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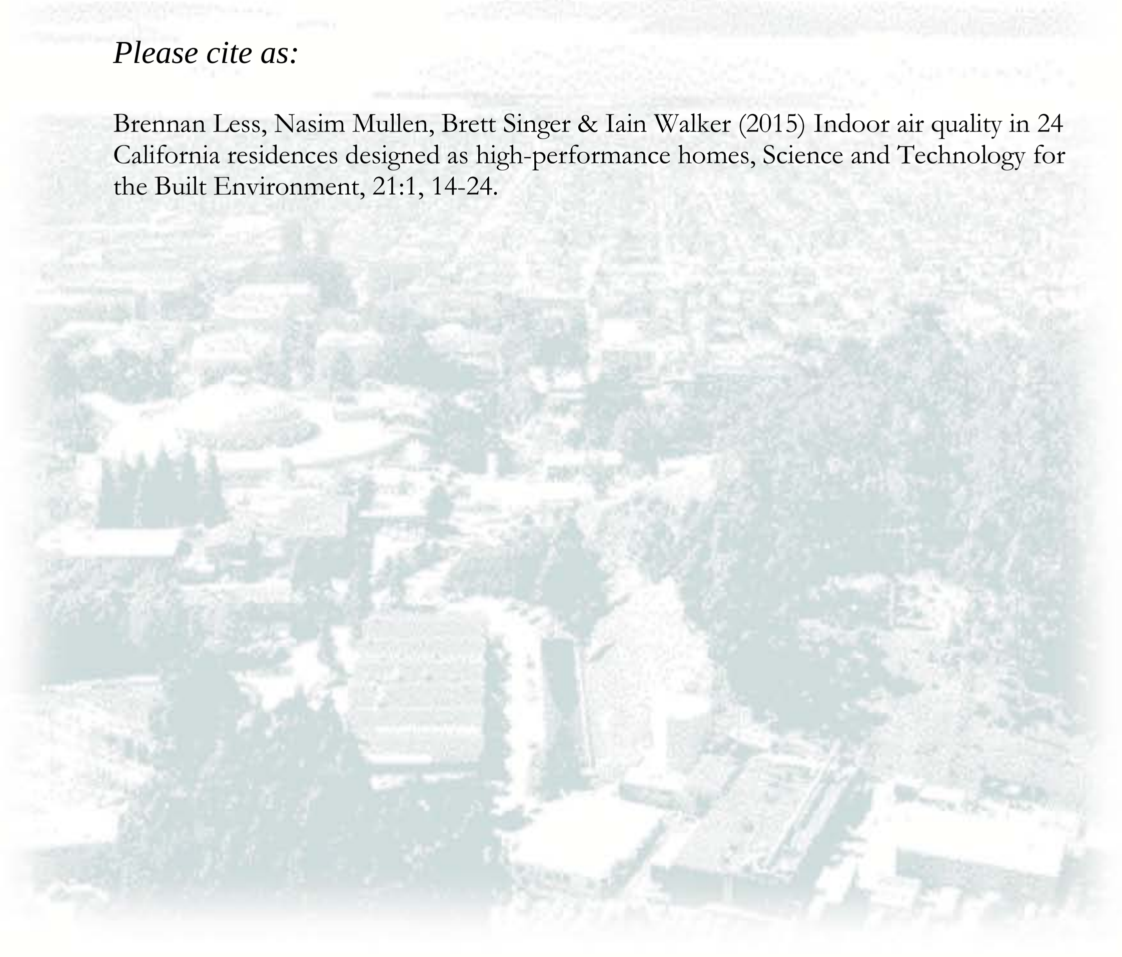

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DISCLAIMER

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ABSTRACT

Today's high performance green homes are reaching previously unheard of levels of airtightness and are using new materials, technologies and strategies, whose impacts on Indoor Air Quality (IAQ) cannot be fully anticipated from prior studies. This research study used pollutant measurements, home inspections, diagnostic testing and occupant surveys to assess IAQ in 24 new or deeply retrofitted homes designed to be high performance green buildings in California. Although the mechanically vented homes were six times as airtight as non-mechanically ventilated homes (medians of 1.1 and 6.1 ACH_{50}, n=11 and n=8, respectively), their use of mechanical ventilation systems and possibly window operation meant their median air exchange rates were almost the same (0.30 versus 0.32 hr^{-1}, n=8 and n=8, respectively). Pollutant levels were also similar in vented and unvented homes. These similarities were achieved despite numerous observed faults in complex mechanical ventilation systems. More rigorous commissioning is still recommended. Cooking exhaust systems were used inconsistently and several suffered from design flaws. Failure to follow best practices led to IAQ problems in some cases. Ambient nitrogen dioxide standards were exceeded or nearly so in four homes that either used gas ranges with standing pilots, or in Passive House-style homes that used gas cooking burners without venting range hoods. Homes without active particle filtration had particle count concentrations approximately double those in homes with enhanced filtration. The majority of homes reported using low-emitting materials; consistent with this, formaldehyde levels were approximately half those in conventional, new CA homes built before 2008. Emissions of ultrafine particles (with diameters <100 nm) were dramatically lower on induction electric cooktops, compared with either gas or resistance electric models. These results indicate that high performance homes can achieve acceptable and even exceptional IAQ by providing adequate general mechanical ventilation, using low-emitting materials, providing mechanical particle filtration, incorporating well-designed exhaust ventilation for kitchens and bathrooms, and educating occupants to use the kitchen and bath ventilation.

INTRODUCTION

As high performance new and existing green homes are deployed on a national scale, there are concerns about the potential negative IAQ and health impacts (Committee on the Effect of Climate Change on Indoor Air Quality and Public Health, 2011; Crump et al., 2009; Manuel, 2011). These concerns may be valid, as most U.S. building codes and energy codes have not traditionally focused on ensuring acceptable IAQ (Mudarri, 2010). Others have suggested that healthy housing interventions, including energy efficiency, can improve occupant health, especially in distressed housing (Kuholski et al., 2010). This belief that energy efficient green homes can have better IAQ than conventional homes has been enshrined in high performance green home certification systems, which aggressively market their health and IAQ benefits, as well as incorporate measures to address IAQ alongside other environmental concerns. While past research has addressed IAQ in efficient homes, the high performance green homes built today may present different challenges and opportunities than those of the past. Factors that could affect IAQ in high performance green homes include changes in building materials, consumer products and airtightness levels, as well as changes in the standards, designs and equipment used in mechanical ventilation systems. High performance green homes generally have a suite of features that could either improve or degrade IAQ (see Table 1), some of which also exist in conventional practice. The impacts will vary depending on how IAQ is defined, what exactly is measured or assessed, and which measures are employed to achieve high performance green designation.

Table 1 Summary of the risks and benefits associated with common features in high performance green homes

Common Features	Benefits	Liabilities
Airtightness	Improves thermal comfort; May reduce indoor levels of outdoor pollutants[1]; May limit pollutant transport from undesirable locations.	Increases levels of indoor generated pollutants; Ventilation depends on mechanical system.
General, "whole house" mechanical ventilation	Reduces levels of indoor generated pollutants; Avoid periods of variable natural infiltration.	Increases indoor levels of outdoor pollutants relative to no airtight w/o mechanical ventilation; More energy efficient designs may be prone to installation, operation errors
Exhaust ventilation in kitchens and bathrooms	Efficient removal of indoor generated pollutants and excess moisture.	Commonly used products require manual operation, which is unreliable.
Particle filtration	Reduces indoor particle levels.	Potential pollutant source if not maintained
Equipment commissioning	Ensures installed performance meets design intent.	NA
Moisture-managed construction	Reduces potential moisture degradation in structure/materials.	NA
Humidity control	Reduces indoor humidity levels and associated health risks from biological agents.	NA
Low-emitting materials	Reduces pollutant emissions and indoor levels.	NA
Increased insulation and air	Improves thermal comfort.	Additional indoor pollutant

sealing materials	sources.

[1] Indoor levels of outdoor pollutants lower if there are loss or removal mechanisms indoors or during transport indoors.

The effects of energy conservation on indoor air quality in homes have been intermittently debated and documented in the building science and air quality literatures. Canadian R-2000 homes—notable for their airtightness, heat recovery ventilation systems, and low-emitting materials requirements—repeatedly have been compared with conventional Canadian homes and found to have equivalent or lower pollutant levels (Gusdorf and Hamlin, 1995; Gusdorf and Parekh, 2000; Riley and Piersol, 1988). In U.S. homes, uncoordinated efforts, smaller sample sizes, and inconsistent program requirements have produced more variable findings. While early research efforts suggested that energy efficient homes might have poorer IAQ (Berk et al., 1980; Burkart and Chakraborty, 1984; Fleischer et al., 1982; Hollowell et al., 1978), subsequent research employed with more rigorous methods suggested that energy efficiency (i.e., airtightness and ventilation rates) was less important than other determinants of IAQ in residences (i.e., pollutant source strength and geographical location for radon) (Grimsrud et al., 1988; Harris, 1987; Hekmat et al., 1986; Offermann et al., 1982; Turk et al., 1988).

Subsequently, a general consensus has evolved that energy efficiency and IAQ are compatible. For example, envelope and duct airtightness, as well as air sealing have been shown to reduce air and pollutant transport from areas such as attics, garages and crawlspaces (Coulter et al., 2007; Emmerich et al., 2003). Consistent with this, the *Indoor Air Quality & Its Impact on Man* project in the European Union has spelled out the fundamental issues and strategies related to the potential for energy conservation to degrade IAQ, as well as ways to manage these potential liabilities (Alvarez et al., 1996). More recently, methods have been developed to plan synergistic energy and IEQ retrofits (Noris et al., 2013b). The consensus that energy efficiency and IAQ can be compatible has been formalized into the high performance home program specifications of today, such as the U.S. EPA's Indoor airPLUS, green building certifications (e.g., LEED for Homes, National Green Building Standard), and energy retrofit best practices (e.g., Healthy Indoor Environment Protocols for Home Energy Upgrades).

Current research assessing the IAQ and health impacts of new and existing high performance green homes has demonstrated that IAQ and energy efficiency can be compatible, if established best practices (source control, ventilation, filtration, occupant education, etc.) are implemented. Research efforts including both simulations and field measurements have demonstrated increased negative health effects or poor IAQ in efficient or retrofitted residences that did not sufficiently address IAQ provisions (Emmerich et al., 2005; Milner et al., 2014; Offermann, 2009; Wilson et al., 2013). Yet, other research efforts that have consistently included IAQ best practices have demonstrated improved health outcomes and generally reduced pollutant levels (Breysse et al., 2011; Jacobs, 2013; Kovesi et al., 2009; Leech et al., 2004; Noris et al., 2013a; Weichenthal et al., 2013). These mixed research findings substantiate the concerns of those who are concerned that efficiency may be implemented in residences without sufficient IAQ countermeasures. In this literature, very little comprehensive air pollutant data has been reported for today's high performance green homes.

METHODS

This study examined ventilation and IAQ in a convenience sample of 24, non-smoking California high performance green homes: 12 new homes and 12 deeply retrofitted homes. The study included home inspections, ventilation system measurement, occupant surveys, and 6-day active and passive air pollutant sampling (see Table 2). The surveys and IAQ measurement methods are described in detail in published reports (Less, 2012; Mullen et al., 2012). The survey and IAQ methods and equipment packages were developed and used in a large study of California homes, the California *Healthy Homes* IAQ study of 2011-2013. IAQ measurements in the high performance homes were performed between January and April of 2012. Outdoor particle number concentrations were not measured, so particulate mass-based data were retrieved for the measurement periods from the California Air Resources Board monitoring stations nearest to the project homes. This paper will focus on the results for six-day passive samples of NO_2 and NO_x, formaldehyde and acetaldehyde, and air exchange rate; time-resolved kitchen particle counts were measured using a laser particle counter (no published accuracy data). Accuracy (i.e., the average relative deviation for all pairs of co-located duplicate pollutant samplers, n=30) was ±6%, ±4%, ±5% and ±6% for NO_2, NO_x, formaldehyde and acetaldehyde, respectively. For air exchange rate, the accuracy was estimated at ±11%, using the average relative deviation of the four samplers located in each of 16 project homes. Notably, eight AER measurements were discarded due to contamination, and some substantial variation between samplers was observed in several other test homes suggesting non-mixed air volumes, which can lead to sizeable measurement errors, as discussed in Less (2012). Pollutant samples were taken in kitchen (K), bedroom (B) and outdoor (O) locations (see Table 2).

Table 2 Summary of IAQ parameters, measurements methods, types, and location

Measurement	Method	Type	Location(s)
T/RH (indoor)	HOBO U10-003	1-min.	K,B,O
T/RH (outdoor)	HOBO U23 Pro v.2	1-min.	K,B,O
CO_2	Extech SD800 CO_2	1-min.	B
CO	Lascar, USB-EL-CO300	1-min.	K
NO, NO_2, NO_x	Ogawa NO_x/NO_2 sampler	6-day	K,B,O
Aldehydes	Waters, Sep-Pak XPoSure	6-day	K,B,O
Particle Counts ($PN_{>0.5}$ and $PN_{>2.5}$)	Dylos DC1700	1-min.	K
Air Exchange Rate (AER)	Passive Sorbent Tube, Tenax TA	6-day	K,B,O,+2[1]
Ultra Fine Particle Count, $PN_{0.1}$ (stove top test during site visit)	TSI P-Track 8525	1-min	K

[1] Passive sorbent tubes were located in the kitchen, bedroom, and outside locations, as well as two additional indoor locations (i.e., "+2").

RESULTS AND DISCUSSION

House Characteristics, Systems and Airtightness

General. All of the project homes were located within 161 km (100 mile) of Berkeley, CA, with the exception of a single home in Southern California, which could not be visited and was measured under a reduced protocol. The mean age was 4.3 years (range = 0 to 28 years), with the age of retrofitted homes being calculated from the date of renovation completion. This was done because the retrofitted homes were major remodeling projects (generally "gut-rehabs"), which included new mechanical, structural and finish materials throughout, making them similar to newly constructed homes. Twenty-three of the homes were less than eight years old, and 18 homes were five years old or less, making the sample largely representative of new homes. The average home size was 198 m^2 (range = 121 to 465 m^2) (2,128 ft^2; range = 1,306 to 5,006 ft^2), and the average number of persons per house was 2.8 (range = 1 to 5). These are very close to the U.S. national averages of 202 m^2 (2,169 ft^2) and 2.55 persons per household (U.S. Census Bureau, n.d., n.d.).

Efficiency Designations. The energy and sustainability designations for the study homes were reported by occupants during initial surveying. The most common designations were deep energy retrofit (n=12), green certified (n=10), Passive House-style (n=7), and net-zero energy (n=6). The homes were intended to represent the higher echelons of high performance homes; accordingly, participant homes included LEED Platinum homes, Passive House-style homes, and a home certified to the Living Building Challenge. Some homes combined multiple designations (e.g., Deep Energy Retrofit and Passive House).

Airtightness. Envelope airtightness was measured or gathered from third-party tests in 19 of 24 homes. Study homes had a median airtightness of 2.8 air changes per hour at -50 Pascals (ACH_{50}). This airtightness level is compatible with that required in the 2015 IECC for new construction. There was considerable variability from 0.4 to 10.3 ACH_{50}. Homes that used the Passive House standard to guide planning were the tightest, with ACH_{50} values ranging from 0.4 to 2.4. Non-Passive House homes were generally more leaky, with less emphasis placed on airtightness by many builders and designers in the mild California climate. These results show the wide range of airtightness targeted in new and existing high performance homes, while also demonstrating that some homes have airtightness levels that are much tighter than achieved historically: 3 ACH_{50} roughly corresponds to the 5th percentile of home air leakage in the national air leakage database maintained by LBNL (Chan et al., 2013). This substantiates the concern that air exchange rates will be sharply reduced, unless mechanical ventilation is provided.

Ventilation System Descriptions and Installed Performance Assessments

Continuous Mechanical Ventilation. Whole house mechanical ventilation systems were installed in only 13 of 24 projects and installation rates were roughly consistent with those found in the U.S. DER literature (Less and Walker, 2014). The mechanically vented homes in this study had tighter envelopes, with a median of 1.1 ACH_{50} compared to 6.1 ACH_{50} for homes without mechanical ventilation. This suggests that project designers generally recognized the increased need for mechanical ventilation with increasing levels of airtightness. Of the 13 systems in this study, only one was a simple exhaust fan, while the other 12 were “complex” systems—Energy Recovery Ventilator (ERV) (n=3), Heat Recovery Ventilator (HRV) (n=6) and Central Fan Integrated Supply (CFIS) (n=3). “Complex” systems in this research had some or all of the following: advanced controls, dedicated duct systems, multiple wall controllers, variable speed settings, air filters and dampers. This added complexity may have contributed to the faults that were observed in some of these systems, as detailed below. CFIS, HRV, ERV and non-ventilation forced air systems all provided particle filtration (mix of HEPA and MERV 7, 8, 12 and 14) and air distribution.

A number of performance issues were found or had been reported (and previously remedied) by occupants in project home ventilation systems. Faults included failed duct attachments to unit, air recirculation due to incorrect connections, erratic cycling from low to high speed outside occupant control, clogged outdoor air inlet, ERV turned off by occupants, and poor control strategies and operation (or lack thereof) of CFIS. Similar faults have been commonly reported elsewhere, including low airflow, noise, unclean systems, poor design and/or installation, insufficient maintenance, operational errors, blocked air intakes and recirculation in ERV/HRV (Balvers et al., 2012; Hill, 1998; Offermann, 2009). Clearly, even in high performance homes, ventilation system design should be improved and possibly simplified, and commissioning and verification are required, as is occupant education on building systems operation.

Kitchen and Bathroom Ventilation. While continuous mechanical ventilation was not consistently provided in all homes, projects more reliably installed other exhaust fans in the kitchen (17/24 homes) and bathrooms (23/24 homes). Furthermore, occupants in 11 homes reported always using bathroom exhaust fans when showering, and only four homes reported not using bathroom exhaust fans. Unfortunately, kitchen exhaust usage was much more variable, with 11 occupants reporting infrequent or no usage, and most occupants reporting only using the lowest fan speed. In addition, six homes lacked kitchen exhaust directly to outdoors, mostly due to recirculating range hood use in Passive House-style kitchens. There was a strong sense amongst respondents that kitchen exhaust fans were only necessary to remove acute odors or smoke, which contrasts with the current state of the science related to kitchen pollutants that emphasizes the health risk from cooking-related pollutants (Kim et al., 2011; Logue et al., 2014; Stratton and Singer, 2014). Research in existing California homes has shown some benefit to the operation of range hoods in existing, non-high performance California homes, despite the low airflows and poor hood design expected in existing homes (Singer et al., In-Preparation). A standard for capture efficiency of kitchen range hoods is currently under development, which may provide a feedback loop by which manufacturers can produce more effective products.

Less & Walker (2013) compared actual fan flow rates in DERs (including the 12 in this study) to requirements found in ASHRAE 62.2-2013: 50% of kitchen fans failed and 46% of bathroom exhaust fans failed. Failures occurred for two primary reasons: (1) duct airflow restrictions and (2) system design flaws, namely the inability of continuously operated ERV/HRV exhausts inlets to provide kitchen and bathroom ventilation at acceptable rates. An evaluation of ventilation airflows in 15 CA homes similarly found that while almost all homes met whole-house ventilation requirements, 52% of bathroom fans failed ASHRAE 62.2 criteria (Stratton et al., 2012). In contrast, installed airflows in 14 of 15 vented range hoods in California residences met 62.2-2013 airflow requirements on high-speed, but six cases failed on low-speed (Singer et al., 2012). These results, combined with the faults detected in continuous mechanical ventilation systems, highlight the importance of appropriate system design and commissioning prior to occupancy, particularly in very airtight homes.

Air Pollutant and Air Exchange Rate Measurements

Figure 1 shows the pollutant concentrations sampled in each study home, and Table 3 summarizes this data. Median values across the sample were below relevant health guidelines for all pollutants, with the exception of formaldehyde.

Table 3 6-day median levels of pollutants and environmental parameters measured in energy efficient residences

Pollutant	Bedroom	Kitchen	Outside	Number of homes sampled
NO_2 (ppb)	9.2	8.7	7.6	24
NO (ppb)	9.1	8.7	4.8	24
NO_x (ppb)	18.7	23.5	12.7	24
Formaldehyde (μg/m^3)	17.5	20.1	4.0	24
Acetaldehyde (μg/m^3)	16.2	16.1	2.0	24
$PN_{>0.5}$ (#/m^3)	NA	4,114,000	NA	23
$PN_{>2.5}$ (#/m^3)	NA	253,000	NA	21
Temperature (°C)	20.8	20.8	11.6	24
Humidity (%)	47.4	47.2	70.9	24
AER (hr^{-1})	0.304	NA	NA	16

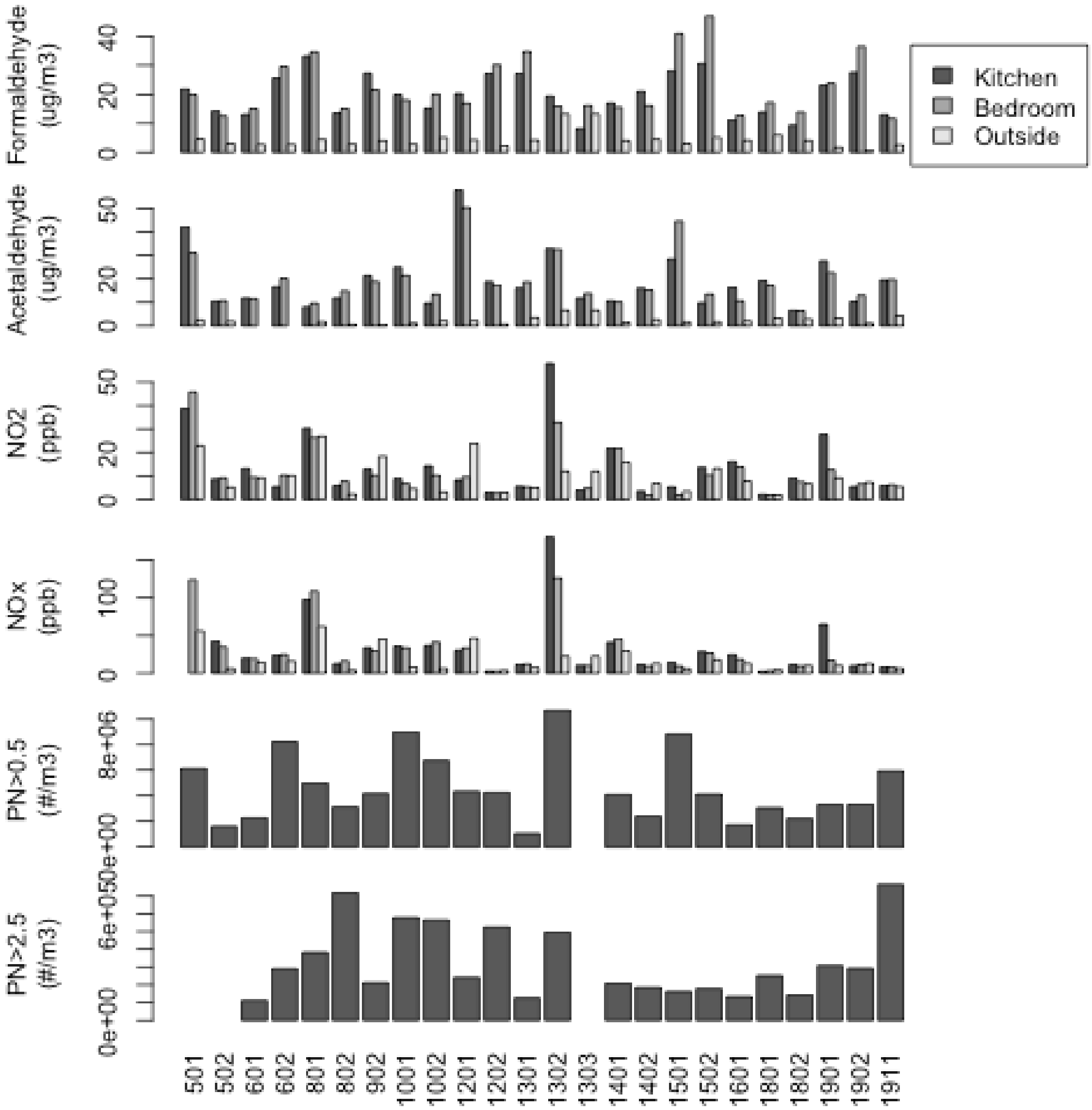

Figure 1 Six-day pollutant concentrations in high performance green homes

Air Exchange Rates. Six-day average AERs in mechanically and naturally ventilated homes were statistically indistinguishable (medians of 0.30 and 0.32 hr^{-1}, n=8 and n=8, respectively), indicating that the mechanical ventilation systems in the more airtight homes acted to provide roughly the same average ventilation rate as infiltration did in the looser homes. Yet, ventilation rates were more consistent in mechanically vented homes, as characterized by the smaller range of AER values. The use of mechanical ventilation in these airtight homes meant that fewer of them were either over- or under-ventilated, with resulting impacts of energy use and pollutant concentrations. In isolation, neither airtightness nor the presence of mechanical ventilation significantly predicted AERs, which likely due to the relationship between airtightness and installation of mechanical ventilation noted above. Furthermore, measurements were short-term, not weather normalized and included window operation in some homes. The median AER in these homes was between the median of 0.26 hr^{-1} reported for 106 new CA homes in Offermann (2009) and the average winter AER in 105 existing CA homes of 0.61 hr^{-1} (Yamamoto et al., 2010).

Aldehydes. Six-day formaldehyde concentrations (see Table 4) exceeded the California EPA Chronic Reference Exposure Level (REL) of 9 μg/m^3 (OEHHA, 2008) in 23 of 24 homes, yet levels in study homes were substantially lower than the 36 μg/m^3 reported in 106 new California homes by Offermann (2009). Furthermore, not a single study home exceeded the CA Acute REL of 55 μg/m^3, whereas 28% of new California homes measured in the winter by Offermann exceeded this threshold. Formaldehyde levels in study homes did not vary reliably with AER, presence of mechanical ventilation, presence of new materials, or cooking fuel. Distributions were indistinguishable between deep retrofit and new homes. Formaldehyde levels in high performance Californian homes were similar to those measured in existing residences (Avol et al., 1996; Mullen et al., 2012).

Table 4 Six-day formaldehyde concentrations (μg/m^3) measured in high performance green homes

Location	Min	25th	Median	Mean	75th	Max	n
Bedroom	11.7	15.5	17.5	22.3	29.7	47.0	24
Kitchen	8.1	13.8	20.1	20.0	27.2	33.2	24
Outside	0.5	2.8	4.0	4.4	4.5	13.2	24

Six-day acetaldehyde concentrations (see Table 5) in all homes exceeded the California Proposition 65 No Significant Risk Level for carcinogens of 4.5 μg/m^3, but all study homes were well beneath the California Chronic REL of 140 μg/m^3. The maximum value in any study home was 59% below the chronic standard. Acetaldehyde concentrations were somewhat higher in new homes (18 versus 15 μg/m^3). Levels of acetaldehyde in study homes were similar to those measured in existing California homes by Mullen et al. (2012) (16.2 μg/m^3), both of which were somewhat lower than the new homes measured by Offermann (2009) (20 μg/m^3).

Table 5 Six-day acetaldehyde concentrations (μg/m^3) measured in high performance green homes

Location	Min	25th	Median	Mean	75th	Max	n
Bedroom	6.3	12.6	16.2	19.0	20.4	50.3	24
Kitchen	6.4	10.5	16.1	19.1	22.2	58.0	24
Outside	bd[1]	1.1	2.0	2.2	3.0	6.5	24

[1] "bd" stands for below-detection.

A number of factors likely contributed to low formaldehyde levels in these high performance homes: (1) deliberate selection of low-emitting building materials, (2) presence of some existing materials in retrofitted homes, and (3) new California limits on formaldehyde emissions from engineered wood products. Twenty-two of 24 homes reported using low-emitting and healthy building materials, and 10 homes explicitly received credit for this through green home certification. Eleven LEED certified New Mexico homes using low-formaldehyde emitting materials were similarly found to have formaldehyde concentrations 42% lower than those measured by Offermann (2009) (Hult et al., Submitted). Furthermore, while the 12 retrofitted study homes were gut-rehab projects with new materials and finishes throughout, they likely still contained some existing materials whose formaldehyde had already been emitted. Finally, materials used in both the new and existing homes built after 2009 may[1] have been subject to the California Formaldehyde Air Toxic Control Measure (ATCM), which placed strict limits of formaldehyde emissions from engineered wood products (Office of Administrative Law, n.d.). In 2010, the U.S. congress ordered the U.S. EPA to implement national formaldehyde emission standards that mimic the existing CA standards. Though this regulation is not yet in place, it will reduce formaldehyde exposure in all conventional and high performance future homes.

Nitrogen Oxides. Median kitchen concentrations of NO_2, NO, and NO_x (see Table 6) were higher in the 15 homes using gas-cooking appliances (13.1, 13.8, and 29.9 ppb, respectively), compared to the nine with electric appliances (5.4, 7.4, and 10.9 ppb, respectively). Consistent with this, simulation and field studies in California have demonstrated the dominant role played by unvented gas cooking on chronic and acute exposures to nitrogen oxides and other combustion pollutants in residences (Logue et al., 2014; Mullen et al., 2012). Notably, Mullen et al. (2012) did not find that vented combustion appliances (e.g., gas furnace or water heater) contributed significantly to indoor pollutant levels. Outdoor NO_2, NO, and NO_x levels at electric cooking study homes were approximately 50-100% higher than those occurring outside of gas cooking homes. Note that indoor NO_2 concentrations are expected to be less than outdoor concentrations, if no indoor sources are present, due to deposition losses. Yet, median ratios of indoor-to-outdoor concentrations of NO_2 were much higher in gas cooking homes (1.7 versus 0.7), which suggests that there are substantial uncontrolled indoor sources. Nevertheless, indoor concentrations remained below health-relevant guidelines in most gas and electric cooking homes.

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[1] The Air Resources Board delayed implementation of the formaldehyde ATCM, so we cannot be sure if materials were compliant.

Table 6 Six-day average concentrations of nitrogen oxides (ppb) in high performance green homes

Fuel[1]	Loc[2]	Min	25th	Median	Mean	75th	Max	n
NO_2								
E	B	1.9	2.7	6.2	6.5	10.2	10.4	9
E	K	2.2	3.6	5.4	6.6	8.3	13.6	9
G	B	1.9	7.2	9.4	14.5	17.8	45.7	15
G	K	5.3	7.3	13.1	17.9	24.7	57.9	15
E	O	1.9	5.5	10.1	10.5	13.2	23.8	9
G	O	2.3	4.8	7.3	9.4	10.6	26.9	15
NO								
E	B	0.8	1.3	7.1	9.9	15.9	23.8	9
E	K	bd	2.1	7.4	10.2	18.0	22.1	8
G	B	1.8	5.4	9.8	27.2	28.8	93.6	15
G	K	1.9	6.7	13.8	26.5	31.8	122.8	14
E	O	0.7	2.4	6.0	8.9	10.5	26.6	9
G	O	0.9	2.2	3.3	8.3	7.9	35.2	15
NO_x								
E	B	2.7	7.6	10.0	16.3	26.4	33.4	9
E	K	2.3	8.1	10.9	16.7	28.8	33.8	9
G	B	9.2	14.1	19.2	41.7	43.2	126.3	15
G	K	9.7	12.9	29.9	42.9	41.7	180.7	14
E	O	3.6	6.2	16.0	19.4	22.5	46.2	9
G	O	3.9	6.8	10.1	17.8	18.5	62.0	15

[1] Fuel is designated by an "E" for electric cooktop or a "G" for a gas cooktop.

[2] Location is designated by a "K" for kitchen, "B" for bedroom or "O" for outside.

A few high performance green homes had indoor NO_2 levels that exceed health-relevant standards. Kitchens in three homes exceeded the California EPA annual ambient air quality standard of 30 ppb for nitrogen dioxide (Office of Administrative Law, 2008, sec. 70200) [2], and a fourth was just barely below the standard (28 ppb). One of these homes also exceeded the U.S. EPA annual ambient standard of 53 ppb (U.S. EPA, 2012). A fifth home had a high indoor-outdoor ratio, while having indoor levels below the standards. Each of these five cases of high concentrations or high indoor-outdoor ratios included one or more of the following: (1) historic gas ranges with pilot lights, (2) Passive House-style kitchen ventilation, with a recirculating range hood and low level continuous kitchen exhaust via either an ERV or HRV, and (3) high outdoor NO_2 levels, due to ambient pollution. With the exception of the high outdoor NO_2 levels, the other issues can be easily fixed in high performance homes by not using historic gas ranges with pilot lights, and by installation (with use by occupants) of appropriate kitchen range hoods exhausted to outside, even in very airtight homes (as one gas cooking Passive House successfully did so, using an automated make-up air system to provide pressure relief).

Despite these issues, NO_2 levels in high performance green homes were lower than those found in previous large surveys in existing homes, which reported mean and median indoor levels of 25 to 28 ppb, and much higher outdoor levels, averaging between 20 and 35 ppb (Lee et al., 2002; Spengler et al., 1994).

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[2] Annual standards cannot be directly compared with six-day measurement averages, but they provide the best available benchmark for acceptability of non-acute measurement periods.

Particle Number Counts. Compared to 7 homes without any filtration, the 16 homes with enhanced filtration (MERV 7 to MERV 14) had particle count levels that were 48% and 57% lower in the $PN_{>05}$ and $PN_{>2.5}$ size bins (see average particle count concentrations for all homes in Table 7). The differences in average weekly outdoor $PM_{2.5}$ concentrations were small in filtered and unfiltered homes (5.5 and 6.0 μg/m^3, respectively). Nine homes filtered air using a central forced air system, and eight filtered the ventilation supply air. From first principles, we can assume that recirculating filtration will be more effective than ventilation supply filtration, because it removes particles of both indoor and outdoor origin. This assumes that the recirculating system operates continuously or on a daily schedule. While not significant (due to small sample sizes), we saw this expected difference when comparing recirculating and ventilation supply filtration homes. Filtration on the supply may perform similarly to filtration in recirculating systems, if indoor particle sources are well managed (e.g., by use of vented kitchen range hood). Homes that failed to provide active filtration generally used radiant or point-source gas or gas heating, in lieu of a central forced air system, and they did not have filtered ventilation systems. Our findings are consistent with field measurements and simulation efforts that have shown filtration to provide health benefits through lower indoor particle concentrations (Burroughs and Kinzer, 1998; MacIntosh et al., 2009). Due to their dominance of the health effects of chronic pollutant exposure in homes (Logue et al., 2010), controlling particle levels should be a primary goal of any high performance green home. Further research is needed to determine exactly what systems, filter types, and airflows are required to achieve the most cost-efficient results.

Table 7 Six-day average particle number concentrations (PN/m^3) in high performance green home kitchens

	Min	25th	Median	Mean	75th	Max	n
$PN_{>0.5}$	1.04E+06	2.72E+06	4.11E+06	4.58E+06	6.01E+06	1.07E+07	23
$PN_{>2.5}$	1.12E+05	1.78E+05	2.53E+05	3.27E+05	4.95E+05	7.65E+05	21

Stovetop Ultrafine Particle Testing. During each site visit, a short stovetop water boiling test was conducted, with an ultrafine particle (<0.1 micron) sensor positioned on the counter top nearby. The maximum one-minute UFP concentration was determined for each test. The median of these maximum values was dramatically lower in kitchens with electric induction cooktops (5,430 #/cm^3; n=5), compared with either gas or electric resistance burners (181,265 and 231,583 #/cm^3; n=13 and 4, respectively). We recommend additional research be performed on emissions from induction burners to assess whether these results are robust.

SUMMARY

This study provides evidence that acceptable IAQ is achievable in high performance green homes, and the key to success is consideration of best practices in both design and operations. Mechanically ventilated homes were much more airtight than their naturally ventilated peers, yet they provided equivalent levels of air exchange, despite some noted performance faults. Nearly all homes reported using low-emitting building materials, and their indoor aldehyde levels were approximately 50% lower than in new CA homes built before 2008. Similarly, particle number concentrations in those homes providing enhanced particle filtration were approximately half those in the unfiltered homes. IAQ issues appeared when either design or operations were not good. For example, some homes had levels of nitrogen oxides exceeding outdoor standards, resulting from either gas ranges with pilot lights, or a lack of a vented range hood (or failure to use range hood during burner operation). The majority of mechanical ventilation systems were complex and were found or reported to have numerous design, installation and operational faults, which are a particular liability in very airtight homes. Yet, air exchange rates and pollutant levels were indistinguishable in vented and unvented homes, suggesting that the mechanical systems still performed adequately, relative to the leakier, unvented homes. High performance green homes should strive to include all IAQ best practices—source control, local exhaust, continuous ventilation, filtration, commissioning and occupant education—and this research supports the premise that failure to do so may compromise some element of IAQ.

The net-effect on IAQ of the measures undertaken in a high performance new or existing home depends on outdoor air quality, indoor emissions, occupant behavior, ventilation equipment design and usage, as well as natural and mechanical air exchange. Due to their increased risk resulting from airtightness, high performance homes should be designed at a minimum to comply with ASHRAE 62.2-2013. Special emphasis should be placed on source control, properly designed kitchen exhaust, and particle filtration. Continuous mechanical ventilation is also very important, particularly in projects targeting aggressive airtightness goals. Future research efforts would benefit from a control group of current, conventional homes, as well as a larger sample of high performance green homes with more consistent features.

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