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DISCLAIMER

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ABSTRACT

Because airtightening is a significant part of Deep Energy Retrofits (DERs), concerns about ventilation and Indoor Air Quality (IAQ) have emerged. To investigate this, ventilation and IAQ were assessed in 17 non-smoking California Deep Energy Retrofit homes. Inspections and surveys were used to assess household activities and ventilation systems. Pollutant sampling performed in 12 homes included six-day passive samples of nitrogen dioxide (NO_2), formaldehyde and air exchange rate (AER); time-resolved data loggers were used to measure particle counts. Half of the homes provided continuous mechanical ventilation. Despite these homes being twice as airtight (3.0 and 7.6 ACH_{50}, respectively), their median AER was indistinguishable from naturally vented homes (0.36 versus 0.37 hr^{-1}). Numerous problems were found with ventilation systems; however, pollutant levels did not reach levels of concern in most homes. Ambient NO_2 standards were exceeded in some gas cooking homes that used legacy ranges with standing pilots, and in Passive House-style homes without range hoods exhausted to outside. Cooking exhaust systems were installed and used inconsistently. The majority of homes reported using low-emitting materials, and formaldehyde levels were approximately half those in conventional new CA homes (19.7 versus 36 $\mu g/m^3$), with emissions rates nearly 40% less (12.3 versus 20.6 $\mu g/m^2/hr.$). Presence of air filtration systems led to lower indoor particle number concentrations ($PN_{>0.5}$: 8.80E+06 PN/m^3 versus 2.99E+06; $PN_{>2.5}$: 5.46E+0.5 PN/m^3 versus 2.59E+05). The results indicate that DERs can provide adequate ventilation and IAQ, and that DERs should prioritize source control, particle filtration and well-designed local exhaust systems, while still providing adequate continuous ventilation.

INTRODUCTION

As home energy upgrades are deployed on a national scale, there are some concerns about the potential health pitfalls of retrofits (Manuel, 2011), while others suggest they can improve occupant health, especially in distressed housing (Kuholski, Morley, & Tohn, 2010). The most aggressive energy reduction efforts in existing homes are termed Deep Energy Retrofits, which are aimed at energy reductions above and beyond those achieved in the traditional retrofit programs, typically targeting 70% or more energy reductions. For DERs, occupant comfort, health and safety must be addressed and are often part of the stated purpose of the retrofit. DERs are uniquely situated to both resolve and create IEQ issues. They have the potential to cause degradations in IEQ, because they: (1) introduce new construction materials and finishes, (2) pursue aggressive air tightness goals and changes in ventilation rates, (3) may either fail to install mechanical ventilation or use unreliable systems, and (4) may increase exposure to existing household hazards. Because DERs address potential IAQ issues such as air and moisture leakage, replacement of interior finishes and appliances and upgrading of HVAC systems, the indoor environment and occupant health can be substantially improved. This study examined the IAQ in 17 DERs and compared the measured results to appropriate standards. The performance of completed DERs will be presented, rather than the changes in home performance, because of lack of access to pre-retrofit homes.

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. Less (2012) provides a thorough summary of past research in energy efficient and conventional homes in the U.S. and Canada. Despite mixed findings, a general consensus in the literature is that energy efficiency and IAQ are compatible, if proper precautions are employed. More recently, energy conservation has been argued to improve IAQ by eliminating exposures. In fact, envelope and duct airtightness and 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, both the Healthy Homes approach to improving degraded housing (Kuholski et al., 2010), and the home performance industry have argued that IEQ improvements are a key aspect of energy conservation projects. This view has been formally recognized in recently published U.S. DOE and U.S. EPA retrofit guideline documents—*Workforce Guidelines for Home Energy Upgrades* and *Healthy Indoor Environment Protocols for Home Energy Upgrades*. Yet, doubt and concern still exists, with concerns centering around failure of IAQ protections in building codes, total reliance on potentially unreliable mechanical ventilation systems in airtight homes, lack of quality assurance and control for ventilation systems, and lack of occupant education (Crump, Dengel, & Swainson, 2009).

Research assessing the IAQ impacts of today's energy retrofits is sparse. Radon measurements in 50 Maine homes before and after weatherization showed that 18% of the homes changed from below to above the U.S. EPA Radon threshold of 4 pCi/L. Presence of dirt floor basements and open sump pumps were statistically significant risk factors for the increases, but the change in building airtightness was not a statistically significant factor (Tohn, 2012). No significant changes in pollutant concentrations were reported for 248 Boston multifamily units that were energy retrofitted, and significant improvements were reported in occupants' general health, sinusitis, hypertension and reduced used of asthma medication, while several respiratory symptoms were reported more frequently, and the number of days reported with trouble sleeping increased due to asthma problems (National Center for Healthy Housing, 2012). A CONTAM simulation effort assessed the IAQ impacts of Healthy Homes interventions, and found that airtightening the building envelope by 40% was the worst intervention in terms of occupant pollutant exposure, with the exception of some particle sizes. In many cases, compensatory measures, such as continuous ventilation, local exhaust and filtration, did not sufficiently offset increases in exposure (Emmerich et al., 2005). DERs can be considered at even higher risk than typical retrofits, due to more extreme airtightening efforts and new construction materials, and this study is the first IEQ evaluation in DERs.

METHODS

In an effort to address these issues, ventilation and post-retrofit IAQ have been assessed in 17 non-smoking, California DER homes, using a combination of occupant surveys, home inspections, ventilation system commissioning and air pollutant sampling. Projects included in this paper participated in one of two LBNL research studies (Less, Fisher, & Walker, 2012; Less, 2012), the latter of which was part of a larger, ongoing effort at LBNL called the *Healthy Homes* study of IAQ in California homes with gas appliances. Both were samples of convenience, including locally available DER projects. Assessments were restricted to the post-retrofit period, due to project completion by the owners prior to recruitment. All 17 homes were visited and inspected, including diagnostic tests of airtightness and ventilation, when feasible. Only 12 homes included occupant surveys, pollutant sampling and tracer gas testing (two tracer gas tests were found to be invalid, due to contamination of outdoor samplers, these were removed from analysis). IAQ measurements were performed in these 12 homes between January and April of 2012. This paper will focus on the results for six-day passive samples of nitrogen dioxide (accuracy ±6.3%), formaldehyde (±5.2%), and air exchange rate (±10.7%); time-resolved data loggers were used to measure particle counts (no published accuracy data). Pollutant samples were taken in kitchen, bedroom and outdoor locations. A full description of protocols is provided in Less (2012).

RESULTS AND DISCUSSION

House Characteristics, Systems and Airtightness

General. All the DER homes were located in Northern California, within a 100-mile (160 km) radius of Berkeley, CA. Of the 12 homes where pollutants were sampled by Less (2012), the median age was 2.5 years (since renovation). The remaining five DERs were all remodeled in 2006 or more recently. Due to the extent of the renovations, new building materials and finishes, these projects are considered comparable to new construction. The average floor area and volume for all 17 homes was 2,095 ft^2 (194.6 m^2) and 19,123 ft^3 (541.5 m^3). The average occupancy rate was 2.8 persons per home.

Energy Use. Less et al. (2012) reported average net-site energy, net-source energy and carbon emissions reductions relative to an average CA single-family home of 52%, 49% and 52%, respectively. Actual, weather-normalized reductions in the five projects with pre-retrofit data were 58%, 43% and 54%, respectively. Less (2012) did not report energy data.

Airtightness. Airtightness varied substantially across the 17 homes. Projects varied from 0.43 to 10.8 air changes per hour at -50 Pa (ACH_{50}), with a mean of 5.0 ACH_{50} (median=5.5). Homes that used the Passive House standard to guide retrofit planning were the tightest, with ACH_{50} values ranging from 0.43 to 2.4, averaging 1.0. Other DER homes had substantially higher values, averaging 6.9 ACH_{50}.

The airtightness performance of these DERs was similar to that reported in the DER literature (Affordable Comfort, Inc., 2010; BA-PIRC, 2012; "Building Science Information," n.d.; Chandra, Widder, & Jackson, 2011; Christian, Gehl, Boudreaux, & Munk, 2011; Janet McIlvaine, 2010; Keesee, 2012; McIlvaine, Sutherland, Schleith, & Chandra, 2010; Neuhauser, 2012; Osser, Neuhauser, & Ueno, 2012; PNNL, 2012). Air leakage reductions for 24 homes in the literature averaged 72% (±19.4%), compared with 36% in this research (n=2). Average pre-retrofit airtightness was 19.8 ± 13.3 ACH_{50} (n=23) and post-retrofit averaged 4.5 ± 2.9 ACH_{50} (n=43). For comparison, standard airtightness retrofits in the U.S. for non-WAP (n=9,999) and WAP projects (n=13,093) achieved average reductions in ACH_{50} of 20% and 30%, respectively (Chan & Sherman, 2013). DERs have roughly doubled and tripled these average reductions. 13 of 17 project homes met the 2009 IECC requirement (7 ACH_{50}), and six project homes met the 2012 IECC requirement (3 ACH_{50}). These results show that tight post-retrofit homes and large air leakage reductions are being achieved in DER homes. This substantiates the concern that air exchange rates will be sharply reduced, unless mechanical ventilation is provided.

Ventilation System Descriptions and Assessments

Continuous Mechanical Ventilation. Whole house mechanical ventilation systems were installed in nine of seventeen projects (53%). In the DER literature (see above), 34 of 44 projects provided mechanical ventilation (77%). Excluding Cold climate DERs, installation rates were similar to those observed in the current study (seven of sixteen, 44%). The mechanically ventilated homes in this study had tighter envelopes, averaging 3.0 ACH_{50} compared to 7.6 ACH_{50} for homes without mechanical ventilation. These are similar to levels in the literature of 3.0 and 6.0 ACH_{50}, respectively. Of the nine systems in this study, only one was a simple exhaust fan, while the other eight could be characterized as "complex" systems—Energy Recovery Ventilator (ERV) (n=3), Heat Recovery Ventilator (HRV) (n=3) and Central Fan Integrated Supply (CFIS) (n=2) (one of which used integrated, passive ERVs). Ventilation systems in the literature suggest a similar preference for "complex" systems—ERV (n=4), HRV (n=15), CFIS (n=7), combined ERV/CFIS (n=3) and HRV/CFIS (n=1) systems, with only one simple exhaust and two simple supply systems. "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 these systems, as detailed below. CFIS, HRV, ERV and non-ventilation forced air systems all provided particle filtration (mix of MERV 7, 8, 12 and 14) and air distribution.

A number of performance issues were found or reported 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) due to occupant interaction of CFIS. Less (2012) noted similar system faults in the non-DER homes that were studied. Such faults have been commonly reported, 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, system design should be improved, and commissioning and verification are required, as well as occupant education on ventilation system operation.

Continuous mechanical ventilation and local ventilation consistent with ASHRAE 62.2-2007 are required in new California homes by the building code, but this does not extend to DERs, unless they add more than 1,000 ft^2 (93 m^2) of floor area. This places all responsibility for ventilation provision on DER designers or contractors. Organizations, including BPI, RESNET and the Weatherization Assistance Program, have begun to include mechanical ventilation provisions in their standards and protocols (referring to ASHRAE 62.2) so these issues may be reduced in the future.

Kitchen and Bathroom Ventilation. While continuous mechanical ventilation was not consistently provided in all DERs, projects did reliably install other exhaust fans in the kitchen and bathrooms. ASHRAE 62.2-2013 airflow requirements for bathrooms (*demand-controlled*: 50 ft^3/min (23.6 l/s); *continuous*: 20 ft^3/min (9.4 l/s)) and kitchens (*demand-controlled*: vented range hood (100 ft^3/min (47.2 l/s)) required if exhaust fan flow rate is less than 5 kitchen air changes per hour; or *continuous*: 5 kitchen air changes per hour) were used to assess installed equipment performance. 12 kitchen systems were assessed, and half failed to meet the criteria. 26 bathroom fans were assessed, with a failure rate of 46% (12 of 26). 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 CA homes similarly found that almost all homes met whole-house ventilation requirements, however 52% of the 44 bathroom fans measured failed ASHRAE 62.2 criteria (Stratton, Walker, & Wray, 2012). These results highlight the importance of appropriate system design and commissioning prior to occupancy.

Air Pollutant and Air Exchange Rate Measurements

Air Exchange Rates. Six-day average AERs are summarized by ventilation system type in Table 1. AERs in mechanically and naturally ventilated homes were statistically indistinguishable. Neither airtightness nor the presence of mechanical ventilation significantly predicted AERs. This is not unexpected, because measurements were short-term, not weather normalized and included window operation in some homes. Unfortunately, one mechanically vented home still had a very low AER (0.17 hr^{-1}). This project used a CFIS system whose operation could not be confirmed, and it was the most airtight of non-Passive House inspired projects (2.4 ACH_{50}). The median AER in these DERs 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, Shendell, Winer, & Zhang, 2010).

Table 1 Six-Day Average Air Exchange Rates (ACH) in DER As Measured by Passive Tracer Gas Test, by Ventilation System Type

Ventilation Type	Min	25^{th}	Median	Mean	75^{th}	Max	N
Mechanical	0.17	0.29	0.36	0.36	0.42	0.54	4
Natural	0.15	0.26	0.37	0.41	0.54	0.75	6
All	0.15	0.26	0.37	0.38	0.50	0.75	10

Formaldehyde. Six-day formaldehyde concentrations are summarized by location in Table 2. Only one home had an indoor formaldehyde concentration below the California EPA Chronic Reference Exposure Level (REL) of 9 $\mu g/m^3$, but all homes were below the OEHHA Acute REL of 55 $\mu g/m^3$ (OEHHA, 2008). Median formaldehyde levels in DER homes were substantially lower than the 36 $\mu g/m^3$ reported in new CA homes by Offermann (2009).

Low emitting materials in DERs appear to have played a key role in maintaining indoor formaldehyde levels below those in conventional new homes. Use of low-emitting and healthy building materials were reported in 11 of 12 homes where pollutant sampling occurred. Median floor area normalized emission rates (the product of the indoor minus the outdoor formaldehyde concentrations, the AER, and the house volume, divided by the floor area.) in these DERs were 12.8 and 11.8 $\mu g/m^2$/hr. in bedrooms and kitchens, respectively, which are approximately 40% lower than median values in conventional new homes calculated using the Offermann (2009) winter dataset (20.6 $\mu g/m^2/hr.$, n=61) and reported by Sherman & Hodgson (2004) (45.2 $\mu g/m^2/hr.$, n=14). Similar rates were found in the non-DER new homes studied by Less (12.0 and 12.5 $\mu g/m^2/hr.$ in bedrooms and kitchens). In addition to low-emitting material specification, low emissions could have also resulted from either the aging of existing materials not replaced during the renovation, or the California Air Resources Board (CARB) restrictions on emissions rates from common building materials, which were phased-in beginning in 2009 (due to extensions issued by CARB, it is not clear how many materials have met these standards in practice). Such regulation can remove the burden of low-emitting material selection from the project team/homeowner.

No relationship was found between AERs and DER formaldehyde concentrations. But formaldehyde levels were, somewhat inexplicably, higher in mechanically vented homes (median 27.0 versus 17.0 $\mu g/m^3$), which were much more airtight, but had similar AER as naturally vented homes.

Table 2 Summaries of Six-Day Formaldehyde Concentrations ($\mu g/m^3$) in DER Homes, by Location

Location	Min	25th	Median	Mean	75th	Max	N
Bedroom	12.5	16.0	19.0	23.7	31.3	47.0	12
Kitchen	8.1	14.9	20.4	21.0	27.2	33.2	12
Outside	1.6	2.8	4.3	5.2	5.1	13.2	11

Nitrogen Dioxide. Six-day nitrogen dioxide concentrations are summarized by cooktop fuel type and location in Table 3. Median kitchen concentrations were higher in those homes using gas-cooking appliances (13.7 ppb), compared to those with electric appliances (3.7 ppb). Outdoor levels at gas cooking homes were lower on average (7.1 vs. 9.5 ppb). Note that indoor NO_2 concentrations are expected to be less than outdoor concentrations, if no indoor sources are present, due to deposition losses. NO_2 levels in DER 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 outdoor levels averaging between 20 and 35 ppb (Lee et al., 2002; Spengler et al., 1994). The lower levels sampled in DER homes are most likely due to a combination of lower outdoor concentrations, reduced air exchange rates (in those homes with higher outdoor than indoor concentrations), no smoking, newer gas cooking appliances with lower pollutant emission rates, enhanced kitchen ventilation, and use of sealed combustion space and water heating appliances.

Yet, NO_2 gas-cooking emissions were not always sufficiently controlled in DERs homes. Two homes exceeded the California EPA annual reference level of 30 ppb for nitrogen dioxide, and a third was just below the threshold (28 ppb) (Office of Administrative Law, 2008, sec. 70200), and one of these homes also exceeded the U.S. EPA annual reference level of 53 ppb (U.S. EPA, 2012). Indoor/outdoor ratios (I/O) were calculated to assess the impact of outdoor NO_2 levels in these homes, with higher ratios suggesting substantial indoor sources. Two of the homes with high indoor concentrations also had high I/O ratios, as did a third home whose indoor levels were below outdoor standards. One of the homes that exceeded outdoor standards had a relatively low I/O ratio, implicating high outdoor NO_2, rather than indoor sources. All four homes with either high I/O ratios or indoor levels above outdoor standards used gas cooktops. These homes either: (1) used historic gas ranges with pilot lights, (2) used Passive House style kitchen ventilation, with a recirculating range hood and low level continuous kitchen exhaust via either an ERV or HRV, or (3) had high outdoor NO_2 levels, due to ambient pollution. This is consistent with past research, which demonstrated elevated NO_2 levels in gas-cooking homes; emissions from historic gas ranges with pilots contributed 10 ppb to average indoor NO_2 concentrations, while gas ranges without pilots contributed 4 ppb on average (Spengler et al., 1994). Less (2012) noted the tendency for gas cooking Passive House type homes to have elevated NO_2 concentrations and I/O ratios compared to other gas cooking homes due to inadequate kitchen ventilation.

Table 3 Summaries of Six-Day Nitrogen Dioxide Concentrations (ppb) in DER Homes, by Location and Cooktop Fuel

Fuel	Location	Min	25th	Median	Mean	75th	Max	N
Gas	Bedroom	5.3	8.5	9.8	14.1	16.1	32.8	8
Electric	Bedroom	2.0	2.6	3.8	5.0	6.2	10.4	4
Gas	Kitchen	5.6	8.7	13.7	20.8	28.3	57.9	8
Electric	Kitchen	3.0	3.4	3.7	6.0	6.4	13.6	4
Gas	Outside	3.1	4.9	7.1	9.3	9.8	26.9	8
Electric	Outside	2.9	6.0	9.5	8.8	12.3	13.2	4

Particle Number Counts. Time resolved one-minute particle number concentrations were measured in DER kitchens (See Table 4). Counts were made in two size bins—>0.5 micron and >2.5 micron ($PN_{>0.5}$ and $PN_{>2.5}$)—with units PN/m^3. Outdoor particle number concentrations were not measured, so particulate mass-based data were retrieved from monitoring stations nearest to the project homes. Average particle number concentrations in both size bins were lower in in homes with some sort of deliberate air filtration (n=8) versus unfiltered (n=3) homes ($PN_{>05}$: 2.99E+06 PN/m^3 versus 8.80E+06; $PN_{>2.5}$: 2.59E+05 PN/m^3 versus 5.46E+05), while outdoor $PM_{2.5}$ averages were 7.0 and 6.4 $\mu g/m^3$, respectively. Field measurements and simulation efforts have shown that particle filtration may provide health benefits and can lower indoor particle concentrations, with efficacy varying with filter efficiency, airflow rate through the filter and occupant activity levels (Burroughs & Kinzer, 1998; MacIntosh et al., 2009).

Table 4 Summary of Average Kitchen Particle Number Concentrations (PN/m^3) in DER Homes, by Particle Size

Particle Size	Min	25th	Median	Mean	75th	Max	N
$PN_{>0.5}$	1.04E+6	2.31E+6	4.11E+6	4.57E+6	5.86E+6	1.07E+7	11
$PN_{>2.5}$	1.12E+5	1.80E+5	3.45E+5	3.45E+5	5.16E+5	5.78E+5	10

SUMMARY

Neither airtightness, nor the presence of continuous mechanical ventilation, nor whole house AERs had large impacts on indoor conditions in this sample of DER homes. Rather, the more important elements were provision and usage of local exhaust in kitchens, provision of particle filtration, and source control by limiting formaldehyde-emitting products or removing gas-cooking appliances with standing pilots. The tighter mechanically ventilated homes had similar AERs to the looser, non-mechanically ventilated homes. Unfortunately, the major drawback to this research study was the lack of pre-retrofit measurements, which makes it impossible to report *changes* in indoor air and environmental quality—both positive and negative. However the final post-retrofit performance is probably of greater interest to occupants than the magnitude of changes, i.e., DERs need to meet IEQ standards upon completion, rather than to merely improve performance.

Best practice in residential ventilation has been established for quite some time—source control, local exhaust, continuous ventilation and filtration. Nearly all DERs in this research pursued source control (leading to low formaldehyde levels) and local exhaust in bathrooms, though just less than 50% of bathroom fans failed to meet current ASHRAE criteria, highlighting the importance of commissioning all ventilation equipment. DERs inconsistently implemented kitchen exhaust, continuous ventilation and filtration. Continuous ventilation and filtration were simply missing in a number of projects, contributing to elevated particle levels. While kitchen ventilation was consistently installed, system design, hood design and usage left room for improvement, and some homes exceed outdoor NO_2 standards as a result. All DERs should strive to include all four of these best practices components in the project. Occupant education on the importance of range hood usage and ventilation system maintenance should also be prioritized. This will help avoid the worsening of indoor environmental conditions commonly predicted from new construction materials and increased airtightness in DERs.

It was beyond the scope of this study to determine the health effects of DERs. The health impacts of chronic exposure to indoor air pollutants vary based on the specific pollutant, and acute exposures further complicate the issue. Logue et al. (2012) estimate that $PM_{2.5}$, formaldehyde and NO_2 are amongst the eight air pollutants responsible for the most costly health impacts related to household chronic exposures, and the impacts of $PM_{2.5}$ are estimated to be approximately one and two orders of magnitude greater than those of formaldehyde and NO_2, respectively. This suggests that reductions in $PM_{2.5}$ due to airtightening may be undervalued, and those DER designers seeking lower AERs and tighter envelopes may be providing a net-health benefit to occupants, rather than net-harm.

It is clear that DERs can lead to decreases in some pollutant levels, while potentially increasing others. The net-effect depends on outdoor air quality, indoor emissions, ventilation equipment design and usage, as well as natural and mechanical air exchange. Designers can and should try to plan DERs with these elements in mind, selecting the best path forward based on the circumstances, cognizant of the estimated relative health impacts of indoor pollutants. DERs should be designed with careful attention to best practices and, at a minimum, compliance 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 DERs targeting airtightness levels similar to new homes.

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