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Occupant-in-Place Energy Efficiency Retrofit in a Group Home for 30% Energy Savings in Climate Zone 4

Mike Moore
Building America Partnership for Improved Residential Construction

August 2013

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Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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Definitions

ASHP	Air source heat pump
CFM	Cubic feet per minute
CDH	Cooling degree hour, base 74
DHW	Domestic hot water
ECM	Energy conservation measure
EER	Energy efficiency retrofit
EF	Energy factor
ELA	Equivalent leakage area
HDD	Heating degree day, base 65
HSPF	Heating season performance factor
IAQ	Indoor air quality
SEER	Seasonal energy efficiency ratio
SIR	Savings to investment ratio

Executive Summary

Energy efficiency retrofits (EERs) face many challenges on the path to scalability. Limited budgets, limited accessibility of envelope penetrations, cost effectiveness, and risk factors impact the type and the extent of measures that can be implemented feasibly to achieve energy savings goals. Group home retrofits can face additional challenges to those encountered in single-family homes, such as reduced access (occupant-in-place restrictions) and lack of incentives for occupant behavioral change.

Building owners, operators, and other groups need to have a firm grasp on the feasibility and cost effectiveness of EERs to group homes. These stakeholders also need guidance regarding common risk factors and the potential impact on energy retrofit measures in addition to the impact of occupant behavior on building energy use. This is particularly the case for older buildings.

This project studies the specification, implementation, and energy savings from an EER in a group home, with an energy savings goal of 30%. This final report chronicles the retrofit measures specified, their cost effectiveness based on pre-retrofit and post-retrofit utility bill analysis, and the test results that were used to characterize pre-retrofit and post-retrofit conditions.

The following energy conservation measures were implemented on the group home:

- 17.55 seasonal energy efficiency ratio, 8.8 heating season performance factor air source heat pump (ASHP)
- Electric water heater, 0.92 energy factor
- R-49 ceiling insulation
- Air sealing, as accessible
- Aerosolized duct sealing
- Partial window replacement
- ENERGY STAR® refrigerator, freezer, dishwasher, and clothes washing machines
- Programmable thermostats
- Lighting occupancy sensors.

Significant findings include:

- Sensors installed to monitor the operation of 32 windows and one door showed up to a 19% increase in the minimum dynamic effective leakage area of the building as a result of window openings during hours when the ASHP recorded a cycle. This points to an opportunity to further reduce energy use through future adjustments to occupant behavior (i.e., through reducing window openings during ASHP operation).

- Replacement of ASHPs identified and addressed a risk factor that existed in the pre-retrofit home, which in this case was improper condensate drainage that had resulted in more than 4 in. of water accumulating in one unit's return plenum.
- While air sealing measures may typically garner a 30% reduction in infiltration rates in weatherized dwellings (Blasnik 2007), unless specific, accessible measures are identified and targeted prior to the retrofit, more conservative estimates should be made for older, attached buildings with potential air sealing accessibility issues. A 10% improvement expectation is more reasonable given that certain areas may be inaccessible and certain retrofit measures may be impractical due to restrictions such as project budget or occupancy during construction.
- Based on utility bill data and onsite monitoring of major end loads, the overall savings to investment ratio of the combined retrofit measures over a 10-year time horizon was found to be 2.4.

1 Problem Statement

1.1 Introduction

This project identifies and documents the installation and performance of cost-effective measures for an occupant-in-place energy efficiency retrofit (EER) in a group home in inner city Washington, D.C., called the Sasha Bruce Home. Retrofit measures that were pursued included minimally invasive air sealing, improved ceiling insulation, duct sealing, appliance replacement, high efficacy lamps, improved lighting controls, and mechanical system replacement.

Short-term data were gathered through building diagnostic tests of duct systems and building airtightness. Long-term data were collected on overall performance of measures, cost effectiveness, percent of energy consumed by various end uses, and occupant behavior. This research effort builds upon the current body of knowledge of retrofits, specifically occupant-in-place group home retrofits.

1.2 Background

Recent focus of Building America teams is resulting in more information on cost-effective EERs of 30% or greater energy savings for multifamily buildings. Examples include retrofits of large-scale cold climate apartments (Neuhauser et al. 2012), and forthcoming research on mixed climate dwellings (Building America teams NAHBRC-IP's Greenbelt and BA-PIRC's Bay Ridge retrofits) and hot-humid dwellings (NAHBRC-IP's Fort Benning retrofit). Three of these studies address retrofits in occupied units. The Sasha Bruce Home differs from these previous studies in that it is a group home composed of two attached inner city row houses. Group homes have characteristics of both multifamily (e.g., high occupancy) and single-family dwellings (e.g., common bathrooms and kitchen), and are covered within the scope of the International Building Code, where they are recognized as R-4 occupancies. Built in 1900, the home houses variable, short-term youth occupants who have little to no motivation to save energy. The home includes six bedrooms that house up to eight occupants, three active offices for up to five staff, five bathrooms (two with active bathing facilities), three recreational or TV areas, and a kitchen that is used very heavily to prepare three meals per day for occupants and staff. A floor plan of the unit may be found in Appendix C. Utilities are paid by the owner, and pre-retrofit annual electricity bills for the all-electric 4,392 ft^2 building are extremely high—in excess of $11,000. Annual energy use intensity was high as well, at 65 kBtu/ft^2.

Figure 2. Sasha Bruce Home, front: center and right units

Figure 1. Sasha Bruce Home, rear

Prior to the retrofit, the aged home's appliances and equipment were reaching the end of their useful lives, with most equipment and appliances in need of replacement. The advanced age of the equipment was a key to making the EER more attractive from an economic perspective. (See Section 3.3 for more details.) Funds and support for the retrofit were contributed by Walmart, HomeAid, and the Home Builder's Care Foundation. While a full shell retrofit would have been an attractive research project, the building owner, Sasha Bruce Youthwork, faced practical limitations on the use of the funds, and was required to ensure that, at a minimum, the aging equipment and appliances were replaced. Remaining funds were used to improve the building envelope, reduce the air infiltration, install high efficacy lighting, reduce hot water consumption, and improve lighting controls.

1.3 Relevance to Building America's Goals

Within existing homes, the goal of the U.S. Department of Energy's Building America program is to reduce energy use by 30%–50% versus pre-retrofit conditions. To this end, Building America teams conduct research to advance market-ready energy efficiency solutions in homes across climate zones, with consideration given to improving comfort, safety, and durability.

Building America's energy savings goals are particular to individual climate zones. The project site is located in Washington D.C., in a mixed-humid climate. As related to existing homes within mixed-humid climates, Building America has a goal of 30% energy savings from the pre-retrofit condition by 2013. This EER sought to achieve this goal by specifying a set of retrofit measures expected to provide a minimum of 30% energy savings in the 2011–2012 time frame. A wide breadth of measures were applied to achieve this target, including improvements to or replacements of mechanical equipment and distribution systems, appliances, lighting and lighting controls, the building envelope, and hot water conservation measures.

The results are expected to provide valuable information on the cost effectiveness of retrofit measures to the building owner, who owns and manages several similar properties in the area, as well as be directly applicable to hundreds of other group homes that operate within the same climate zone.

1.4 Cost Effectiveness Relative to Energy Savings

Recommended EER measures were assessed and prioritized based on cost effectiveness relative to predicted energy savings. Installed costs were recorded, and energy modeling with REM/Rate was conducted to project the cost effectiveness of various measures on the basis of savings to investment ratio (SIR, which is highly relevant to multifamily projects that receive weatherization funding) and other metrics. The SIR can be defined as the present value of savings over a given time relative to the incremental cost of the measure. BEopt software was also evaluated for this task, but was ultimately bypassed due to lack of functionality in several key areas; more detail is provided in Section 3.1. As is typical in the industry, a SIR of ≥ 1.0 was considered to be cost effective within the confines of this project.

Equipment and appliances that were near the end of their useful lives were assumed to require replacement, in which case, the costs associated with the measures were taken as the incremental cost between an energy-efficient replacement and a baseline, standard efficiency replacement plus the residual value of the existing equipment or appliance. Residual value of existing equipment was calculated as the cost of a new standard efficiency replacement, depreciated linearly with the age of the equipment, until it reached a value of zero at the equipment's useful life, as determined by industry sources.

Estimates of energy savings associated with selected retrofit measures were made using building energy simulations and were refined with data from short-term testing. Long-term monitoring of utility bills and individual end uses confirmed energy savings.

1.5 Tradeoffs and Other Benefits

Targeted retrofit measures were identified through REM/Rate building energy simulations. Initial REM/Rate simulations were completed by modeling individual measures separately, but final simulations included the projected energy savings of multiple combined measures.

The final measures, listed in Table 1, were selected by the building owner, who had additional concerns besides maximizing cost effectiveness, such the desire to replace as much equipment as possible while funds were available. Hence, some moderately efficient equipment was replaced prior to the end of its useful life (e.g., a 13 seasonal energy efficiency ratio [SEER]/7.7 heating season performance factor [HSPF] heat pump that was only 3 years old). However, because the building, equipment, and appliances were in a general state of disrepair, some of the measures were necessitated by the age of the equipment (such as replacement of a 19-year-old air source heat pump [ASHP]). When possible, higher efficiency appliances and equipment were selected for replacement. All considered, cost effectiveness for the project was still demonstrated by maintaining a SIR $\geq$ 1.0.

Advanced controls, such as programmable thermostats and lighting occupancy sensors, were expected to not only reduce energy used at the home, but also to improve the building owner's ability to control the energy used by short-term occupants. Aerosolized duct sealing was specified to improve the supply of conditioned air to registers throughout the home, providing a more comfortable environment and perhaps reducing the impetus for occupants to open windows during the operation of the ASHPs from any overheating or undercooling of zones.

Table 1. EER Measures

Item	Category	Retrofit Measure	Reasons for Retrofit (E,A,O)**	Pre-Retrofit Measure
1	Space heating/cooling	ASHP: 17.55 SEER, 8.8 HSPF with electric resistance backup	O, E	ASHP: 3 years old. Rating when new: 13 SEER, 7.7 HSPF. Adjusted ratings*: 11.9 SEER, 7.0 HSPF. Electric resistance backup.
2	Space heating/cooling	ASHP: 17.55 SEER, 8.8 HSPF with electric resistance backup	E, A	ASHP: ~19 years old. Rating when new: 10 SEER, 6.8 HSPF. Adjusted ratings*: 5.6 SEER, 4.0 HSPF. Electric resistance backup.
3	Water heating	Electric water heater 50 gal., 0.92 energy factor (EF)	A, E	Electric, 80 gal, 15 years old. Rating when new: 0.82 EF. Adjusted rating*: 0.8 EF.
5	Refrigerator	ENERGY STAR qualified	O, E	5 years old, non-ES qualified
5	Freezer	ENERGY STAR qualified	O, E	3 years old, non-ES qualified
6	Clothes washer 1	ENERGY STAR qualified	A, E	18 years old, non-ES qualified
7	Clothes washer 2	ENERGY STAR qualified	A, E, O	9 years old, non-ES qualified
8	Dishwasher	ENERGY STAR qualified	E, O	6 years old, non-ES qualified
9	Thermostat 1	Programmable thermostat compatible with ASHP	E, A	Mercury thermostat
10	Thermostat 2	Programmable thermostat compatible with ASHP	E, A	Mercury thermostat
11	Lighting—occupancy/motion sensor	Occupancy sensors in two recreation rooms and one dining room (6 sensors total)	E	No occupancy sensors
12	Windows	Replace all 18 windows on the front of the building to meet 2012 International Energy Conservation Code requirements (U-0.32)	E, A, O	Vinyl, double-pane. 12 years old. Leaky, in poor operating condition. Assume U = 0.5, SHGC = 0.62, per ASHRAE Fundamentals

Item	Category	Retrofit Measure	Reasons for Retrofit (E,A,O)**	Pre-Retrofit Measure
13	Luminaires	0% of luminaires are incandescent	E	25% of luminaires are incandescent
14	Permanent lighting fixtures	Replace up to 10 permanent lighting fixtures as needed.	A, O	Multiple lighting fixtures broken
15	Attic insulation	Install loose fill cellulose insulation in the attic to reach R-49.	E	R-19
16	Duct sealing	Aerosolized duct sealing to reduce leakage to outside	E	Leaky. See Table 3.
17	Air sealing	Caulk/foam all accessible interior/exterior penetrations	E	Leaky. See Table 2.
18	Water reduction	2 low-flow shower heads (2.2 gpm); 5 aerator faucets (2.0 gpm)	E	2.5 gpm shower heads; 2.2 gpm faucets
19	Clothes dryer 1	Clothes dryer with moisture sensor	O	No moisture sensor
20	Clothes dryer 2	Clothes dryer with moisture sensor	O	No moisture sensor

Table 1 Notes: *Adjusted ratings are a factor of age and maintenance per Building America protocol (Hendron and Engebrecht 2010). **Reasons for Retrofit: Expected energy savings, “E”; Advanced age of equipment or poor operating condition, “A”; Owner preference, “O”.

2 Experiment

2.1 Research Questions

The following *primary* research questions were answered within this project:

- What is the post-retrofit energy use of various end use loads in this group home (i.e., space heating and cooling, water heating, laundry, food storage, offices, entertainment center, etc.); and what percent of the total building energy use is accounted for by the energy end use categories that were monitored?
- What are the estimated annual energy savings from the retrofit based on data collected over the monitoring period?
- What SIR is expected for an EER with a 30% energy savings target?
- What are the challenges and solutions to making the retrofit packages replicable on similar building types?
- How does the occupant operation of windows affect the building airtightness during the operation of the ASHP?

Ancillary research questions answered within this project included the following:

- Based on short-term tests, were targeted airtightness levels achieved, and if not, why?
- How effective is aerosolized duct sealing at reducing total duct leakage?
- Can thermostat setbacks be employed to save more energy?
- What is the typical pre- and post-retrofit hot water consumption? What are the expected energy savings associated with replacement of the large, old water heater with a new, smaller water heater?
- Using Appendix A of ASHRAE 62.2, what are the recommended local exhaust flow rates and whole house ventilation rates for acceptable indoor air quality (IAQ)?

As they pertain to individual retrofit measures, *primary* research questions are addressed in Sections 2.3, 3.2, and 3.3 and then summarized within the Conclusion in Section 4. Additional, *ancillary* research questions that are specific to individual retrofit measures are listed and addressed within Section 2.3.

2.2 Technical Approach

Building energy simulations of pre- and post-retrofit scenarios were used to estimate energy savings. Both pre- and post-retrofit short-term tests and data analysis were used to gauge the performance of the home in relation to the prescribed retrofit measures. Schedule and resource constraints limited the period of pre-retrofit data collection. Prior to retrofit, some parameters were monitored for a period of 3 weeks, whereas others were monitored for only 8 days. Long-term monitoring occurred over a period of 11 months. This was deemed to be a sufficient length of time to accurately characterize performance given the excellent curve fit of post-retrofit whole-building energy use as a function of outdoor dry-bulb temperature. (See Section 3.2 and

Figure 9 for more information.) Across both pre-retrofit and post-retrofit periods, diagnostic tests and monitoring included the following:

- Building airtightness: Blower door test with two Model 3 Minneapolis Blower Doors and DG-700 Digital Gauge. See Section 2.3.1.
- Bathroom ventilation flow rate: Test using the Exhaust Fan Flow Meter from The Energy Conservatory. See Section 2.3.6; pre-retrofit only.
- Duct leakage: Duct leakage test using the Minneapolis Duct Blaster and DG-700 Digital Gauge. See Section 2.3.2.
- Hot water use: Short-term and long-term monitoring of hot water gallons using Jerman Company's DLJ-SJ75C meter with Onset UX120-017M data logger.
- Indoor temperature and relative humidity: Short-term and long-term monitoring of indoor thermal conditions using Onset U10-003s at the following locations: East basement: TV room (ceiling); West basement: unused storage room (ceiling); First floor: laundry/west thermostat (wall), kitchen (ceiling), east hallway at thermostat (wall); Second floor: east bathroom (ceiling), hallway (ceiling), west bathroom (ceiling).
- Appliance energy use:
  - Refrigerator, freezer, and washing machines: Short- and long-term monitoring of appliance energy use (kWh) with P3 International Kill-A-Watt EZ meters.
  - Clothes dryer, water heater, ASHP compressor, electric resistance backup, and fan: Short- and long-term monitoring of appliance energy use (kWh) with CCS' WNB-3Y-208-P Watt Node with associated current transducers and Onset UX120-017M data logger.

2.3 Retrofit Measures and Results

Short- and long-term tests results are grouped according to category impacted and include a narration of the retrofit measure pursued as well pre- and post-retrofit test results where applicable.

2.3.1 Building Airtightness

In an old, leaky home, air sealing of the envelope can be expected to result in about a 30% reduction in infiltration (Blasnik 2007), and is commonly viewed as one of the most cost-effective retrofit measures. Similar expectations were held for this home, but the final implementation of air sealing fell far short of this goal due to limitations in scope, budget, and accessibility of envelope penetrations.

Ancillary Research Question: Based on short-term tests, were targeted airtightness levels achieved, and if not, why?

Figure 3. Exposing a hidden fireplace and flue

The original retrofit scope called for sealing of the three chimneys that were visible from the exterior of the building. This was to be accomplished by sealing the one visible fireplace from the interior and then removing drywall as required to find and seal the two additional fireplaces, also from the interior. Prior to the retrofit, there was no attic access, but when an attic access hatch was created during the retrofit, a fourth chimney was discovered. When first-floor drywall was removed to reveal what was hidden behind, the retrofit crew soon realized that the home housed not three, but 16 fireplaces, with four fireplace flues routed to each chimney. The retrofit crew was able to seal three of the fireplaces flues from within the home, and four additional fireplace flues within the attic. Flues were stuffed with bags of insulation and then air sealed with spray foam.

The remaining nine flues, each measuring approximately 12 in. × 12 in., were not sealed, because the project did not have sufficient funds within its scope to accomplish this work, nor the personnel qualified to access and seal chimneys from the exterior. As a result, most of the air sealing efforts occurred in the attic, including capping and sealing around noninsulation contact rated recessed lights and foaming at top plates and around light boxes and abandoned chimney chases. (See Figure 4.) This work was highly labor intensive, due to limited clearance in one of the attics and the need to move pre-existing batt insulation to access penetrations.

Figure 4. Air sealing in the attics with limited clearance

2.3.1.1 Short-Term Test Results

Pre- and post-retrofit short-term blower door tests revealed significant improvements from the air sealing (a reduction of 935 CFM 50 and improvement of 7%), but the reduction fell far short of the typical 30% improvement in air sealing inferred from weatherization agency data (Blasnik 2007). Given the challenges often presented by group and multifamily buildings and the fact that the Blasnik reference did not differentiate between single family, multifamily, attached, or detached buildings, our initial target was a more conservative 20% improvement in air sealing. The unique characteristics of this building that were discovered during the retrofit process (i.e., 16 flues, 9 of which were inaccessible) would have ultimately required greater funding than was available to fully leverage the potential air sealing improvements. Achieving a 7% improvement in airtightness instead of a 20% improvement resulted in an approximate 4% reduction in projected whole-building energy savings. (See Section 3 for more details.)

Table 2. Building Leakage: Blower Door Test Results

Leakage	Pre-Retrofit	Post-Retrofit	Reduction	Diagnostic Equipment
CFM@50 Pa	12,716	11,781	935	Blower Door
ACH@50 Pa	22.2	20.6	1.6	Blower Door

The modest reduction in air infiltration achieved during this retrofit project is not atypical, especially in older group homes or multifamily buildings. Reasons include limited budgets, limited work scope due to occupant-in-place conditions, inability to fully investigate the building and identify all deficiencies, and limitations in the skills of the available workforce. It is also true that a few very large leakage pathways will dominate, and unless those can be accessed, it will be difficult to realize significant improvement.

2.3.2 Duct Tightness

Two old, leaky central duct systems offered a good opportunity for energy savings and improved comfort. Because the ducts were inaccessible, aerosolized duct sealing was specified to seal the ducts. All ducts were located within conditioned space.

Ancillary Research Question: How effective is aerosolized duct sealing at reducing total duct leakage?

Aerosolized duct sealing began with a thorough duct cleaning to ensure that aerosolized particles would be able to adhere to the duct walls. Next, supply registers were sealed with duct mask or temporarily blocked with foam, and the supply plenum was capped just above the ASHP's indoor coil. Using a fan, a compressor, and a spray nozzle, the sealant was released into the ducts as an aerosolized spray. Technicians monitored the air leakage through the ducts, and when the leakage bottomed out, the equipment was relocated to the return ducts to perform sealing on that side as well. The system works best when addressing small holes, but does have its limitations, as in the case of large holes or disconnected ducts. Even with the aerosolized sealant doing the work, sealing of each individual duct system took several hours for a two-man crew to complete. Due to the complex layout of the home, a significant portion of this time was spent locating obscure supply registers. On retrofit applications, an infrared camera can save hours of work by quickly identifying hard to find registers.

2.3.2.1 Short-Term Test Results

After sealing, the west side ducts showed a total leakage reduction of 201 CFM @ 25 Pa, representing a 38% reduction in leakage. During the pre-retrofit testing, the east side ducts were too leaky to successfully pressurize with the duct blaster, so a leakage-to-outside test was performed instead. The pre- and post-retrofit tests of leakage to the outside for the east side ducts showed a leakage reduction of 323 CFM @ 25 Pa, a 62% reduction in leakage. These measures were considered successful (Table 3).

Table 3. Duct Leakage Test Results

Duct System Location	Pre-Retrofit Leakage (CFM@25 Pa)	Post-Retrofit Leakage (CFM@25 Pa)	Leakage Reduction (CFM@25 Pa)
East, Total Leakage	Unable to quantify due to instrument limitations	521	?
East, Leakage to Outside	543	220	323
West, Total Leakage	534	333	201

2.3.3 Appliance and Plug Loads Energy End Use and Savings

The retrofit featured the replacement of several major appliances that were nearing the end of their useful lives, including two clothes washers, two clothes dryers, a dishwasher, a refrigerator, and a freezer. Because these appliances were old, the building owner, Sasha Bruce Youthwork, stipulated that these appliances be replaced. While the building owner elected to replace the old clothes dryers, they were not recommended as part of the energy retrofit and were excluded from the energy savings analysis due to low expectations for energy savings. Additionally, several plug loads were not targeted for replacement but were monitored for post-retrofit energy use to determine their impact on overall building energy consumption (i.e., three offices and one entertainment center).

Primary Research Question: What is the post-retrofit energy use of various end use loads in this group home?

For those appliances targeted for replacement as part of the energy retrofit (i.e., one refrigerator, one freezer, two clothes washers, and a dishwasher), modeled annual energy use was estimated using various sources, including Energy Guide labels and ENERGY STAR calculators. From these sources, total energy savings from replacement of these appliances were projected at 898 kWh. (See Table 4.)

Table 4. Annual Appliance and Plug Load Energy Consumption, Modeled Versus In-Situ

Appliance	Annual Energy Profile From Models			Annualized Energy Profile From In-Situ Data		
	Old Appliance Energy Use (kWh)	New Appliance Energy Use (kWh)	Modeled Savings (kWh)	Old Appliance Energy Use[d] (kWh)	New Appliance Energy Use[e] (kWh)	In-Situ Savings (kWh)
Refrigerator	527[a]	415[a]	112	753	667	86
Freezer, First Floor	621[a]	559 [a]	62	880	546	334
Clothes Washer 1	438[c]	200[c]	238	174	87[f]	87
Clothes Washer 2	438[c]	200[c]	238	Data logger failure	87[f]	Unknown
Dishwasher	892[a]	644[a]	248	No Monitoring	No Monitoring	No Monitoring
Clothes Dryer 1 and 2	1951	1951	0	No Monitoring	1956	No Monitoring
Entertainment Center	Not Modeled	N/A	0	346	N/A	0
Offices (3 total)	Not Modeled	N/A	0	478	N/A	0

Table 4 Notes: a). Energy Guide label, with energy use doubled to assume 8 loads per week instead of 4; b). ENERGY STAR Refrigerator Retirement Calculator; c). Energy Guide label for new clothes washer. For old clothes washer, assumed EF of 1.18, based on minimum allowable by federal standards in effect at the time of manufacture; d). Annualized data are based on short term energy monitoring that occurred over a period of 20 days for all appliances but Clothes Washer 1, which spanned a 10 day period. Data are projected forward to 8760 hours to estimate totals for a full year of operation; e). Annualized data are based on long term energy monitoring over 8064 hours that are projected forward to 8,760 hours to estimate totals for a full year of operation; f). One data logger was used to monitor the energy use of the two new clothes washers. Total clothes washer energy use is divided evenly between the two washers.

2.3.3.1 Short- and Long-Term Test Results

Prior to the replacement of appliances, Kill-A-Watt meters were installed on the refrigerator, freezer, and both clothes washers, and monitored for a period of 10–20 days; a longer period was desired, but not possible. These in-situ data were then used to project their pre-retrofit energy consumption over a typical year. Of these meters, one washing machine's meter failed during this period, so no data were available. Due to budget and scheduling restrictions, no energy monitoring equipment was installed on the pre-retrofit clothes dryers, dishwasher, office equipment, or entertainment center; no energy monitoring equipment was installed on the post-retrofit dishwasher either. Using the short-term in-situ monitoring results of the three reporting meters to estimate the energy consumption of the associated appliances over the entire year, the result was 14% higher than what was modeled. As a whole, the difference was deemed reasonable given the difficulty in estimating frequency of use. Taken individually, however, there were some large discrepancies between the modeled energy use estimates and the short-term measured results when projected over the course of a year, for instance, the freezer and the clothes washer. Further detail is provided below and grouped according to end use category. A summary of the results below can be found in Table 4 and Table 5. Note that Table 4 contains annualized values while Table 5 reports on data collected on 11 months of post-retrofit monitoring. Therefore, the values in Table 4 and Table 5 do not match for this reason.

Table 5. 11-Month Monitoring Period Appliance and Plug Load Post-Retrofit Energy Consumption

End Use Category	Average Daily Energy Use (kWh)	Total Energy Use During 11-Month Period (kWh)	Energy Use as Percent of Whole-Building Energy
Food Storage[a]	5.3	1775	5%
Laundry[b]	5.8	1960	5%
Entertainment Center[c]	1.0	319	1%
Offices (3 total)[d]	1.3	440	1%

Table 5 Notes: a). Includes two freezers (one old, one new) and one new refrigerator; b). Includes two new clothes washers and dryers; c). Includes a DVD player, TV, and cable box; d). Includes a printer, 4 desktop computers and monitors, two sets of speakers, two lamps, a radio, a router, and a paper shredder.

2.3.3.1.1 Food Storage

The modeled pre-retrofit annual energy use for the refrigerator and freezer (527 kWh and 621 kWh, respectively) was lower than the annual energy use projections developed from the short-term monitoring (753 kWh and 880 kWh), by about 30%. (See Table 4.) Similarly, the modeled annual post-retrofit energy use for the refrigerator (415 kWh) was much lower than the post-retrofit annualized energy use based on in-situ monitoring (667 kWh). The modeled annual post-retrofit energy use for the freezer (559 kWh) was slightly larger than the post-retrofit annual energy use based on in-situ data (546 kWh). With results that included both overestimation and underestimation of actual energy use, there is no clear explanation for the discrepancy between modeled and actual energy use.

Over the 11 months of post-retrofit data monitoring that occurred, the energy use for food storage (one new refrigerator, one new freezer, and one old refrigerator) was 1,775 kWh, which represented 5% of total building energy consumption. (See Table 5.)

2.3.3.1.2 Laundry

The ENERGY STAR clothes washer calculator was used to estimate the pre- and post-retrofit annual energy use of the clothes washers. This calculator estimates energy use by combining the effects of machine energy, water heating energy, and clothes drying energy required for additional moisture removal, without disaggregating the individual effects. Using this calculator, the pre-retrofit estimated combined energy use was 438 kWh for each of two washers. Based on in-situ monitoring over a 10-day period, the imputed annual machine energy use was 174 kWh for each of two washers. (See Table 4.) In-situ energy use for coincidental water heating and additional clothes drying was deemed too expensive to collect.

Using the same ENERGY STAR clothes washer calculator, the modeled post-retrofit combined annual energy use (machine, water heating, and additional clothes drying energy) was 200 kWh for each of two washers. Based on in-situ monitoring, the post-retrofit annual machine energy use was calculated as 87 kWh for each of two washers. Any coincidental water heating and clothes drying energy savings from the specification of new clothes washers could not be verified due to limitations of the data logging equipment; however, if these savings were realized, they were accounted for within the whole-house energy savings. (See Section 3.2 for more information.)

The post-retrofit clothes drying energy use (1,951 kWh) was as modeled (1,956 kWh), based on the assumption of 16 loads/week, suggesting that the assumption of 16 loads/week was reasonable. Based on the energy data collected for clothes washing and drying, it seems reasonable to estimate one to two loads per week per group home resident. Over the 11 months of post-retrofit data monitoring that occurred, the total post-retrofit energy use for laundry (machine energy use and electric resistance heating for clothes drying and washing) was 1,960 kWh, which represented 5% of total building energy consumption. (See Table 5.)

2.3.3.1.3 Entertainment Center

The entertainment center consisted of a TV, cable box, and DVD player. It was not targeted as part of the energy efficiency retrofit, so no modeling of the energy use was performed prior to the retrofit. Post-retrofit, a Kill-A-Watt meter was installed to estimate the total energy use over the full period monitoring period. Based on 1,593 hours of data collected, the projected energy use over the 11 months of post-retrofit site-monitoring was 319 kWh, accounting for 1% of the total building energy consumption. (See Table 5.)

2.3.3.1.4 Office Plug Loads

Similar to the entertainment center, office plug loads were not targeted as part of the energy efficiency retrofit. However, the energy use of the offices was of interest. Office plug loads that were monitored included a printer, four desktop computers and monitors, two sets of speakers, two lamps, a radio, a router, and a paper shredder. Based on 3,432 hours of data collected from four Kill-A-Watt Power Strips installed in three offices, the projected energy use over the 11 months of post-retrofit site-monitoring was 440 kWh, accounting for 1% of the total building energy consumption. (See Table 5.)

2.3.4 Air Source Heat Pump Energy End Use

Replacement of the existing ASHPs was prioritized based on building energy simulations that showed great opportunity for energy savings. See Section 3.1 for more detailed information on the simulations.)

Research Question: What is the post-retrofit energy use of various end use loads (e.g., ASHPs) in this group home?

2.3.4.1 Short- and Long-Term Test Results

Due to the aggressive schedule for the retrofit, short-term in-situ data on the energy consumption of the compressor and fan for both ASHPs was available for only 21 days prior to the scheduled retrofit. During this period, which occurred from September 23 to October 14, weather conditions were mixed and very mild, resulting in a total of just 40 heating degree days (HDDs, Base 65) and 495 cooling degree hours

> ***Risk Mitigation Opportunity***
> When removing the west ASHP during the retrofit, the mechanical contractor discovered that the existing condensate line was plumbed into the sewage disposal line, a practice that is against code and could result in sewage effluent backing into the return plenum. The line had clogged—whether due to sewage or other blockage was not determined—and resulted in more than 4 in. of stagnant water that was sitting in the return plenum. This situation was corrected when the new unit was installed, resulting in a great improvement in expected IAQ!

(CDHs, Base 74). Without a strong demand for heating or cooling, it was not possible to develop a meaningful correlation between space conditioning energy use and outdoor temperatures.

While short term, pre-retrofit data were inconclusive, 11 months of long-term, post-retrofit data on the energy consumption of both ASHPs provided conclusive findings. Combined space heating and cooling energy use (i.e., blower, compressor, and resistance heating) for the two ASHPs came to 9,570 kWh, accounting for 23% of the total building energy use. This compared well with the building energy simulations performed with REM/Rate v12.95 over a typical year, which estimated that combined space heating and cooling energy use would account for 28% of total building energy use.

However, once heating and cooling energy use were separated and normalized for weather, the in-situ data and modeling data were not as closely aligned. Based on the building energy simulation, 25% of post-retrofit total building energy use was expected to be used for heating (16,881 kWh over 4,459 HDDs, or 3.6 kWh/HDD), with just 3% required for cooling (2,031 kWh over 10,034 CDHs, or 0.20 kWh/CDH). According to the in-situ post-retrofit data, however, just 10% of the total building energy use over the 11 months of monitoring (4,014 kWh over 2,651 HDDs, or 1.5 kWh/HDD) was required for heating, while 14% (5,556 kWh over 19,080 CDHs, or 0.29 kWh/CDH) was required for cooling. In other words, normalized post-retrofit heating energy use was 58% less than expected, and normalized post-retrofit cooling energy use was 45% more than expected. (See Table 6 for a summary.)

Table 6. Post-Retrofit Normalized ASHP Energy Use, Heating, and Cooling

End Use Category	Modeled, Normalized Energy Use	In-Situ Normalized Energy Use	Percent Increase for In-Situ Versus Modeled
Space Heating	3.6 kWh/HDD	1.5 kWh/HDD	–58%
Space Cooling	0.20 kWh/CDH	0.29 kWh/CDH	45%

The most probable explanation for the increase in normalized cooling energy use and decreased heating energy use versus the modeled prediction is the larger-than-expected internal load from excessive kitchen operation (and the model's inability to account for this). Software tools that are equipped to handle typical single- and multifamily buildings are not equipped to handle group home kitchens where cooking can occur over several hours each day. In the Sasha Bruce home, staff typically cooked two to three meals each day for five to 13 people. This resulted in very large internal heat gains, as shown by Figure 5, which profiles average kitchen dry-bulb temperatures versus average hallway dry-bulb temperatures during the month of February. The data showed consistently elevated temperatures in the well-used kitchen, which was typically locked when not in use, resulting in elevated temperatures even at night. The lesson learned here is that cooking frequency can have a major impact on heating and cooling energy use in group homes, and projected savings should be adjusted accordingly.

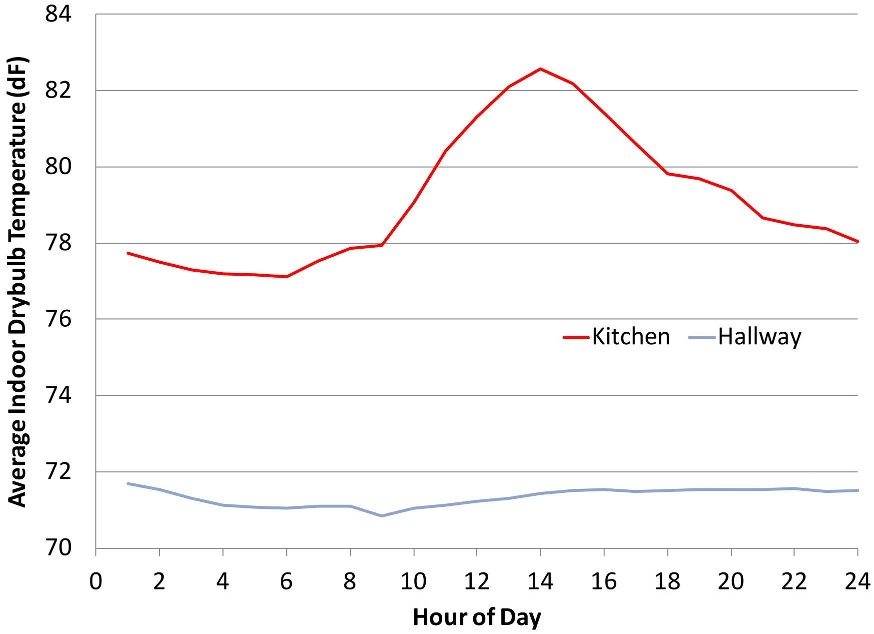


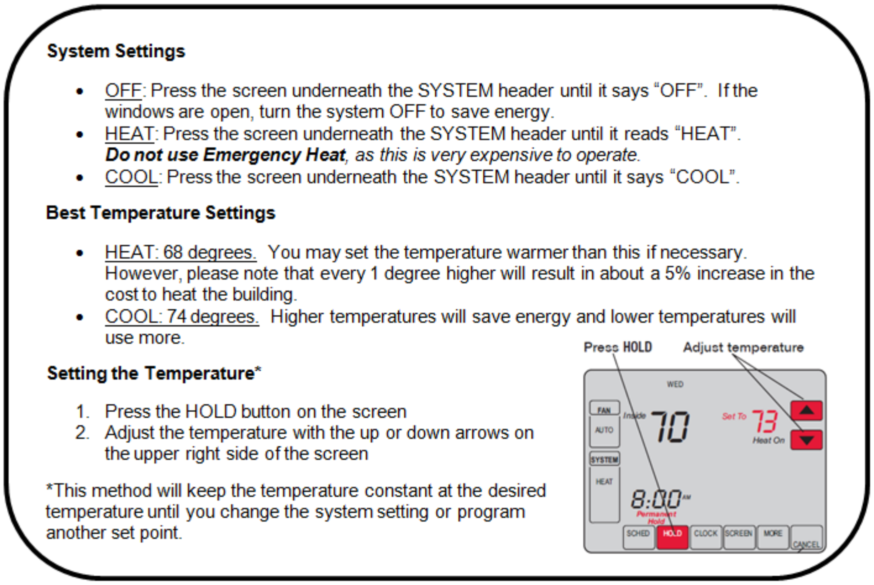
Figure 5. Kitchen and hallway average dry-bulb temperature profile during the month of February

2.3.5 Indoor Temperatures

Pre-retrofit temperature and relative humidity data were collected near the first-floor thermostats and within the west and east basements. Because the weather conditions during the pre-retrofit monitoring period were mixed and mild, it was not possible to draw any conclusions (e.g., energy use as a function of indoor and outdoor temperature difference, typical set points under cooling and heating) from the short-term monitoring of indoor temperatures. However, there was sufficient information collected from short-term tests and onsite observations to address the following research question related to indoor conditions.

Ancillary Research Question: Can thermostat setbacks be employed to save more energy?

Regarding the opportunity for employing setbacks for the home's thermostats, transitioning from a mechanical thermostat to a digital, programmable thermostat proved difficult for the building staff. On multiple post-retrofit site visits, Newport staff noted that "emergency heat" was selected as the heating mode, meaning the ASHP was running in electric resistance mode, and consuming far more electricity than necessary to heat the home. Initially, maintaining a consistent set point also proved difficult for the staff, and thermostat setbacks were deemed unacceptable based on concerns for maintaining comfort for staff working the night shift at the group home. To address these challenges, the staff was provided a thermostat "cheat sheet," which helped to provide an easy reference for maintaining comfort and equipment efficiency, while stressing the importance of closing windows during system operation.



System Settings

- OFF: Press the screen underneath the SYSTEM header until it says "OFF". If the windows are open, turn the system OFF to save energy.
- HEAT: Press the screen underneath the SYSTEM header until it reads "HEAT". ***Do not use Emergency Heat**, as this is very expensive to operate.*
- COOL: Press the screen underneath the SYSTEM header until it says "COOL".

Best Temperature Settings

- HEAT: 68 degrees. You may set the temperature warmer than this if necessary. However, please note that every 1 degree higher will result in about a 5% increase in the cost to heat the building.
- COOL: 74 degrees. Higher temperatures will save energy and lower temperatures will use more.

Setting the Temperature*

1. Press the HOLD button on the screen
2. Adjust the temperature with the up or down arrows on the upper right side of the screen

*This method will keep the temperature constant at the desired temperature until you change the system setting or program another set point.

Figure 6. Thermostat "cheat sheet" provided for the building staff

Perhaps a better solution than cheat sheets and re-education is automation and centralization of controls. Internet programmable thermostats are now available that cost less than $300, can lock out the maximum heating setting and minimum cooling setting, and can ensure that there are no options for "emergency heat" settings. With such a thermostat, the building owner could exercise reasonable control over the heating and cooling settings remotely, with little expected sacrifice in occupant comfort.

2.3.6 Domestic Hot Water Consumption

At the time of the retrofit, the home had two electric resistance tank water heaters, one 15-year-old 80-gal model, and one 3-year-old 50-gal model. Each tank served one shower. An inspection of the 80-gal model revealed that this unit was plumbed incorrectly, with the cold water inlet piped to the hot water outlet of the tank, and restricting the volume of hot water that could be supplied to the home. There were no complaints from the building owners regarding the hot water supply from the 50-gal or 80-gal tank, so the design team elected to replace the 80-gal with a 50-gal and replumb the unit correctly, which would have the dual benefit of reducing standby energy losses and supplying more hot water on demand. A heat pump water heater was considered for this application, but was ultimately bypassed due to space constraints in the mechanical room.

Ancillary Research Questions: What is the typical pre- and post-retrofit hot water consumption? What are the expected energy savings associated with replacement of the large, old water heater with a new, smaller water heater?

Primary Research Question: What is the post-retrofit energy use of various end use loads (e.g., water heating) in this group home?

2.3.6.1 Short- and Long-Term Test Results

Pre-retrofit hot water consumption was estimated through short-term monitoring over an 8-day period, from September 22 to September 30, for both the west and east side water heaters. A longer monitoring period was preferred, but was not feasible based on tight scheduling. Monitoring was accomplished with a DLJ-SJ75C single-jet water meter that provided 1 pulse per gallon. On an hourly basis, total pulses were recorded by an Onset UX120-017M data logger. During the 8-day period, the building occupants (approximately eight overnight residents and up to five office staff) used an average of 191 gal/day of domestic hot water (DHW). (See Table 7.)

Table 7. DHW Gallons and Energy Use

Pre-Retrofit, 8-Day Monitoring Period	Post-Retrofit, 11-Month Monitoring Period				
Average Daily DHW Use (gal/day)	Modeled Average Daily DHW Use (gal/day)	In-Situ Average Daily DHW Use (gal/day)	In-Situ Maximum Average Daily DHW Use of Any Consecutive 8-Day Period (gal/day)	In-Situ Normalized Energy Use (kWh/gal)	In-Situ DHW Energy Use as % of Total Building
191	90	104	190	0.2	18%

Reductions in hot water use were expected in the post-retrofit home based on the retrofit of two clothes washers, a dishwasher, low-flow shower heads, and a faucet aerator with improved water use efficiency. Eleven months of long-term post-retrofit data showed a much smaller average daily consumption (104 gal/day over the full period), but the same long-term data taken in blocks of consecutive 8-day periods contained one 8-day period where the average DHW consumption was 190 gal/day.

A histogram of the post-retrofit 8-day periods showed that the frequency of measuring an average daily DHW consumption of 190 gal/day across any 8-day period was less than 1%. Assuming the average daily consumption over the 8-day periods was normally distributed, the likelihood of any 8-day sample underestimating or overestimating the mean by two standard deviations is ~5%. For the post-retrofit dataset, this meant that there was a 95% confidence level that any 8-day period of monitoring would fall between 55 and 153 gal/day (i.e., within ± 47% of the mean of 104 gal/day). If the monitoring periods were extended to 30-day segments within the 11 months of long-term data, then there would be a 95% confidence that any 30-day monitoring period would fall within ± 36% of the mean. In other words, extending the short-term monitoring period from 8 days to 30 days would likely result in a closer approximation of the true mean, but the difference is not huge; so, collecting water heating and use data over as short of a period of 8 days does have some merit. Based on these considerations, it is likely that the post-retrofit hot water gallons used were significantly reduced, though the magnitude of the reduction cannot be conclusively determined due to the limited period of the pre-retrofit dataset.

Building energy simulations were performed to estimate the energy savings associated with replacement of the 15-year-old, 80-gal electric resistance water heater with a 50-gal electric resistance water heater. Using REM/Rate v12.95, the estimated savings were 506 kWh (7%

savings) with an average consumption of 90 DHW gal/day, representing a normalized post-retrofit energy use of 0.2 kWh/gal. A detailed explanation of the building energy simulations and assumptions can be found in Section 3 of this report.

Based on in-situ data, the model slightly underestimated the post-retrofit average gal/day (102 gal/day, actual). However, the model of post-retrofit normalized energy use of 0.2 kWh/gal, was right on the mark, as confirmed through in-situ data. Over the 11 months of post-retrofit data monitoring that occurred, the energy use for water heating was 7,143 kWh, which represented 18% of total building energy consumption over the period. (See Table 7.)

2.3.7 Ventilation

To mitigate any negative effects that the retrofit's air sealing measures could have on IAQ, ASHRAE 62.2-2010 was referenced to determine the recommended ventilation rates for the building. Normative Appendix A of this standard is provided for the specific application of calculating local exhaust and whole-house mechanical ventilation requirements for existing buildings. Using Appendix A, the designer has more flexibility to credit the infiltration rate of the building as well as the ventilation rate of local exhaust toward the required whole-house ventilation rate, Qfan. Further, the designer also has the option to increase Qfan to offset any local exhaust rates in kitchens and bathrooms that would otherwise be required.

Ancillary Research Question: Using Appendix A of ASHRAE 62.2, what are the recommended local exhaust flow rates and whole house ventilation rates for acceptable IAQ?

2.3.7.1 Short-Term Test Results

Across two bathrooms and one kitchen, there was only one exhaust fan installed in the pre-retrofit home. Using the Energy Conservatory's Exhaust Fan Flow Meter, the measured flow rate of the east bathroom fan was 54 cfm. (See Table 8.) The post-retrofit building infiltration rate was 11,781 cfm at 50 Pascals, as described previously in Section 2.3.1. Using these inputs, and following the methodology in ASHRAE 62.2-2010, no additional ventilation requirements were identified beyond what was provided in the pre-retrofit case; see the calculation worksheet in Appendix A of this report.

Table 8. Ventilation Location and Flow Rates

Ventilation Location	Pre-Retrofit Flow Rate (CFM)	Diagnostic Equipment
East Bath	54	Energy Conservatory's Exhaust Fan Flow Meter, Accuracy ± 10%
West Bath	No fan	N/A
Kitchen	Recirc only	N/A
Whole House	No fan	N/A

When following the methodology of ASHRAE 62.2-2010 Appendix A, it is important to remember that the standard is meant to identify the *minimum* airflows that are recommended for maintaining *acceptable* IAQ. No doubt the IAQ of this group home could have been improved by increasing ventilation and filtration. In fact, the preference of the design team was for installation of humidity-controlled local exhaust in the kitchen and bathrooms. However, this measure was ultimately not pursued due to budget constraints and lack of any recommended changes to ventilation rates using ASHRAE 62.2-2010. One of the lessons learned from this project was that to achieve IAQ objectives, buy-in from the project sponsor should be pursued as early in the process as possible.

2.3.8 Window Operation

Historically, inefficient occupant window operation has posed a challenge to temperature control and efficient operation of space conditioning equipment. When building occupants are not responsible for utility bills (the case for this and other group homes), there is often little motivation for the occupants to consider the energy impact of window operation.

Primary Research Question: What is the estimated impact of window openings on the equivalent leakage area (ELA) of the building?

2.3.8.1 Long-Term Test Results

During the energy retrofit, window state sensors were installed at each window and one door of the home, a total of 33 sensors in all. These on/off remote state sensors recorded the time interval that a window was open and closed. Window state sensors measured 1.8 × 2.4 × 0.8 in. and were easily installed on the surface of a vinyl window frame. Because state sensors measure only on/off events, they were not capable of indicating the actual opening dimension (i.e., the opening height would be an analog measurement, not an on/off digital measurement), but they were useful in recording the time during which the window was known to be open a minimum distance. These particular state sensors tripped when a window was opened a minimum of 1.5 in.

Figure 7. Window state sensor

To estimate the minimum impact of window openings on the building leakage, the following steps were taken (a detailed explanation of these calculations may be found in Appendix B).

- The building's baseline ELA was calculated using results from a multipoint depressurization test with windows closed.
- The minimum opening area for each monitored window and door was calculated using measurements taken on-site, and assuming that the minimum opening distance was 1.5 in., based on the minimum distance required to trigger an "open" event.
- Flow through the opening was calculated at a pressure difference of 4 Pa, assuming the window opening can be characterized as a sharp-edged orifice.
- For each hour during the monitoring period, the ELA of each window was calculated based on the flow through the opening at 4 Pa, and the fraction of the hour that the window was open.
- The minimum "dynamic ELA" (i.e., the real-time minimum ELA of the building calculated based on window openings) was determined at each hour of the monitoring period by summing the baseline ELA with the ELA of each open window.

Once the minimum dynamic ELA was calculated on an hourly basis (8,064 hours total during the period of monitoring), the data were filtered to qualify the interaction of window operation and ASHP energy use; all hours where no ASHP cycles were recorded were dismissed, leaving 6,273 hours of data. The dynamic ELA percent increase was calculated versus the building's baseline ELA on an hourly basis. Data were then grouped into bins based on the hourly outdoor temperature minus the indoor dry-bulb temperature, resulting in Figure 8.

From Figure 8, it is obvious that dynamic ELA and use of the ASHP are not well coordinated. Generally speaking, in a building operated for maximum efficiency, ASHP energy use and window openings would not overlap. The operators of this building, however, had windows open each hour of the 11 months monitored, regardless of whether the ASHP was operating. Occupants also tended to open more windows as outdoor temperatures became colder, increasing the minimum dynamic ELA by more than 19% when temperature differentials across the envelope were the largest. Interestingly, window openings fell off as outdoor temperatures increased, suggesting that occupants were less tolerant to the introduction of warmer outdoor air than colder outdoor air. Overall, the data point to opportunities for energy savings through better management of window operation by the occupants, especially during periods of colder outdoor temperatures.

Building occupants were not surveyed as to reasons for window operation. However, staff did communicate that the basement was typically cold in the winter, regardless of how high they set the first-floor thermostat. Cold basements in old buildings are not unusual, and could be a factor of poor insulation, stack effect, undersized ducts, etc. However, the large internal heat gains produced by extensive cooking without exhaust ventilation could be partially to blame for temperature variation across floors that could lead to overheating of the first and second floors and ultimately, occupant operation of windows. For this reason (and for reasons of IAQ), installation and operation of kitchen exhaust ventilation merit consideration. Without further study, it is unclear whether venting the kitchen would reduce or increase heating season energy use.

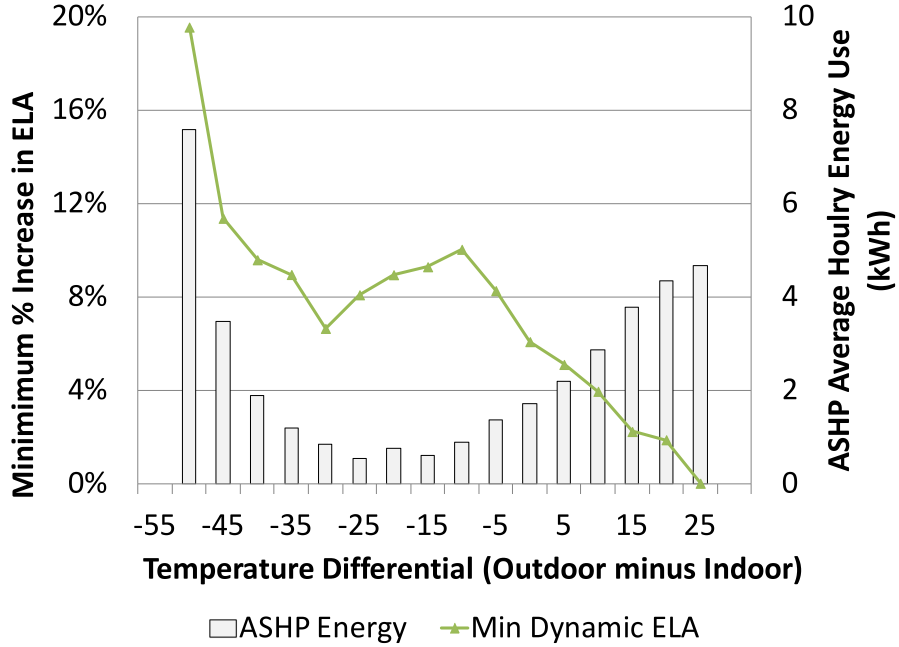


Figure 8. Effect of window operation (during hours with ASHP cycles) on building ELA at various outdoor to indoor temperature differentials

3 Analysis

This section contains information on the methods and results of building energy simulations, a summary of post-retrofit energy end use and savings, and an economic analysis.

3.1 Building Energy Simulations

Building energy simulations were used to estimate expected savings. While the latest version of BEopt (v1.2 at the time the simulations were conducted) was the preferred simulation tool for this effort, use of the tool proved difficult due to its inability to model the following site-specific parameters:

- Exterior wall orientations of multiple wall types (e.g., a common wall and exterior wall sharing the same orientation)
- Number of bedrooms exceeding maximum permitted by BEopt
- Finished basement wall height of less than 8 feet
- Multiple ceiling sections with different insulation configurations (e.g., blown-in cellulose in vented attic and fiberglass batts in vaulted ceiling)
- Multiple ASHPs of different efficiencies and equipment ages
- Multiple water heaters of different sizes and EFs.

Based on these limitations, and prior to the retrofit, an initial round of simulations was conducted using REM/Rate v12.95. Where possible, building and mechanical characteristics were verified through short-term testing and onsite inspection. Where site inspections or measurements were not possible, critical assumptions were made regarding expected performance or characteristics. For example, lacking a low-cost, reliable protocol for field verification of ASHP performance, performance parameters were estimated based on Building America House Simulation Protocols, as a function of assumed maintenance schedules and equipment age (Hendron and Engebrecht 2010). (See Table 9.)

Table 9. Pre-Retrofit Mechanical Equipment Performance Assumptions

Equipment	Assumed Performance	Age (years)	Maintenance
ASHP, West	11.9 SEER; 7.0 HSPF	3	Seldom
ASHP, East	5.6 SEER; 4.0 HSPF	19	Seldom
DHW, West	80 gallon, 0.80 EF	15	Seldom
DHW, East	50 gallon, 0.89 EF	3	Seldom

Other assumptions were made for the pre-retrofit condition of the building envelope as well as the expected impact of retrofit measures. For example, because the home was built in 1900, and because there was no attic access, it was assumed that there was no attic insulation. However, when an attic hatch was created for access during the retrofit, the attic was found to have R-19 fiberglass batt insulation. Similarly, it was assumed that retrofit air sealing efforts would result in a 20% improvement in the building leakage, which was thought to be conservative based on weatherization program reports that are typically in the range of 30% (Blasnik 2007). However, the post-retrofit measured improvement was a 7% reduction in leakage. (See Section 2 for more information.)

These findings warranted a revision to the building energy simulation heating and cooling energy use estimates. Initial and revised expected energy savings are shown in Table 10. The data show an initial expected site and source energy savings of 44%, and a revised expected site and source energy savings of 22%. The majority of this gap between the initial projections and revised projections was due to under estimating the R-value of the ceiling insulation, though it was also impacted by correcting for the overestimation of the air sealing benefit.

Table 10. Building Envelope Modeling Assumptions

	Assumed Performance			
Parameter	Initial Simulation Set		Revised Simulation Set	
Ceiling Insulation	R-0	R-30	R-19	R-49
Air Sealing (ACH 50)	22.2	17.7	22.2	20.6

Interestingly, both the initial and revised simulations of the pre-retrofit home fell short of predicting the total energy consumed by the home, as determined by pre-retrofit utility bill data. The difference between actual (based on utility bill data) and expected annual site energy consumption was found by subtracting modeled heating, cooling, DHW, lighting, and targeted appliance energy use from the utility bill use, and is listed as "Other, Unaccounted" in Table 11. The initial simulation's projections were 20% short of the actual total site energy consumed, which seemed acceptable due to high variability in occupants, high cooking loads, and the existence of three fully staffed offices within the building. However, the revised simulation was ~40% short of the total – pointing toward some gaps between the modeled home and its operation (e.g., window operation, likely higher cooking loads, three offices, etc.). The data acquisition system, which included individual energy monitoring for the refrigerator, freezers, washing machines, clothes dryers, water heaters, and ASHPs and post-retrofit utility bill collection were helpful in clarifying the actual, post-retrofit savings.

Table 11. Estimated Annual Site Energy, Initial and Revised Simulations

End Use	Estimated Annual Site Energy (kWh)							
	Initial Simulation				Revised Simulation			
	Pre-Retrofit	Post-Retrofit	Savings	Percent Savings	Pre-Retrofit	Post-Retrofit	Savings	Percent Savings
Heating	44,285	16,881	27,404	62%	28,457	16,026	12,431	44%
Cooling	8,015	2,310	5,705	71%	5,361	2,031	3,330	62%
DHW	7,233	5,795	1,438	20%	7,233	6,727	506	7%
Lighting	2,218	1,277	941	42%	2,218	1,277	941	42%
Targeted Appliances	2,916	2,018	898	31%	2,916	2,018	898	31%
Other, Unaccounted	18,377	18,377	0	0%	36,859	36,859	0	0%
Total	83,044	46,658	36,386	44%	83,044	64,938	18,106	22%

3.2 Building Energy Use—Utility Bills and End Use Disaggregation

Pre-retrofit and post-retrofit performance data are the ultimate basis for quantifying energy savings. When overlaid with in-situ data on energy end use (collected via discrete data loggers) and normalized for outdoor temperature, a good approximation of the energy and dollar savings can be made.

Primary Research Questions: What is the estimated annual energy savings from the retrofit based on data collected over the monitoring period? What percent of the total building energy use is accounted for by the energy end use categories that were monitored?

3.2.1 Post-Retrofit Energy Savings

By examining a graph of 19 months of pre-retrofit utility bills versus outdoor temperature, it was obvious that outdoor temperature was a large driver in the monthly whole-building energy consumption. A second-order polynomial regression of these data yielded an acceptable curve fit, with an R^2 of 0.84. A similar exercise on 11 months of post-retrofit data yielded an even closer fit, with an R^2 of 0.92. Based on this close correlation, the post-retrofit monitoring period was curtailed at 11 months, which was deemed to be a sufficient length of time to accurately characterize post-retrofit performance. The one missing month was November, which had low space conditioning loads and an outdoor average temperature that fell within the range of temperatures recorded for other months.

By applying the polynomial regressions from the pre- and post-retrofit data to 30-year climate normal monthly average temperatures, annual energy use under pre- and post- conditions were estimated for a typical year. This method resulted in an estimated 41% savings for the post-retrofit home, or roughly 33,867 kWh of energy savings valued at $4,403 in the first year of operation (based on a utility rate of $0.13/kWh).

3.2.2 Post-Retrofit Energy End Uses

Energy end use as a percent of total building energy use was computed by comparing end use logged data with whole building energy use as reported on utility bills. Hourly, in-situ energy use data on clothes drying, water heating, space heating and cooling was collected through monitoring over an 11-month period. In-situ energy use data on clothes washing, food storage (refrigerator and freezers), office plug loads, and an entertainment center were collected for discrete periods during this time, averaged on a daily basis, and projected onto monthly billing periods based on the number of days in the month.

Total building energy use was derived from utility bills, after subtracting the energy use of a dehumidifier. A stand-alone dehumidifier was installed post-retrofit to address pre-retrofit moisture conditions in the basement, and so was excluded from the post-retrofit analysis. Monthly energy end uses were then subtracted from the total building energy use across the same period to quantify the energy end use for lighting, cooking, and other miscellaneous plug loads. The largest metered end use over the 11 months of monitoring belonged to the ASHPs at 24% (with roughly 10% for heating and 14% for cooling), followed by the water heaters at 18%. Laundry and food storage each accounted for 5%, and three offices and the entertainment center each accounted for 1%. Unmonitored loads such as lighting, cooking, and other miscellaneous loads accounted for 46%.

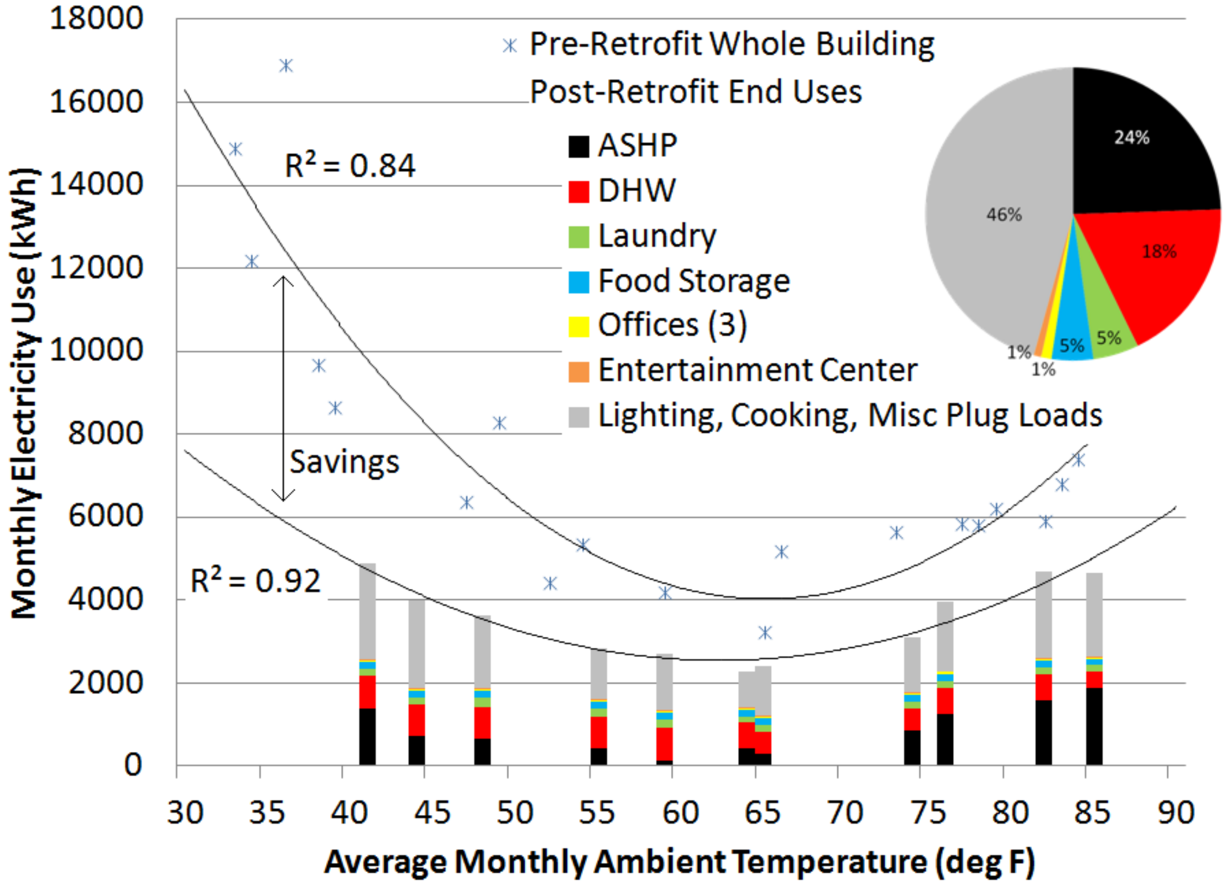


Figure 9. Total energy use (pre- and post-retrofit) and disaggregated energy use (post-retrofit only) as a function of outdoor dry-bulb temperature

3.3 Cost Effectiveness

While cost effectiveness of energy retrofits relative to energy savings can be measured by many methods, the metric typically used for multifamily retrofits is the SIR. Stated simply, the SIR evaluates the present value of total expected savings over a time horizon, divided by the investment cost of the measures. Within typical industry guidelines, and for the purposes of this project, a SIR of ≥ 1.0 was considered to be cost effective.

Primary Research Question: What SIR can be expected for an EER with a 30% energy savings target?

For this exercise, the following assumptions were made in calculating the SIR:

- 10-year time horizon
- Discount rate of 2% (based on survey of currently available, 5-year CD rates)
- Retail pricing for installed cost of measures (incentives and other discounts were ignored).

- Residual value of existing equipment is equal to the cost of a standard efficiency replacement at year zero, and decreases linearly over time. When the equipment reaches its industry accepted useful life, it is assumed to have a residual value of zero.
- Useful life derived from an NAHB/Bank of America survey (Seiders et al. 2007), or estimated from industry data/experience.
- Investment cost of retrofit measures taken as installed cost of the high efficiency replacement less the installed cost of a standard efficiency replacement, plus the residual value of the existing measure
- Year zero electricity price of $0.13/kWh
- Annual electricity price escalation rate of 3%.

The total incremental energy retrofit investment cost was determined to be $22,678. (See Table 12.) A project's SIR is highly dependent on the incremental investment cost of the individual energy conservation measures (ECMs) (high efficiency replacement cost less low efficiency replacement cost plus residual value of existing equipment). So, as much as possible, the team focused on recommending replacement of existing equipment with low residual value and minimal incremental costs. However, some individual ECMs with high incremental investment costs were selected based on their expected energy savings benefit, as determined by modeling or calculations (e.g., the ASHP).

The total incremental investment cost of the retrofit was also significantly impacted by the choice to replace some items that still had high residual value, such as an ASHP that was only 3 years old and appliances that performed fairly well but not as well as new ENERGY STAR appliances. The SIR would likely have been even more attractive without specifying some of these measures, but the magnitude of energy savings would not have been as high, and the goal of the team was to maximize energy savings while maintaining a SIR > 1, not to maximize the SIR.

Table 12. Investment Cost of Retrofit Measures

Retrofit Measure	Retrofit Action	Estimated Age	Estimated Useful Life	Estimated Installed Costs, High Efficiency Replacement	Estimated Installed Costs, Standard Efficiency Replacement	Residual Value of Existing Measure at Time of Retrofit	Retrofit Net Investment Cost
ASHP, West	Replace	3	16	$8,790	$6,422	$5,218	$7,585
ASHP, East	Replace	19	16	$13,184	$9,634	$1,606	$5,156
DHW, West	Replace	15	11	$1,200	$1,800	$0	($600)
TStat, West	Replace	*The incremental costs of programmable thermostats are not included in the analysis because replacement is typical with new HVAC equipment. Also, programmable thermostats are required by the 2009 International Energy Conservation Code.*					$0
TStat, East	Replace						$0
Windows	Replace	12	20	$8,775	$8,775	$0	$0
Luminaires	Replace	1	0.11	$125	$100	$0	$25
Exterior Light Fixtures	Replace	15	15	$687	$687	$0	$0
Attic Insulation	Improve	N/A	N/A	N/A	N/A	N/A	$1,979
Duct Sealing	Improve	N/A	N/A	N/A	N/A	N/A	$5,550
Air Sealing	Improve	N/A	N/A	N/A	N/A	N/A	$500
Interior Lighting Occupancy Sensors	Improve	N/A	N/A	N/A	N/A	N/A	$950
Refrigerator	Replace	5	13	$949	$949	$584	$584
Freezer	Replace	2	11	$579	$579	$474	$474
Clothes Washer 1	Replace	9	10	$999	$999	$100	$100
Clothes Washer 2	Replace	18	10	$999	$999	$0	$0
Dishwasher	Replace	6	9	$549	$449	$150	$250
Low-Flow Aerators	Replace	N/A	N/A	$125	N/A	N/A	$125
Total	–	–	–	–	–		$22,678

Though the SIR is a measure of the economic performance across a basket of ECMs, further detail on some of the individual measures is warranted. The high cost of the ASHP was driven both by its high efficiency (equipment costs for 17 SEER versus a standard 13 SEER can be about 80% higher) and also by unique challenges of its installation. For example, the east outdoor unit was located on the roof and required special equipment to access, which is reflected in the pricing, assumed to account for 60% of the total quote for both the east and west units. While duct sealing can be an effective measure for energy savings, its investment cost was high because it was regarded as an elective measure or an improvement, rather than a replacement. Clothes dryers were not included in the investment cost because they were not expected to significantly contribute to energy savings. In several cases, the installed cost of the high efficiency replacement was equal to the installed cost of the standard efficiency replacement. This generally occurred when the high efficiency replacement was a commoditized product, and lower efficiency products were not readily available (e.g., it was difficult to find non-ENERGY STAR appliances). In one case, the replacement of an 80-gal water heater with a 50-gal water heater, the selected ECM was actually lower cost than the standard efficiency measure.

Based on the initial building energy simulation results, expected annual electricity savings were 36,386 kWh, valued at $54,659 over 10 years (after applying discount and electricity price escalation rates). This resulted in an initial SIR of 2.4 ($54,659/$22,678=2.4). The SIR was adjusted to 1.2 after short-term test results were incorporated into a revised building energy simulation set, and expected annual electricity savings were adjusted to 18,106 kWh ($27,199 valuation over 10 years). Once long-term energy use data were collected, it was apparent that the project saved much more than the revised simulations had projected, at 33,867 kWh over a typical year for a SIR of 2.2 ($50,875 valuation over 10 years). The simple payback of the retrofit was calculated at 5.2 years ($22,678 net investment to provide annual energy savings of $4,403).

In practice, decisions are made not on a purely economic basis, but on the basis of other factors as well, such as comfort, function, safety, age of equipment, quality, and consumer preferences. For example, the pre-retrofit home had nonfunctioning exterior lighting that, in its nonfunctioning state, was not consuming any energy. Replacement of the lighting with any type of fixture, no matter how efficient, will ultimately result in higher post-retrofit energy consumption. Nonetheless, this measure was incorporated within the scope of the retrofit because having adequate lighting was considered a safety feature.

It is also important to note that the revised building energy simulations used to project cost effectiveness fell short of projecting the total energy consumption on site and the energy savings, suggesting gaps between the model's assumptions and actual operation of the group home. For more accurate modeling, more flexibility is needed within the inputs of software models to adequately characterize the unique characteristics of group homes.

4 Conclusion

Conclusions are grouped according to primary research questions, as listed below.

What are the estimated annual energy savings from the retrofit based on data collected over the monitoring period?

Post-retrofit annual energy savings versus pre-retrofit conditions were estimated at 44%, well above the Building America target of 30% savings. This estimate was built up through a second-order polynomial regression of pre- and post-retrofit monthly energy use as a function of average monthly outdoor dry-bulb temperature. Using 30-year climate normal monthly average dry-bulb temperatures, the regressions were then used to approximate the monthly and annual energy use for a typical year under both the pre- and post-retrofit scenarios. Energy savings were then calculated by subtracting the post-retrofit estimated energy use from the pre-retrofit estimated energy use, showing 41% annual savings. The monetized value of the 41% savings was $4,403 (based on an electric utility rate at $0.13/kWh). (See Section 3.2 for more information.)

What SIR can be expected for an EER with a 30% energy savings target?

Based on initial, utility-bill calibrated simulations, this group home was expected to save 44% of site and source energy and to achieve a SIR of 2.4. Due to limitations in accomplishing retrofit measures (e.g., air sealing limitations due to restricted accessibility) and the mid-retrofit discovery of higher than expected ceiling insulation, the initial simulated energy savings estimate was revised from 44% to 22% with an associated SIR of 1.2. (See Sections 2.3.1 and 3.1 for more detail.) However, based on long-term data collection, a 41% annual energy savings was achieved, corresponding to a SIR of 2.2. From these results, a group home EER with a target of 30% energy savings may expect to achieve a SIR between 1 and 2.

What is the post-retrofit energy use of various end use loads in this group home (i.e., space heating and cooling, water heating, laundry, food storage, offices, entertainment center, etc.); and what percent of the total building energy use is accounted for by the energy end use categories that were monitored?

Over the 11-month monitoring period (deemed a sufficient length of time to characterize post-retrofit performance based on the goodness of fit of a regression of building energy use as a function of outdoor dry-bulb temperature), post-retrofit energy use was tabulated at 24% for space heating and cooling (~10% for heating at 4,014 kWh and 14% for cooling at 5,556 kWh), 18% for DHW (at 71,43 kWh), 5% for laundry (at 1,960 kWh), 5% for food storage (at 17,75 kWh), 1% for offices (at 440 kWh), and 1% for the entertainment center (at 319 kWh). It is important to note that the space heating and cooling percentages are expected to shift with variations in weather. The 11 months of monitoring covered a very mild winter, so in typical years, space heating could be expected to account for a larger percentage of energy use.

Taken as the difference between whole-building energy use on utility bills and the energy end uses annotated above, lighting, cooking, dishwashing, and other miscellaneous plug loads accounted for 46% of the post-retrofit energy use (17,850 kWh). Based on observations while onsite and on kitchen dry-bulb temperatures, cooking loads were extremely high. The extensive cooking had the effect of increasing expected internal gains, reducing heating loads, and increasing cooling loads. Most residential building energy simulation packages are not adequately equipped to deal with the cooking loads and internal heat gains that are associated with group homes.

How does the occupant operation of windows affect the building airtightness during the operation of the ASHP?

Data on window operation showed that dynamic ELA and use of the ASHP were not well coordinated, with windows open each hour of the 11 months monitored, regardless of whether the ASHP was operating. Occupants also tended to open more windows as outdoor temperatures became colder, increasing the minimum dynamic ELA by more than 19% when temperature differentials across the envelope were the largest. Conversely, window openings fell off as outdoor temperatures increased, suggesting that occupants were less tolerant to the introduction of warmer outdoor air than colder outdoor air. Overall, the data point to opportunities for energy savings through better management of window operation by the occupants, especially during periods of colder outdoor temperatures.

What are the challenges and solutions to making the retrofit package replicable on similar building types?

Key characteristics of the pre-retrofit building that lent themselves to the success of this project from an energy and economic perspective were:

- Utility bills indicating high energy use intensity (65 kBtu/ft^2 in this case)
- Old, inefficient heating and cooling equipment in need of replacement
- A leaky building envelope with opportunities for air sealing
- Lighting loads that could be reduced through replacement of low-efficacy luminaires and installation of occupancy sensors
- Poor ceiling insulation.

Buildings that exhibit similar characteristics are likely to be good candidates for replicating energy savings at a very low incremental cost.

Even if the building is a great candidate for an energy retrofit, multiple challenges to achieving targeted energy savings goals should be expected, and budgets/schedules should be adjusted accordingly. Two of the largest challenges to achieving energy savings targets within this project were 1) hidden and inaccessible flues and 2) occupant opening of windows during operation of the ASHPs. Several hidden and inaccessible flues were not air sealed during this project because their presence was only discovered after a wall and attic were opened during the retrofit and because there were insufficient funds at that time to open all the additional walls to address all of them. This example illustrated the value of having sufficient flexibility in a retrofit budget and schedule to address surprises as they arise. As feasible, retrofit measures that are expected to have a high return on investment (e.g., air sealing) should be scheduled earlier in the project to ensure that sufficient funds are available for making changes to the scope when surprises do occur.

Inefficient window operation by occupants was identified through data collected with state sensors that were installed during the retrofit. Feedback was provided to the building owner and staff, but window operation during space heating or cooling continued to be significant. Motivation for staff and occupants to save energy remains a challenge, and educating occupants in such a high turnover environment can be a large drain on staff. Considering these limitations, one option to improve performance of energy retrofit measures that was not explored in this project would be to reduce occupant and staff control of energy savings measures. For example, replacing the current thermostat (which has a confusing "emergency heat" setting that can seem like a good choice for a chilly occupant) with an internet-programmable thermostat that can be controlled remotely by the building owner, would ensure that the ASHPs do not operate needlessly in resistance heating and could also ensure that heating and cooling thermostat set points do not exceed recommended limits. The practice of centralizing thermostat control is much more common in commercial buildings, but less so in residential settings, such as this group home.

Another opportunity for reducing operation of the windows during the winter that merits consideration is improving indoor climate control through installation and use of kitchen ventilation. Daily, prolonged use of cooking appliances without ventilation increases internal gains on the first floor, which could result in greater temperature stratification (e.g., cold basement and warm upstairs—a complaint logged by the occupants), increased stack effect, poorer temperature and air distribution from fewer heat pump cycles, etc. Without further study, it is unclear whether venting the kitchen would reduce or increase heating season energy use, but it would certainly be expected to improve IAQ, and should be explored further.

And while these challenges deserve attention in this building and other similar buildings, they by no means undermine the feasibility of cost-effective energy retrofits in such projects. Despite less than stellar occupant management of energy retrofit measures, significant energy savings were still realized.

5 References

ANSI/ASHRAE 136-1993. A Method of Determining Air Change Rates in Detached Dwellings.

ANSI/ASHRAE 62.2-2010. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

ASHRAE 119-1988. Air Leakage Performance for Detached Single-Family Residential Buildings.

ASHRAE Handbook of Fundamentals. 2009. American Society of Heating, Refrigerating and Air Conditioning Engineers Inc., Atlanta.

Blasnik, M. (2007). Energy Conservation: What are my choices? What can I save? Presented at: The 21st Annual National Low Income Energy Conference. Nashville, TN. June 5, 2007. Available at www.nliec.org/2007%20Conference/Presentations/MBlasnik_Energy%20Conservation.pdf.

Hendron, R.; Engebrecht, C. (2010). Building America House Simulation Protocols. Golden, CO: National Renewable Energy Laboratory, NREL Report No. TP-550-49426.

Neuhauser, K.; Bergey, D; and Osser, R. 2012. Leveraging Limited Scope for Maximum Benefit in Occupied Renovation of Uninsulated Cold Climate Multifamily Housing. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/renovation_uninsul_multifamily.pdf.

Seiders, D. et al (2007). National Association of Home Builders/Bank of America Home Equity Study of Life Expectancy of Home Components.

Appendix A. ASHRAE 62.2-2010 Whole-House Mechanical Ventilation Calculations

Using Normative Appendix A of ASHRAE 62.2-2010, and accounting for building infiltration, geometry, and local exhaust rates, it was shown that no additional mechanical ventilation was required for the building. Results from the procedure, which references ASHRAE Standard 136 and ASHRAE Standard 119 are shown below.

Sasha Bruce, ASHRAE 62.2-2010 Normative Appendix A; WHMV requirement calculator, including credit for infiltration and calculation of local exhaust deficit

Green cells are Inputs	Yellow cells are Outputs

Building Characteristics

4392	floor area of space (ft2)
16	occupants, assumed (2 per bedroom, 4 in offices)
9	"bedrooms" (6 dedicated bedrooms on 3rd story, 3 offices on main level)
3	stories
8	avg ceiling height
24	building height

	CFM50	ACH50	ELA (in2)
Pre-Retrofit	12716	21.7	700
Post-Retrofit	11781	20.1	648

ASHRAE 119

L, post	4.50	leakage (ft2)
(h/ho)^0.3	1.39	
Ln	1.43	normalized leakage

ASHRAE 136

W	0.76	weather factor for Washington, D.C. from ASHRAE 136 table
Ai	1.08	infiltration, ASHRAE 136_4.2 (ACHnat)
	634	infiltration (cfm nat)

ASHRAE 62.2-2010, 4.1.3

87.8	default infiltration rate based on sqft, 4.1.3 (cfm)
273	infiltration credit, 4.1.3 (cfm)

Ventilation required

119	Qfan, Equn 4.1a
10	persons assumed by Equn 4.1a
6	additional persons
164	adjusted Qfan, 4.1.1
54	Bath 1 flow, measured on-site (cfm)
0	Bath 2 flow, measured on-site (cfm)
0	Kitchen flow, measured on-site (cfm)

20	Bath 1 window credit, A3.2 (cfm)?
20	Bath 2 window credit, A3.2 (cfm)?
20	Kitchen window credit, A3.2 (cfm)?
0	Bath 1 deficit, A3.1 (cfm)
30	Bath 2 deficit, A3.1 (cfm)
80	Kitchen deficit, A3.1 (cfm)

110	Local exhaust deficit (cfm)
27.5	Required additional airflow ASHRAE 62.2-2010 A3.3 (cfm)

0	Qfan, less infiltration credit, includes local exhaust deficit compensation (cfm)

Appendix B. Calculation of Minimum Dynamic Equivalent Leakage Area

1. Using air flow and pressure differential data pairs from a post-retrofit multipoint building pressurization test with all windows closed, calculate the flow exponent, n, and the flow coefficient, c, of the building using Equation B1, below:

$Q = c(\Delta p)^n$ [Equation B1]

where

Q = air flow, cfm

c = flow coefficient, cfm/(in. of water)

Δp = pressure differential, in. of water

n = pressure exponent, dimensionless

Source: ASHRAE Handbook of Fundamentals 2009 16.15, equation 40

2. Calculate the baseline ELA for the post-retrofit building at 4 Pa (0.016 in w.g.) with windows closed using Equation B2, below:

$A_L = \frac{c}{5.39\mathrm{C_D}}\sqrt{\frac{\rho}{2}}\Delta \mathrm{p_r}^{(\mathrm{n}-0.5)}$ [Equation B2]

where

A_L = equivalent leakage area, in^2

$\mathrm{C_D}$ = discharge coefficient, dimensionless (use 1.0)

ρ = density of air, lb_m/ft^3

$\Delta \mathrm{p_r}$ = reference pressure difference (use 0.016 in. of water)

n = pressure exponent, dimensionless

Source: ASHRAE Handbook of Fundamentals 2009 16.15, equation 44

3. Calculate the cross sectional opening area for each individual window (in^2). Based on the state sensors used in this project, the minimum height of the opening required to trigger an open event was 1.5 in.

4. Calculate the air flow through each opening at 4 Pa (0.016 in w.g.), using Equation B3, below.

$Q = 776 C_D A \sqrt{2\Delta p / \rho}$ [Equation B3]

where

Q = air flow rate through open window, cfm

776 = unit conversion factor

C_D = discharge coefficient, dimensionless (use 0.6, assuming the window behaves like a flat plate orifice)

A = leakage area of opening, in^2

Δp = pressure difference across opening (use 0.016 in. of water)

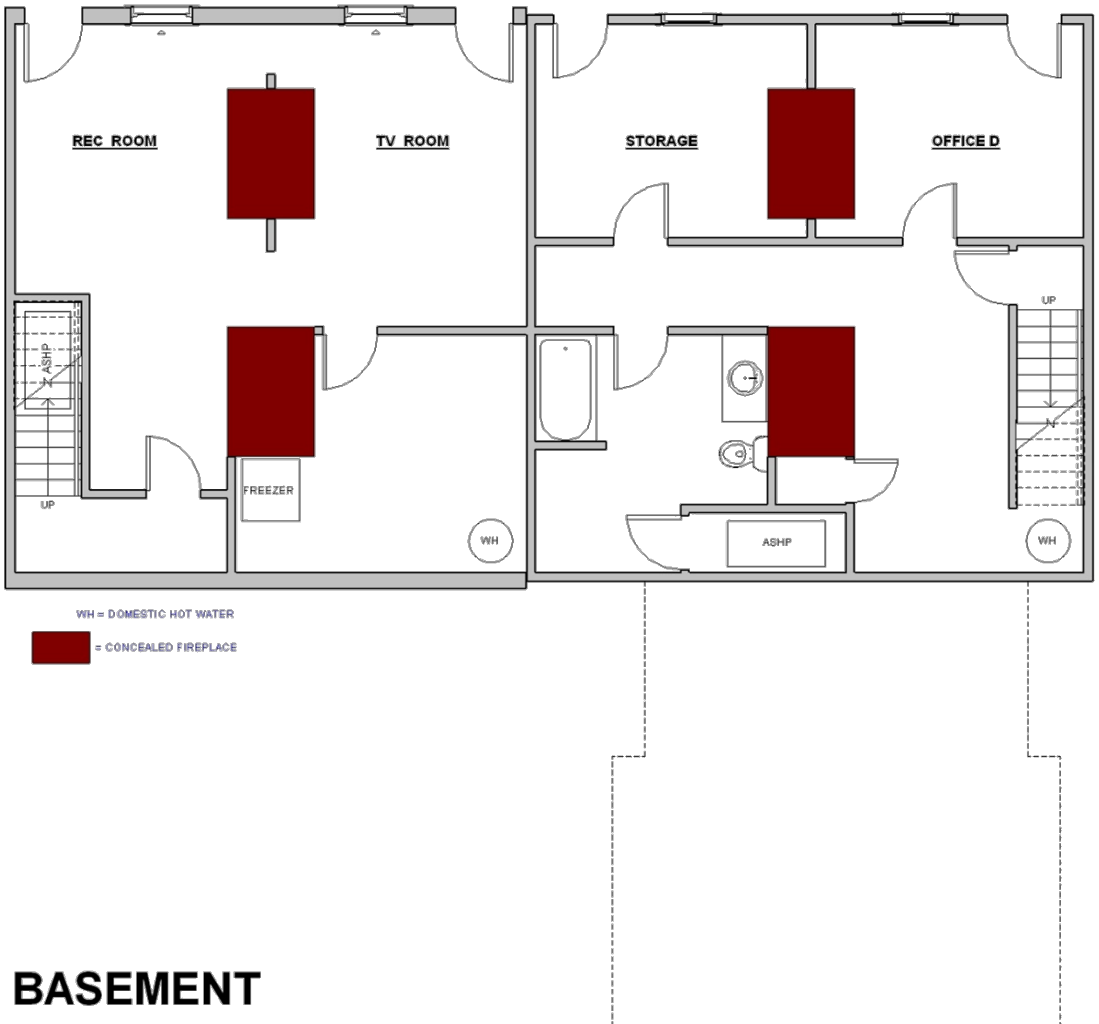
ρ = density of air, lb_m/ft^3

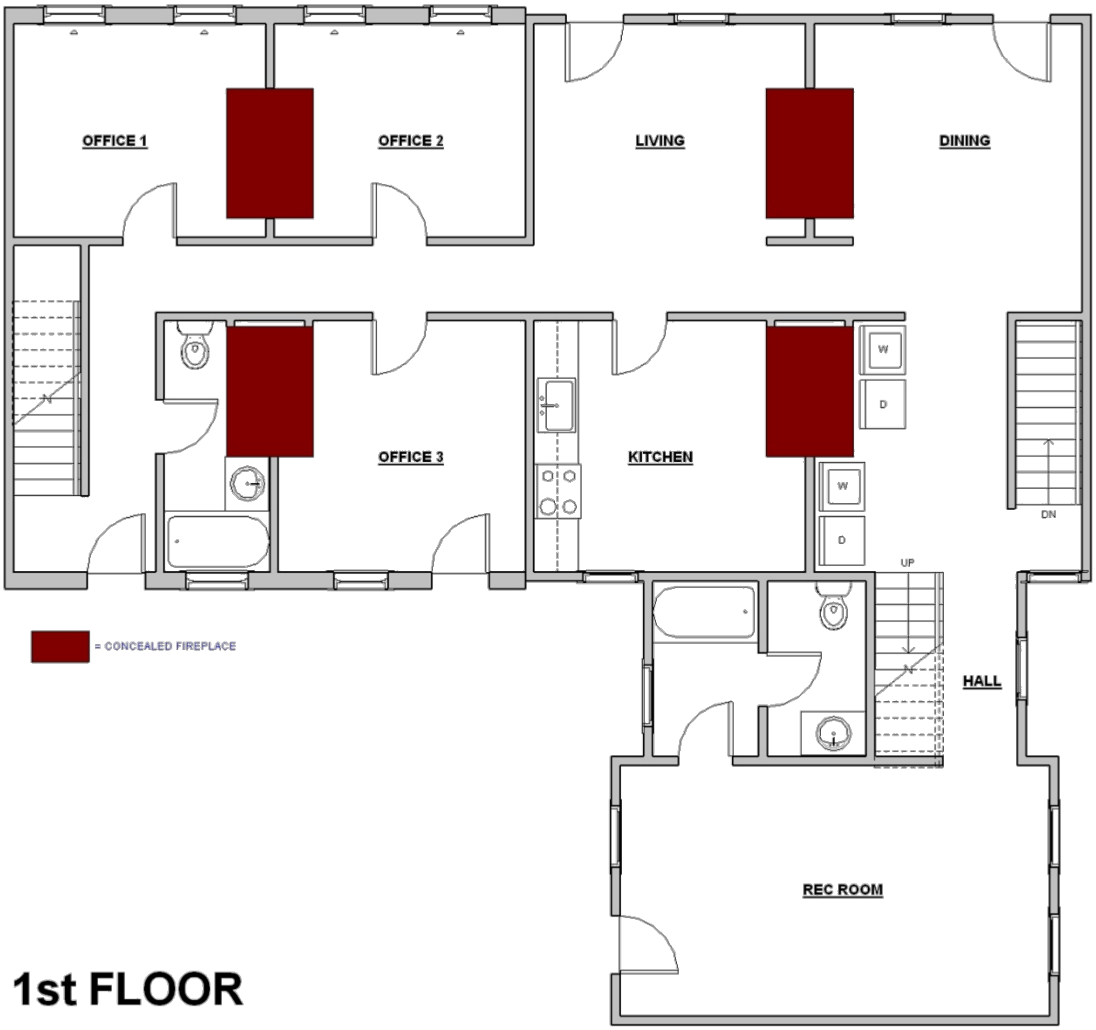
Reference: ASHRAE Handbook of Fundamentals 2009, 16.13, equation 36.

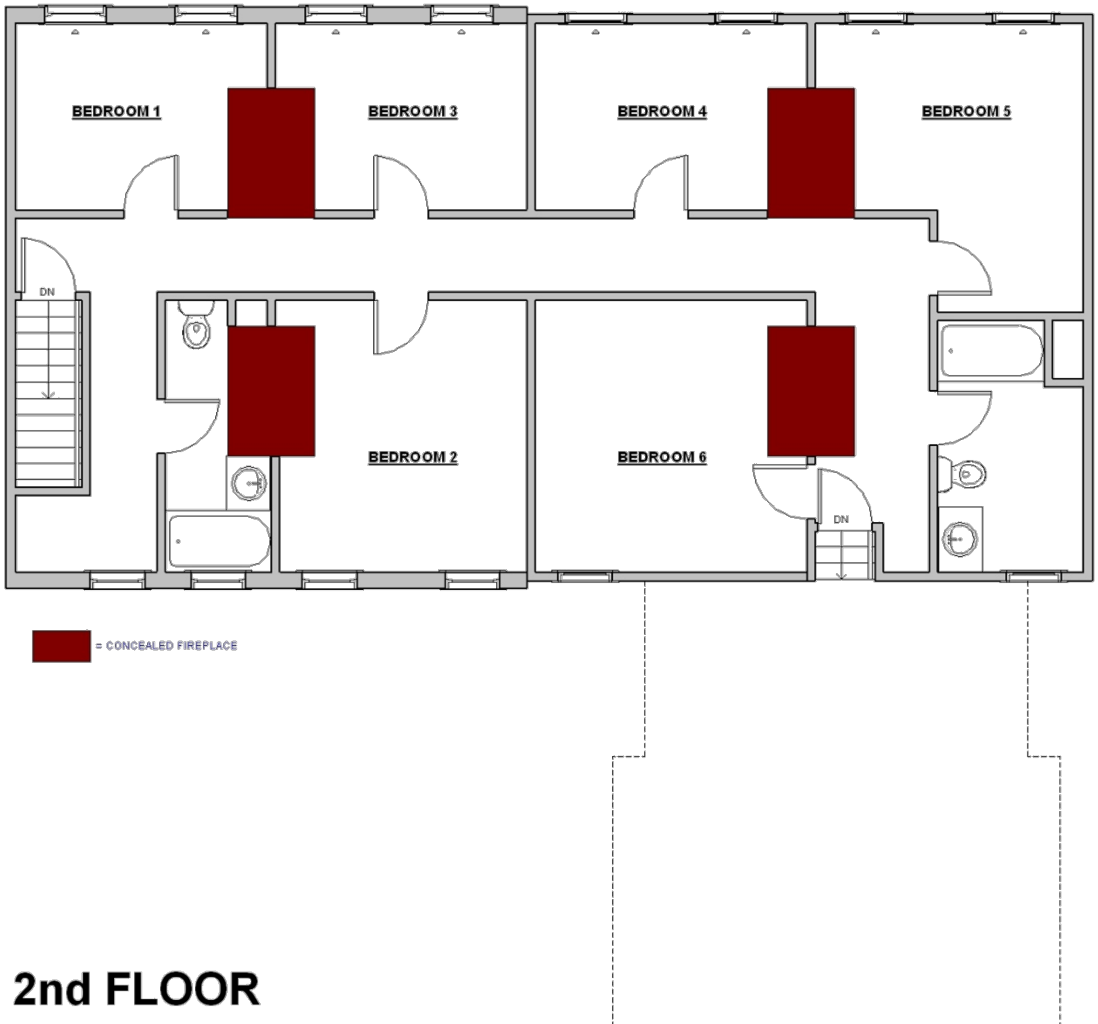
5. Using equation B3, calculate the ELA of each window opening (solve for *A*), assuming a discharge coefficient of 1.0 (typical for whole building calculations). All other variables (*Q*, Δp, and ρ) retain their values from the previous step.

6. Add the ELA of each window to the baseline ELA of the building to determine the minimum dynamic ELA over the period of observation.

Appendix C. Floor Plan of Sasha Bruce Group Home




OFFICE 1
OFFICE 2
LIVING
DINING
OFFICE 3
KITCHEN
W
D
W
D
DN
UP
HALL
REC ROOM
= CONCEALED FIREPLACE
1st FLOOR


BEDROOM 1
BEDROOM 3
BEDROOM 4
BEDROOM 5
DN
BEDROOM 2
BEDROOM 6
DN
= CONCEALED FIREPLACE

2nd FLOOR

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