1]	93	2	nd[1]	nd[1]	96	2

[1] No data.

S.2.3 Performance for Indoor Particles

Example data from an experiment assessing performance for indoor-generated particles are provided here for System D (supply ventilation and MERV16 filtration on the FAU return on 20/60 operation). The figures show the time series of SF_6 (indicating AER) and calculated $PM_{2.5}$ from before cooking through two cycles of FAU operation. The SF_6 tracer time series in Figure S.**17** shows the higher AERs that occurred during system operation and the lower AERs during the intervals without mechanical ventilation.

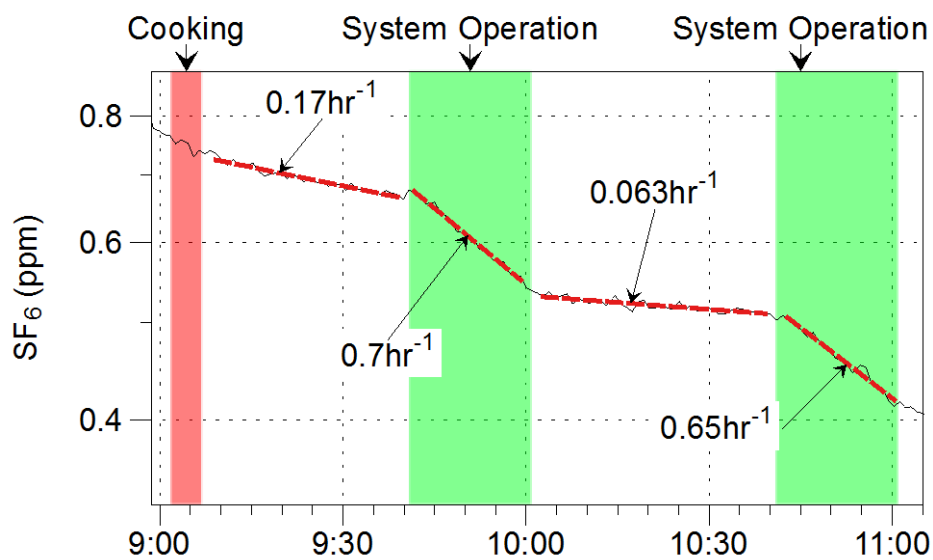

Figure S.17**. Time series of SF_6 tracer concentrations during cooking experiment with System D on July 16, 2014.** Refer to text for a detailed description.

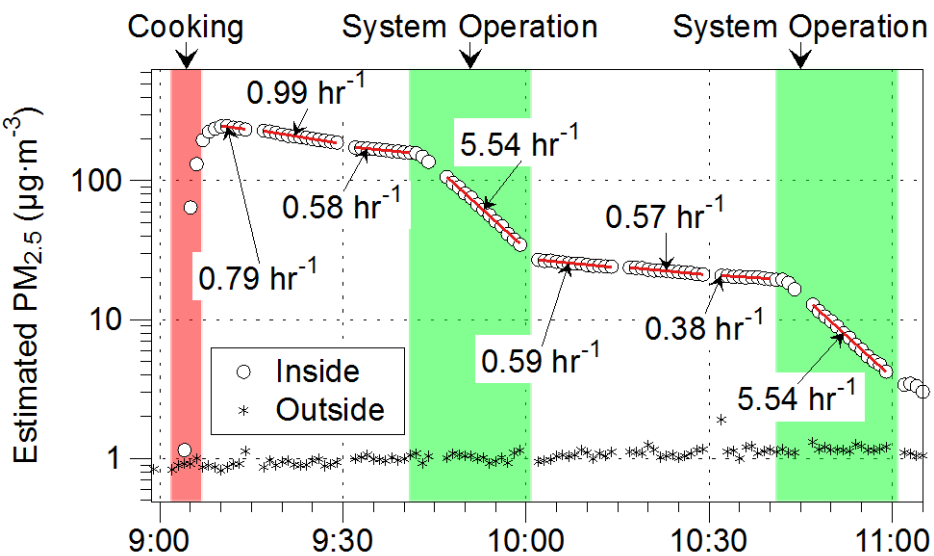

Figure S.18. Time series of estimated $PM_{2.5}$ concentration calculated from size-resolved particle number concentrations during cooking experiment with System D on July 16, 2014.
Refer to Methods for details on this calculation. Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

Figure S.18 presents $PM_{2.5}$ mass estimated from particle number concentrations. In this experiment, indoor $PM_{2.5}$ from cooking reached a peak that was more than two orders of magnitude higher than outdoor levels. Over the two hourly cycles of intermittent system operation, indoor concentrations dropped to within 2x outdoor levels. $PM_{2.5}$ decay rates during both periods of system operation were 5.5 h^{-1}, which is 4.8 h^{-1} higher than the AER of 0.7 h^{-1}. Results for all particle size fractions will be included as appendices to the final project report at https://www.arb.ca.gov/html/publications.htm.

Figure 6 presents the reduction in time-integrated UFP relative to the baseline condition of no FAU operation. UFP data were missing from several of the experiments. "As tested" results represent a minimum benefit because intermittent systems operated only at the end of the hour. For the first 40 min, intermittent systems were identical to the Reference. Figure 6 also presents calculated reductions for systems operating over the entire hour ("Always On"). For intermittent systems (B, D, and G) the reduction was estimated by calculating the concentration over the hour assuming the first order removal rate observed during intermittent system operation. For the Reference, reductions for Always On are assumed to result from deposition of large particles in the FAU and ductwork.

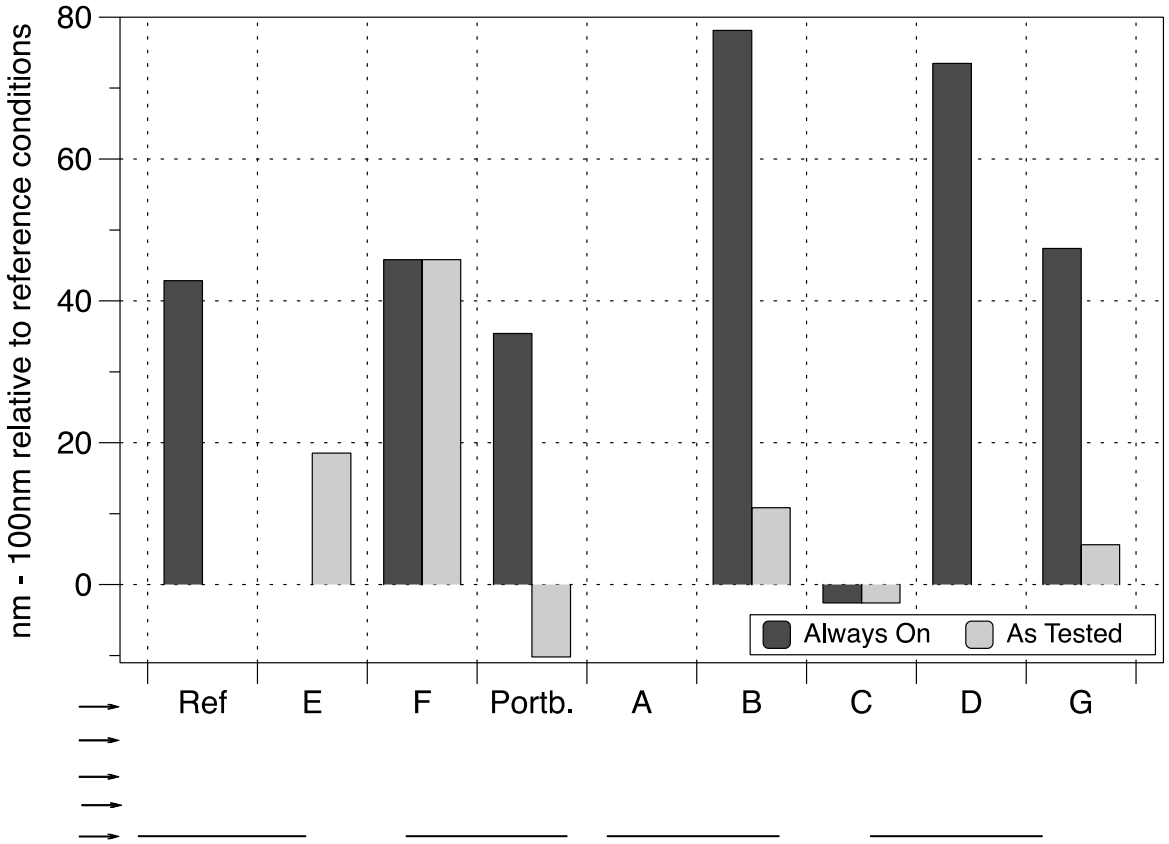

Figure S.19. Reductions in estimated UFP concentrations over 1h following an indoor cooking event, relative to Reference system. Systems with intermittent filtration were tested at the start of a cycle, i.e., with cooking occurring at the start of the 40 min interval between air handler operating periods. "Always on" is the estimated reduction with the recirculating filtration system operating continuously for the hour.

S.2.4 Performance for Ozone

Figure S.20 presents an example plot of processed ozone data from Reference system operation during the summer. During this period, outdoor ozone varied diurnally with daily 1h peaks of 30-60 ppb and troughs between 10 and 20 ppb. Indoor ozone determination was limited by instrument sensitivity, causing uncertainty in the 24h and 1h IO ratios.

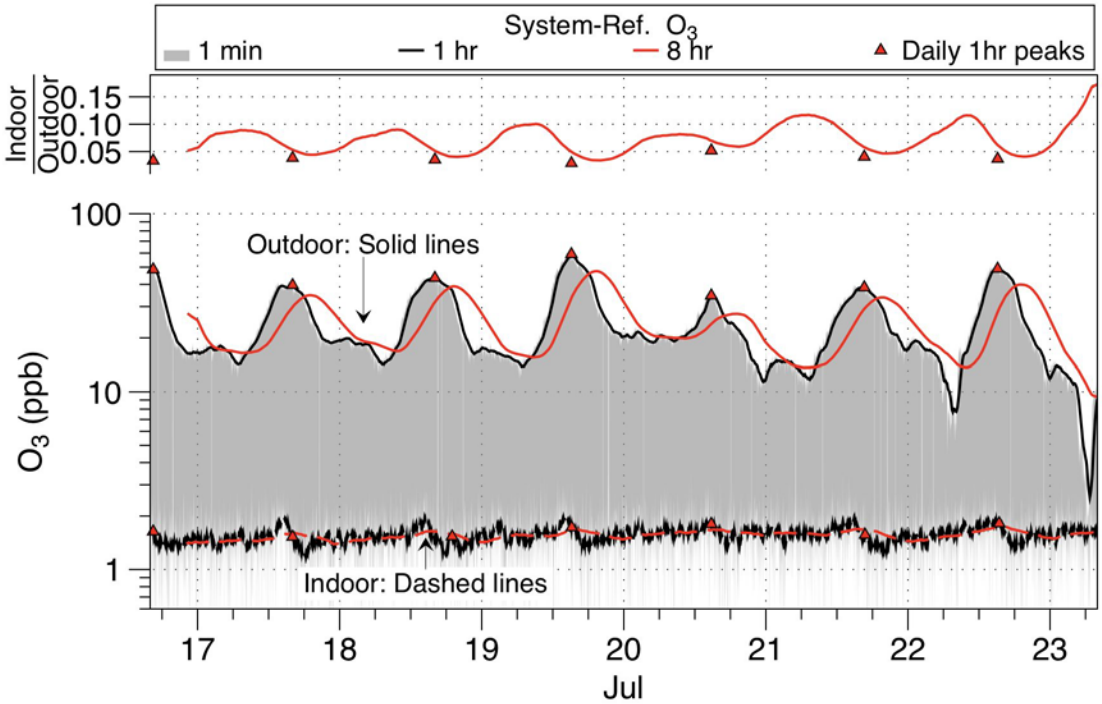

Figure S.20. Ozone concentrations measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

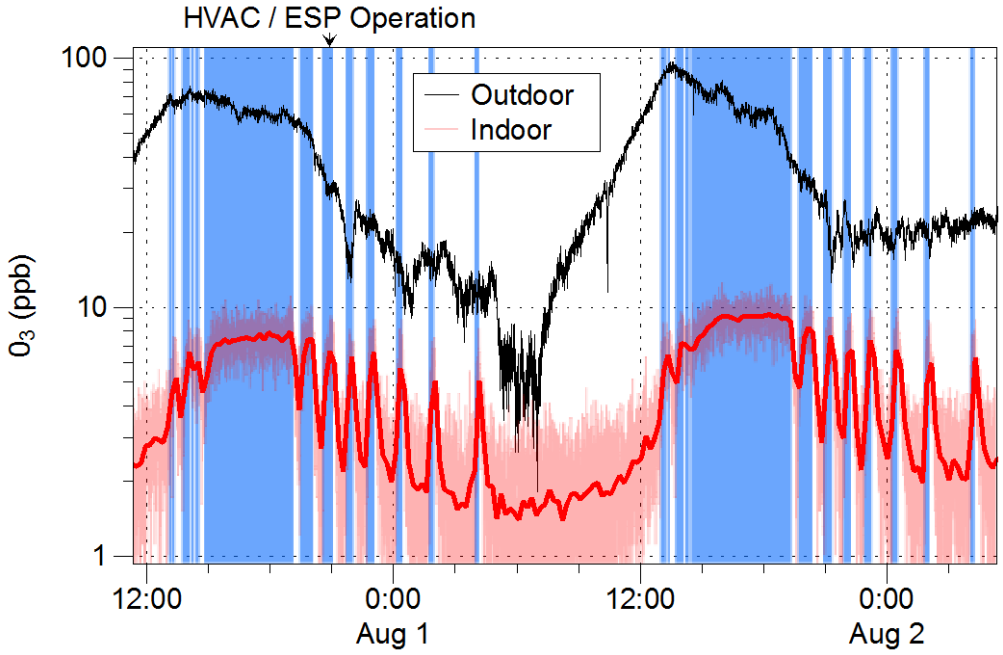

Figure S.21. Time series of ozone concentration for System B indicating ozone production when the FAU with electronic air cleaner operated (shown in blue shading).
For indoor data, the figure shows both the minutely measurements – which are noisy because the concentrations are close to the quantitation limit – and a smoothed fit.

S.2.5 Filter Impacts on Airflow and Power Consumption

The effect of filter resistance on airflow and power consumption is displayed in Figure S.22, which shows the FAU fan curves along with system curves representing the various filters. The two fan curves represent the two operating speeds of the FAU. Typical for this type of system, the fan was set at a higher speed for cooling than for heating. Fan curve data were obtained from the manufacturer's specification sheet. The system curves represent the combined resistance of the ductwork, FAU cabinet, cooling coils, and the filters. The actual flow delivered by a system is the intersection of the system and fan curves. We used filter curves from manufacturer specification sheets and adjusted the other resistance such that the combined resistance profile of the system curve matched the measured flow at the intersection with the fan curve for cooling mode. The close agreement between the measured heating mode airflow and the intersection of the fitted system curve with the heating fan curve provides some assurance that the system curve is correct.

The effect of resistance on airflow and power is presented in Table S.12. The PSC-motor used in the FAU is essentially a constant speed motor. Adding resistance to this system produces lower flows. The least restrictive system was the MERV4 filter. The ESP had very little internal resistance (which, for an ESP, is determined by the distance between the charging grids), and it had essentially the same effect as the MERV4 filter on system performance. We show for comparison purposes the calculated airflow and fan efficacy of the MERV16 filter without the PuraGrid product, even though we did not test pollutant removal of this configuration. The 2.5 cm MERV13 filter was more restrictive than the deep pleat MERV16 and it cut the flow by 4.9%. Combining the PuraGrid cartridge with the MERV16 filter created the highest resistance, which cut the flow by 12.3%. The drop in flow (determined from system and fan curves) caused a drop in power consumption (measured) and the fan efficacy remained nearly constant.

It is important to note that for some FAU fans and installed ducting, the increase in resistance of a higher rated filter could result in a larger reduction in airflow. In cooling mode, a drop in flow causes a drop in cooling coil temperatures and cooling efficiency. If flow drops too much the coil temperature can drop below freezing and block airflow. Concerns about these effects inhibit HVAC contractors from installing or recommending filters that are rated for higher fine PM removal. While use of low resistance filters mitigates the risk of a problem developing, it is important and valuable to design or retrofit ductwork for low resistance irrespective of filtration.

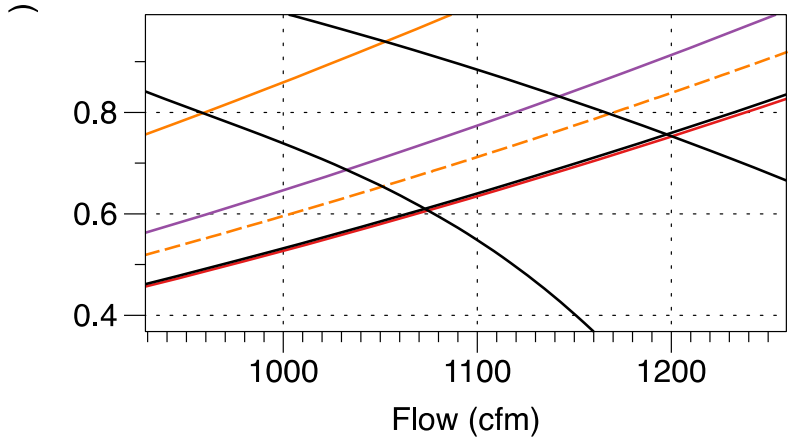

Figure S.22. Intersections of forced air unit (FAU) fan curves and inferred systems curves based on product specification sheets and measured airflows.

Table S.15. Calculated effect of filters on airflow, power, and fan efficacy.

Filter	System	Flow (cfm) [1]	Change in flow (%)	Power (W)	Change in Power (%)	Efficacy (cfm/W) [1]
MERV4	Ref, A, C, G	1200	-	660	-	1.82
ESP	B	1198	-0.2%	659	-0.2%	1.82
MERV16 (deep pleat) only	Not tested[2]	1168	-2.7%	647	-2.0%	1.81
MERV13 (2.5 cm)	E	1142	-4.9%	626	-5.1%	1.82
MERV16 (deep pleat) + PuraGrid	D	1052	-12.3%	605	-8.4%	1.74

[1] Flow and fan efficacy provided in units most commonly used for evaluation of home and HVAC energy efficiency.
[2] Flow and power for the MERV16 filter without PuraGrid provided as relevant to system configuration without VOC removal media; this study did not test that configuration independently of System D.

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