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Sunnyvale Marine Climate Deep Retrofit

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Alliance for Residential Building Innovation (ARBI)

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Sunnyvale Marine Climate Deep Retrofit

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

ACCA	Air Conditioning Contractors of America
ACH50	Air Changes per Hour at 50 Pascals
ARBI	Alliance for Residential Building Innovation
BA	Building America Program
BEopt®	Building Energy Optimization software
CDD	Cooling Degree Day
EF	Energy Factor
ERV	Energy Recovery Ventilator
HDD	Heating Degree Day
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilator, Heat Recovery Ventilation
HSP	House Simulation Protocols
HSPF	Heating Season Performance Factor
HVAC	Heating, Ventilation, And Air Conditioning
IAQ	Indoor Air Quality
LED	Light-Emitting Diode
MEL	Miscellaneous Electric Load
MSHP	Mini-Split Heat Pump
PH	Passive House
PHPP	Passive House Planning Package
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year
T/RH	Temperature/Relative Humidity

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Davis Energy Group would like to acknowledge the U.S. Department of Energy Building America program for its funding and support of this technical report as well as the research that informed it. In addition, we would like to acknowledge Allen Gilliland and Bronwyn Brown of One Sky Homes for their innovation in the design of this project and cooperation throughout the monitoring and reporting.

Executive Summary

The Alliance for Residential Building Innovation worked with builder Allen Gilliland of One Sky Homes on a single-family home retrofit project located in the marine climate of Sunnyvale, California. The subject of this retrofit is a 1,658-ft², single-story, three-bedroom house; it is a ranch design originally constructed around 1957 with a low-slope roof and no attic. The homeowners were motivated to upgrade their home to address comfort and indoor air quality concerns. The retrofit, which was completed in April 2013, was designed to meet both Passive House (PH) and Building America program standards with a scope that included air sealing; installing wall, roof and floor insulation (previously lacking); replacing windows; upgrading the heating and cooling system; and installing mechanical ventilation.

The intents of this research are to evaluate the pre- and post-retrofit energy consumption of a marine climate retrofit, compare actual energy use to original predictions, and identify opportunities for cost savings in other similar retrofits in this climate. Twelve months of post-retrofit monitoring data are evaluated along with 24 months of pre-retrofit utility bill data; the same family occupied the home before and after the retrofit.

An additional evaluation focus is the effectiveness of the heating and cooling strategy. The home has a single mini-split heat pump (MSHP) unit located in a great room that connects the living, dining, and kitchen spaces. A separate compact distribution system uses a small fan that continuously extracts air from the great room and distributes it to the bedrooms.

The retrofit resulted in annual weather normalized utility cost savings of $500. Annual gas savings were 504 therms; electricity use increased by 129 kWh because the fuel was switched for heating and space cooling was added. Source energy savings were 54 MMBtu/yr (40% savings relative to pre-retrofit energy use), largely driven by space heating. The homeowners reported being very satisfied with the retrofit and the overall comfort of the home.

Building Energy Optimization software (BEopt®) modeling overpredicted heating energy use in the pre-retrofit case by 61%. However, in the post-retrofit case heating energy was underpredicted by 88% while cooling electricity overpredicted by 300%. The Passive House Planning Package overpredicted heating and cooling post-retrofit energy use by 48% and 23%, respectively. Although the percentage differences in heating and cooling energy use between actual and modeling estimates may be high, the magnitudes of the actual values are relatively insignificant compared to total energy use. However, these differences highlight the importance of correct occupancy assumptions in models to accurately evaluate the impacts of internal gains on space conditioning. This is most apparent in high performance homes in mild climates, where cooling loads from internal gains can be more significant than externally driven loads from solar gains and conduction from outdoors. Scheduling of internal gains and how this interacts with thermostat setbacks, heat recovery ventilation (HRV) free-cooling, and natural ventilation can have a significant impact on energy use. Low infiltration rates and HRV further reduce the effective passive removal of heat during cooler times of the day.

There were differences between measured values for lighting, appliance, and plug load energy use and estimates from the House Simulation Protocols. These differences are largely driven by occupancy, and modeling tools are often not able or designed to anticipate house-by-house occupancy. Further research and expansion of long-term monitoring datasets will help improve industry understanding of the range of occupancy patterns that can be expected in residential

homes and the impact on annual energy use, and ultimately improve modeling assumptions. Because occupancy patterns can lead to extremely varied energy consumption, future energy modeling tools may provide predictions within a range rather than finite estimates.

The strategy of installing a single MSHP and separate compact distribution system effectively maintained comfortable temperature distribution in the home during the cooling season with no spaces operating outside the Air Conditioning Contractors of America Manual RS comfort standards. During the heating season, the bedrooms frequently operated outside the Air Conditioning Contractors of America temperature difference recommendation, particularly in the coldest months. The 4°F maximum room-to-room temperature difference was exceeded 31% of the time during the heating season. Future work could isolate the effect of the distribution system on room-to-room comfort, measuring room temperatures with and without the central distribution fan operating. Distribution may be improved with revisions to the distribution system design such as increased fan airflow or altering the locations of supply and exhaust points.

Capital costs for the MSHP, distribution fan, and associated ductwork were $4,500, saving the builder $3,500 relative to a split system heat pump with ducted delivery of conditioned air to all rooms. These cost savings are substantial and warrant further work to validate this strategy, which has significant potential to be a cost-effective means of providing space conditioning in small- to medium-size low-load homes.

Comparisons of BEopt and The Passive House Planning Package recommended packages highlight certain major differences. BEopt modeling indicates that similar energy savings—but substantial cost savings—can be achieved in mild climates by using standard exhaust ventilation instead of an HRV, dual-pane instead of triple-pane windows, and reducing insulation levels in certain envelope assemblies. However, other factors influence final design decisions. For example, balanced ventilation is a smart strategy, particularly in tight homes, and while there are affordable balanced residential solutions that don't include HRV, they are limited. This limited availability may encourage more projects to incorporate HRV systems, ultimately reducing costs over time.

1 Problem Statement

1.1 Introduction

The goal of Building America (BA) is to demonstrate how cost-effective strategies can reduce home energy use by up to 50% for new and existing homes in all climate regions by 2017. Significant energy savings can be difficult to achieve in California's temperate marine climates. Unlike the Pacific Northwest, heating and cooling loads in California coastal regions are small and energy use tends to be dominated by lighting, appliance, and miscellaneous electric load use. Despite the low cooling loads, most builders are convinced that the market demands air conditioning, even though it may be used only a few hours of the year. Typical furnaces and air conditioners are often not available in small enough sizes for low-load homes, particularly in mild climates. Identifying cost-effective heating and cooling strategies for low-load homes that can be implemented in a retrofit is a need that has been identified by BA teams.

The Alliance for Residential Building Innovation (ARBI) worked with builder Allen Gilliland of One Sky Homes on a single-family home retrofit project located in the marine climate of Sunnyvale, California. The subject of this retrofit is a 1,658-ft² single-story house; it is a ranch design originally constructed around 1957 with a low-slope roof and no attic. The homeowners were motivated to upgrade their home to address current comfort and indoor air quality (IAQ) concerns. The retrofit was designed to meet both Passive House (PH)[1] and BA program standards with a scope that included sealing; installing wall, roof, and floor insulation (previously lacking); replacing windows; upgrading the heating and cooling system; and installing mechanical ventilation. It also attempted to demonstrate reductions in lighting, appliance, and miscellaneous electric load energy use through careful selection of lighting and appliances, and engaging the homeowners as participants in energy efficiency by providing convenient controls. A "one switch" type control was installed to test the potential to reduce miscellaneous electric use. Aside from BA participation, this retrofit also joined the Thousand Home Challenge.

Figure 1. Sunnyvale deep retrofit house, post-retrofit conditions

[1] The house was ultimately not certified through the PH program because of difficulties in achieving the 1 ACH50 target for retrofits.

The intents of this project are to evaluate pre- and post-retrofit energy consumption data from a marine climate retrofit, compare actual energy use to original predictions, and identify opportunities for cost savings in other similar retrofits in this climate. Twelve months of post-retrofit monitoring data are available along with 24 months of pre-retrofit utility bill data; the same family occupied the home before and after the retrofit. The effectiveness of the heating and cooling distribution strategy is also evaluated. The home has a single mini-split heat pump (MSHP) unit located in a great room; a separate compact distribution system uses a small fan to extract air from the great room and distribute it the bedrooms. The small fan operates continuously.

Information obtained from this project can be used to develop recommendations for energy efficiency retrofits in temperate California marine climates. These include California climate zones 1–6, which are all located along the coast from Humboldt County in the north to Ventura County in the south. Most of this region, including Sunnyvale, falls within International Energy Conservation Code climate zone 3.

1.2 Background

The coastal regions of California tend to be densely populated and are close to commercial centers that offer high-paying jobs. Because these regions also have mild climates, they are highly desirable places to live and home values are far above the statewide and national averages. The single-family house that is the subject of this project is representative of homes in the highly populated, older communities located in California coastal communities from the San Francisco North Bay to Santa Barbara. Most were built in the 1940s and 1950s, lack wall insulation, have single-pane windows, and are leaky. Sunnyvale is located in Santa Clara County, which includes 345,000 single-family residences, most of which are probably good retrofit candidates. There are more than 1.5 million single-family homes throughout California's marine climate counties, representing 19% of the statewide total. Despite the mild climate, heating energy use can be nontrivial and there is a large opportunity for energy savings. Cooler temperatures and seasonal rainfall also contribute to mold and moisture problems.

In comparison to other climate zones, little BA research has been carried out in temperate marine climates, especially with regard to retrofits. All the case studies included in the Pacific Northwest National Laboratory/Oak Ridge National Laboratory *Best Practice Guide for Marine Climates, 40% Whole House Energy Savings in Marine Climate* (Baechler et al. 2010) are for buildings located in the Pacific Northwest. The 99.6% winter design temperature for Seattle is 12°F cooler than for Sunnyvale (24.0°F versus 36.4°F). Sunnyvale has 2,153 heating degree days (HDDs) compared to Seattle's 4,280.

Returns from the large investments in programmatic efforts to support home energy retrofits in California have been disappointing. For example, more than $40 million of state and federal funds expended by local governments working under the Southern California Regional Energy Network resulted in only 521 completed retrofits.[2] Davis Energy Group has been working under a California Energy Commission Public Interest Energy Research grant with Energy Upgrade

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[2] "Motion for Consideration of the Southern California Regional Energy Network for Southern California Edison's Service Territory for 2013-2014." Submitted by the County of Los Angeles Office of Sustainability to the California Public Utilities Commission, July 12, 2012.

California and BA on projects that emphasize a large-scale retrofit approach that targets whole neighborhoods. The lesson learned from this experience is that mass market approaches in targeted neighborhoods are not as successful as programs that focus on early adopters and that use them to build interest through local press releases, open house events, and word of mouth (Berman et al. 2013).

Builder Allen Gilliland of One Sky Homes leveraged his success constructing the first certified zero net energy house in California (Cottle Zero Net Energy Home) to attract additional clients, including the owner of the house that is the subject of this test plan. The primary motives expressed by the owner were to address IAQ and comfort issues. The owner suffers from chronic respiratory problems that are compounded by a poorly sealed crawlspace and mold. Condensation would form on the interior surfaces of walls during the winter, causing damage to walls and furnishings. The owner also wanted to improve thermal comfort—the house was drafty and cold in winter and too warm in summer. Reducing energy costs was considered a side benefit. As this example demonstrates, health and comfort can be much stronger drivers in retrofits than lower utility bills, particularly in relatively affluent coastal communities.

The PH design standard is accepted as one of most rigorous worldwide. Although the program originated in Europe, it has gained popularity in the United States over the past few years and the Passive House Institute US formed a partnership with the U.S. Department of Energy's Zero Energy Ready Home program in 2012. PH sets an aggressive requirement for the maximum allowable heating load and therefore encourages load reduction measures, including high levels of insulation, very tight construction, and heat recovery ventilators (HRVs). It is of interest to both the BA and PH communities to learn whether alternate, lower cost strategies than those required to meet PH criteria can be applied to achieve an equivalent level of energy performance. PH sets a high bar, but alternatives to efficiency measures may be included in many PH homes such as 0.6 ACH50 (1.0 ACH50 in retrofits),[3] triple-pane windows, and HRV that will not significantly affect performance in this mild marine climate. Differences between the PH and BA approaches and how they impact design decisions and cost effectiveness are reported. The Passive House Institute US is currently engaged in a study that is expected to yield climate-specific standards for certification.

1.3 Research Questions

ARBI connected with the builder in early 2012 toward the end of the retrofit design phase. This project was determined to be a good candidate for the BA program because the information gained through this research would help answer the following key research questions:

1. Were the anticipated results of the retrofit achieved, including the estimated energy savings and expected comfort enhancements?
2. How does measured energy use compare to the modeled predictions?
3. How effectively can the MSHP and 100 cfm distribution fan deliver comfort to individual rooms?

[3] The infiltration targets are prescriptive requirements for PH certification; triple-pane windows and HRV are recommendations only.

4. How do the BA- and PH-recommended efficiency packages differ and how can they best be combined to cost effectively achieve deep energy savings?

Other objectives were to assess to what extent the owner uses the “one switch” control and its possible effect on household energy use.

1.4 Project Description, Retrofit Measures, and Costs

Retrofit work was initiated in July 2012 and completed in April 2013. The Passive House Planning Package (PHPP) was used as a design guide to develop the retrofit measure package. A parallel evaluation was conducted using Building Energy Optimization software (BEopt®); however, the aggressive PH requirements drove the final decision-making process. Table 1 summarizes the pre-retrofit conditions and the energy efficiency improvements made on the Sunnyvale house. The major retrofit components are described below.

Aside from energy savings, the major non-energy benefits associated with the retrofit measures include:

- Improved occupant comfort by reducing infiltration, eliminating drafts, and better regulating interior temperatures.
- Improved IAQ by filtering outdoor air introduced to the home and eliminating mold growth.
- Enhanced building durability and lifetime extension by repairing failing envelope components and properly sealing and placing vapor barriers to inhibit future degradation, such as mold growth.
- Improved health and safety by updating house components to the most recent building codes, including those regarding mechanical ventilation, insulation, and electrical safety.

Table 1. List of Efficiency Specifications

Measure	Pre-Retrofit Specification	Post-Retrofit Specification
Building Type/Stories	Single-family, 1 story	
Conditioned Floor Area	1,658	
Number of Bedrooms	3	
Envelope		
Exterior Wall Construction and Insulation	2 × 4 16 in. o.c., uninsulated	2 × 4 16 in. o.c. w/R-13 DensePack cellulose insulation + 2 in. polyiso (R-12) exterior foam
Foundation Type and Insulation	Raised floor, uninsulated (+ small uninsulated slab area)	Raised floor w/4 in. polyiso (R-24) foam in cavity and spray foam on girders and rim joists. 2 in. polyiso (R-12) over slab
Roof Insulation	Rafter roof, uninsulated	6 in. polyiso (R-38) over roof deck
House Infiltration	10.4 ACH50	1.47 ACH50
All Windows and Glass Doors	Single metal pane	Triple-pane Serious: U-value/SHGC = 0.17/0.27 and 0.21/0.49, tuned by orientation for passive solar design
HVAC Equipment		
Heating Type and Efficiency	Gas furnace, 78 annual fuel utilization efficiency	1-ton Fujitsu 12RLS2 MSHP, 12 HSPF/25 SEER
Air Conditioner Type and Efficiency	No cooling	
Heating and Cooling Distribution	Ducted	MSHP w/direct supply to great room. Dedicated 10 W + 100 cfm Panasonic circulation fan w/short supply ducts from great room to bedrooms
Duct Specification	Crawlspace R-0, 217 CFM50, ~30% leakage of supply cfm	Secondary compact ducted system in conditioned space
Mechanical Ventilation	Spot	HRV, Zehnder ComfoAir 350 + make-up air system for kitchen exhaust hood*
Water Heating Equipment		
Water Heater Type Efficiency	Existing Gas Storage (atmospheric) 0.62 energy factor (EF)	
Appliances, Lighting, and Miscellaneous		
ENERGY STAR Appliances	None	Refrigerator, dishwasher, clothes washer
Miscellaneous Load Control	None	One-switch using Insteon controls
Lighting	All incandescent	90% compact fluorescent lamps and LEDs on hardwired fixtures

* Make-up air system not evaluated in modeling or cost analysis exercises.

1.4.1 Description of Retrofit Measures

1.4.1.1 Insulation Upgrade

All exterior assemblies were upgraded with high levels of insulation, including continuous rigid insulation on both the walls and roof. The raised floor was insulated with 4 in. of rigid polyiso insulation in the joist cavities. The cathedral style roof was insulated at the roof deck with 6 in. of polyiso. DensePack cellulose insulation was blown into the 2 × 4 walls and 2 in. of polyiso was installed along the exterior. Care was taken to ensure quality installation and to minimize thermal bridging, as this building was aiming for PH standards.

Figure 2. Six inches of roof deck insulation

1.4.1.2 Windows

The single-pane metal windows caused interior condensation during the winter as well as occupant discomfort during the winter and summer months. The new windows are Serious triple-pane windows, which were selected for passive solar design. The house faces northeast, so a solar analysis was conducted that included a review of site shading to evaluate which windows would experience direct summer sun. These windows have a U-value of 0.17 and a solar heat gain coefficient (SHGC) of 0.27. The remaining windows have a U-value of 0.21 and an SHGC of 0.49 to allow improved passive heating from the winter sun. This upgrade is expected to contribute significantly to occupant comfort through reduced radiant heat transfer, noise reduction, and reduced drafts from induced sources and direct air leakage. Window replacement also reduces the detrimental effects of condensation common with single-pane, aluminum-frame windows. The window replacements also provided home and resale-value benefits to the homeowner.

1.4.1.3 Envelope Sealing

During a blower door test, air leakage was estimated to be above average at 10.4 ACH50. Target infiltration for this retrofit was 1.0 ACH50 based on the PH requirement for retrofits. Measured post-retrofit air leakage at test out approached this with 1.47 ACH50. The primary challenge for the builder was working within the existing framing, particularly the 2 × 6 tongue-and-groove subflooring, which was difficult to access in certain areas. Although the PH level was not quite achieved, the reduction in envelope leakage was significant.

Figure 3. Applying spray foam

1.4.1.4 Heating, Ventilation, and Air Conditioning

The original heating, ventilation, and air conditioning (HVAC) system was an older gas furnace with ductwork located in the crawlspace and no cooling system. Building envelope upgrades reduced heating and cooling loads. A ducted split system would have been oversized. In its place a 1-ton ductless Fujitsu MSHP was installed, allowing for simplification of the HVAC system, cost savings, and higher rated operating efficiencies. The intalled unit was more appropriately sized for the loads and has variable speed capability. A single indoor unit was selected with a rated efficiency of 12 heating season performance factor (HSPF) in heating and 25 seasonal energy efficiency ratio (SEER) in cooling. The MSHP is located in the great room which includes the family room and the kitchen/dining area. To minimize temperature stratification throughout the house and deliver conditioned air in the great room to the bedrooms, a Panasonic fan was installed to pull air from the great room and supply it to each bedroom via short duct runs. See Figure 6 for a layout of the distribution system. The Panasonic fan operates at about 10 W and 100 cfm. The fan and ductwork are concealed within interior chases.

Figure 4. Taping of joints

A Zehnder ComfoAir was installed for mechanical ventilation, which supplies a continuous stream of fresh filtered air (70 cfm) to the great room (see Figure 5). The HRV is equipped with a free cooling function that allows for the supply air to bypass the heat exchanger during the cooling season when outdoor air temperatures are lower than indoor. Exhaust air is removed from the two bathrooms.

Figure 5. Zehnder ComfoAir HRV

1.4.1.5 Water Heating

The homeowners chose to not replace their water heater.

1.4.1.6 Appliance, Lighting, and Plugs

All major appliances, including the refrigerator, clothes washer, and dishwasher, were upgraded to ENERGY STAR® models. All the lighting was incandescent and was upgraded to ~90% compact fluorescent lamps or light-emitting diode (LED) fixtures. However, not all spaces have hardwired lighting. High wall outlets allow for track lighting to be installed later. An Insteon plug-load control system, or “one-switch” was also installed. A standard switch was located inside the house adjacent to both the garage and front entrances. The switch wirelessly controls “on/off” modules, which plug in directly to any outlet in the house. Power to any device that is plugged into a module can be controlled via the master switch. Two modules were left with the homeowners, who were also provided instructions for their use.

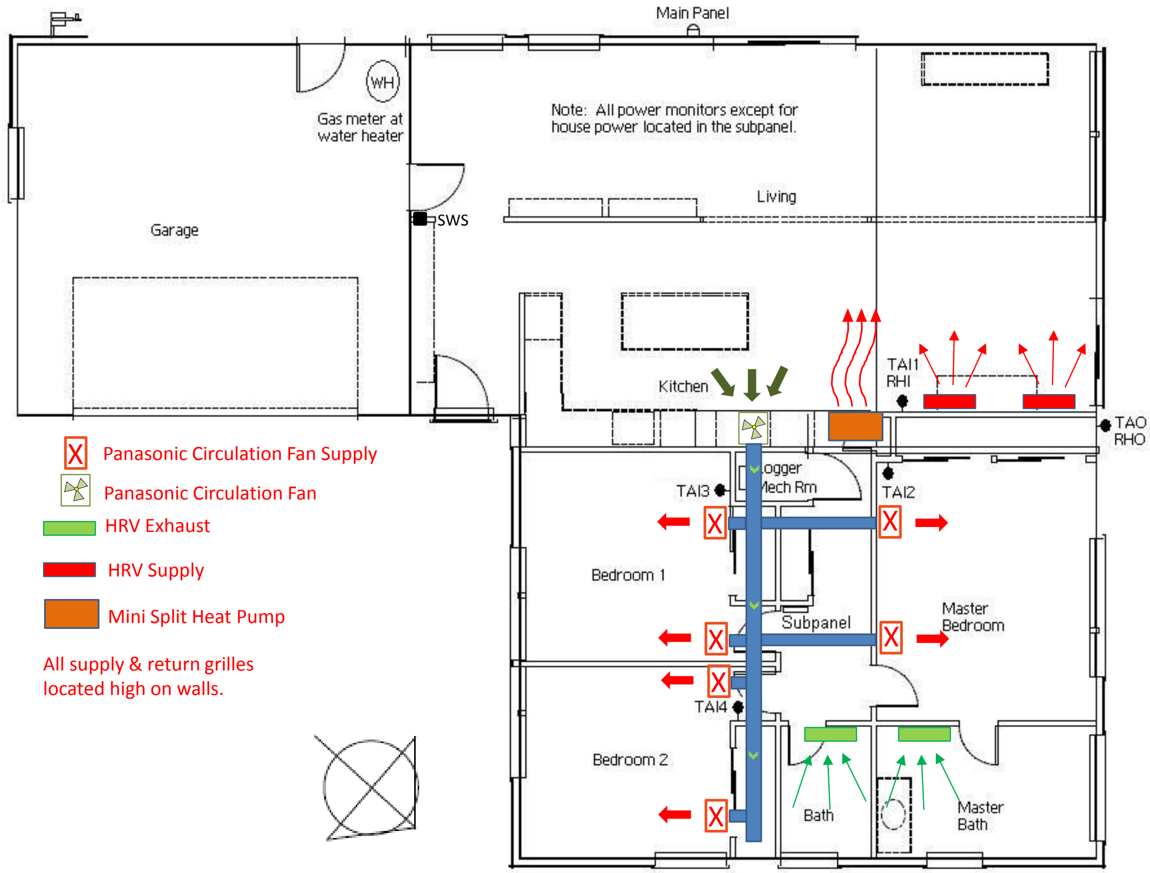

Figure 6. Floor plan showing distribution system

1.4.2 Costs

Table 2 summarizes the total retrofit costs by measures as well as incremental costs over the base case. The base case was defined by the builder and was based on California's 2008 Title-24 energy code. The base case assumed that any building components that were to be retrofitted would be upgraded to meet minimum requirements per the energy code. Cost data were provided directly by the builder. The total retrofit cost for the efficiency measures was calculated to be $57,300; incremental costs were $21,200.

Although cost is a key consideration in the selection of efficiency measures for this relatively affordable home, the high value of homes in this Silicon Valley location makes it easier to implement improvements that may be more difficult to support in lower income neighborhoods.

Table 2. Total and Incremental Costs

Component	Base Case[a]	As Built Prototype	Base Cost	As-Built Cost	Inc. Cost
Envelope					
Exterior Walls: Cavity	2 × 4 frame 16 in. o.c. R-13 batt	2 × 4 frame 16 in. o.c. R-13 DensePack cellulose	$2,000	$2,800	$800
Exterior Walls: Rigid	None	2 in. PolyIso R6.2/in. (1200 matl/2400 labor)		$3,600	$3,600
Floor Insulation	R19 batt	4 in. PolyIso rigid R6.2/in. @ raised floor; 2 in. PolyIso over slab (2500 matl/5000 labor)	$3,000	$7,500	$4,500
Roof/Ceiling Insulation	R30 Rigid	6 in. Polyiso R 38 rigid	$6,000	$10,000	$4,000
Windows/Exterior Glass Doors	U-value/SHGC = 0.40/0.40	Serious triple-pane: U-value/SHGC = 0.17/0.27 and 0.21/0.49	$16,000	$20,000	$4,000
Envelope Sealing	Standard caulking and sealing	High performance sealants; PH retrofit standards. ACH50 1.47	$300	$2,500	$2,200
HVAC Equipment					
Heat/Cool Efficiency	7.7 HSPF/13 SEER 3-ton heat pump	12 HSPF/25 SEER 1-ton MSHP	$8,000	$3,300	$(4,700)
Ducting	1600 cfm system R-6 ducts in crawlspace	Wall-mounted unit in conditioned space			
Air Circulation System	Not used	Panasonic WhisperGreen FV13VKS3; 3 ducts/reg.		$1,200	$1,200
Mechanical Ventilation	Exhaust fans, continuous	HRV Zehnder ComfoAir 350	$800	$4,400	$3,600
Water Heating Equipment					
Water Heating	50 gal gas EF = 0.62	No change			
Hot Water Recirculation	None	Pump, demand recirculation		$600	$600
Home Energy Rating System Measures	None	Tight ducts, QII, blower door, EER verification		$800	$800
Appliances, Lighting, and Miscellaneous					
Lighting	Lighting per Title-24 per CA Title 24 only	90% fluorescent and LED on hardwired fixtures[b]			
Miscellaneous Electric Load (MEL) Controls	None	One-switch using Insteon controls		$250	$250
Total Costs			$36,100	$57,300	$21,200

[a] Base case assumptions based on current California code (Title 24) prescriptive requirements.
[b] No cost information was provided by the builder.

1.4.3 BEopt Optimization

BEopt optimization was completed during the design phase using BEoptE+ v1.3 to compare various efficiency measures and identify the differences between BEopt and PHPP recommendations. Certain degraded and damaged components, such as the walls, roof, and windows, needed replacing. In these cases, the existing conditions were not included as an option. The costs reported in Table 2 were used for this evaluation. Additional measures included in the optimization that are not listed in the table were evaluated using costs from BEopt's database. Figure 7 shows the results of the optimization compared to the proposed package point. Design decisions guided by PH principles are primarily responsible for the proposed package point landing above the least cost curve. The following measures reflect the difference between the proposed package and a package on the least cost curve resulting in similar savings (see orange circle in Figure 7).

- Three inches exterior foam on roof (versus 6 in.)
- No underfloor insulation (incremental savings were not enough to justify $4,500 incremental cost)
- Dual-pane versus triple-pane windows
- 1.9 ACH50 (note that the project actually achieved only 1.5 ACH50 instead of the targeted 1.0 ACH50)
- Exhaust mechanical ventilation (versus HRV).

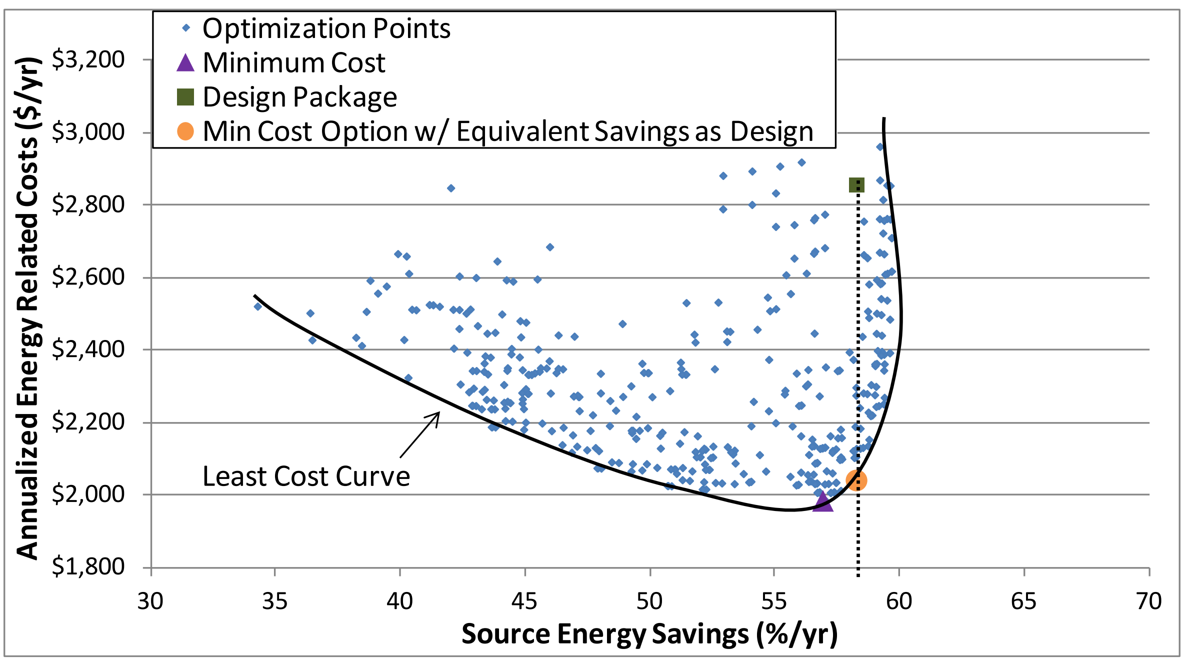

Figure 7. BEopt optimization least cost curve

Some of these discrepancies reflect the differences in priority between PH and BA approaches. PH encourages envelope measures that significantly reduce heating and cooling loads without a direct cost-effectiveness reference point; BA uses the least-cost curve as the design basis. Table 3 quantifies these differences in relation to PH requirements and recommendations. Although not evaluated in this study, elimination of these additional envelope measures may limit the effectiveness of the simplified distribution system employed in this house.

Table 3. PH and BA Requirements

	PH Requirements and Recommendations	As Designed[a]	BA Equivalent Savings on Least-Cost Curve	BA Minimum Cost
Source Energy Savings	–	58%	58%	57%
PH Requirements				
Space Heating (kBtu/ft^2*yr)	≤ 4.75	0.29	1.45	1.76
"Primary" Energy (kBtu/ft^2*yr)[c]	≤ 38.1	50.7	51.9	52.3
ACH50	≤ 0.6	1.0	1.9	3.7
PH Recommendations Window U-Value (Btu/ft^2*h*°F)	≤ 0.224	0.23	0.37	0.37
HRV/ERV	Yes	Yes	No	No

[a] These values are based on BEopt modeling results.
[b] This represents the PH recommendation for warm/temperatures climates. http://passiv.de/downloads/03_certification_criteria_transparent_components_en.pdf. Note that this U-value is calculated in accordance with European testing protocol ISO 10077 and cannot be directly compared to those calculated using the National Fenestration Rating Council 100 testing protocol.
c Using PH source multipliers of 2.7 for electricity and 1.1 for natural gas.

As the market shifts and incremental costs for efficient products are reduced, these products become more cost effective and move closer to the least-cost curve. Costs for certain items installed at the Sunnyvale house, such as triple-pane windows and MSHPs, have come down over the past few years and may continue to do so. This trend will result in better alignment between the PH and BA design recommendations.

2 Technical Approach and Methodology

Short-term tests, long-term monitoring, homeowner feedback, and detailed analyses of results were used to identify the attributes of performance, cost, and comfort related to retrofit measures. Post-retrofit monitoring data for 12 months were compiled for whole-house and end-use electricity and gas use, along with indoor and outdoor temperature and relative humidity (T/RH). The monitoring discussed in this report extends from May 1, 2013 through April 30, 2014. The data were compared to pre-retrofit utility bill data and a calibrated model was developed to estimate energy savings. At the conclusion of the monitoring period, the homeowners were surveyed to qualitatively evaluate their satisfaction and perception of comfort in the retrofit home. Actual pre-retrofit and post-retrofit energy consumption was compared relative to the modeling estimate to evaluate retrofit savings.

2.1 Measurements

2.1.1 Short-Term Tests

ARBI collected additional data using the following short-term tests. The tests include:

- Measurement of pre-retrofit and post-retrofit house leakage using a blower door test and standard protocols.
- Pre-retrofit duct leakage measurement using a Duct Blaster.
- Airflow measurements of the central circulating fan and the HRV using a small balometer.

2.1.2 Monitoring Methods

A monitoring system was installed to collect key data, including T/RH data, whole-house electricity and gas energy use, electricity use for HVAC components, gas use for water heating, and user interactions with the MEL control. A Datalogger, DT-50 programmable data logger and cellular modem were used to continuously collect, store, and transfer data back to Davis Energy Group servers. Sensors were scanned every 15 seconds; data were summed or averaged as appropriate and stored in the data logger memory every 15 minutes. Data were downloaded to a server every 24 hours, and range checks were automatically performed to identify problems with monitoring sensors or the systems being monitored.

Table 4 lists the measurement points that were continuously monitored. Sensor type and model are also listed. Standard specifications for the sensors used in testing are listed in Table 5. Sensor selection was based on functionality, accuracy, cost, reliability, and durability.

Electrical measurement points were obtained from an eMonitor energy monitor installed by the builder to provide for additional disaggregation, including all individual major appliances (refrigerator, oven/and stove, dishwasher, and clothes washer/and dryer) and, grouped together, lighting and plug loads. Total gas usage data were obtained from monthly utility bills and gas cooking energy calculated as the difference between total and monitored water heating energy.

Table 4. Measurement Points and Sensors

Point No.	Abbreviation	Description	Location	Sensor Type	Sensor Mfg./Model	Channel
1	TAO	Temp, air, outdoor	North side of house in shaded location	RTD, 4-20ma	RM Young 41372VF	1+
2	RHO	RH, air, outdoor		RH, 4-20ma		1-
3	TAI1	Temperature, air, indoor, living area	Living room near thermostat	RTD, 4-20ma	Gen Eastern MRHT3-2-I	2+
4	RHI1	RH, air, indoor, living area		RH, 4-20ma		2-
5	TAI2	Temperature, air, indoor, master bedroom	Interior wall	RTD, 4-20ma	TCS/1000-T2	3
6	TAI3	Temperature, air, indoor, bedroom 1	Interior wall	RTD, 4-20ma	TCS/1000-T2	4
7	TAI4	Temperature, air, indoor, bedroom 2	Interior wall	RTD, 4-20ma	TCS/1000-T2	5
8	EHSE	Energy, electric, whole house	Subpanel	Power Meter	Wattnode/ WNA-1-P-240P	D1
9	EHP	Energy, heat pump	Subpanel	Power Meter	Wattnode/ WNA-1-P-240P	D2
10	EHTR	Energy, bathroom heaters	Subpanel	Power Meter	Wattnode/ WNA-1-P-240P	D3
11	EFAN	Circulation fan	Subpanel	Power Meter	Wattnode/WNA-1-P-240P	D4
12	SWS	One switch status	Subpanel	Status	One-Switch Receiver	D5
13	GWH	Gas, water heater	Water heater – garage	Gas Meter	Equimeter S-275P	1C
14	EHRV	Energy, HRV	Subpanel	Power Meter	Wattnode/ WNA-1-P-240P	2C

Table 5. Sensor Specifications

Type	Application	Mfg/Model	Signal	Span	Accuracy
RTD	Outdoor T/RH	RM Young	4-20 mA	–50° to 150°F 0%–100%	±1.5% +2% RH
RTD	Indoor/duct T/RH	ACI	4-20 mA	50°–90°F 0%–100%	±1.5% +2% RH
Small Power Monitor	Fan, outdoor unit, bathroom heaters, HRV, whole-house power	WattNode WNA-1-P-240-P	Pulse	CTA/40	±0.5%
Diaphragm Gas Meter	Domestic hot water gas use	IMAC/Rockwell	Pulse	10 pulses/ SCFM	±1ft³

Figure 8 provides a post-retrofit floor plan indicating the location of the data sensors.

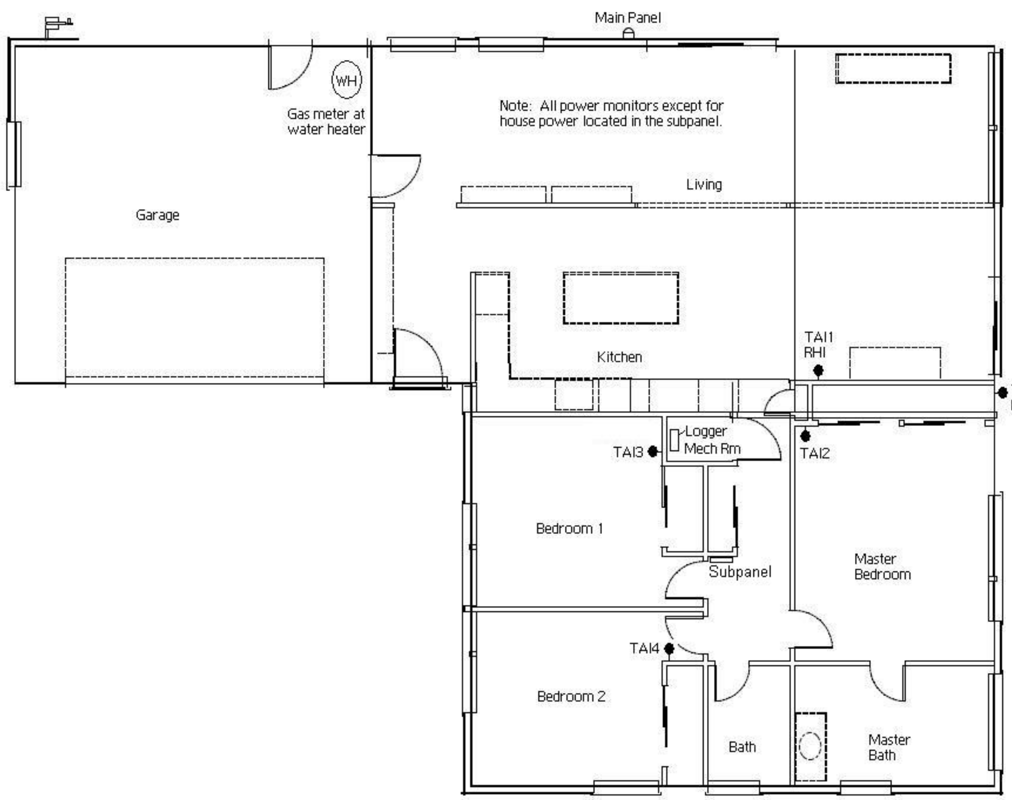

Figure 8. Floor plan showing T/RH sensor locations

Individual room temperatures were monitored to assess the effectiveness of the interior circulation fan according to the minimum performance standards for single zone system set forth in Air Conditioning Contractors of America (ACCA) Manual RS: Comfort, Air Quality and Efficiency by Design (Rutkowski 1997). Table 6 shows the minimum requirement for room-to-room air temperature difference.

Table 6. Manual RS Standard for Room-to-Room Air Temperature Difference

	Heating Season	Cooling Season
Maximum	4°F	6°F
Average	2°F	3°F

A recent BA report, *Simplified Space Conditioning in Low-Load Homes: Results from the Fresno, California, Retrofit Unoccupied Test House* (Stecher and Poerschke 2014) looked at the effectiveness of compact distribution systems. The authors found that systems with a single point of delivery to a living room and limited or no distribution to the remainder of the house complied well with occupancy comfort requirements defined in ASHRAE Standard 55-2010 (ASHRAE 2010) but did result in regular failures with Manual RS.

The specifications outlined in the NREL report, *Field Monitoring Protocol: Mini-Split Heat Pumps* (Christensen et al. 2011) have been referenced, but determining the MSHP's field performance (i.e., energy efficiency ratio, SEER, and HSPF) is not within the scope of this project. Calibration of BEopt's MSHP model using field data is a complex process that warrants a dedicated project.

2.2 Disaggregation, Normalization, and Pre- and Post-Retrofit Energy Comparisons

Pre-retrofit monthly electricity and natural gas utility bill data from 24 months prior to the retrofit were obtained. Pre-retrofit space conditioning loads were disaggregated from the monthly utility bills. Pre- and post-retrofit data were also normalized to Typical Meteorological Year 3 (TMY3)[5] weather data using the San Jose International Airport weather file. This normalization procedure is necessary because weather profiles change yearly, necessitating standardization of energy use for comparison purposes.

The methodology outlined in ASHRAE's Inverse Modeling Toolkit (Kissock et al. 2002) (developed in support of ASHRAE Guideline 14) (ASHRAE 2002) was followed for the disaggregation and normalization process. Pre-retrofit energy use was disaggregated into two main categories: baseload and weather dependent. Post-retrofit energy use was already disaggregated with monitoring data. First, a regression model was identified to describe energy use as a function of influential variables, in this case weather. The regression capability of Excel and the LINEST function, which uses the least squares method, was used to develop a linear relationship between energy use, monthly HDDs, and monthly cooling degree days (CDDs). Separate regressions were developed for electricity and natural gas energy, as well as for pre- and post-retrofit periods.

A variable-base degree-day model of the following type was used:

$$Y_{elec} = \beta_1 + \beta_2 * CDD + \beta_3 * HDD$$

$$Y_{gas} = \beta_1 + \beta_2 * HDD$$

[5] TMY3 weather data represent typical weather data from a particular weather station derived from 1991–2005 National Solar Radiation Data Base archives.

Where Y is monthly energy consumption, β_1 represents the constant term or baseload, and β_2 and β_3 represent the variable coefficients that characterize dependence on weather. CDDs and HDDs were used in the electricity regression to account for space cooling in the summer, fan energy during the heating season for the pre-retrofit case, and heat pump energy during the heating season for the post-retrofit case. There was no space cooling in the pre-retrofit scenario; therefore, the β_2 term should be zero.

HDDs and CDDs in any given period are calculated as follows:

$$CDD = \sum_{i=1}^{n}(T_i - a)$$

$$HDD = \sum_{i=1}^{n}(b - T_i)$$

where T_i is the daily average temperature and a and b are the base temperatures for cooling and heating, respectively. The base temperatures represent the average daily outdoor temperature above and below which space heating is requested. The base temperatures were determined by solving for that which results in a regression model with the highest coefficient of determination or R-squared (R^2). This was accomplished by conducting the regression for successive base temperatures between 41°F and 80°F to maximize R^2. Pre- and post-retrofit periods were evaluated separately to account for changes in interior conditions and comfort that may affect the base temperature.

The natural gas baseload is representative of water heating and cooking end uses. The calculated natural gas baseload from the regression was revised to reflect the seasonality and weather dependence of water heating. The monthly load profile from post-retrofit monitoring of the water heater was applied to the results. In effect, this increased the water heating gas use during the colder months.

Lastly, CDDs and HDDs calculated from TMY3 weather data were applied to the identified relationship to estimate normalized heating and cooling energy use and subsequently energy savings between the pre-retrofit and the post-retrofit period. Baseload energy use was assumed to be the same for actual and TMY3 weather conditions.

Table 7 lists some of the results and statistics from the regression exercise. In the pre-retrofit case, because there was no cooling, the regression on the electricity data provided poor results. The calculated heating electricity use was much higher than expected based on the calculated heating gas use, which was generated from the gas regression that yielded a very high R^2. Therefore, an assumption was made for the space heating fan energy use based on 1 kWh/therm, which was a reasonable average from other Davis Energy Group monitoring projects. A comparison of actual and normalized energy use is presented in the Appendix.

Table 7. Regression Results and Statistics

	Heating Base Temp	Cooling Base Temp	Natural Gas R2	Electricity R2
Pre-Retrofit	62°F	–	96%	–
Post Retrofit	55°F	66°F	–	92%

2.3 Modeling

The BEoptE+v1.3 model used during design was updated to v2.2 for final analysis. Efforts were made to calibrate the BEopt model using monitored data. This process included incorporating the following measurements into the model:

- Infiltration rates from blower door testing
- Heating and cooling thermostat set points based on post-retrofit monitored average living room seasonal temperatures (see Figure 9).[6] Living room instead of whole-house temperature was used because the thermostat is located in the living room and it is the only directly conditioned space.
- Appliance, lighting, and plug load energy use to accurately reflect actual average internal gains
- The scheduling of natural ventilation was changed from the standard assumption, which allows ventilation only 3 days per week, to all days during the cooling season. This change was made because the occupants indicated they regularly opened windows during the summer.

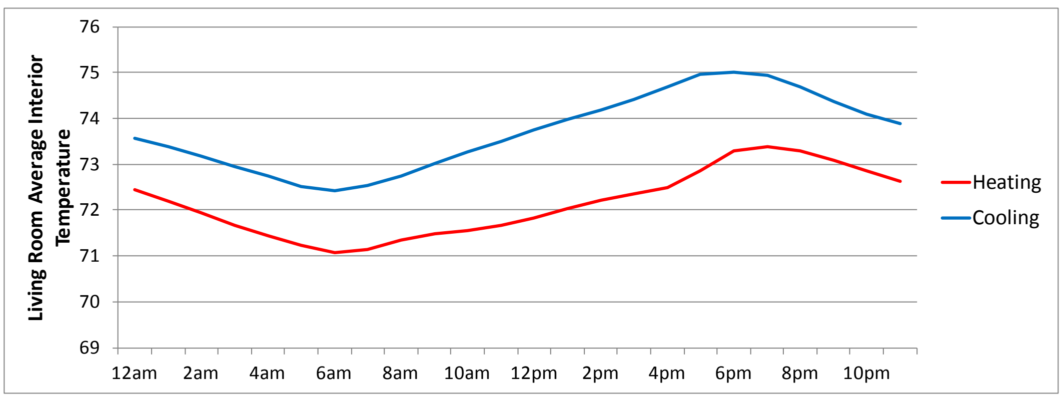

Figure 9. Average living room interior hourly temperature

The calibrated model was simulated using the San Jose TMY3 weather file and HVAC and water heating energy use is compared to measured values. Because the PHPP model was used as a design tool, PHPP estimates are also compared to monitored data. Appliance, lighting, and plug load energy use is also compared to the BEopt estimates from the pre-calibrated model to ascertain how these values compare based on typical occupancy assumptions and characteristics of the appliances (size, EF, fuel, etc.) as specified in the BA House Simulation Protocols (HSP) (Wilson et al. 2014).

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[6] Post-retrofit heating set point was applied to both the post-retrofit and the pre-retrofit model.

3 Results of Data Analysis

3.1 Energy Use over the Post-Retrofit Monitoring Period

3.1.1 Monthly and Annual Energy Use

Figure 10 presents monthly electricity consumption and Figure 11 demonstrates the end-use breakdown as a percentage of total energy over the 1-year post-retrofit period. As expected (because of the mild climate and high performance envelope), space cooling energy use is relatively low. In December, January, and February, heating is about one fourth of monthly electricity. Total heat pump energy represents 15% of total electricity. Total HVAC energy, including the circulation fan, is 17% of total electricity. The "other" category includes circuits not explicitly monitored by the eMONITOR system, including garage and exterior loads.

Appliances are the largest contributor to total electricity use at 40% of total electricity or 2,360 kWh. Of that about one fourth is attributed to refrigeration and one fourth to cooking,[7] one third to clothes washing, and the remainder to dishwashing. The refrigerator, dishwasher, and clothes washer are all ENERGY STAR-certified models and the clothes dryer is electric.

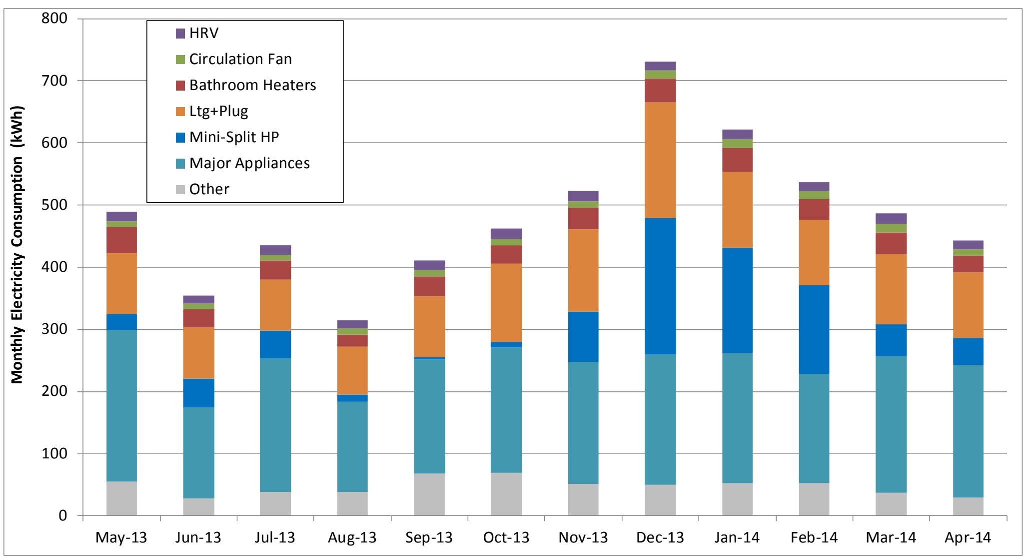

Figure 10. Monthly electricity use (kWh)

In Figure 12, a similar comparison is presented for natural gas consumption. Annual gas use is 150 therms; 93% of this is for water heating and the remainder is for the gas range. Although the water heater was not upgraded as part of the retrofit, a demand recirculation pump (counted in "other" category) and new water fixtures were installed. Range fuel was also switched from electricity to gas.

A typical daily electricity load profile is presented over 48 hours with no space conditioning operation, except for the bathroom heaters, in Figure 13. Bathroom heaters were used fairly regularly throughout the year in the evenings and early mornings. The house base load, which

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[7] The oven is electric and the stovetop is gas.

occurs during the evenings or unoccupied periods, is close to 200 Watts. There is no space cooling during these two September days and 5 W power draw from the MSHP represents standby usage. The low-power, continuous operation of both the HRV and the Panasonic circulation fan can be seen at 20 W and 15 W, respectively. The largest power draw during this period is a result of appliances, lighting, and plug loads, which is consistent with annual results shown in the graphs above.

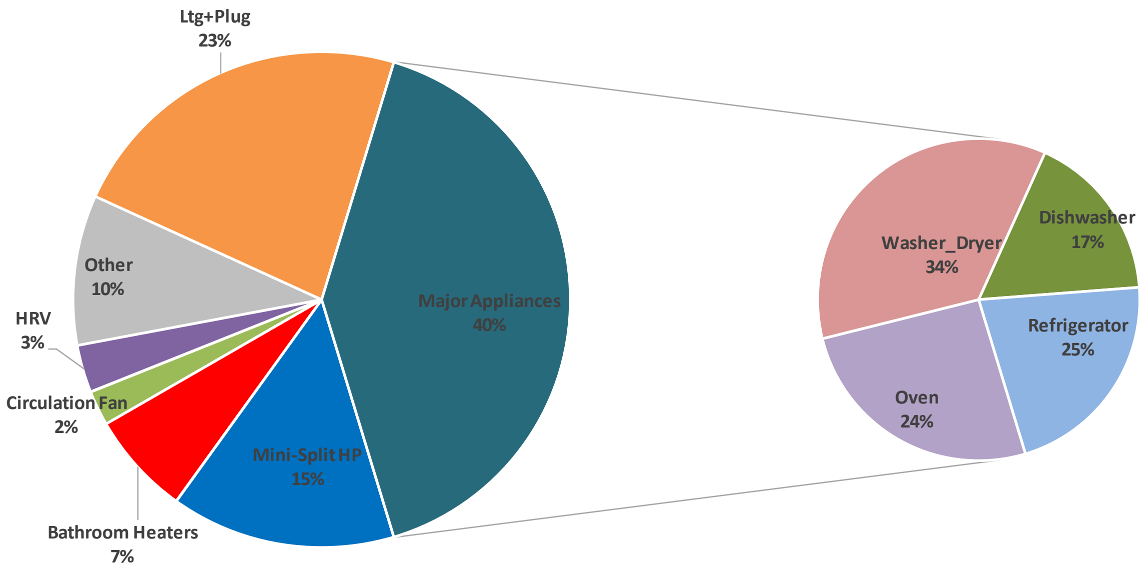

Figure 11. Post-retrofit electricity end-use breakdown over the 12-month monitoring period

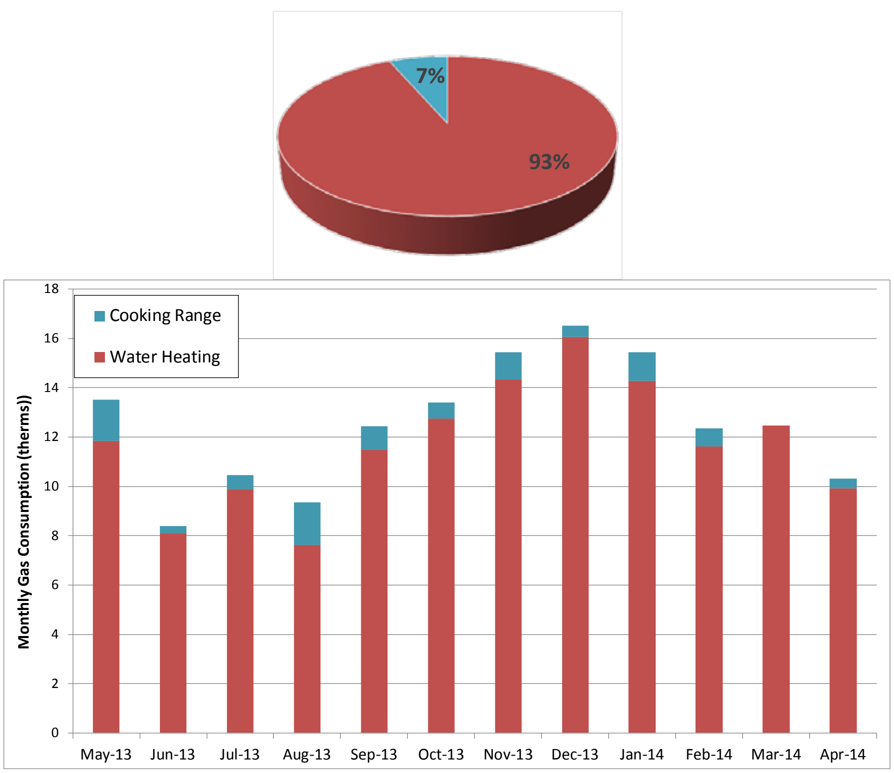

Figure 12. Monthly post-retrofit natural gas use and breakdown for 12-month monitoring period

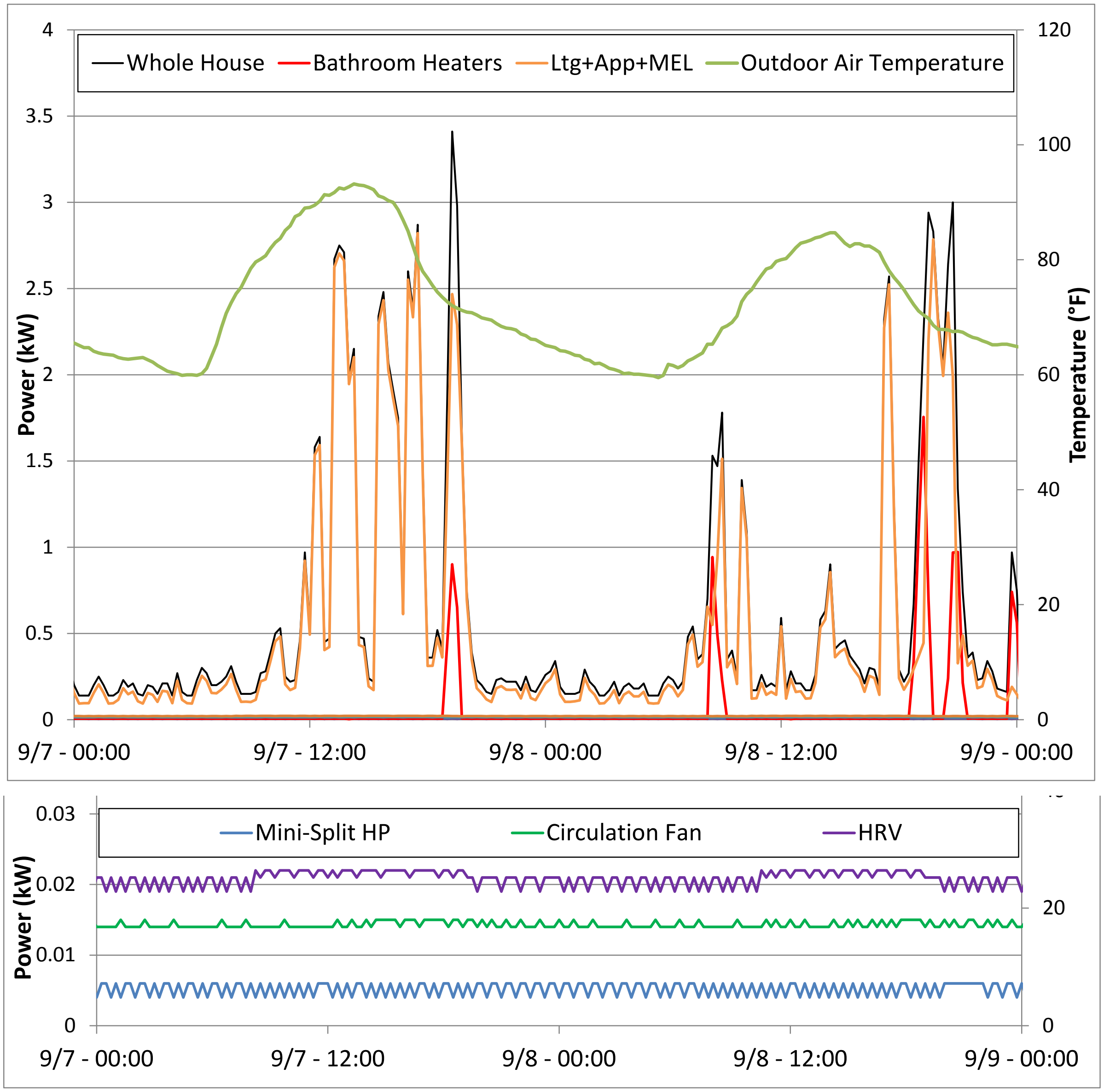

Figure 13. Electricity power profile over 48 hours (no space conditioning)

3.1.2 HVAC Distribution System and Comfort

The effectiveness of the distribution strategy was evaluated by measuring room-to-room temperature differences throughout the house. Table 8 compares measured room-to-room temperature differences with the requirements as set forth by ACCA Manual RS (Rutkowski 1997). Reported values are based on 15-minute average monitored data. Figure 14 demonstrates the monthly average temperature profiles of the four monitored spaces over the 12-month period. Also presented in Figure 14 are the percentages of time the maximum room-to-room temperature difference was outside the acceptable range as defined by Manual RS.

In the cooling season, temperature differences across all four rooms remained relatively small and the guidelines set forth by Manual RS were met 100% of the time. Temperatures in the bedroom remained lower than in the living room, indicating that cooling requirements in those spaces may be minimal because of good thermal design.

Table 8. Comparison of Observed Room-to-Room Temperature Differences

	Space Cooling	Space Heating
ACCA Manual RS	Maximum 6°F Average 3°F	Maximum 4°F Average 2°F
Measured Average	0.88	1.73
% Failure – Average	0%	34%
Measured Maximum	5.6	8.2
% Failure – Maximum	0%	31%
Measured Minimum	0	0

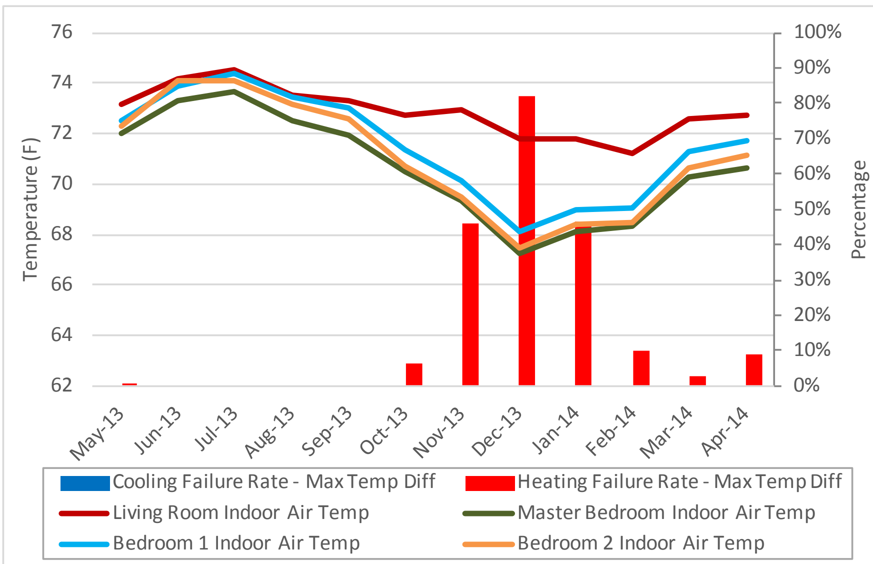

Figure 14. Average monthly temperature profiles in the conditioned space

Larger room-to-room deviations were observed during the heating season. The maximum temperature difference observed was 8.2°F (4.2°F higher than the 4°F maximum allowed by Manual RS for heating). The standard was exceeded 34% of the time based on average temperature differences and 31% based on maximum temperature differences. Operation outside the standard's recommended range was greatest during the coldest months, coinciding with increased heat pump operation. The heat pump also operated much more during the winter than in the summer, which may have contributed to the seasonal difference.

If the occupants were comfortable with the same temperature requirements defined for the cooling season (maximum 6°F and average 3°F), the system would have been within the temperature range for all but 3% of the time (154 hours).

Figure 15 and Figure 16 demonstrate typical daily temperature profiles within the home during the summer and winter, respectively. The summer temperature distribution is relatively small, even during heat pump operation. In the winter, temperatures vary much more, not only between the living room and the bedrooms, but also bedroom-to-bedroom. The temperature increase in bedrooms 1 and 2 during the morning is likely caused by solar gain through the southeast-facing windows. Most of the windows in the other rooms are substantially shaded.

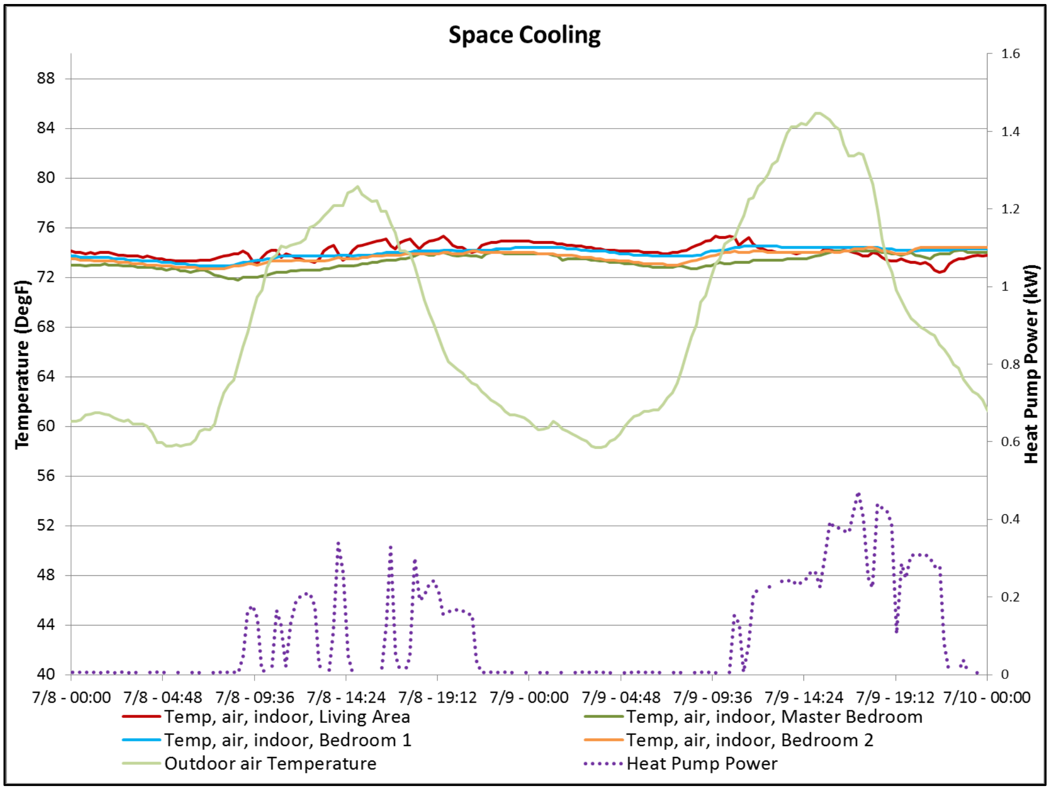

Figure 15. Space cooling temperature and heat pump operating profile for typical summer day

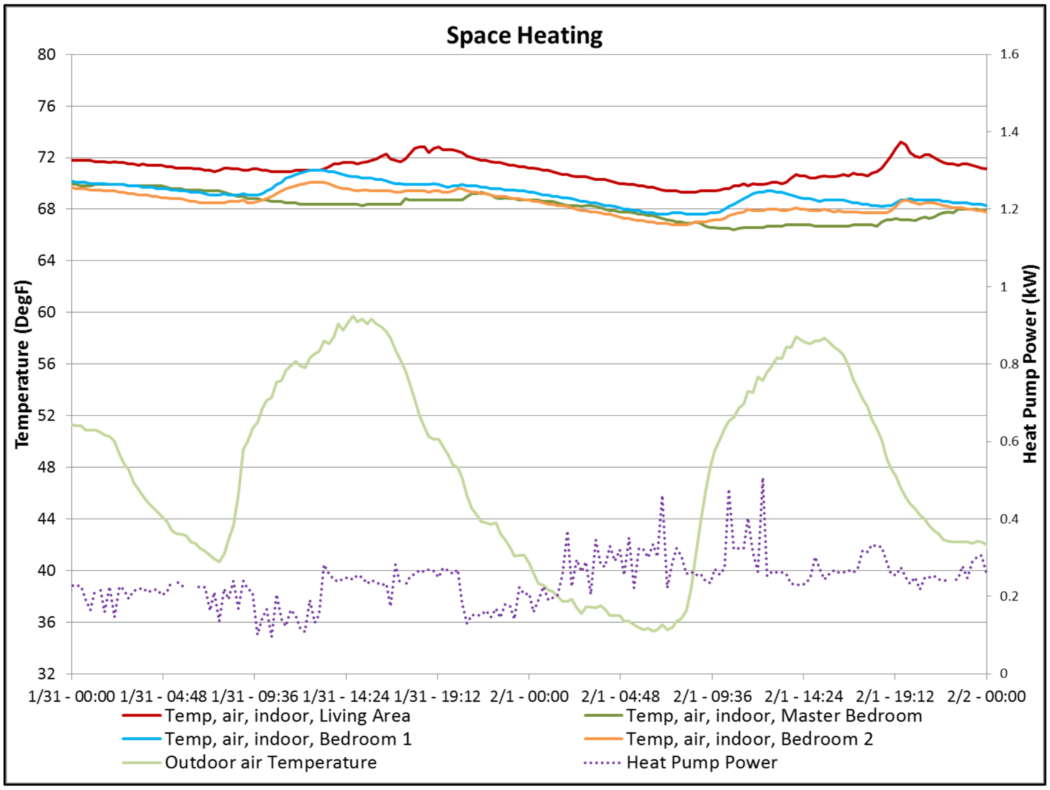

Figure 16. Space heating temperature and heat pump operating profile for typical winter day

3.1.3 Plug Load Control

The effectiveness of the one-switch plug load control could not be evaluated because the system was not connected. In the middle of the monitoring period the homeowners were sent a reminder about the system and how they could use it. However, the system continued to be unemployed.

3.2 Energy Savings

Normalized pre-retrofit and post-retrofit energy use is compared in Table 9. Electricity savings are negative at –129 kWh because the heating fuel switched from gas to electricity and the mechanical cooling was added. Annual gas savings are 504 therms, resulting in utility cost savings of $500. Total source energy savings are 54 MMBtu/year or 40%, which are almost entirely a result of space heating savings. Original estimates predicted 129 MMBtu annual source energy savings, or 58%. Two major components of this were heating energy use with 98% source savings and lighting with 46% source savings. Actual heating source savings are 87%. Lighting savings could not be verified based on mointoring limitations.

Table 9. Annual Site and Source Energy Savings Normalized to TMY3

	Pre-Retrofit	Post-Retrofit	Annual Savings
Electricity			
Space Heating (kWh/yr)	508	718	–208
Space Cooling (kWh/yr)	0	90	–90
Total Electricity (kWh/yr)	5,636	5,765	–129
Natural Gas			
Space Heating (therms)	508	0	510
Total Natural Gas (therms)	654	150	504
Source Energy (MMBtu/yr)[a]	132	78	54
Utility Cost[b]	$1,462	$963	$500

[a] Source multipliers of 3.15 for electricity and 1.09 for natural gas based on BEopt v2.2

[b] Utility rates for Pacific Gas & Electric rate based on averages from actual utility bills of 1.03/Therm and 0.14 /kWh.

3.3 Comparison to Energy Model

The calibrated energy model results were compared to monitoring post-retrofit data and utility pre-retrofit data, all normalized to TMY3 weather to compare HVAC and water heating estimates with actual data. In this exercise lighting, appliances, and plug loads were adjusted in the model to match measured values and reflect average internal gains. Although the homeowners reported operating their thermostat manually, average interior living room operating temperatures for the cooling and heating seasons were obtained from the post-retrofit monitoring data and thermostat set points were adjusted accordingly (see Figure 9). Monitored post-retrofit heating energy use does not include the bathroom electric resistance space heaters. Little seasonality was observed in this appliance (see Figure 10) and the winter room-to-room temperature profiles indicate that the heat pump thermostat probably is not influenced by an increase in air temperature caused by bathroom heater operation. Energy use of the bathroom heaters was included in the adjusted plug loads in the model and therefore their internal gains were accounted for.

Figure 17 and Figure 18 present this comparison for the pre-retrofit and post-retrofit cases, respectively. BEopt estimates 61% higher space heating gas consumption for the pre-retrofit case (821 therms versus 510 therms); however, it underestimates heating by 84% in the post-retrofit case (114 kWh versus 718 kWh). Post-retrofit cooling electricity use is overestimated by 300% (360 kWh versus 90 kWh).

The free-cooling function of the HRV, whereby cool outdoor air bypasses the heat exchanger and is supplied directly to the house in cooling season, could not be directly modeled in BEopt. To estimate the effect of this, a second model was run with the sensible heat recovery of the HRV set to zero and cooling energy use during hours when the outdoor temperature was cooler than indoors was compared. The removal of heat recovery resulted in savings of 57 kWh annually thereby reducing the 300% overprediction to 237%.

Estimates for domestic hot water gas use (1% higher) and the HRV vent fan (12% lower) are both very close to measured values.

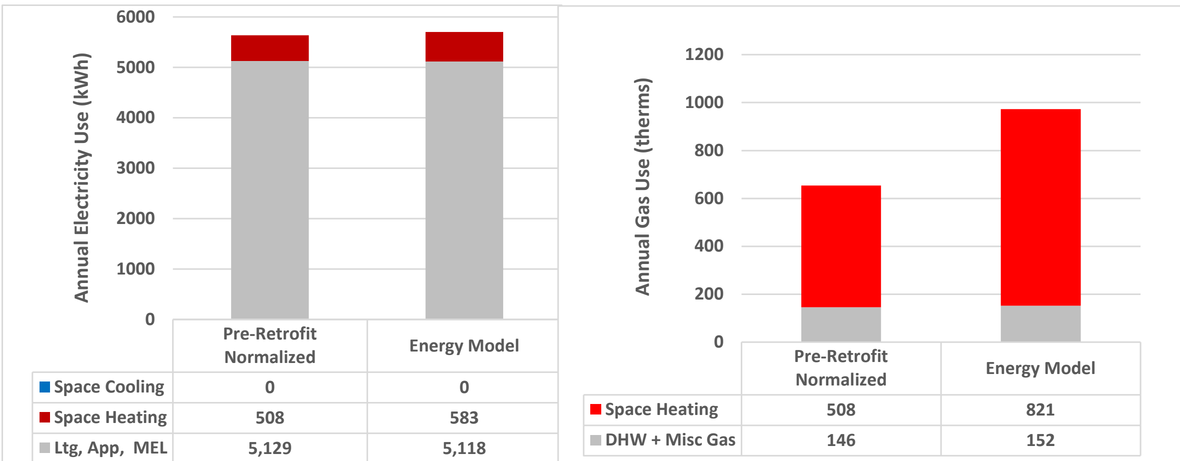

Figure 17. Annual pre-retrofit comparison to BEopt model estimates

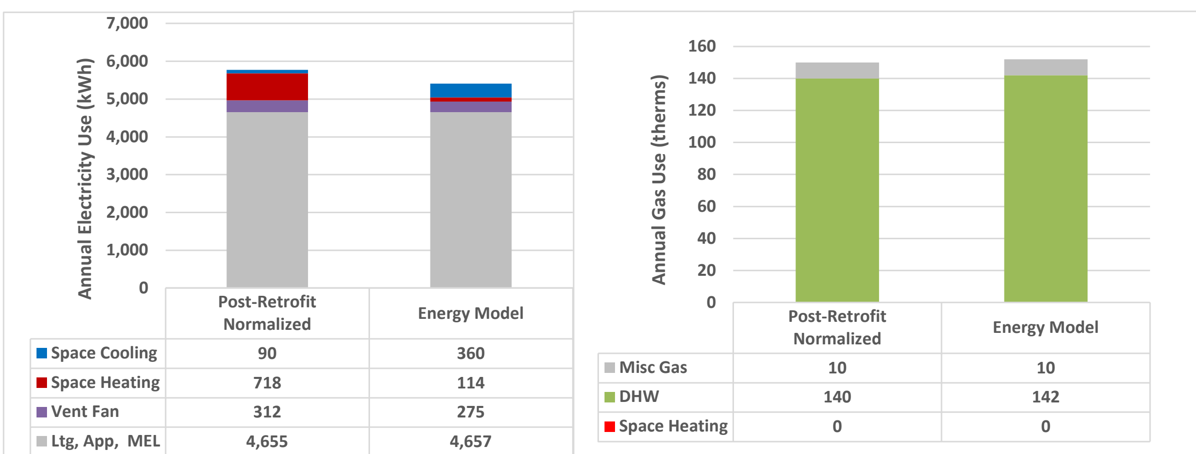

Figure 18. Annual post-retrofit comparison to BEopt model estimates

Figure 19 provides a comparison to the PHPP estimates for heating and cooling. The same thermostat set points were applied to the PHPP as in BEopt except setbacks and setups cannot be modeled; therefore, average daily living room temperatures were used (74°F cooling and 72°F heating). Internal gains were also adjusted to reflect average conditions.

PHPP estimated heating energy to be 48% higher than actual and cooling to be 23% higher. Of interest is how differently BEopt and the PHPP estimate the relative heating and cooling loads. BEopt predicts predominant cooling loads; the PHPP predicts predominant heating loads (which was observed).

Attempts were made to model internal gains, equipment efficiencies and operational schedules per actual conditions; however, differences may remain that contribute to the observed discrepancies. Although the percentage differences in heating and cooling energy use between actual and modeling estimates may be high, the magnitudes of the total energy use values are relatively insignificant.

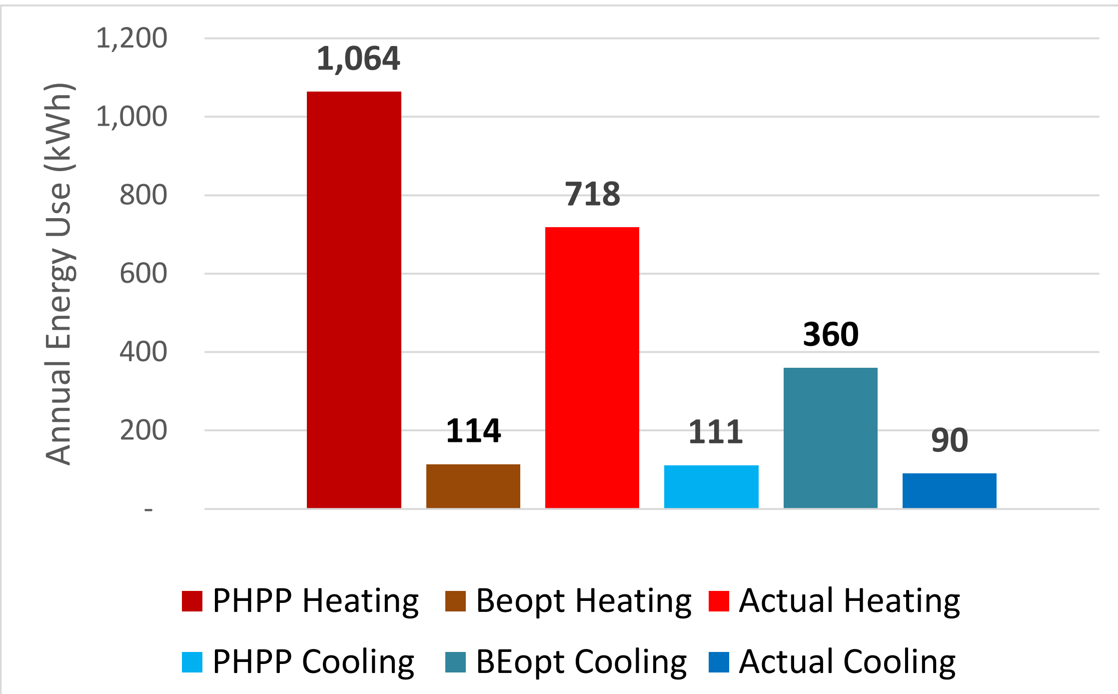

Figure 19. Annual post-retrofit comparison to PHPP estimates

Specific appliance, plug load, and lighting energy uses were also compared with the BA HSP estimates (see Table 10). ENERGY GUIDE estimated annual consumption values for two appliances are also presented, data for the other appliances either couldn’t be obtained or were not published for that product type. For this comparison no calibration adjustments were made in BEopt and the options were selected based on the HSP and general characteristics of the appliances (size, EF, fuel, etc.).

Lighting and MEL combined electricity uses were 30% lower than the HSP estimate. Total appliance electricity use was 88% higher. Clothes washing and refrigeration were both relatively close to estimates. Actual cooking energy use was almost twice as high as HSP estimates and dishwasher use was 200% higher than BEopt estimates and 40% higher than the ENERGY GUIDE label. This seems to be largely driven by occupancy patterns. The house is occupied by a family of five and they use the kitchen appliances regularly.

Table 10. Appliance, Lighting, and MEL Post-Retrofit Electricity Use Comparison With HSP and ENERGY GUIDE Estimates

End Use	Actual Annual Use (kWh)	HSP Annual Use (kWh)	ENERGY GUIDE Annual Use (kWh)
Lighting + MEL	1895	2685	–
Major Appliances	2,359	1,912	–
Refrigerator (21.6 ft^3)	508	459	459
Dishwasher (0.76 EF)	401	129	285
Clothes Washer/Dryer	841	824	–
Cooking*	608	500	–

*Actual use only includes oven because the range is gas, this cannot be separated in BEopt and the 500 kWh estimate includes both electric oven and range.

3.4 Homeowner Feedback

The homeowners were surveyed to better understand general occupancy patterns and thermostat operation, identify any behavioral changes across the evaluation period, and evaluate their satisfaction with the retrofit. They reported limited change in occupancy or use from pre-retrofit conditions to post-retrofit. The only change is that only one occupant is now home on weekdays but two occupants were generally home pre-retrofit.

Primary motivations for the home energy retrofit were to improve thermal comfort and IAQ, reduce the maintenance burden, and improve energy efficiency. The homeowners report being very comfortable in their house since the retrofit and are noticing improvements in both comfort and IAQ. When asked if all the rooms in the house were equally comfortable their response was that they “somewhat agreed.” The monitoring data show temperature differences throughout the house during the heating season that would be perceptible as one walks from room to room throughout the house. They also “somewhat agree” with the statement that “my retrofit was a good value at the price I paid for it,” which indicates the high cost of retrofitting certain measures (such as windows and particularly envelope measures), and the need to further improve cost effectiveness of energy upgrades. Overall, the occupants are very satisfied with the retrofit.

Responses to home comfort questions are below in Table 11. The respondent was asked to respond with the following choices: Strongly Agree, Agree, Somewhat Agree, Neutral, Somewhat Disagree, Disagree, Strongly Disagree, Not Applicable.

Table 11. Occupant Survey Results

1. My home is comfortable in the winter.	Strongly Agree
2. My home is comfortable in the summer.	Strongly Agree
3. All rooms in my home are equally comfortable.	Somewhat Agree
4. I am satisfied with the overall comfort of my home.	Strongly Agree
5. My home has low utility bills for its size and vintage.	Agree
6. My retrofit was a good value at the price I paid for it.	Somewhat Agree
7. I am satisfied with my retrofit overall.	Strongly Agree

4 Discussion and Conclusions

Following are responses to the research questions.

1. *Were the anticipated results of the retrofit achieved, including the estimated energy savings and expected comfort enhancements?*

Annual weather-normalized savings were $500 in utility costs and 504 therms in gas use along with an increase of 129 kWh in electricity use. Source energy savings were 54 MMBtu/yr (40% savings relative to pre-retrofit energy use) compared to original BEopt estimates of 129 MMBtu/yr (58% savings). Two major components of the 58% estimated savings were heating energy use with 98% source savings and lighting with 46% source savings. Actual heating source savings were measured at 87%. Lighting savings could not be verified because of monitoring limitations.

Although the magnitude of savings originally estimated was not achieved, average monthly utility bill savings of $42 are not trivial, particularly in mild climate homes. The homeowners reported being very satisfied with the retrofit and the overall comfort of the home.

2. *How does measured energy use compare to the modeled predictions?*

BEopt model estimates overpredicted heating energy use in the pre-retrofit case by 61%. Differences between model assumptions and actual conditions that could cause this difference include:

- Interior temperatures were not monitored during the pre-retrofit period and were assumed to be similar to those monitored during the post-retrofit period. Occupants may have used a different thermostat set point during the pre-retrofit winter period.
- Site shading, such as trees and structures, that could not be accurately modeled in BEopt.
- Qualifying the thermal and mass properties of existing assemblies presents difficulties caused by accessibility, availability of information, and limited model validations.
- Improper quantification of assemblies may result in large errors for estimated conduction losses/and gains across those assemblies.

In the post-retrofit case heating energy was underpredicted by 88% and cooling electricity was overpredicted by 300%. This represents a shift in the dominant space conditioning load, which BEopt represents as cooling and in actuality was heating. Differences between model assumptions and actual conditions that could cause this difference include:

- Site shading, such as trees and structures, that could not be accurately modeled in BEopt.
- The effects of zoning: This model was evaluated as a single zone without any space separation.
- Direct effects of the bathroom space heaters.
- Scheduling of internal gains and how these interact with thermostat setbacks, HRV free-cooling, and natural ventilation.

- Natural ventilation: The occupants indicated that they open windows at night to take advantage of natural ventilation. Even though natural ventilation was modeled in BEopt, the actual effectiveness may be greater because of the window open area and ventilation cross-flows than the model assumes, or the scheduling may be different than model assumptions.

The last two points highlight the importance of correct occupancy assumptions for accurate evaluation of the impacts of internal gains on space conditioning. This is most apparent in high performance homes in mild climates where cooling loads from internal gains can be more significant than externally driven loads from solar gains and conduction from outdoors. Low infiltration rates and HRV reduce the effective passive removal of heat during cooler times of the day. Energy use esimates will be impacted if these modes aren't modeled accurately.

The PHPP predicted space heating as the dominant space conditioning load, but heating and cooling energy use were overpredicted by 48% and 23%, respectively. The PHPP does take into account site shading characteristics and individual window properties (SHGC differed based on orientation and shading) as well as the free-cooling function of the HRV. Better characterization of these passive cooling strategies may explain why the estimated cooling is closer to actual values. However, better representation of the passive strategies should have also resulted in lower estimated heating energy consumption. The model may have overvalued shading during the winter months. PHPP is not a dynamic model and uses monthly averages for calculation purposes, which also may introduce errors.

The percentage differences in heating and cooling energy use between actual and modeling estimates may be high; however, the magnitudes of the total energy use actual values are relatively insignificant.

There were differences between measured values for lighting, appliance, and plug load energy use and estimates from the HSP. These differences, which are largely driven by occupancy and modeling tools, are often not able or designed to anticipate actual occupancy on a house-by-house basis. Furthur research and expansion of long-term monitoring datasets will help improve industry understanding of the range of occupancy patterns that can be expected in residential homes and the impact on annual energy use, and ultimately improve modeling assumptions. Because occupancy patterns can lead to extremely varied energy consumption, future energy modeling tools may provide predictions within a range rather than finite estimates.

3. *How effectively can the MSHP and 100 cfm distribution fan deliver comfort to individual rooms?*

The distribution system effectiveley maintained comfortable temperature conditions in the home during the cooling season with no operation outside the ACCA Manual RS comfort standards. During the heating season, temperature distribution between rooms was frequently outside the ACCA recommended maximum of 4°F, particularly in the coldest months, and the maximum room-to-room temperature difference exceeded 4°F 31% of the time. This study did not isolate the effectiveness of the distribution system separately from the heat pump and high performance envelope. Future work could investigate the impact of distribution system performance on room-to-room comfort, measuring room temperatures with and without the central distribution fan operating and at varying airflow rates. Distribution may be improved with revisions to the distribution system design such as increased fan airflow or altering the locations of supply and exhaust points. If the Manual RS heating temperature guidelines are relaxed to those set forth for cooling (6°F maximum room-to-room temperature difference), the failure rate falls from 31% to 3%. These temperature conditions may be acceptable to some occupants, particularly those who prefer cooler sleeping quarters. However, the occupants in this house indicated they were somewhat satisfied with the level of comfort room-to-room, indicating opportunities for improvements in providing evener temperature distribution.

Capital costs for the MSHP, distribution fan and associated ductwork were $4,500, saving the builder $3,500 relative to a split system heat pump with ducted delivery of conditioned air to all rooms. These costs savings are substantial and warrant further work to validate this strategy, which has significant potential to be a cost effective means of providing space conditioning in small- to medium-size low-load homes.

4. *How do the BA- and PH-recommended efficiency packages differ and how can they best be combined to cost effectively achieve deep energy savings?*

Comparisons of BEopt- and PHPP-recommended packages highlight certain major differences. BEopt modeling indicates that similar energy savings but substantial cost savings can be achieved in mild climates with the following changes to the design package for this project.

- Single-fan ventilation instead of HRV/ERV – The energy savings for heat recovery are minimal in mild climates, making it hard to justify the incremental costs. However, balanced ventilation is a smart strategy in tight homes, and although there exist some affordable balanced residential solutions that don't include heat recovery, they are limited. This limited availability may encourage more projects to incorporate heat recovery systems, ultimately reducing costs over time.
- Dual-pane versus triple-pane windows – Costs for triple-pane windows are currently very high, making them cost prohibitive for most projects in all but the most extreme climates.
- Reduced insulation levels at roof and floor – BEopt recommends lower levels of insulation for most assemblies compared to the PHPP. In this case BEopt recommended leaving the floor uninsulated because of the high costs of insulating an existing floor. Even though this may represent the lowest cost option, any uninsulated assembly would likely compromise occupant comfort.

Without the efficiency measures described above, the house would not comply with PH criteria for certification. Designing to the PH standard was an important goal for this project, so inclusion of these measures was justified.

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Appendix: Normalized Energy Use for Space Heating and Cooling

Table 12 compares actual and weather normalized energy use for space heating and cooling for both the pre-retrofit and post-retrofit cases.

Table 12. Actual Versus Normalized Energy Use for Weather Dependent End-Uses

	Pre-Retrofit		Post-Retrofit	
	Actual	Normalized	Actual	Normalized
Electricity				
Space Heating (kWh/yr)	404	508	707	718
Space Cooling (kWh/yr)	0	0	143	90
Total Electricity (kWh/yr)	5,533	5,636	5,817	5,775
Natural Gas				
Space Heating (therms/yr)	404	508	0	0
Total Natural Gas (therms/yr)	551	654	150	150

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