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Retrofitting a 1960s Split-Level, Cold-Climate Home

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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

ACH_{50}	Air Changes Per Hour at ±50 Pascal
BEopt™	Building Energy Optimization Software
CARB	Consortium for Advanced Residential Buildings
ccSPF	Closed-Cell Spray Polyurethane Foam
cfm	Cubic feet per minute
DHW	Domestic Hot Water
kW	Kilowatt
kWh	Kilowatt-Hour
PV	Photovoltaic
RH	Relative Humidity
SPB	Simple Payback
WRB	Weather-Resistant Barrier

Executive Summary

National programs such as Home Performance with ENERGY STAR® and numerous other utility air-sealing programs have made homeowners aware of the benefits of energy-efficiency retrofits. Yet these programs tend to focus only on the low-hanging fruit: they recommend air sealing the thermal envelope and ductwork where accessible, switching to efficient lighting and low-flow fixtures, and improving the efficiency of mechanical systems (though insufficient funds or lack of knowledge to implement these improvements commonly prevent the implementation of these higher cost upgrades). At the other end of the spectrum, various utilities across the country are encouraging deep energy retrofit programs. Although deep energy retrofits typically seek 50% energy savings, they are often quite costly and are most applicable to gut-rehab projects. A significant potential for lowering energy use in existing homes lies between the low-hanging fruit and deep energy retrofit approaches—retrofits that save approximately 30% in energy compared to the pre-retrofit conditions. The energy-efficiency measures need to be nonintrusive so the retrofit projects can be accomplished in occupied homes.

The U.S. Department of Energy Building America research team Consortium for Advanced Residential Buildings (CARB) partnered with Preferred Builders, a previous CARB partner and builder of the Performance House (DOE 2013) and the owners of a 1960s split-level home in Westport, Connecticut, to evaluate and implement a cost-effective solution package that met the requirements of 30% source energy savings compared to the pre-retrofit performance. This home had already been updated aesthetically (kitchen and bathrooms), so the owners wanted the energy-efficiency measures to be as nondisruptive to the interior finishes as possible.

The final solution package focused on increasing the thermal resistance and airtightness of the building enclosure and providing more efficient and effective space conditioning before a 5.2-kW grid-connected photovoltaic (PV) system was installed. For the building enclosure, dense-packed cellulose was applied into the exterior walls from the exterior of the home to minimize impact on interior finishes. In the attic, closed-cell spray polyurethane foam (ccSPF) was applied at the roof deck. The two rooms with vaulted ceilings were insulated through a combination of ccSPF and dense-packed cellulose at the roof deck, but the interior ceiling drywall had to be removed. Careful coordination of trades was essential to ensure the shortest time frame possible for the vaulted ceiling work to be nondisruptive to the occupants.

The oil boiler was replaced with a natural gas condensing tankless boiler, because natural gas was available at the street. This boiler feeds the hydronic baseboard heaters and provides domestic hot water. The configuration of the split-level home does not allow for the integration of a central distribution system for cooling, so a multiport air-source heat pump was installed. Although the heat pump was primarily installed for air conditioning throughout the home, it also provides auxiliary space heating.

Analysis using the National Renewable Energy Laboratory's Building Energy Optimization software suggested that the solution package would be cost-effective and would reduce source energy use by 35.5% without PV (69.4% with PV). Annual energy-related costs were estimated to be $1,238 lower without PV and $1,999 lower with PV. The actual source energy savings was 30.2% without PV (65.5% with PV). From the homeowner's perspective, the critical criterion was operational cost reductions, which were 38.4% without PV and 70.3% with PV.

The simple payback for the final solution package with PV would be 13.2 years with incentives and 17.9 years without incentives. According to the U.S. Department of Energy's new green appraisal methodology, the added value to the home is $69,712, or 14% more than the incentivized cost of the retrofit improvements.

The mechanical systems were able to maintain temperatures at ±2°F between rooms (and the thermostat set point) during the winter and at ±3°F between rooms during the summer. Relative humidity levels were in desirable ranges (25%–45% for the winter and 48%–62% for the summer).

The CARB team implemented this cold-climate retrofit project, which involved the design and optimization of a home in Connecticut to improve energy savings by at least 30% without PV compared to the pre-retrofit performance. This report documents the successful implementation of a cost-effective solution package that achieved performance greater than 30% compared to the pre-retrofit—what worked, what did not, and what improvements could be made. The 30% source energy savings was confirmed by comparing the utility bills pre- and post-retrofit.

1 Problem Statement

1.1 Introduction

The 1960s split-level home in Figure 1 may appear to be move-in ready, because it is clean and the kitchen and bathrooms have been updated. Yet this home's heat is supplied by an oil boiler through hydronic baseboards, and its cooling is supplied by a combination of a poorly fitted through-wall air conditioner in the kitchen and three window air conditioners. Overall insulation condition was marginal, with severely deteriorated fiberglass batts in the wall cavities and ceiling. Blower door testing revealed a building infiltration rate that was slightly higher than 7 ACH50. The end result, based on information from the previous homeowners, was an annual utility cost of slightly more than $5,700 for this 2,000-ft^2 home, which is double that of a comparable home built to the 2009 International Energy Conservation Code requirements. According to 2009 estimates by the Joint Center for Housing Studies, nearly 40% of residential energy consumption is attributable to homes built before 1970 (JCHS 2009).

Figure 1. Interior of existing home

According to Lee (2010), fewer than 1% of homes have had energy retrofits specifically to save energy. A survey of 479 home energy auditors by Resources for the Future suggests that a lack of funding is the primary barrier that prevents homeowners from making energy improvements (Palmer et al. 2011). According to Creyts et al. (2010), core spending for most families absorbs 90% of average household budgets, so a "typical" retrofit costing $1,500 absorbs 30% of annual discretionary spending. The next major barrier for energy retrofits is a lack of information about cost-effective investments and how to properly implement them.

The U.S. Department of Energy's Building America research team Consortium for Advanced Residential Retrofits (CARB) conducted this cold-climate retrofit project, which involved the design and optimization of a home in Connecticut to improve energy savings by at least 30% without photovoltaics (PV). This home already had aesthetic updates (kitchen and bathrooms), so the homeowner wanted the energy-efficiency measures pursued in the project to be as nondisruptive to the interior finishes as possible. This project was also interesting because the home used oil for heating and propane for cooking, but natural gas was available at the street.

The goal of this research was to document the successful implementation of a cost-effective solution package that achieved savings greater than 30% compared to the pre-retrofit—what worked, what did not, and what improvements could be made. The 30% source energy savings was confirmed by comparing the utility bills pre- and post-retrofit.

1.2 Background

National programs such as Home Performance with ENERGY STAR® and numerous other utility air-sealing programs have made homeowners aware of the benefits of energy-efficiency retrofits. Yet these programs tend to focus only on the low-hanging fruit: they suggest air sealing the thermal envelope and ductwork where accessible, switching to efficient lighting and low-flow fixtures, and improving the efficiency of mechanical systems (though these upgrades are rarely implemented).

At the other end of the spectrum, various utilities across the country are pursuing deep energy retrofit programs. These typically seek 50% energy savings but often are quite costly and more applicable to gut-rehab projects. Building America teams have documented several deep energy retrofit test homes and community projects in various climate zones: mixed-humid (Lyons et al. 2013); hot-dry (Puttagunta 2013); and cold (Osser et al. 2012). McIlvaine et al. (2013) wrote a technical report on *The Next Step Toward Widespread Residential Deep Energy Retrofits*.

Although deep energy retrofits provide valuable research, a substantial opportunity for lowering energy use in existing homes is to address retrofits that save approximately 30% in energy costs. The key is that the energy-efficiency measures need to be as nonintrusive as possible, because many of these potential retrofit projects will need to be occupant-in-place retrofits. Building America research in the mixed-humid (Moore 2013) and hot-humid (Zoeller et al. 2013) climates provided a starting basis for these types of solution packages, but additional field vetting is needed for various housing types and climate zones.

1.3 Relevance to Building America's Goals

Although many of the key resale components (kitchen, baths, and windows) of this 1960s home had been updated in terms of aesthetics and efficiency (low-e glass, ENERGY STAR appliances, low-flow fixtures), CARB still found numerous opportunities to improve its overall performance and comfort. CARB sought to identify and implement energy-efficient retrofit measures that provided the most value to the homeowners without PV. Key health, safety, and durability issues were addressed, such as:

- Isolating the tuck-under garage from the adjoining living spaces
- Improving insulation while minimizing damage to interior walls
- Providing alternative heating solutions so that oil boiler use could be eliminated
- Providing alternative cooling solutions that are more efficient than the through-wall and window air conditioners
- Eliminating pest problems.

According to Palmer et al. (2011), a "lack of information about specific ways to improve energy efficiency and reduce unnecessary energy use has long been identified as an important reason why all types of building owners, including homeowners, do not make apparently cost-effective improvements in their buildings or upgrade to more efficient appliances or equipment." Therefore, the design process, motivation for the homeowners, and implementation of the renovations for this project are presented in a pictorial step-by-step guide.

2 Research Questions

CARB worked with the homeowners to optimize the enclosure and mechanical systems with respect to efficiency, performance, comfort, and cost.

This team sought to answer the following research questions:

- Which energy savings solution packages are viable for reaching the 30% improvement level for this home?
- How cost-effective was the 30% source energy savings solution package implemented on this home?
- How well was comfort maintained throughout the home after the energy-efficiency package was implemented?

CARB worked with the project team to support the implementation of a solution package to demonstrate the viability of a 30% whole-house energy savings retrofit. CARB visited the project site during construction and worked with contractors to track retrofit costs. CARB performed short-term testing and commissioning on the various systems of the home. The long-term system performance monitoring focused on the ability of the mechanical systems to provide uniform comfort throughout the living space and the performance of the PV system.

CARB monitored the home to better understand the comfort levels. The homeowners placed a high priority on temperature uniformity, so it was imperative that the mechanical system improvements achieve this goal. Along with feedback from the homeowners, the Air Conditioning Contractors of America's Manual RS comfort criteria were used as the metric to determine if comfort had been achieved. In addition to the standard measurement protocol, an additional temperature and relative humidity (RH) sensor was placed in each room along the exterior perimeter (though situated so it was not in the path of direct solar gain) to determine the temperature differentials in each room and whether any additional modifications needed to be made to the standard methodology of placing thermostat controls.

3 Design Considerations

Taking into consideration the homeowners' goals (cost, timeline, comfort criteria, etc.), CARB used the Building Energy Optimization (BEopt™) software to develop a solution package that optimized the enclosure and mechanical systems with respect to efficiency, performance, comfort, and cost. The project team focused on the following key components and potential solutions to enhance these components.

- Ways to improve the exterior wall insulation (the insulation was poorly installed and deteriorated R-11 fiberglass batts) without damaging the interior drywall.
    - Remove the cedar shingle siding to add 1 in. of exterior rigid insulation over the wood sheathing. Finishing details around windows and doors will determine whether this method is feasible.
    - Remove the cedar shingle siding to gain access to cavity bays. Remove fiberglass batts and dense pack with cellulose.
    - Combine both of the above measures.
- Ways to improve the ceiling and roof assembly (the assembly was poorly installed and deteriorated R-19 fiberglass batts were in the ceiling of the vented attic and in vaulted parts of the ceiling).
    - Remove the fiberglass batts and blow R-38+ cellulose at the ceiling plane.
    - Remove the fiberglass batts and apply closed-cell spray polyurethane foam (ccSPF). Where ceilings are vaulted (kitchen and family room), ceiling drywall would have to be removed.
- Ways to improve the isolation of the tuck-under garage from the living space.
    - Remove the garage side drywall and fiberglass insulation. Install blocking as needed. Air seal and insulate with ccSPF. In the garage ceiling, use a hybrid strategy with netted blown cellulose to fill the remainder of the cavity after spray foam.
- Ways to improve the comfort and efficiency of the mechanical system.
    - Update the forced draft oil boiler with an immersion coil for domestic hot water (DHW). Potential to add an indirect tank for DHW.
    - Replace space conditioning with an inverter-driven, multiport air-source heat pump. Potential for heat pump water heater for DHW.
    - Connect to natural gas that is available at the street. Install a combi-tankless condensing boiler. The method for efficient whole-house space cooling would need to be determined.

Figure 2. Pre-retrofit insulation conditions: exterior wall insulation being pulled from exterior (upper left); wall insulation thickness (upper right); attic insulation (dead rodents were a major issue during this retrofit) (lower right); garage ceiling insulation (no air blocking between conditioned parts of home) (lower left).

3.1 Cost-Effectiveness

A BEopt 2.3.0.2 optimization simulation was performed for a variety of enclosure and heating, ventilating, and air-conditioning features. For the economic analysis, the economic values in Table 1 were used per the 2014 Building America House Simulation Protocols requirements (Wilson et al. 2014). The design was modeled without PV, with PV, and with and without incentives. Cost information for the measures analysis was updated to match quotes the homeowners received for this project. All points from the optimization and design run are shown in Figure 3.

Table 1. Inputs of Economic Analysis

Economic Variables	Modeling Inputs
Project Analysis Period	30 years
Inflation Rate	2.4%
Discount Rate (Real)	3%
Loan Period[a]	30 years
Loan Interest Rate	4%
Marginal Federal Income Tax Rate	28%
Electricity Rate[b]	$0.1937/kWh + $19.25 monthly charge
Natural Gas Rate[b]	$0.8395/therm + $14.00 monthly charge
Oil Rate[b]	$3.04/gal
Propane Rate[b]	$2.923/gal
Fuel Escalation Rate	0%

[a] Cost of improvements rolled into mortgage
[b] Local rates

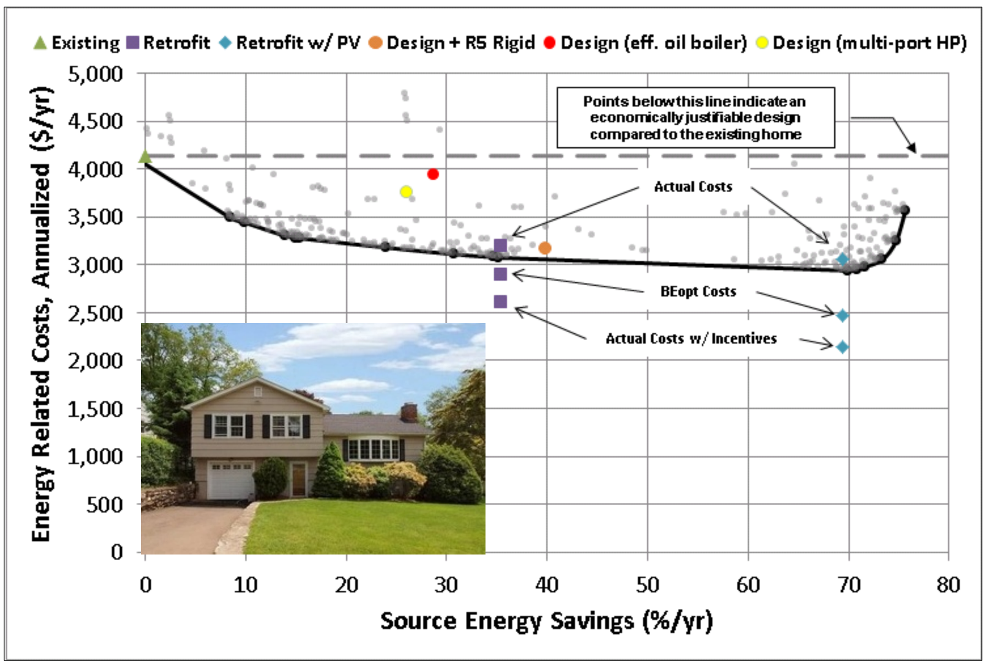

Figure 3. BEopt energy modeling optimization

A summary of the pre-retrofit conditions and final solution package is provided in Table 2. The selection of the final solution package was based on the energy savings potential, first costs, comfort and health goals, and timeline for implementing the retrofits. The final solution package was estimated to achieve 35.5% source energy savings without PV and 69.4% with PV. In terms of a Home Energy Rating System Index, the home pre-retrofit rated at 114 (so 14% worse than an equivalent 2006 International Energy Conservation Code-compliant home). The retrofitted home rated at Home Energy Rating System Index 56 without renewables and 26 with renewables.

Table 2. Design Specifications Summary

Component	Existing Home	Final Solution Package
Basement Insulation	–	–
Crawlspace Insulation	R-19 batts	R-19 batts
Above-Grade Wall Assembly	Poorly installed and deteriorated 2-in. fiberglass batts (R~7)	Dense-packed cellulose (R-13)
Interzonal Wall Insulation	Poorly installed and deteriorated 2-in. fiberglass batts (R~7)	3 in. of ccSPF (R-20)
Ceiling/Roof Insulation	Poorly installed and deteriorated 6-in. fiberglass batts (R~19)	3-½ in. of ccSPF (R-20) + blown cellulose (R-24) to fill the remainder of the joist bays
Interzonal Floor Insulation	Poorly installed and deteriorated 6-in. fiberglass batts (R~19)	3 in. of ccSPF (R-17) + blown cellulose (R-26) to fill the remainder of the joist bays
Window Glazing	Dual pane, low-e windows with vinyl frame (U 0.35/solar heat gain coefficient 0.28)	Dual-pane, low-e windows with vinyl frame (U 0.35/solar heat gain coefficient 0.28)
Infiltration	7.1 ACH50	1.9 ACH50
Ventilation	–-	Exhaust-only (ASHRAE 62.2-2010 minimum ventilation rate)
Heating and DHW System	Poorly maintained oil boiler (~72 annual fuel utilization efficiency)	Natural gas condensing hydronic boiler (95 annual fuel utilization efficiency)
Cooling System	Through-wall air conditioning in kitchen and window air conditioning in bedrooms (energy-efficiency ratio 8)	Multiport air-source heat pump (seasonal energy-efficiency ratio 15.5)
Lighting	20% fluorescent	100% light-emitting diodes
Appliances	ENERGY STAR refrigerator and dishwasher. Propane cooking range and electric clothes dryer.	ENERGY STAR refrigerator, dishwasher, clothes washer, and exhaust fans. Natural gas cooking range and electric clothes dryer.
Site Generation	–	5.2-kW PV system

A 6% additional source energy savings and a $735 annualized energy related cost reduction accrued based on fuel swapping from oil to natural gas for heating and hot water. If natural gas had not been available, the homeowners would have likely eliminated the oil boiler and used an all-electric solution with a multiport air-source heat pump and electric resistance water heater (a heat pump water heater was not suitable for this home). The propane range would have also likely been switched to an induction range. This would have resulted in source energy savings of only 26%, but would have still resulted in a $380 annualized energy-related cost reduction over the pre-retrofit conditions.

3.2 Other Benefits

In addition to reducing energy consumption and lowering annual operational costs, the homeowner placed a significant level of priority on comfort and indoor environmental quality.

3.2.1 Comfort

A key goal of the homeowners was to provide better zonal temperature control. In their previous townhome, two systems conditioned the space (one for the lower two floors and one for the upper two floors). The homeowners constantly had to deal with under- and overheating in spaces that did not have control thermostats. Figure 4 shows the temperature differential between the control thermostats on the second and third floors and the other rooms being serviced by those systems. Bedrooms tended to be 2°–5°F warmer during heating periods and up to 3°F cooler between heating cycles. The fourth-floor loft could be 10°F warmer than the control thermostat on the third floor. The bottom floor was typically 10°F cooler than the control thermostat on the second floor. Some efforts to balance the system were made, but resulted in loud ductwork from overdampered supply registers.

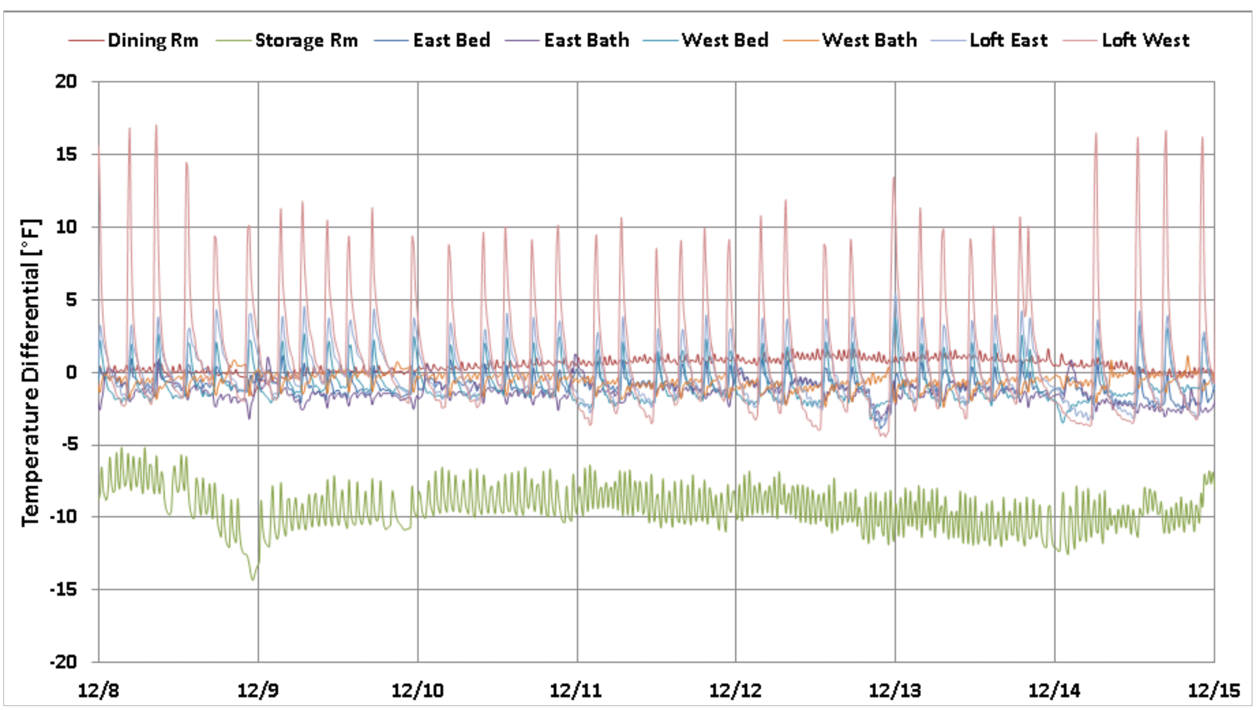

Figure 4. Temperature differential between control thermostats and other rooms being served by each heating, ventilating, and air-conditioning system

The improvements in air leakage rates, insulation levels, modulating boiler, and multiport heat pump should allow for more uniform temperature control from room to room. Still, this requires more controls than a typical heating, ventilating, and air-conditioning system that might have only one or two zone controls.

A significant amount of natural daylight comes through the windows and skylights of this home, so the thermostats had to be appropriately situated to avoid false readings. Therefore, an internal solar path study was performed to ensure the thermostats would not be in the path of sunlight, especially in the family room, which has windows and a sliding glass door on the east, south, and west façades.

While thermostats are typically located in interior walls out of the direct path of sunlight, the CARB team was interested in monitoring the difference in temperatures between the thermostats and the exterior walls in the various control zones. Onset Hobo U12 temperature and RH remote data loggers (accuracy of ±0.63°F and ±2.5%) were installed to measure temperature and RH at an interior location (thermostat) and exterior location of each room.

3.2.2 Health

The retrofit quickly revealed numerous health and safety issues that needed to be addressed.

3.2.2.1 Pests

Mice droppings and dead mice (more than two dozen) were removed from the insulated attic and vaulted ceilings. Several active wasp nests were found in the soffit eaves of the family room. Pathways in the building enclosure also allowed wasps inside the house (an interior nest was being formed in the skylight shaft). The French doors leading from the family room to the backyard were water damaged. Further investigation revealed that termites had started to infest the backer board behind the siding and sheathing. Fortunately this was the only evidence of termites and was eliminated quickly.

During the process of air sealing, identifying entry pathways for these and other pests (spiders, ants, etc.) was essential to prevent further intrusion. Solid blocking was used to seal entry pathways before air sealing. All accessible ceiling joist bays were vacuumed to remove the fecal droppings. The homeowner indicated that there hasn't been any evidence of pests within the home since the retrofit was completed.

Figure 5. Pest hazards: dead mice were found in the vented attic space over the bedrooms and in the vaulted ceilings (upper right and left); active wasp nests were found throughout the soffit eaves and in several cases had a pathway into the home (lower left); termites had started to infest the exterior wood components under the rear French doors (lower right).

3.2.2.2 Other Hazards

In any retrofit, the more you look, the more you are likely to find. This project was no different. When the vaulted ceiling in the kitchen was opened to insulate and air seal, the plumbing vent pipe in the ceiling was found to be disconnected. Figure 6 (upper left photo) shows mice droppings even on this plumbing concealed in the vaulted ceiling, so this was likely one entry point. In fixing this pipe, it was also discovered that an active wasp nest was in the part of pipe that extended through the roof and may have been the pathway that allowed wasps to enter the skylight shaft.

The laundry room, located in the basement, vented to the outside roughly 20 ft away (the vent ran under the unvented crawlspace of the family room). No evidence of a problem was observed except that a coffee can was used to connect the flex duct to the clothes dryer. When the coffee can connection was removed, the vent pipe was found to have roughly an inch of lint built up along the entire pipe length to outside.

Figure 6. Piping/duct hazards: disconnected plumbing vent pipe (upper left); coffee can used as clothes dryer vent splice (upper right); clothes dryer exhaust duct was lined with a significant amount of lint (lower right); the second-floor bathroom exhaust terminates in the unvented attic (lower left).

The homeowners knew that the kitchen exhaust hood was a recirculation microwave hood when they purchased the home. With a propane gas range (converted to natural gas during the retrofit), this was not an appropriate system for indoor air quality. Also, the second-floor bathroom exhaust terminated in the vented attic and the first-floor bathroom had no ventilation or exterior window. Exhaust ducts should always terminate outdoors (refer to applicable codes for vent termination clearance requirements). Running exhaust ductwork up to a vented attic or just in front of an attic vent (gable, ridge, or soffit) is not sufficient. This can result in deterioration of the roof structure over time as condensation is likely to form on the roof framing members in the winter.

4 Implementation

4.1 Building Enclosure Control Layers

To ensure the performance and durability of a building enclosure, three control layers must be established and maintained in every assembly:

- Air barrier (exterior and interior)
- Moisture barrier (drainage plane for bulk water and vapor barrier for water vapor diffusion)
- Thermal barrier (continuous and in alignment with the air barrier).

4.1.1 Air Barrier

After providing structural support and stopping bulk water (rain, snow, etc.) from entering the building enclosure, the next critical detail is the building's air barriers. This is plural because continuity is required in both the exterior and interior air barriers.

For the above-grade walls, all plywood sheathing seams were taped before a weather resistance barrier (WRB) was applied (see Holladay 2013), which was also taped at the seams. For the second-floor overhang, rigid insulation and ccSPF were used to block air from entering the floor joists. On the interior, the airtight drywall approach was implemented to all accessible areas (caulking drywall gap around light switches and fixtures, outlets, baseboards, exhaust fans, foaming around brick fireplace, etc.).

The dense-packed cellulose also helped with any additional leakage pathways that were not accessible. Lstiburek (2010) suggests that dense-packing an empty wall (for all intents and purposes, the all cavities could be considered as equivalent) could result in leakage rates of between 0.4 to 4 cfm/ft^2 at 75 Pa being reduced to 0.04 to 0.2 cfm/ft^2 at 75 Pa.

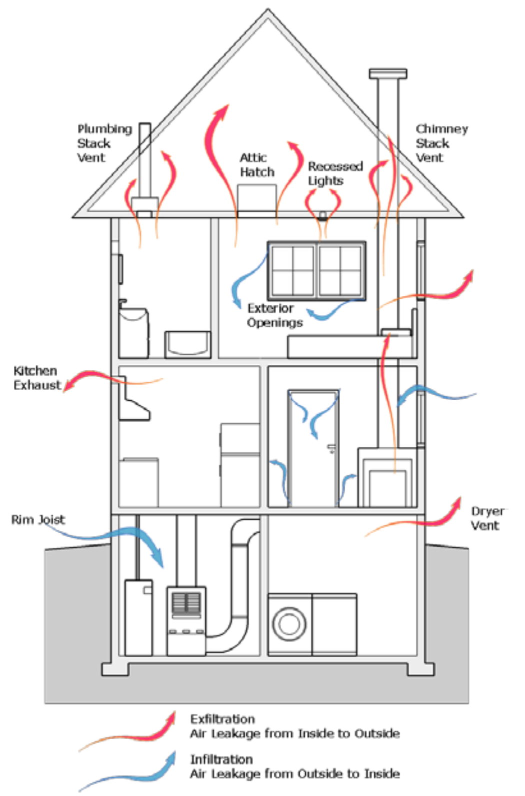

Figure 7. Typical sources of air leakage in residential homes

The greatest air exfiltration is typically through the ceiling/roof plane. Therefore, the entire roof structure was air sealed using ccSPF. On the opposite end of the spectrum, the greatest air infiltration is at the lower levels of the home, so in addition to the air sealing of above-grade walls, ccSPF was applied at the rim/band joist connection to the concrete foundation.

The last component of air sealing was isolating the tuck-under garage from the conditioned spaces of the home. Isolating attached garages from the living space is critical for preventing the potential infiltration of carbon monoxide and other contaminants into the dwelling. Open joist bays above the garage that extend into living spaces are unwanted air pathways. Air can also flow through cracks between and around the boards of the rim joist, the top plate, and the sill plate-foundation wall intersections if seams are not adequately sealed. In addition, certain conditions in the home can cause the home to become depressurized, making it even more likely for garage air to be drawn into the home through leaks in and around the rim joists. Depressurization can occur when the house is airtight and an exhaust fan, range hood, clothes dryer, or combustion appliance is operated. Specific details about air sealing attached garages can be found at the Building America Solution Center (DOE n.d.).

Figure 8. Air-sealing details: all seams and penetrations in exterior sheathing were taped (upper left); blocking was installed to eliminate cold air from the overhang from entering the floor system (upper right); the attached garage was isolated from the living space with ccSPF (lower center).

4.1.2 Moisture Barrier

A dimpled house wrap was use to provide a drainable WRB over the plywood. All the windows were properly flashed to the WRB and a metal drip edge was installed over the top edge of windows, doors, and water table trim boards. The rear French doors were replaced by a sliding glass door after the termite damage was fixed, so a metal pan was used in combination with a peel-and-stick membrane to ensure proper drainage and to protect against termites. A final layer to provide the continuous drainage plane occurred during the installation of the fiber-cement siding. At the butt joint of any two pieces of siding, a piece of metal flashing (the same color as the siding) was installed behind the siding to maintain the drainage plane even when the siding pieces slightly shrink during winter conditions.

Figure 9. Continuity of the drainage plane: a dimpled WRB was applied over the sheathing (upper left); windows were properly flashed and drip edges were installed over all windows, doors, and trim board (upper right); a door pan and flashing were used to prevent further water damage at the rear sliding door (lower right); fiber-cement siding was installed over the WRB (lower left).

The air-sealing measures at the exterior and interior surfaces, along with dense-packed cellulose in the walls and ccSPF at the roof deck, have resulted in a tight building enclosure (1.9 ACH50). Because most vapor transmission is through air movement, the concerns about a vapor barrier are diminished. In removing the batt insulation from the walls, technically, the class II vapor retarder was removed (though it was likely of little benefit based on poor installation and air leakage bypasses). No vapor barrier, other than latex paint on the interior drywall, a class III vapor retarder, was provided. There was minimal concern about potential vapor diffusion issues and condensation on the interior side of the exterior sheathing as the house is kept slightly depressurized with an ASHRAE 62.2-2010-compliant exhaust-only ventilation strategy. In addition, interior moisture is being actively managed with a standalone dehumidifier in the basement and air conditioning is provided through the multiport heat pump.

4.1.3 Thermal Barrier

Dense-packed cellulose and ccSPF were used to provide the thermal barrier for the home. The siding needed to be replaced; thus, the walls could be properly insulated when the old siding was removed. A strip of sheathing was removed along the perimeter of the home to allow the old batt insulation to be removed. Once the sheathing was repaired, holes were made to blow cellulose into the wall cavities. An infrared imaging camera was used to verify that the wall cavities were completely filled.

Ideally an inch of rigid insulation (extruded polystyrene or polyisocyanurate) would have been applied over the plywood sheathing before the dimpled house wrap and siding were installed. This specific project would have incurred a significant additional cost (in particular with the large bay window in the front of the home) to address the window detail finishes. The family room at the back of the home would have also required additional modification to the shallow roof. Although these changes would have been desirable from an energy-efficiency standpoint, the decision was made to avoid the additional cost and construction time for this retrofit project.

For the roof insulation, all insulation was moved to the roof deck. With the larger 2 × 10 rafters in the primary living spaces (living room, kitchen, family room), a combination of 3-½ in. of ccSPF against the roof deck to control vapor diffusion and dense-packed cellulose was used. This was the only time the interior drywall was removed to gain access to the roof structure. To minimize the impact to the homeowners, the work was sequenced to be completed in a week and all cabinets, countertops, appliances, and floors in the kitchen and family room were covered to expedite the cleanup after the interior ceiling drywall was rehung. In these vaulted ceilings, a shallow light housing for 4-in. light-emitting diode fixtures (5- to 6-in. diameter lights are typical) was used to allow for the full 3-½ in. of ccSPF between the light housing and the roof deck.

The vented attic over the bedrooms was being used as cold storage, so this space was converted to warm storage by applying ccSPF to the roof deck to make an unvented attic. The roof rafters in this space were shallower, so ~7 in. of ccSPF was applied (R-40). This space is used for storage, so an intumescent coating was applied over the ccSPF to comply with the 15-minute thermal barrier requirement of International Residential Code (2009 IRC Section R316.4).

Ensuring Success

In climate zone 5, the 2009 International Residential Code Section R806.4 requires that unvented attic assemblies have a minimum of R-20 air impermeable insulation. In addition, the air-impermeable insulation needs to either be a vapor retarder, such as ccSPF, or have a vapor retarder covering in direct contact with the underside of the insulation. In the later case, it can be difficult to maintain the continuity of the vapor retarder, so additional oversight during implementation is recommended.

Regardless of the type of insulation used on a project, it is important to follow a current International Code Council evaluation services report for the specific product being used on a project. This report will provide all necessary information in terms of performance, proper application, and correct installation.

Most of the bedrooms are over the tuck-under garage, so the homeowners wanted to insulate this space and to isolate any potential contaminants in the garage from entering the living space. Therefore, the drywall in the garage was removed to provide access to the living space from the exterior. The shared walls with the living space were insulated with 3 in. of ccSPF. The underside of the subfloor to the bedrooms above was insulated with 3 in. of ccSPF before the remainder of the floor joists were filled with dense-packed cellulose.

The basement was not insulated because it was a finished space, but the rim/band joist area was air sealed with 2 in. of ccSPF to address the common leakage pathway. The basement had a drop acoustic ceiling, so access to the rim/band joist was easy and nondestructive to interior finishes.

Figure 10. Continuity of the thermal barrier: dense-packed cellulose blown into the walls from the exterior (upper left); the vented attic over the bedrooms was being used as cold storage, so this space was converted to warm storage by applying ccSPF to the roof deck to make an unvented attic (upper right); the vaulted ceiling drywall was removed to allow for 3 in. of ccSPF to be applied to the roof deck before dense packing the remainder of the roof rafters with cellulose (lower right); drywall from the garage was removed to allow the bedroom floors to be properly insulated and to isolate the garage contaminants from the living space (lower left).

4.2 Mechanical Equipment

For the mechanical equipment, the homeowners had two key criteria: (1) to eliminate the use of oil for space heating and (2) to provide whole-house air conditioning.

4.2.1 Space Conditioning

The home had an atmospheric oil boiler that fed a four-zone hydronic baseboard heating system. An immersion coil in the boiler provided DHW. This system would have had a maximum efficiency of 78 annual fuel utilization efficiency, but it was poorly maintained and already at the end of its serviceable life. Initial inquiries with the local gas company indicated that no natural gas was available for the site. Because air conditioning was also desired, CARB focused on how best to incorporate a multiport air-source heat pump (the split-level configuration and vaulted ceilings did not allow space for central ductwork). Though, upon further investigation, a gas line was identified in the street. This home is on a corner lot, so apparently no gas line is situated on the opposite side of the cross street, but a gas line was available for this property. The homeowners liked the idea of keeping the radiant heat, even though it was redundant with the air-source heat pump. Thus, a combi-boiler and variable-speed pump was installed to supply the hydronic baseboard system and the DHW. Some issues with "cold water sandwich" arose (small amounts of cold water that pass through the boiler during frequent on/off operation as the heat exchanger comes up to temperature) resulting from the tankless boiler, so a 10-gal storage tank was installed later to provide a buffer of hot water when needed.

The homeowners wanted to eliminate the through-wall air conditioner in the kitchen and the window air-conditioning units in the bedrooms. A central system was not a viable option given the layout of the home, so CARB recommended a multiport air-source heat pump. This selection was primarily predicated on the desires of the homeowner and not on energy cost-effectiveness. The multiport heat pump allows up to eight indoor units to be connected to a single outdoor unit. CARB worked on a system layout that would be least intrusive to run refrigerant and condensate lines to seven zones to allow for the level of individualized control desired by the homeowner. In vaulted spaces, the typical wall-mounted indoor unit was specified. In the bedrooms and living room, ceiling cassettes were installed. In addition to providing air conditioning, this system acts as auxiliary space heating in the guest bedrooms. In case the system was used for heating, to ensure that the unit could continue to operate uninhibited even when there were large accumulations of snow, the outdoor unit was installed on wall brackets 3 ft above grade.

Figure 11. Mechanical equipment updates: new natural gas combi-boiler provides heat to the hydronic baseboards and for DHW (left); wall-mounted indoor unit for the multiport heat pump provides air conditioning for family room (center); ceiling cassette indoor unit provides air conditioning and auxiliary heating for bedroom (right).

4.2.2 Ventilation

In addition to the improvements on the space conditioning equipment, ventilation was also addressed during the retrofit. Both bathrooms had proper exhaust fans installed that ducted directly to the exterior. The installed exhaust fans have built-in low speed continuous ventilation and delay of timer controls. These provide local exhaust during showers (~90 cfm on boost) and the exhaust fan in the second-floor bathroom was set up to provide continuous exhaust-only ventilation (~45 cfm continuously).

Ensuring Success
The following bathroom ventilation guidance is based on field research by Camroden Associates, Inc. and validated by Steven Winter Associates, Inc. This design criterion is intended to sufficiently remove locally generated moisture from bathroom shower events at a rate to prevent or significantly minimize the potential for condensation (mirrors to remain "fog-free"). Research by both companies indicates a ventilation rate of 10 air changes per hour should be sufficient in most instances to achieve this goal. This rate is higher than minimum ventilation rates recommended by codes, standards, and industry organizations, but is achievable in most instances with minimal additional first and operational costs. This ventilation rate (in cfm) can be quickly calculated by dividing the volume of the bathroom bv 6.

As mentioned previously, the kitchen exhaust was just a recirculation system, so the microwave fan was repositioned to allow for ducting to outside and ductwork was installed to outside. While it required pulling down two sheets of drywall to run the microwave exhaust to the outside, CARB and the homeowners felt it was worth the added cost.

Ensuring Success
Over-the-range microwave exhausts typically come from the manufacturer in the recirculating configuration. Before installing the unit, the fan direction will likely need to be adjusted to exhaust to outside. Check the manufacturer's directions for specific guidance on your unit.

Kitchen hoods that can exhaust at least 400 cfm are required under the 2009 International Residential Code Section M1503.4 to provide a makeup air system that supplies approximately an equal amount of air as exhausted.

4.2.3 Miscellaneous Items
The last two items to be addressed were the clothes dryer vent and the fireplace. For the clothes dryer vent, the ductwork under the crawlspace was cleaned of lint. The connection of that part of duct to the clothes dryer was re-ducted using round sheet metal ducts and a secondary lint trap was installed. This provides an additional clean out to prevent the ductwork from being lined with lint.

The homeowners did not anticipate using the wood-burning fireplace much, if at all. With the house being so airtight now, it is not clear how well the fireplace would work if used. The CARB team recommended that the homeowner not use the fireplace, but there was no budget to remove it. Therefore, a lock-top chimney damper was installed to minimize heat loss up the chimney. Heat is still lost through the uninsulated brick of the chimney, but the draft up the chimney was significantly reduced.

Figure 12. Additional improvements: a secondary lint trap was installed on the clothes dryer (upper left); the microwave over the kitchen range was exhausted to outdoors (upper right); an exhaust fan was added to the first-floor bathroom that had no fan or window previously (lower right); a lock-top chimney damper was installed on the wood-burning fireplace (lower left).

4.3 On-Site Electricity Generation

While energy efficiency can drastically reduce energy consumption, it can never reduce it to zero. Therefore, on-site electricity generation through a PV system was incorporated. Based on the available roof area with favorable orientation and federal and state incentives, a 5.2-kW PV system was incorporated. This system was anticipated to provide 5,721 kWh/yr of renewable energy, which equates to an annual energy cost savings of ~$1,100. After incentives, the PV system cost just over $13,000, equating to a simple payback (SPB) of slightly less than 12 years.

Figure 13. A 5.2-kW PV system was installed on this 1960s retrofit project.

5 Performance Results and Discussion

To assess the success of the final solution package, CARB validated whole-house performance, uniformity of temperatures across living space, and PV electricity generation estimates.

Figure 14. Exterior of the split-level home after the retrofit

5.1 Whole-House Performance

To validate the source energy savings estimates of the BEopt energy modeling analysis, consumption for the previous homeowners (estimated based on utility costs provided) versus a full year of data from the new homeowners was evaluated. The source energy savings was 30.2% without PV (65.5% with PV). The lower savings are a result of the retrofitted home having higher electricity consumption than previously (without PV). This was likely a result of the whole-house air conditioning that was maintained all day long during the summer versus window units that were typically operated only in the evenings, according to the previous homeowners. A dehumidifier was placed in the basement to control moisture because the basement windows are single pane and initially experienced condensation buildup until the dehumidifier was installed.

From a homeowner's perspective, the critical criterion is operational cost reductions, so CARB performed a utility bill cost comparison. While the occupants changed, this analysis provides a reasonable degree of validation of the performance improvements. The previous homeowners provided a summary of their utility costs from their last 12 months at the residence in 2012–2013 before selling to the new homeowners. The utility bills totaled $5,733/yr ($2,120 electricity, $3,480 oil, and $133 propane). A year's worth of utility bills from the current homeowners after the retrofit is provided in Table 3 and Table 4. The utility bills totaled $1,701/yr ($496 electricity and $1,206 natural gas) or a savings of 70.3% compared to the previous homeowners. About 21% of the annual utility costs were simply for the access (monthly service charge) to natural gas and electricity. If the PV electricity generation is removed from the analysis, the total bill was estimated to be $3,534 for a year. This would still equate to an operational cost savings of 38.4% compared to the previous homeowners.

Table 3. Electricity Utility Bill Summary

Electricity							
Billing Period			Consumption	Generation	Total	Cost	Average Temperature
Start	End	Days	kWh	kWh	kWh	$	°F
1/15/2014	2/12/2014	29	536	111	425	85	26
2/13/2014	3/13/2014	29	533	335	198	48	30
3/14/2014	4/10/2014	28	628	584	44	23	40
4/11/2014	5/13/2014	33	401	525	–124	16	54
5/14/2014	6/12/2014	30	386	427	–41	16	64
6/13/2014	7/15/2014	33	539	459	80	16	73
7/16/2015	8/14/2014	30	567	340	227	39	73
8/15/2014	9/12/2014	29	502	348	154	41	72
9/13/2014	10/10/2014	28	399	331	68	27	61
10/11/2014	11/12/2014	33	399	271	128	37	53
11/13/2014	12/12/2014	30	426	165	261	59	38
12/13/2015	1/14/2015	33	563	158	405	89	29
TOTAL		365	5,879	4,054	1,825	496	

Table 4. Natural Gas Utility Bill Summary

Natural Gas					
Billing Period			Consumption	Cost	Average Temperature
Start	End	Days	ccf	$	°F
1/15/2014	2/13/2014	30	159	198	27
2/14/2014	3/14/2014	29	151	197	31
3/15/2014	4/11/2014	28	90	138	41
4/12/2014	5/13/2014	32	53	88	53
5/14/2014	6/12/2014	30	22	47	64
6/13/2014	7/14/2014	32	17	35	73
7/15/2014	8/13/2014	30	15	33	74
8/14/2014	9/12/2014	30	11	28	73
9/13/2014	10/13/2014	31	24	46	62
10/14/2015	11/13/2014	31	65	91	54
11/14/2014	12/11/2014	28	112	136	40
12/12/2014	1/13/2015	33	145	168	36
Total		364	864	1,206	

The cost of the energy-efficiency measures is provided in Table 5. While the homeowners received lower bids for several of these efficiency measures, contractors with a history of high-quality workmanship and attention to detail were selected. In terms of an SPB, not accounting for the additional benefits beyond energy savings, the final solution package resulted in an SPB of 15.2 years with incentives and 19.8 years without incentives. At least $8,000 of additional cost would be necessary just to replace equipment that was at the end of its serviceable life (boiler, through-wall and window air conditioners, and bathroom exhaust fan), so in that case, the SPB would be closer to 13.2 years with incentives and 17.9 years without incentives. While compromising slightly on the comfort and controllability of each room, a slightly cheaper multiport mini-split system with fewer heads could have been installed for roughly 65% of the heat pump cost incurred by the homeowner. This would further reduce the SPB to 11.3 years with incentives and 16 years without incentives.

Table 5. Cost of Energy-Efficiency Measures

Efficiency Measure	Cost	Utility Rebate	Federal Tax Credit	Total Cost
Boiler*	$10,875	$750	–	$10,125
Heat Pump	$21,600	$1,000	–	$20,600
Insulation	$20,742	$3,559	$500	$16,683
Light-Emitting Diodes	$687	$176	–	$511
Solar	$26,108	$7,293	$5,645	$13,171
Total	$80,012	$12,778	$6,145	$61,090

* Included removal of existing boiler and oil tank

The U.S. Department of Energy is working to have green appraisals adopted to appropriately value energy-efficiency measures in homes. A “cost approach” can be used to calculate this added value. That approach calculates a net present value based on additional cash flows that the homeowners would have from energy savings (using term length and rate of the mortgage loan). If the cost of the measures is rolled into a 30-year mortgage at a 4% interest rate, the net present value or added value to the home would be $69,712 or 14% more than the cost of the retrofit improvements.

5.2 Comfort

To quantify comfort, the temperature and RH of all rooms were monitored per the Building America Indoor Temperature and Humidity Measurement Protocol (Metzger and Norton 2014). According to ACCA’s Manual RS (Rutkowski 1997), the temperature differential should not exceed a maximum of ±4°F and should average to no more than ±2°F between rooms and floor-to-floor. Figure 15 shows that the temperature maintained a ±2°F between rooms (70°F set point throughout the home). Over the winter monitoring period, the home met these comfort guidelines. The only instances in which the temperature exceeded this range were a result of cooking that increased temperatures in the kitchen and adjoining family room. Also, the second-floor bathroom likely was not maintaining a similar temperature to the master bedroom, where the controlling thermostat is located, due to undersized baseboard heating (configuration of bathroom left a minimal length of hydronic baseboard heater on the bathroom’s exterior wall).

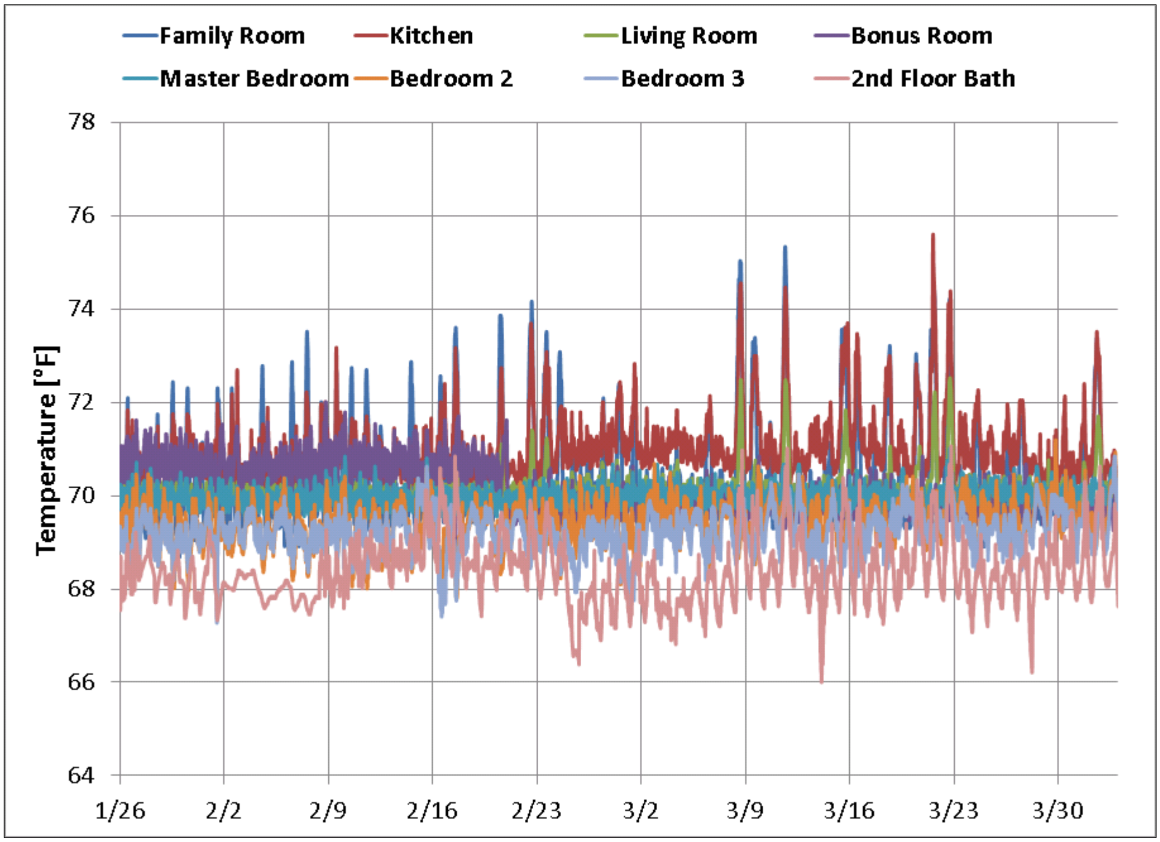

Figure 15. Temperature conditions in each room over the winter 2014

All the measurements referenced in Figure 15 are based on interior wall measurements (in line with typical guidance for placing thermostats). CARB was interested to see the variation in each room's temperature profile between the interior and exterior walls. The exterior temperature measurement was taken at the same height as the interior wall measurement and was carefully planned to avoid potential impacts from direct solar gain through the windows. Figure 16 shows that temperature variation within rooms was between +2°F and –5°F. The family room and master bedroom had the least variation in temperature between the inner and outer measurements. These rooms also had thermostats for the hydronic baseboard system. Bedrooms 2 and 3 are on the same zone as the master bedroom and were within ±2°F. The two spaces that had the largest temperature variation were the living room and bonus room. The bonus room is a longer room, so it had the greatest distance between the inner and outer measurements of any of the rooms. The living room has the fireplace and large bay window, which is older than all the other windows in the home. So while the bay window has double pane glass, its larger size and potential lower performance U-value, along with the uninsulated masonry fireplace, are likely resulting in the outer portion of the room being 2-4°F cooler than the inner portion. These two spaces are the least used by the homeowners, so it has not been an issue. If these rooms are used more in the future and the temperature variation is uncomfortable, the controls could be adjusted. Each of these spaces has a thermostat for the hydronic heating system, so the set point temperature could be raised 2°F to have the average center of room temperature be 70°F.

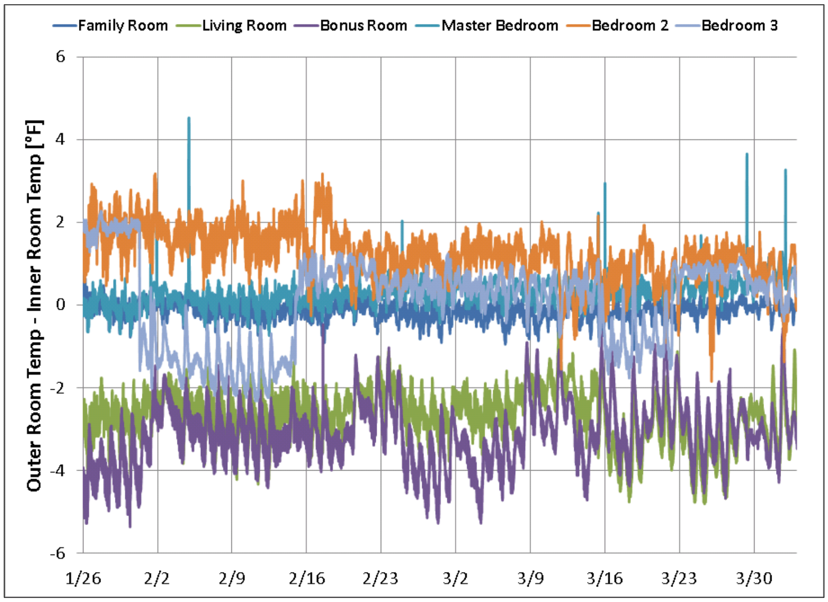

Figure 16. Temperature variation within each room

The home now has a multiport heat pump for cooling, so each room has its own cooling system and can be maintained at the desired temperature. Minimal space conditioning was used during the April and May swing season. Air conditioning was used more starting in late May. Figure 17 shows that the temperature fluctuated within ±3°F of the 75°F set point. This makes sense with the thermostat dead band configured at 2°F.

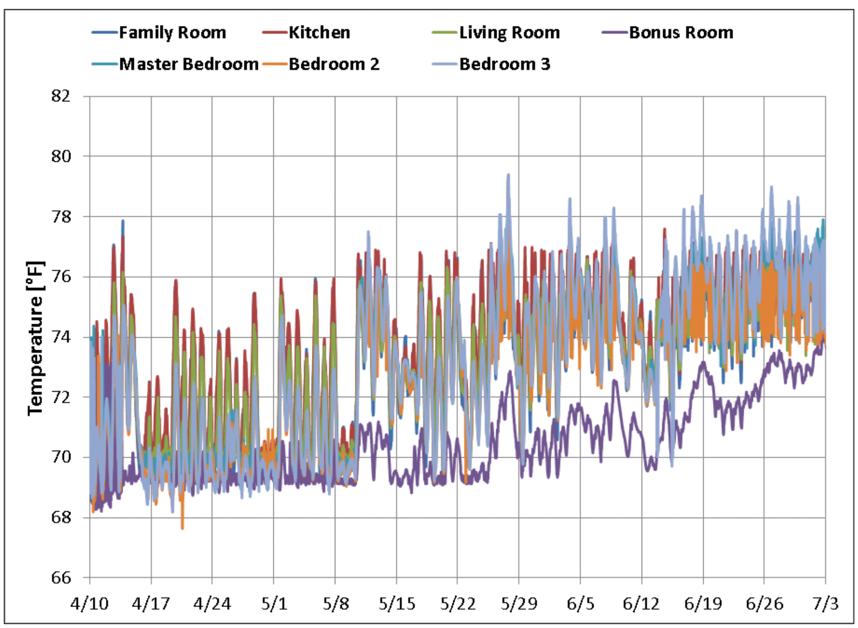

Figure 17. Temperature conditions in each room over spring and summer 2014

More important than the summer sensible cooling (temperature) control is the latent cooling (humidity) control. Over the initial summer months, RH was controlled at 48%–62%, well within the desired RH range (Figure 18).

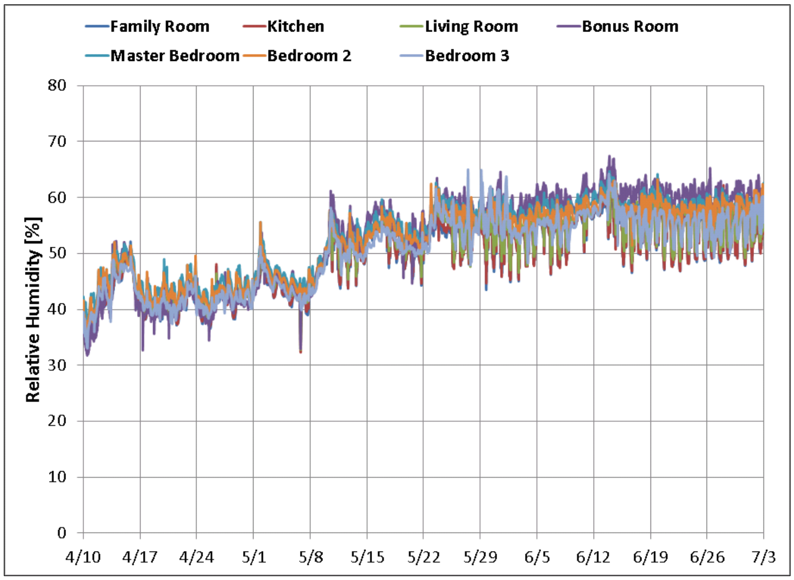

Figure 18. RH conditions in each room over the spring/summer 2014

The RH throughout the heating season was also measured to see whether it was maintained higher than 25% in the winter months. During the winter, it is common practice for humidifiers to be added to cold climate homes to ensure that the home's air is not too dry (<20% RH). The primary cause of this dry air is high infiltration. Air-sealed homes (≤3 ACH50) tend to maintain suitable RH levels in the winter from interior moisture generation. In many really tight homes, heat recovery ventilators introduce dry air and remove excess interior moisture during the winter. In extreme cases, a dehumidifier may even be necessary in these cold climates.

Figure 19 shows that RH naturally remained at 25%–45% for most of the rooms in this retrofit home. The second-floor bathroom saw spikes in RH up to 55% during shower events, but this was quickly exhausted to outdoors and the RH returned to normal levels.

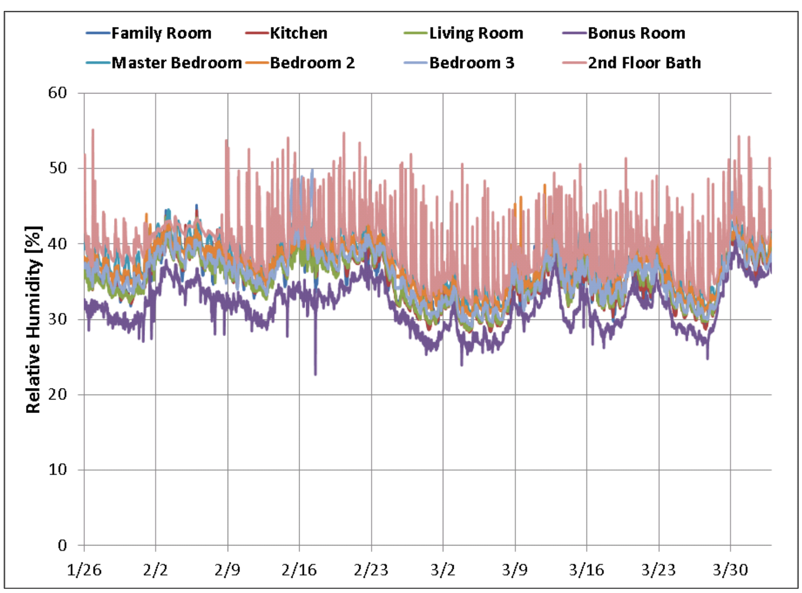

Figure 19. RH conditions in each room over the winter 2014

5.3 Photovoltaics Electricity Generation

The local utility incentive requires the PV system is required be monitored. Therefore, daily monitoring of actual production of the system was possible through an online portal. The actual generation of the PV system (6,243 kWh) versus estimates by the National Renewable Energy Laboratory's PVWatts (5,721 kWh) was evaluated. Overall generation was actually higher than projected and would have been even higher (estimated to be an additional 2% of output generation) except for the 25 days during the winter when the PV system was covered by snow. The additional output of the system means that the estimated SPB would actually be 11 years versus the original 12 year estimate, assuming similar annual output year to year.

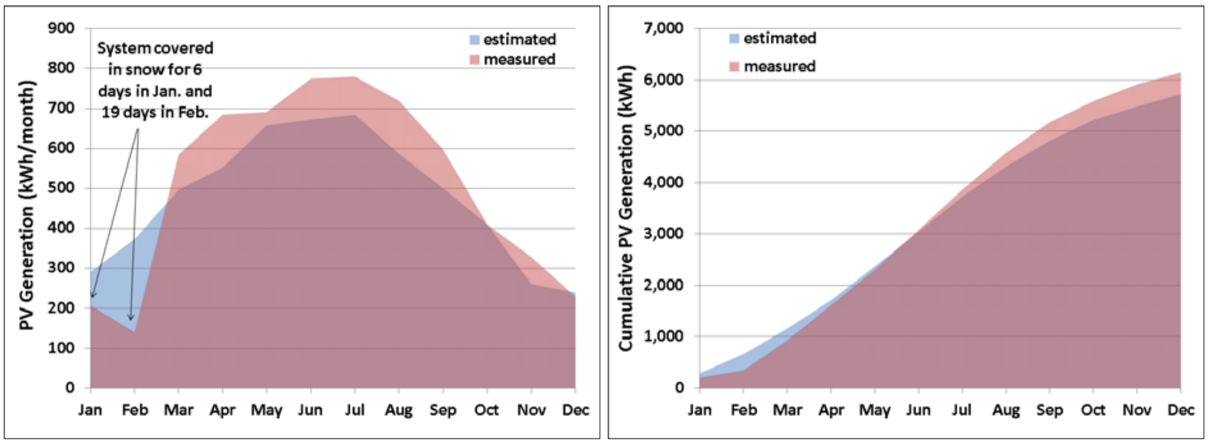

Figure 20. Actual PV electricity generation compared to projected estimates

While the greatest amount of the PV electricity generation (37% of the annual production) was during the summer months (June, July, and August), the highest daily PV outputs (35 kWh) actually occurred in April and May. The high solar irradiance and cooler PV panels resulted in higher daily output, but this was not consistent.

6 Conclusion

At the start of this project, the homeowners had three goals for the project:

- Eliminate the oil heating.
- Reduce annual operations and maintenance costs.
- Improve comfort (based on their experiences at their previous townhome).

An all-electric option for the mechanical systems was originally considered until it was discovered that natural gas was available at the street. The overarching research focus was to identify and vet a viable solution package that could be readily implemented in the cold climate zone for existing single-family detached homes to achieve 30% source energy savings compared to pre-retrofit performance. The initial inspection quickly revealed that improved indoor environmental quality would also need to be addressed, because pests and fecal matter were found.

The primary questions addressed by this research were:

- Which energy savings solution packages are viable for reaching the 30% improvement level for this home?

In existing homes, energy-efficiency options are more limited than for new construction, especially if the homeowners want the measures to be nonintrusive to protect interior finishes. In this project home, the exterior siding was already in poor condition and needed to be replaced. This provided an ideal opportunity to use dense-packed insulation to insulate the exterior wall cavities from the exterior and to address the exterior air barrier, which was accomplished using high-quality tape on the sheathing joints.

Ideally, if the casing and trim details around the windows, doors, and roof could have been accomplished without a significant added cost and complications, an inch or more of exterior rigid insulation would have been beneficial. In this home, R-5 of continuous insulation would have boosted the BEopt estimated source energy savings from 35.5% to 39.4%. The rigid insulation (with seams taped) could also act as the drainage plane, minimize potential condensation risk within the wall cavity even further, improve the overall airtightness of the building enclosure, and provide more sound attenuation when inside the home.

The roof shingles were replaced 2 years before the retrofit, so applying rigid insulation over the roof sheathing would not have been cost effective. In accessible attic spaces, the two primary insulating options are to air seal the ceiling plane before applying loose fill insulation and to apply ccSPF to the roof deck. The homeowners wanted to keep the storage space and convert it from cold storage to warm, so ccSPF was applied to the roof deck to create an unvented attic. No unobtrusive methods are available to insulate the rafter cavities in vaulted ceilings. Although many in the industry are still installing less-intrusive dense-packed insulation in vaulted ceilings, condensation is a concern. Exposing the rafter spaces is unavoidable, so careful coordination of trades is essential to ensure that the air sealing, insulating, and refinishing of the ceiling occur in as quick a time frame as possible to minimize disruption to the occupants.

Regardless of the mechanical system being implemented (boilers for hydronic baseboards, central forced-air furnaces with air conditioners, mini-split heat pumps, etc.), distribution and controls are as important as equipment efficiency. In the cold climate region, heating efficiency should be prioritized. Maximizing the cooling efficiency in the cold climate region is less critical. The key is to appropriately select and size the cooling equipment to ensure adequate latent cooling to control interior humidity levels.

- How cost-effective was the 30% source energy savings solution package implemented on this home?

BEopt analysis suggested that the solution package would be cost-effective and reduce source energy savings by 35.5% without PV (69.4% with PV). Annual energy-related costs were estimated to be $1,238 lower than the pre-retrofit costs without PV and $1,999 lower with PV. The actual source energy savings was 30.2% without PV (65.5% with PV). From a homeowner's perspective, the critical criterion was operational cost reductions, which were 38.4% without PV and 70.3% with PV.

In terms of an SPB, the final solution package with PV would be closer to 13.2 years with incentives and 17.9 years without incentives (after accounting for ~$8,000 of required equipment that needed to be updated because it had reached the end of its serviceable life). Looking at the new green appraisal methodology being developed by the U.S. Department of Energy, the added value to the home would be $69,712 or 14% more than the incentivized cost of the retrofit improvements.

- How well was comfort maintained throughout the home after the energy-efficiency package was implemented?

The improved envelope and mechanical systems were able to maintain temperatures at ±2°F between rooms during the winter and at ±3°F between rooms during the summer. RH levels were maintained in desirable ranges (25%–45% during the winter and 48%–62% during the summer) throughout the monitoring period.

High-performance homes, whether new construction or retrofits, can provide benefits to homeowners that are not monetarily accounted for in today's market. Financial decisions are made based on SPB of typically 7 years or less. A simple economic metric is not a complete method of evaluating and comparing high-performance homes or even individual energy-efficiency measures. The benefit and value of a high-performance home were well described by one of CARB's builder partners, Mike Trolle of BPC Green Builders: "People have all sorts of misconceptions about the sacrifices that they feel they have to make in high-performance homes, and it is completely untrue. It is exactly the opposite. The even temperatures, the lack of drafts, the feeling of warmth, comfort, and right levels of humidity and fresh air…they are unrivaled. Comfort is something you have never experienced properly in a home until you have a high-performance home."

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