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Technical Report
NREL/TP-5500-54009
Revised June 2014

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NATIONAL RENEWABLE ENERGY LABORATORY

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Note

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

The laboratory and/or field site 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.

About the Revision

This report was revised in June 2014 to clarify that the performance of a water heater installed in the field is not comparable to efficiency as defined by standard ratings tests. The results presented here are only applicable to this installation's unique conditions.

Acknowledgments

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The authors wish to acknowledge others who contributed to this project. Several NREL researchers helped plan the project and install the monitoring and test equipment at the house. Special thanks to: Lee Magnusson (formerly of NREL), Dave Roberts, Stacey Rothgeb, Cheryn Metzger, and Paul Norton (formerly of NREL). This work would never have been possible without the support of Jim Bayless (Greenbuilt Construction) and Mike Keesee (SMUD). Their flexibility and assistance throughout the year made the long-distance aspect of this project feasible. The authors also wish to thank Dan Roberts (Mountain Energy Partnership) for providing local assistance in a number of tests.

Executive Summary

One of the homes that was part of Sacramento Municipal Utility District's (SMUD) Energy Efficiency Retrofit Demonstration (EERD) project was a 1980's era home in Fair Oaks, California, referred to as the Greenbuilt house, as Greenbuilt Construction completed the retrofit of the home. The home underwent an extensive energy efficiency retrofit with a goal of achieving a 50% reduction in energy use to demonstrate the potential for other builders and homeowners in the area. The retrofit measures included installing: ENERGY STAR® appliances; high efficiency lights; roof radiant barrier; additional ceiling and wall insulation; double-pane, low-e windows; external motorized shading and solar tubes; a 16 SEER/9.75 HSPF heat pump; improved ducts; a whole-house fan; a heat pump water heater (HPWH); integrated collector storage solar water heater (ICS SWH); and 3.2 kW of PV. In addition, the home was air sealed to reduce infiltration.

Researchers from the National Renewable Energy Laboratory (NREL) performed short-term tests on the major systems installed as part of the retrofit to ensure that they were performing as expected. The systems evaluated included the space conditioning heat pump, the air handler and ducts, the HPWH, the ICS SWH, and the PV array. Some ducts were untwisted after testing revealed that two rooms were not getting sufficient airflow. Afterwards, all systems were performing as expected.

In addition to testing to confirm adequate performance of all new systems, NREL was given the opportunity to use the Greenbuilt house as a laboratory house for a year. The space conditioning system and home water systems were subjected to a series of tests to determine optimal control strategies for lowering energy consumption and reducing peak (4:00–7:00 p.m.) energy consumption during the summer. The different cooling strategies considered included two different precooling schedules, drawing the external shades during the day and using the whole-house fan at night, and combinations of those. The most effective strategy for reducing overall energy consumption was the use of external shades, which cut the daily cooling load by 34% and reduced the energy use during peak hours by 40%. The different precooling strategies eliminated the peak load entirely but actually increased daily cooling energy use. The use of shades and the advanced precooling strategy increased the daily energy use by 5% but eliminated all peak use and maintained a comfortable home. These results were verified over the entire summer using an Energy Plus model of the home.

The hot water system was tested in two configurations: the HPWH alone and the ICS solar water heater paired with the HPWH. Six hot water draw profiles, varying in terms of daily hot water volume, time of day for hot water use, and the duration of the draws, were imposed on the hot water system to test their effects on performance. When operating alone in the summer, the HPWH operated with a COP around 2.2, except for a draw that used a quarter of the averaged daily hot water usage, which had an average COP of 1.6. The combination of ICS and HPWH resulted in larger COPs, but also more variability depending on the draw profile. The standard, hourly draw profile produced the highest COP of 6.4. The quarter volume draw profile had the lowest COP of 2.8 for the combined system. Relative to a standard electric water heater, the HPWH operating alone reduced the peak load by 56% and the combined ICS and HPWH system completely eliminated the peak load.

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Definitions

AC	Alternating current
BEopt	Building Energy Optimization program
Btu	British thermal unit
CFL	Compact fluorescent lamp
CFM	Cubic feet per minute
COP	Coefficient of performance
DAQ	Data acquisition system
DHW	Domestic hot water
DOE	U.S. Department of Energy
EERD	Energy efficient remodel demonstration
gpm	Gallons per minute
HERS	Home Energy Rating System
HPWH	Heat pump water heater
HVAC	Heating, ventilation, and air conditioning
ICS	Integrated collector storage
kW	Kilowatt
kWh	Kilowatt-hour
MEL	Miscellaneous electric load
NREL	National Renewable Energy Laboratory
Pa	Pascals
PV	Photovoltaic
RH	Relative humidity
SMUD	Sacramento Municipal Utility District
STC	Standard test conditions
SWH	Solar water heater, solar water heating
TMY	Typical Meteorological Year
TOU	Time of use

1 Introduction

The Greenbuilt house is an all-electric, 1980s era home in the eastern Sacramento suburb of Fair Oaks (see Figure 1). It was retrofitted by Greenbuilt Construction as part of the Sacramento Municipal Utility District's (SMUD) Energy Efficient Remodel Demonstration (EERD) program. The project was a joint effort between the design-build team at Greenbuilt Construction, led by Jim Bayless, Mike Keesee of SMUD, and the National Renewable Energy Laboratory (NREL). The EERD program works with local builders to renovate homes with cost-effective energy-efficiency retrofit measures. The homes remodeled under this program are intended to showcase energy-efficient retrofit options for homeowners and other builders. The Greenbuilt house is one of five EERD projects that NREL has supported. NREL mainly provided energy analysis and monitored post-retrofit performance to verify that the energy consumption is in line with the modeling predictions. NREL also performed detailed monitoring on the more innovative equipment included in these remodels, such as an add-on heat pump water heater (HPWH).

Figure 1. The Greenbuilt house

NREL/PIX 19611, Credit: Lieko Earle

The Greenbuilt house, like all the other EERD projects, was subject to an extensive remodel to improve overall energy efficiency. The installed systems include common retrofit measures, such as increasing wall and attic insulation, and more advanced technologies, such as motorized exterior shading and a home control system. A photovoltaic (PV) array and a solar water heating (SWH) system were also installed to maximize energy savings. This home was intended to showcase the best in energy efficiency retrofit technologies so builders can use some of the features in future projects. SMUD rented the home from Greenbuilt Construction for one year to demonstrate the retrofit measures to builders and homeowners and to conduct extensive tests on the performance of the house as a whole and on some individual retrofit measures. NREL and SMUD also performed tests on the home's heating, ventilation, and air-conditioning (HVAC) and water heating systems to determine the best control strategies for the local climate.

NREL’s role at the Greenbuilt house began after construction was complete and consisted of two main goals:

- Characterize the advanced systems installed during the retrofit to ensure that all were performing as intended. This task also involved verifying that the expected energy savings were achieved.
- Use the advanced control systems to simulate occupancy and run experiments on the cooling and water heating systems.

As with other EERD projects, NREL ran a number of short-term tests on major systems, including the PV system, the add-on HPWH, the space conditioning heat pump, and the air distribution system. All these systems were either newly installed or improved during the retrofit and NREL’s tests were designed to verify their installed performance. Whole-house performance was determined by measuring whole-house power consumption for the year SMUD leased the home. A computer model of the house was also created in NREL’s building energy optimization software, BEopt™, and was used to determine the expected energy savings. Based on this model, the annual energy consumption is expected to be 9400 kWh, almost 60% lower than the pre-retrofit annual consumption of approximately 22000 kWh.

In addition to the tests used to gauge performance, extensive monitoring and control equipment was installed to create a laboratory house. Some systems, including all the lights and the thermostat, could be controlled remotely using the Control4 home control system that was installed as part of the retrofit. NREL also added controls that allowed hot water draws and small space heaters to be controlled remotely. These systems were used to simulate occupancy. Once a simulated occupancy schedule was in place, a variety of tests were performed. The cooling system tests focused on finding ways to reduce the daily cooling load and shift the peak cooling load. Tests were also performed on the add-on HPWH and integrated collector storage (ICS) SWH to measure efficiency, which varies according to use patterns and weather conditions. The ability to run these tests in an unoccupied home with an imposed simulated occupancy removes the uncertainty associated with occupants, making it easier to compare results from various tests. It also enabled researchers to investigate some cooling strategies that may have introduced uncomfortable indoor conditions without affecting occupant comfort.

The team learned a great deal about cooling strategies and HPWH efficiency during this year; the conclusions and recommendations for future work are presented in this report. This opportunity also provided experience with simulated occupancy and other aspects of working in a laboratory house. Some interesting research was done at the Greenbuilt house and valuable lessons were learned, making this a very fruitful experience for the entire team.

2 Evaluation of Retrofit Measures

2.1 Summary of Major Retrofit Measures

The Greenbuilt house underwent a total energy efficiency makeover as a part of its retrofit. The goal was to reduce energy consumption by 50%, which required all systems to be evaluated. Greenbuilt Construction and SMUD worked together to determine the most cost-effective means of achieving this goal. In addition to the aesthetic makeover of the interior and exterior, all appliances, the HVAC system, and the envelope were upgraded with an emphasis on energy efficiency.

Even though the house is relatively modern (built in 1983), it was very leaky and needed additional insulation throughout. The roof was replaced, a radiant barrier was added, and additional insulation was installed in the attic. All walls were air sealed, but the cost of complete insulation was prohibitive, so extra insulation was added to the west wall only (see Figure 2).

(a) Dense pack blown-in cellulose being installed in the west wall. Credit: Judy Lew-Loose, SMUD.

(b) Blown-in cellulose in the attic covered fiberglass batts. NREL/PIX 19612, Credit: Lieko Earle

Figure 2. Insulation was added to the west wall and in the attic

All the windows were replaced with double-pane, low-emittance, argon-filled windows. A new, higher efficiency heat pump replaced the earlier model and a whole-house fan was installed in the attic. All appliances were upgraded to ENERGY STAR® and an HPWH add-on unit was installed on top of an older standard electric water heater (see Figure 3).

(a) Whole-house fan in the attic
NREL/PIX 19613,
Credit: Lieko Earle

(b) High efficiency SEER 16, HSPF 9.75
heat pump (condenser unit)
Credit: Judy Lew-Loose, SMUD

(c) Add-on HPWH
NREL/PIX 19614,
Credit: Lieko Earle

Figure 3. Three pieces of equipment that were upgraded for energy efficiency

All lights were replaced with compact fluorescent lamps (CFLs) or light-emitting diodes. Mechanical shades and an awning were installed to shade all west-facing windows. An ISC SWH and 2.3 kW of PV were installed on the roof (see Figure 4).

(a) The motorized exterior shading and awning
on the west side of the house.
Credit: Judy Lew-Loose, SMUD

(b) The 2.3 kW PV array and the ICS SWH. Also shown
is the weather station installed by NREL. NREL/PIX
19615, Credit: Lieko Earle

Figure 4. External shading and on-site renewable energy systems are shown

Appendix A provides a detailed list of all the retrofit measures. These measures reduced the Home Energy Rating Index by 57% (a lower index indicates a lower overall energy use). Before the retrofit, the home was assessed by a certified Home Energy Rating System (HERS) rater and given an index of 181. This is well above the average index of 100 for a new home and 130 for a resale home. After the retrofit, the home's HERS Index decreased to 78, which indicated a dramatic improvement in energy use.

2.2 Floor Plan

The Greenbuilt home has three bedrooms, two bathrooms, a den or office space, a two-car garage, and a large, open living room, dining room, and kitchen area. There is an attic but no basement or crawlspace; the house is built on a slab-on-grade foundation. The air handler and all the air ducts are located in the unconditioned attic. The floor plan remained mostly consistent through the remodel (see Figures 5 and 6). Some walls were removed between the kitchen and the dining room/living room area and walls were added to the den to create a more defined space. Otherwise, most improvements were made to the enclosure, appliances, and systems.

Figure 5. Pre-retrofit layout of the Greenbuilt house

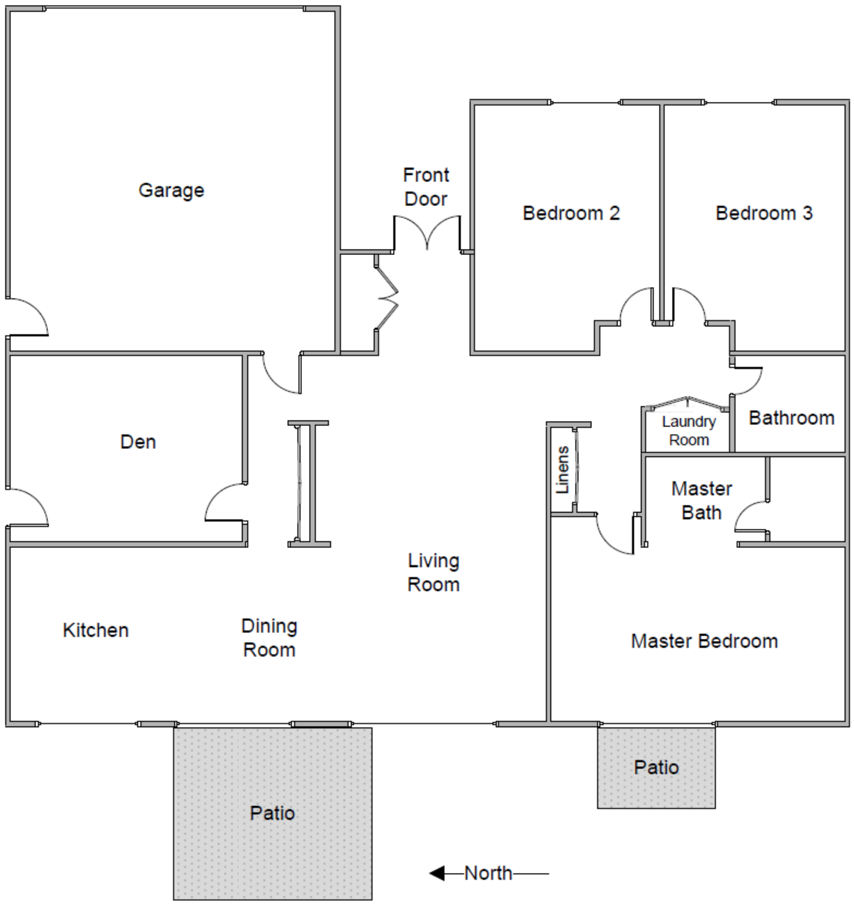

Figure 6. Post-retrofit layout of the Greenbuilt house

2.3 Retrofit Validation Tests

NREL researchers conducted validation tests to ensure the major retrofit measures were performing as expected. Installing insulation was a major part of the retrofit, but an infrared camera was not available to verify that the wall insulation was installed correctly and completely. The attic insulation was visually inspected. A test was conducted during the winter on the space conditioning heat pump to calculate its approximate coefficient of performance (COP) in heating mode, which was compared to the manufacturer's rating at the test conditions. The PV system was monitored to compare actual power output to the expected output based on the actual solar irradiance and the temperature of the panels. A test of airflow distribution was also conducted. The performance of the HPWH and the ICS SWH was tested over the course of several months. These tests and their results are described in more detail in the following sections.

2.4 Rooftop Photovoltaics

The Greenbuilt house is equipped with Suntech's model STP 175S-24/AD-1 rooftop PV to provide onsite solar energy (see Figures 4a, 4b). The manufacturer's technical specifications for this product and the installation configuration are summarized in Tables 1 and 2, respectively. The unit is grid tied and has no local storage capabilities.

Table 1. Manufacturer's Specifications for Suntech Model STP 175S-24/AD PV Panels

Maximum power at STC* (P_{max})	175 W
Open-circuit voltage (v_{oc})	44.7 V
Optimum operating voltage (v_{mp})	35.2 V
Short-circuit current (i_{sc})	5.20 A
Optimum operating current (i_{mp})	4.95 A
Solar cell	Monocrystalline silicon 125 mm × 125 mm

* Standard test conditions (STC) are defined as solar irradiance 1000 W/m^2, module temperature 77°F (25°C).

Table 2. PV Installation Configuration at the Greenbuilt House

Number of modules	16
Number of modules per string	8
Number of parallel strings	2
Array azimuth	90° (due west)
Array tilt	27°

2.4.1 Efficiency Measurements

Short-term testing was conducted on February 17, 2010 using the procedure outlined in (Barker & Norton, 2003). The objectives were to ensure proper operation of the system components and to characterize installed performance so a reasonable prediction of annual electricity delivered to the home could be calculated.

The following measurements were required to compare the power output of the array with the theoretical value:

- The current delivered by the array (measured with a precision shunt resistor)
- The incident global solar radiation (measured using a thermopile-type pyranometer)
- The PV cell temperature.

The cell temperature was approximated to be equal to the back-of-module temperature, which was measured using a surface-mounted temperature sensor fixed to the back of one module. A total of 86 I-V traces were made, one every 5 minutes, between 9:50 a.m. and 5:00 p.m. The resulting I-V curves for are shown in Figure 7 for a range of solar irradiance values. Efficiency at standard test conditions (STC) (I_c =1000 W/m2 , T_c = 77°F [25°C]) is expected to be 13.6% from manufacturer's data, which closely matches the 13.7% predicted efficiency based on measured data extrapolated to STC.

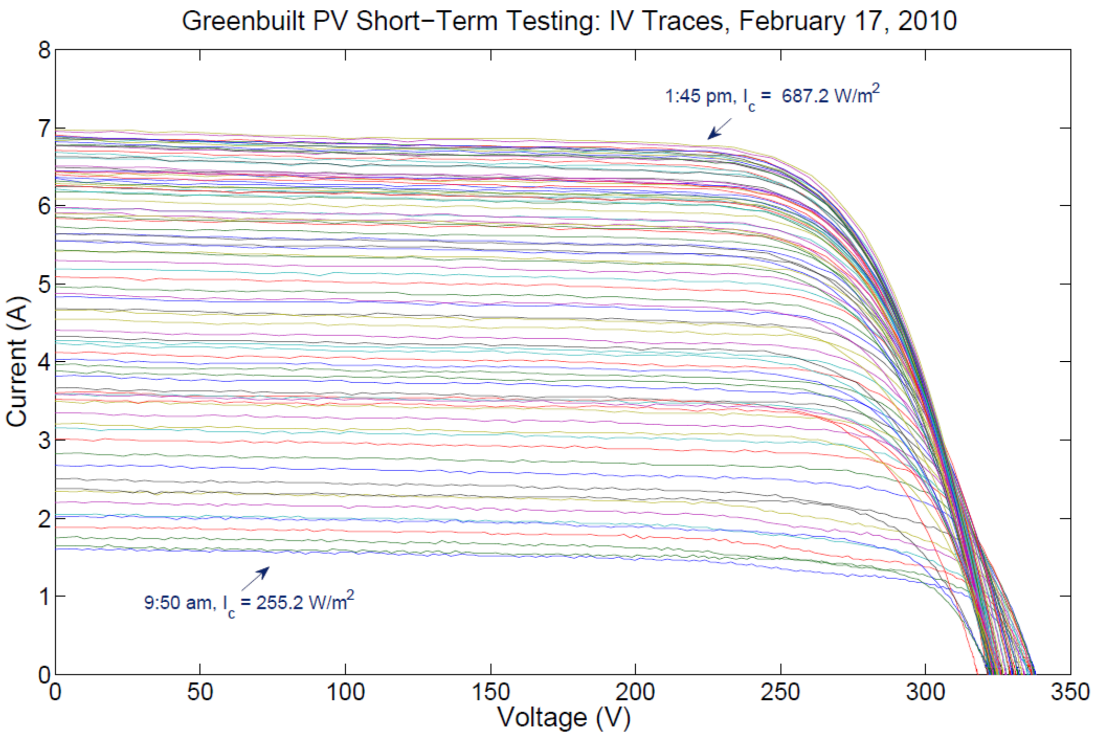

Figure 7. Current-voltage characteristics for a range of solar irradiance values

2.4.2 Measured Versus Modeled Energy Production

It is useful to compare the theoretical and measured power output of the array under test conditions. Hourly TRN-SYS simulations were driven using measured irradiance and module temperature for the period March 21 through September 19, 2010 and compared to the measured alternating current (AC) power output during the same period. The results are summarized in Table 3. The following assumptions were used in the modeling:

- The inverter tracks the maximum power point perfectly.
- The inverter efficiency curve is equal to that of a SunPower SPR 3300x-240 rated at 4 kW.
- In simulating the array using manufacturer's data, incidence angle modifier and air mass modifier are 1.0. (The manufacturer does not supply these data.)

Table 3. Summary of PV Performance Prediction Versus Measurement

Dates (in 2010)	Solar Radiation (kJ/m^2)	AC Delivery From Inverter (kWh)			Measurement/ Model
		Measurement	Model	Model Based on Manufacturer Data	
March 21–31	177217	109.2	118.7	123.2	.9200
April 1–30	503878	317.5	336.1	347.2	.9447
May 1–31	627334	386.4	411.3	423.5	.9395
June 1–30	732690	436.4	465.3	472.6	.9379
July 1–31	765907	444.4	445.7	446.8	.9971
August 1–31	674974	397.9	393.0	396.4	1.012
September 1–19	332647	201.1	194.3	198.3	1.035
Total	3814647	2292.9	2364.4	2408.1	.96976

Over the entire period, the calibrated model overpredicted the measured output by roughly 3%; the actual measured output was 2293 kWh. The percent discrepancy between monthly measured and predicted output was –1% to +9%.

These results give us reasonable confidence that our model can be used to predict the array's performance under a standard set of conditions using Typical Meteorological Year (TMY) data. It is possible to derive a correlation for the module temperature (which affects AC efficiency) as a function of outdoor conditions because we have measured data for solar radiation, ambient temperature, wind speed, and humidity, as well as module temperatures at several locations on the array. A good prediction of delivered energy under TMY conditions can then be made using this correlation.

The solar radiation measurements had two unexpected features (see Figure 8):

- The measured output from the inverter has a similar shape over time as the measured collector-plane insolation, but the AC power curve tends to peak about 40 minutes earlier than the measured insolation. When accepted solar geometry algorithms are used to calculate the expected global solar radiation in the collector plane, the shape and peak coincide with the measured AC power output from the inverter. This implies that the PV array was indeed oriented at tilt = 27°, azimuth = 90°, but the pyranometer's output was somehow skewed by some combination of installation error and spectral sensitivity error. Figure 8 shows the time offset between the measured and modeled AC power output. The model follows the measured collector-plane insolation as expected (peaks at the same time).
- For several days (April 7 and April 18 through April 25) the magnitude of the measured collector-plane insolation was larger than expected relative to the insolation measured in the horizontal plane. For these days the model overestimated the inverter's output. Figure 8 illustrates this feature by comparing April 7 and April 8: The measured horizontal insolation profile is almost identical between the two days, but the measured collector-plane insolation for the first day is notably higher at its peak than that for the second day.

We expect the horizontal peak to be higher than the collector-plane peak, and we are unable to explain this discrepancy.

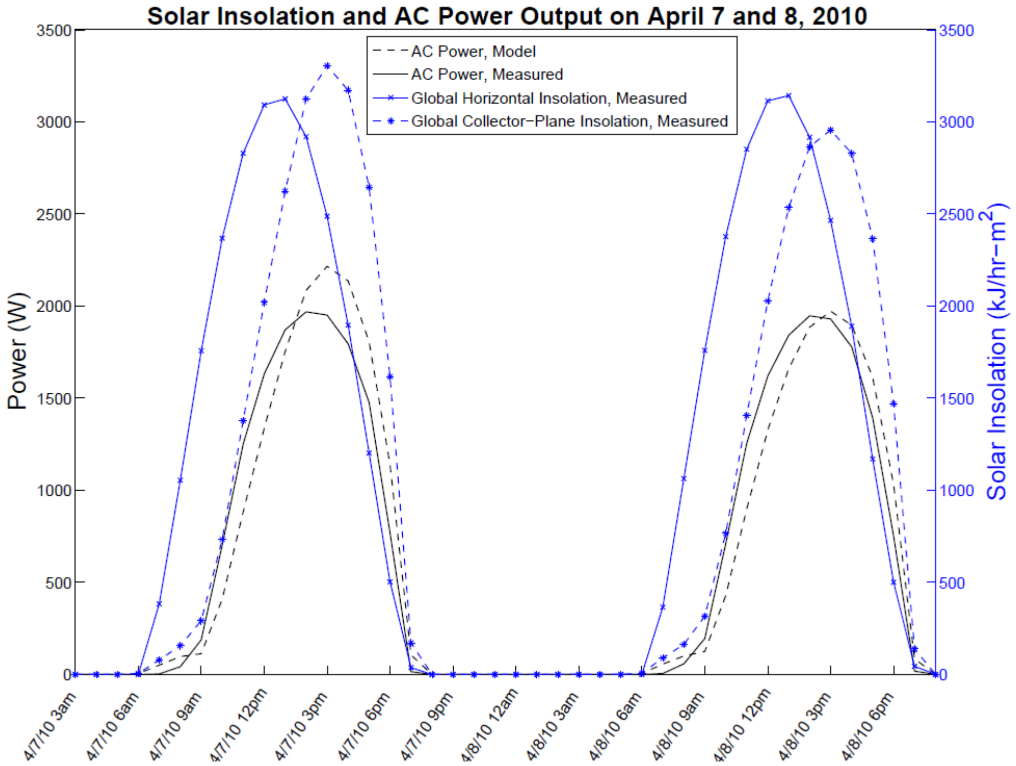

Figure 8. Temporal offset between collector-plane insolation and AC output, and discrepancy in relative magnitude of horizontal and collector-plane insolation

2.5 Coefficient of Performance Test for Space Conditioning Heat Pump

The COP for a heat pump in heating mode is defined to be the ratio of thermal energy (in the form of heat) supplied to the space divided by the electrical energy consumed by the heat pump. Although measuring the electrical energy consumed by the heat pump is straightforward (current transformers are clamped to the dedicated breaker for the heat pump), measuring the heat supplied by the heat pump requires airflow rate and temperature to be measured at the outlet of the heat pump, which are difficult measurements. A simplified method for calculating the COP of a space conditioning heat pump involves comparing the energy needed to heat the house with electric resistance heaters and the energy needed to heat the house using the heat pump. Electric resistance heaters have a COP of 1 (all the input energy is converted to heat), so comparing the two cases will give an approximate COP value for the heat pump. This will estimate COP in heating mode only, for the specific conditions of the test, but this is a valuable exercise, as it helps to verify the expected performance of the heat pump. The coheating test also provides a measure for how the performance of the heat pump is affected in a real installation.

This test included two phases: the coheating phase and the heat pump heating phase. Coheating refers to the period when electric resistance heaters were used to maintain an internal temperature of 68°F (20°C) at all times. Five small space heaters (used later to simulate occupancy) were located around the house and provided the required resistance heating. After about a week of the coheating test, the heat pump and air handler were used to maintain the house at the same set point temperature. Both tests were performed in late January and early February.

Data from the two tests were examined to find periods with similar weather. Three periods with similar outdoor temperatures, all during the night, were chosen for comparison. The duration of each period was 10 hours, starting at 10:00 p.m. The energy consumed by each heating source was determined by looking at the energy required for the entire house and subtracting the submetered loads: the HPWH and the air handler. Some other small loads, such as the refrigerator and a handful of small electronics, contributed to the whole-house energy consumption. These were not submetered but also contributed to heating the house.

The heat pump is made by Goodman Manufacturing, model SSZ160361AC. The manufacturer provides performance data over a variety of heating and cooling conditions. For heating mode, the indoor temperature is 70°F (21°C) (rather than our set point of 68°F [20°C]). The COP is given across a wide range of outdoor temperatures of –10°F to 65°F (12°C to 18°C) in 5°F (15°C) increments. The COP value was extrapolated from the manufacturer's data, based on the actual outdoor temperature averaged over the night, and that value was compared to the calculated COP value from the coheating tests (see Table 4). The time periods used for comparison are referred to as Nights 1, 2, and 3; however, each includes data from two nights: one night when the heat pump was used to heat the home and another night with a similar overnight temperature when the space heaters maintained the indoor temperature.

Table 4. Measured COP and Manufacturer Ratings

	Night 1		**Night 2**		**Night 3**	
Outdoor temperature	48°F	8.9°C	41°F	5.0°C	45.7°F	7.6°C
Space heater energy (kWh)	20.5		25.4		21.9	
Heat pump energy (kWh)	7.9		10.6		8.2	
Calculated COP	2.59		2.41		2.66	
Rated COP	4.02		3.72		3.92	
% difference	35.6		35.1		32.2	

The COP results vary between the three comparison periods, because the outdoor temperature varies. The measured COP is about 35% lower than the manufacturer's rating, which indicates some losses in the system, such as duct losses, that consistently affect the installed performance of the heat pump. The results for calculated COP are only approximate. The periods used for comparison were not exact matches and the energy consumed in both heating cases may include other heat sources. An installed performance below the rating provided by the manufacturer was expected, so a 35% difference between rated and actual performance was reasonable. So, this test confirms that the heat pump operated approximately as expected and system inefficiencies (also expected) reduced the overall performance.

2.6 Performance Tests for Domestic Hot Water System

The domestic hot water (DHW) system consists of a CopperHeart ICS solar panel, model CP-40, and an AirTap HPWH add-on unit, model A7. A specific test was not performed to characterize the performance of the ICS; however, its thermal performance was calculated across several days of testing and compared to the thermal performance ratings defined by the manufacturer. The thermal performance calculations will be discussed in more detail in Section 3.4. These ratings are specified on clear, mildly cloudy, and cloudy days, when the incident solar irradiance is 2000 Btu/ft^2/day, 1500 Btu/ft^2/day, and 1000 Btu/ft^2/day, respectively. Data were selected from days with similar solar irradiance to make the comparison to the rated values; the measured values differed from the rated solar irradiance by up to 6%.

Table 5 shows the manufacturer's quoted performance numbers compared to the measured performance. These numbers imply a performance below the manufacturer's ratings, because thermal energy was calculated based on the temperatures in the pipes entering and exiting the ICS, and not on the temperature of the ICS itself. Therefore, the thermal energy is calculated based only on the amount of hot water used during draws. A direct measurement of the ICS would have given more accurate results, which would likely have been closer to the manufacturer's ratings. Regardless, this comparison shows that the ICS worked effectively as a preheater for the HPWH.

Table 5. ICS Thermal Performance Ratings Versus Measurements

Rating Condition*	Rated Thermal Performance (kWh/Day/Unit)	Measured Thermal Performance (kWh/Day/Unit)	Performance Shortfall (%)
Clear	10.50	6.07	42.1
Mildly cloudy	7.25	5.90	18.7
Cloudy	5.42	2.84	47.7

* The solar irradiance on the days used to calculate measured thermal performance is within 6% of the solar irradiance implied by the rated conditions.

Similar to the COP defined for the heat pump, COP can also be calculated for water heaters as the ratio of the thermal energy delivered to the water and the electrical energy consumed. A standard electric resistance water heater typically has a COP around 0.9. HPWHs are more energy efficient with their COP ranging between 2 and 3, depending on a number of factors, including ambient air conditions and hot water usage. The HPWH was installed in the garage and therefore is subjected to some of the variation in the weather. The same daily draw profile, the hourly benchmark profile, was run for several days in both the summer and winter and an average daily COP for each period was calculated. Those results are given in Table 6. As expected, the COP is slightly lower in the winter when the garage is colder and slightly higher during the warmer summer months. An annual COP around 2 is in line with expectations and cuts hot water energy use relative to a standard electric water heater by more than half.

Table 6. HPWH Measured Performance

Winter Average Daily COP	Summer Average Daily COP
1.95	2.13

2.7 Air Distribution System

A flow hood test was conducted on all the air registers as a part of the retrofit validation tests (see Figure 9). This test captured the volumetric flow of air coming from the register and verified that all the rooms were receiving a balanced amount of air. The test was done with an unassisted flow hood (no fan assistance to ensure zero pressure drop from the register), because the objective was to verify relative balance between the rooms. If the test had been aimed at measuring duct losses, for instance, a more accurate fan-assisted flow hood would have been used. (Volumetric airflow per room should roughly be proportional to the area of that room, but rooms with a higher thermal load should receive more airflow.) The rooms on the west side of the house—the kitchen, dining room, living room, and master bedroom—should have received a bit more air than their relative areas indicate. A flow hood test was initially performed in September 2009 and was repeated in January 2010 because some problems with the duct system were identified during the first round of tests (see Table 7). The room area is also included in the table for reference.

Figure 9. Flow hood test in progress

NREL/PIX 19616, Credit: Lieko Earle

Table 7. Room-by-Room Register Air Flow Measurements

Duct Location	Room Area (ft^2)	Cooling Mode Test 1 (CFM)	Cooling Mode Test 2 (CFM)	Area-Based Airflow (CFM)
Kitchen	242	85	80	86
Dining room		89	80	86
Living room (1)	487	195	185	173
Living room (2)		265	230	173
Den	195	88	82	138
Master bedroom (1)	240	30	105	85
Master bedroom (2)		0	126	85
Master bath	84	0	22	30
Master shower		18	34	30
Main bath	48	26	22	34
Bedroom 2	209	142	131	148
Bedroom 3	209	140	129	148
Total	1732	1078	1227	1227

Some results from the first flow hood test stand out immediately (and are highlighted in red in Table 7). Namely, the master bedroom was receiving almost no airflow, even though it contained two registers, and the master bath was receiving no air. Badly twisted ducts in the attic were unable to deliver any air to the intended rooms. After these ducts were straightened, the balance between the rooms improved considerably.

Based on the total airflow measured in the second flow hood test and the total area of the house, the airflow proportional to room area was determined and applied to the actual area of each room. The result of that calculation is found in the last column of Table 7. The room-by-room results from the second test do not differ significantly from the area-based calculation for airflow per room. The master bedroom and living room received more air than would be prescribed based on area alone, but those rooms are on the west side of the house and have a higher thermal load because of solar heat gain. The kitchen should probably also have received more air than the area-based calculation calls for to compensate for the west-facing windows and the additional loads introduced by cooking. Otherwise, the airflow appears to be reasonably distributed. The total flow rate supplied by the heat pump (which has a 3-ton cooling capacity) was also within the appropriate range. (Each ton of cooling should equate roughly to 350–450 CFM of supplied air and the Greenbuilt heat pump supplied just over 400 CFM per ton.) Based on some reasonable guidelines, the air distribution system appeared to be working as intended.

3 The Greenbuilt House as a Laboratory House

In addition to being an example of a deep energy retrofit, the Greenbuilt house was also instrumented to be used as an unoccupied laboratory house. A laboratory house is intended to include all the same loads as a traditional occupied home but without occupants. It was thus possible to install new and untested equipment and try novel techniques for space conditioning without the risk of making the occupants uncomfortable. Also, occupant behavior is unpredictable and can make test results ambiguous. If occupancy is simulated in a laboratory house, the results of any experiment cannot be affected by human behavior. Also, a laboratory house can be filled with sensors without aesthetic concerns. Laboratory houses allow researchers to study the performance of advanced energy efficiency technologies without the concerns that are inherent in an occupied home, making them the perfect setting for advanced whole-house research.

By their nature, laboratory houses require more instrumentation than a typical field test. When testing innovative technology, additional sensors are needed to ensure that it is working as intended. Especially in the case of testing new space conditioning equipment, conditions throughout the house must be measured to verify functionality. A laboratory house also must have simulated loads imposed on the space to mimic an occupied home. Simulated occupancy involves adding heat to account for the sensible load created by people and appliances, turning lights on and off throughout the day, and inducing hot water draws, as all these pieces affect the energy consumed by the HVAC and water heating systems. All the controls needed for simulated occupancy must be remotely controllable so a researcher does not need to visit the house regularly and so people will not have reason to enter the house, which can change the conditions. The level of monitoring and control capabilities needed to do these functions far exceeds the average field test setup.

3.1 Instrumentation and Controls

To implement a simulated occupancy schedule and run experiments on the space conditioning and water heating systems, remote access to sensors and controls is critical. A Control4 system was installed to control the thermostat, all the lights, and a few electronics. The Control4 software allowed lighting and thermostat schedules to be created and edited remotely. The other pieces of the simulated occupancy schedule, the sensible heat loads and the hot water draws, were controlled by the data acquisition system (DAQ) installed by NREL. A Campbell Scientific DAQ was installed and could be accessed remotely. The DAQ collected temperature data for each room, power data for the house, PV system, and some large appliances, and local weather data from a weather station installed on the roof, among other data collection items. The DAQ also had on/off control that was used to turn the electric heaters for sensible loads on and off. The same relay control was used to open and close a solenoid valve on the hot water faucet in the laundry room. Several unique draw profiles were programmed in the Campbell data logger software and NREL researchers could choose the desired hot water draw schedule remotely. Appendix B provides a full list of sensors and control functions of the Campbell data system.

3.2 Simulated Occupancy

3.2.1 Sensible Heat Gains

Before any experiments could be run, all occupant-related loads needed to be imposed on the house. The main sources of sensible heat in a home are occupants, major appliances (e.g. refrigerator, washer, dryer, oven, and dishwasher), DHW use, and miscellaneous electric loads (MELs). The only large appliance that was installed and operational in the Greenbuilt house was the refrigerator. The combined sensible load from the remaining appliances (including MELs), DHW draws, and occupants was simulated using small space heaters positioned in each room. The Building America Benchmark was used to determine the hourly sensible heat gain for each load (Hendron & Engebrecht, 2010). The benchmark specifies hourly sensible heat gains for three occupants (the average number of residents in a three-bedroom house), but the location is not prescribed. To make the occupancy simulation as realistic as possible, the required sensible heat loads were dispersed throughout the house based on time of day. For instance, during the night, the occupant loads were located in the bedrooms but in the evening, the occupant heat gains were introduced in the kitchen and living room. Each heater produced 930 W of heat and was turned on at the top of each hour and remained on until the sensible heat load for that room and hour was met. **Figure 10** shows the sensible loads used to account for occupants by room over the course of a day.

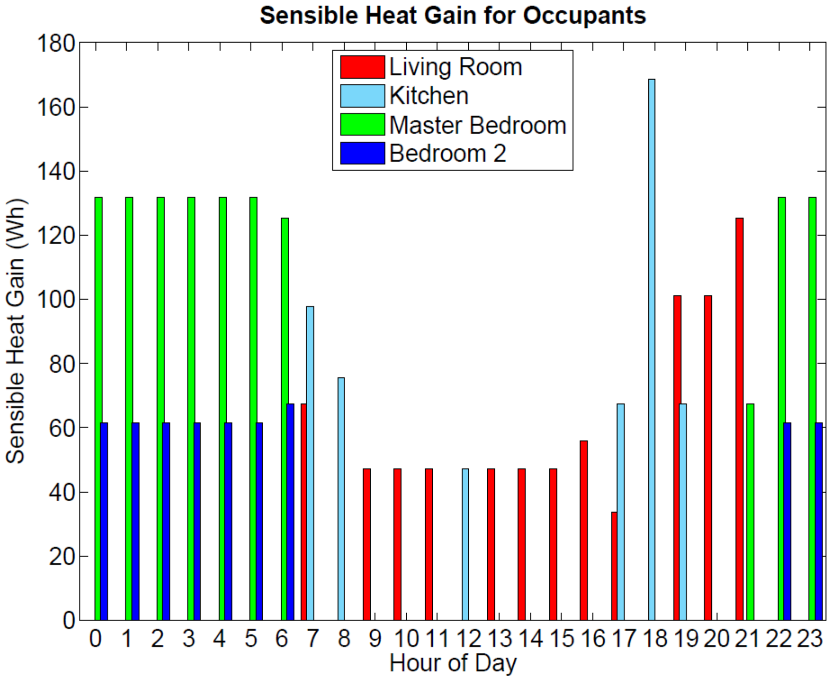

Figure 10. Imposed sensible load schedule, by room, to account for occupants

The sensible heat generated by large appliances, hot water draws, and MELs was taken into account in the simulated occupancy schedule. The loads for large appliances (range, washer, dryer, dishwasher) are evenly distributed over the course of the day in the benchmark, but realistically, these appliances run at specific times of day. Therefore, the entire daily load for each large appliance was introduced at one time, in the most appropriate location. The sensible loads for the range and dishwasher were generated in the kitchen. The washer and dryer would have been located in the hall closet, so their sensible loads were introduced in the closest room: Bedroom 2. All large appliance loads were scheduled to occur in the evening. The daily sensible load generated by MELs was distributed throughout the day, as would happen in an occupied home, and introduced in the living room. The DHW sensible load was introduced in the master bedroom and distributed over the entire day, as hot water is typically used throughout the day.

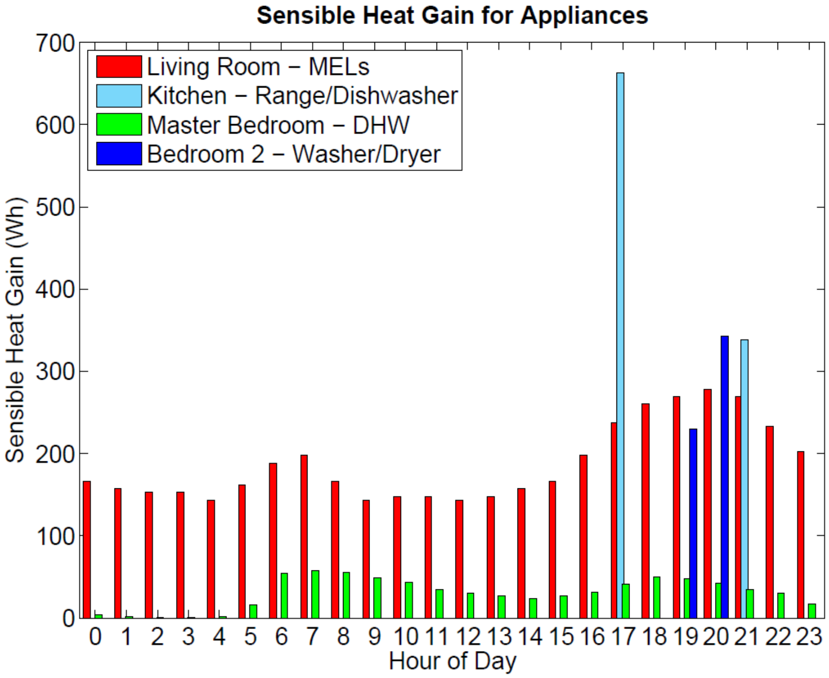

Figure 11. Imposed sensible load schedule, by room, to account for appliances

3.2.2 Lighting Schedule

All the lights were operated on a daily schedule based on the Building America benchmark (Hendron & Engebrecht, 2010). However, the benchmark calls for lights during all hours of the day, including the middle of the night and the middle of the day. The benchmark was modified so lights would not operate between midnight and 5:00 a.m. and between 10:00 a.m. and 4:00 p.m. The remaining hourly lighting loads were used to determine the required fraction of daily lighting energy for each hour. The lighting schedules for each room were adjusted to match that profile, keeping the lighting locations consistent with the occupancy schedule. For instance, in the morning, lights in the bedrooms and bathrooms were turned on first, followed by the kitchen. In the evening, most of the lighting load was in the living room, dining room, and kitchen. Figure 12 shows the whole-house hourly lighting schedule that was implemented as a piece of the occupancy simulation. Nearly all the light bulbs were CFLs with the same power rating, so the lighting profile is described in number of light bulbs multiplied by time in hours. For instance, if one room had two light bulbs that were on for an hour, that was counted as two light bulb-hours.

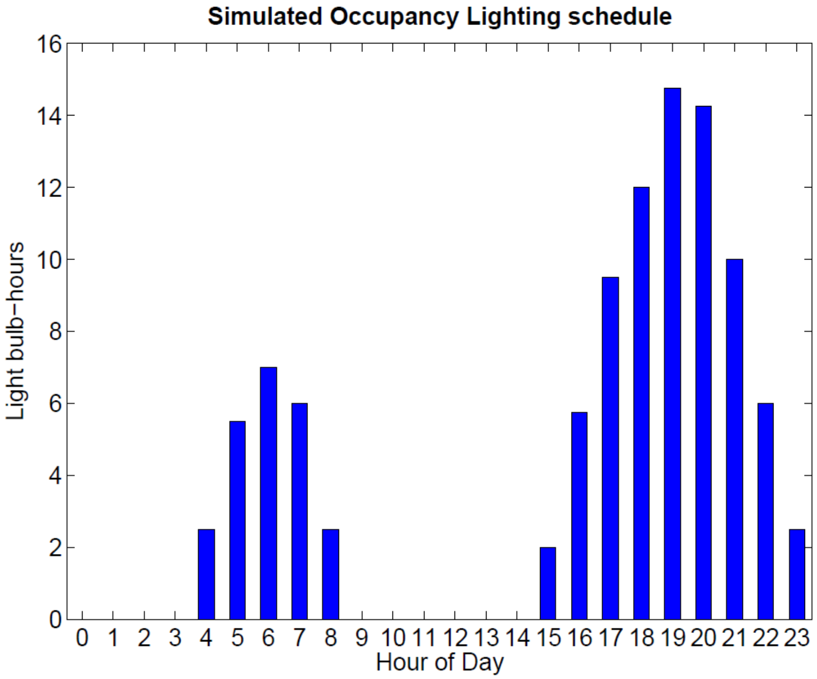

Figure 12. Aggregate lighting schedule for the whole-house, displayed as number of light bulb-hours

3.2.3 Domestic Hot Water Draws

The last piece of simulated occupancy is the DHW draw schedule. Unlike the sensible heat and lighting schedules that remained constant, the DHW schedule was varied approximately once a week to study the effects of draw patterns on system efficiency. Six draw profiles were tested, each with two system configurations. Each was tested with the HPWH alone supplying hot water and with the HPWH and ICS system working together to supply hot water.

The benchmark DHW draw profile prescribes a certain amount of hot water to be drawn every hour; however, their exact schedules and flow rates are not specified. In practice, the benchmark DHW profile is usually implemented by drawing each hour's worth of hot water at the top of the hour. One draw profile followed this practice, with the flow rate set to 3 gpm for all draws. A more realistic draw profile was created based on the standard benchmark draw profile, but with shorter, discrete draws. The total daily volume drawn and total hourly volume drawn were identical to the hourly benchmark draw profile. Two other draw profiles were created to determine whether the efficiency of the DHW system was affected by the time of day that most draws took place. Keeping the daily hot water volume from the hourly benchmark draw profile consistent, a morning-dominated profile and an evening-dominated profile were created using a tool for generating realistic hot water events (Hendron, Burch, & Barker, Tool for Generating Realistic Residential Hot Water Event Schedules, 2010). Lastly, the hourly benchmark hot water profile was doubled and quartered to see the effects of larger and smaller daily hot water draw volumes on system efficiency. (The hourly benchmark, discrete benchmark, morning-dominated and evening-dominated profiles are shown in Figure 13 through Figure 16.) The resulting performance of the individual draw profiles will be discussed in Section 3.4. All draws were performed with a solenoid valve attached to the hot water line in the laundry room, with the flow rate set to 3 gpm for all draws. All other hot water end uses in the house were disabled to control all hot water use.

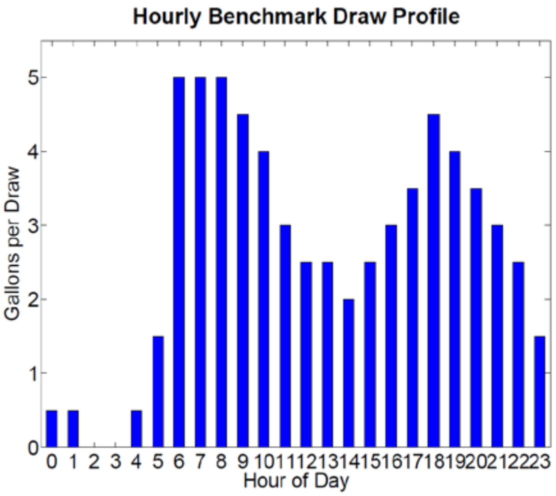

Figure 13. Hourly benchmark DHW draw profile

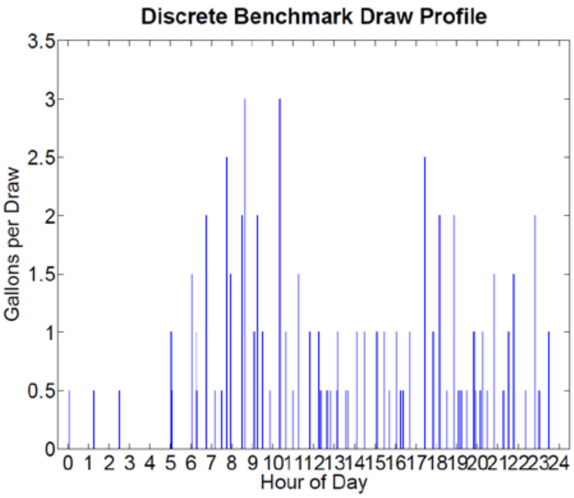

Figure 14. Benchmark hot water draw profile broken into smaller discrete draws

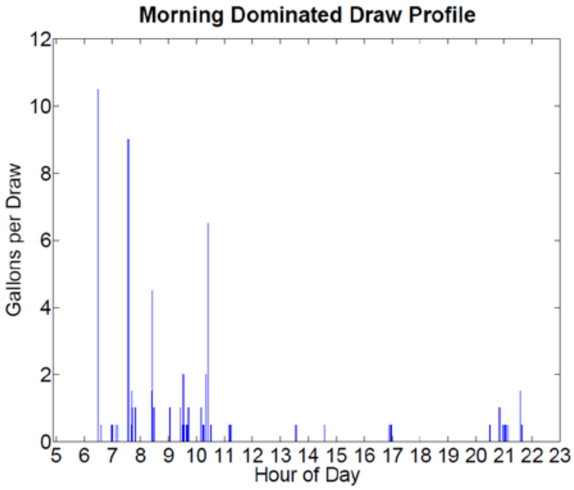

Figure 15. Morning-dominated hot water draw profile

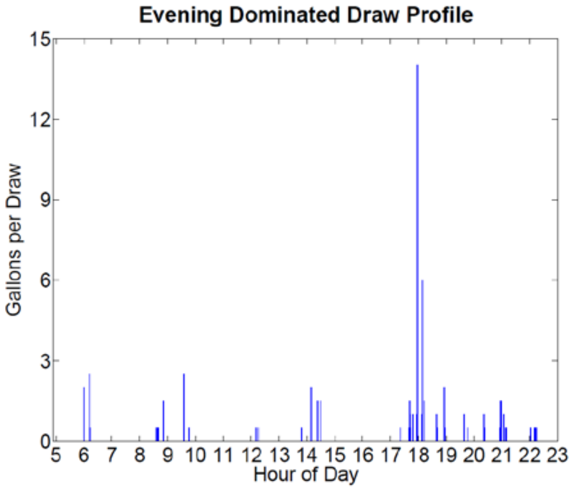

Figure 16. Evening-dominated hot water draw profile

3.3 Control4

A Control4 home control system was installed as part of the extensive retrofit at the Greenbuilt house. Its main control features included control of all hardwired lights, the thermostat, and a few plug loads. The scale of the retrofit was such that wiring all the light switches to the Control4 system was not difficult, but in many remodeling projects, this level of integration would be unrealistic. All systems connected to the Control4 system could be controlled by an interface accessible through the television or through the Control4 Composer computer program, which could be changed from anywhere with Internet access. Appendix B provides a complete list of all the Control4 equipment installed at the Greenbuilt house.

Figure 17. Control4 lighting control interface through the television

Credit: Judy Lew-Loose, SMUD

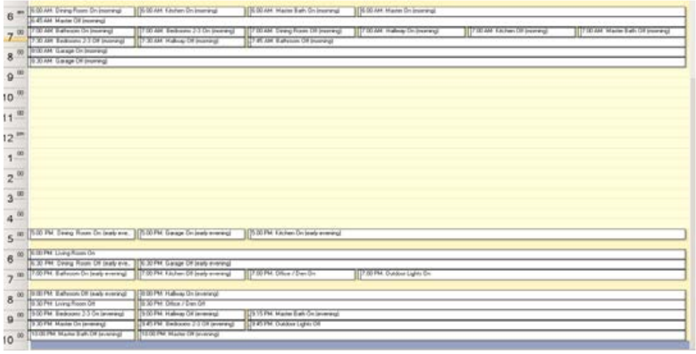

Figure 18. Screen shot of lighting schedule from Composer program

All features controlled by Control4 could be set to follow a daily schedule or changed instantaneously by either control interface. All physical light switches and the thermostat could be used to override the schedule. A whole-house switch at the front door was programmed to turn on a prescribed number of lights and change the thermostat setting when the “Home” button was pressed and turn off lights and set back the thermostat when the “Away” button was pressed. A third button in the entryway, labeled “Green,” could also be programmed to turn lights on or off and set the thermostat set point.

Figure 19. Home, Away, and Green switch buttons in the entryway

Credit: Judy Lew-Loose, SMUD

Figure 20. Control4 thermostat can be controlled manually or remotely

Credit: Judy Lew-Loose, SMUD

Several other functionalities are available with Control4 systems, including the ability to control motorized shades, integrate sensors from around the house, and gather whole-house energy use from a smart meter. The purpose of a home control system, from the perspective of energy efficiency, is to take some energy-related decisions out of the occupants’ hands to make smarter decisions. For instance, occupancy sensors could be installed in infrequently used rooms, allowing the lights to turn off automatically when the room is empty. Shades could automatically be drawn when the sun comes out during the summer. The thermostat set point could be changed based on the weather. So aside from creating a technologically advanced house, a home control system could also reduce energy costs by making smarter energy choices.

3.3.1 Role of Control4 in the Greenbuilt Laboratory House

The full functionality of the Control4 control system was used during this project, but with a different intent than in typical installations. For the laboratory house implementation, the Control4 system was used as an extension of the DAQ and enabled NREL researchers to control all lights and the thermostat on a schedule and remotely view and change settings. The lights were a part of the simulated occupancy schedule (see Section 3.2), and it would have been very difficult, if not impossible, to implement a lighting schedule without the Control4 system. The thermostat was changed regularly for various space conditioning strategies (see Section 3.4). All space conditioning schedules were created remotely and the Control4 thermostat had enough flexibility to implement the complicated schedules.

The "Home" and "Away" buttons were programmed similarly to a typical installation, with one additional feature. When the "Home" button was pressed, several lights in the main living area turned on and an email alert was sent to NREL researchers. When the "Away" button was pressed, lights were turned off and another email alert was sent. This functionality was added a few months into the project, because there were many visitors during the winter and the researchers needed to know when people were inside. The ability to send emails based on certain action items is a useful feature in Control4, especially in the laboratory house application.

3.4 Space Conditioning

3.4.1 Introduction

Building America classified Sacramento as a "hot-dry" climate, so cooling loads are the primary concern (ORNL & PNNL, 2010). However, the performance of some systems, such as the ICS and HPWH, are affected by winter temperatures, so testing began at Greenbuilt in February 2010. The baseline HVAC case for both summer and winter refers to when a constant set point is used throughout the day and simulated occupancy is enabled. During the baseline schedule in the winter, the house was kept at 68°F (20°C) and simulated occupancy (including lights, space heaters, and hot water draws) was enabled. In the summer, the baseline case consisted of a constant set point of 78°F (25.5°C) all day while the simulated occupancy schedule was running. Figure 21 shows the hourly HVAC loads throughout a typical winter day relative to a typical summer cooling day. The outdoor temperatures are also shown to illustrate the difference between summer and winter weather.

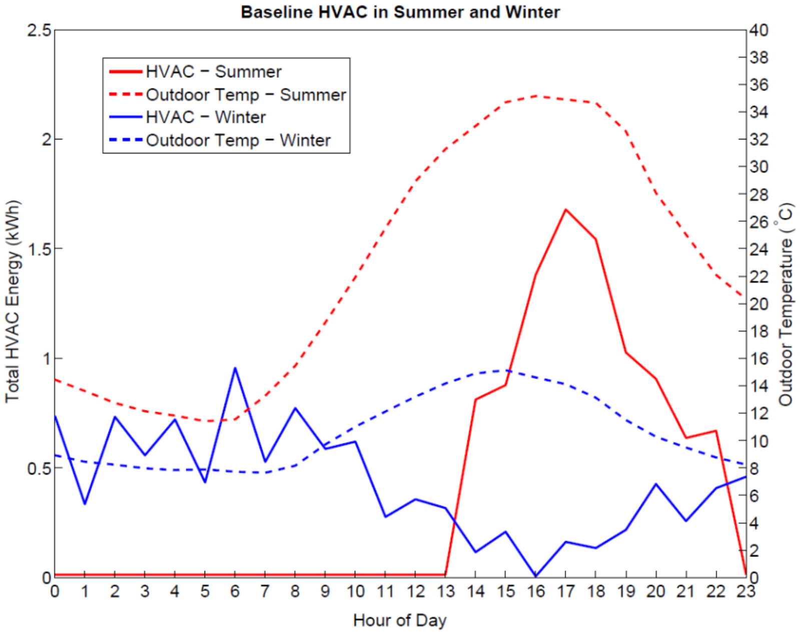

Figure 21. Energy use comparison for the baseline HVAC case during the summer and winter

The days shown in Figure 21 represent average temperature days for the 2010 summer and winter seasons. Winters are mild in Sacramento, so a typical winter day has a high of 60°F (16°C) and a low of 45°F (7.5°C). A typical summer day reaches a high of 95°F (35°C) and a low of 52°F (11°C). Summer and winter days have very different daily HVAC load profiles: the heating load is highest for winter nights and early mornings, whereas the late afternoon cooling load represents the peak load for summer days. There is no dramatic spike in winter heating loads, so they do not stress the electricity distribution in the same way that summer peak loads do. In Sacramento, the peak electricity demand in the summer occurs between 4:00 p.m. and 7:00 p.m. (which coincides with the peak in the summer HVAC consumption), so reducing cooling demand during this time is a priority for SMUD.

Despite the lack of a winter peak load, the typical daily heating load is nearly identical to the typical daily cooling load. Table 8 shows the daily energy consumption by the space conditioning heat pump and air handler for the same typical days shown in Figure 21. For comparison, the daily space conditioning loads for an extremely hot summer day (high of 104°F [40°C]) and an abnormally cold winter night (low of 35°F [2°C]) are also shown. The extreme heating and cooling loads are still similar, but the daily summer cooling load is slightly higher. Again, the cooling load is more important, especially during extended periods of hot weather, because it is concentrated over a short period in the afternoon. The daily heating load, even on especially cold days, is less a concern as it is spread out over the night and day, making the energy demand more manageable for SMUD. The electricity demand during the summer peak hours is also shown in Table 8 to further illustrate the interest in cooling loads, especially during the peak hours. Even though the summer peak only accounts for three hours of the day, the peak cooling load on a typical summer day is nearly half the daily total; on an extremely hot day, the peak load represents about 40% of the daily cooling load.

Table 8. Total Daily and Peak HVAC Energy Consumption for Baseline HVAC in Summer and Winter for Typical and Extreme Weather Days

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Summer—typical	8.3	1.4	**9.7**	**4.6**
Winter—typical	8.9	1.4	**10.3**	**0.9**
Summer—very hot	15.2	2.3	**17.5**	**6.6**
Winter—very cold	13.8	2.1	**15.9**	**1.0**

3.4.2 Research Questions for Cooling Experiments

A series of space conditioning experiments were run at the Greenbuilt laboratory house, designed to determine the most effective way to cut cooling costs and the best way to shift peak loads. The space conditioning experiments were designed to answer the following research questions:

- In the hot, dry climate of Sacramento, are there ways to reduce cooling loads throughout the day and during peak hours?
- Can the afternoon peak load be shifted using precooling without making residents uncomfortable?
- How does precooling affect the total daily cooling load?
- Are there variations on the precooling schedule that shift the peak energy consumption without increasing overall energy use?
- Is precooling still effective at shifting peak and maintaining comfortable indoor conditions during a heat storm (three consecutive days that reach 100°F [38°C])? Does precooling during a heat storm increase the daily cooling load?
- Are external shades an effective means of cutting cooling costs?
- Is a whole-house fan an effective means of cutting cooling costs?

All the tests were run with simulated occupancy to mimic the additional load on the occupied house. (The simulated occupancy schedule is discussed in more detail in Section 3.1.) Each test schedule, except the heat storm precooling test and the whole-house fan test, was run for 1–2 weeks. A brief description of each test follows. The set points were suggested by SMUD to be consistent with Title 24 recommendations.

- **Baseline.** As with all the other tests, simulated occupancy was enabled. The thermostat was kept at a constant temperature of 78°F (25.5°C) at all times of day and night.
- **Simple precooling.** The house was precooled to 74°F (23.3°C) between 10:00 a.m. and 4:00 p.m. The heat pump was turned off all other times of day. This test was conducted to see if a well-insulated home could remain comfortable with limited cooling during a summer day.

- **Advanced precooling.** The thermostat was set to 74°F (23.3°C) between 10:00 a.m. and 4:00 p.m., 80°F (26.7°C) between 4:00 p.m. and 8:00 p.m., and 78°F (25.5°C) all other times. This is a more typical precooling schedule and will be compared to the "simple precooling" case for energy use and indoor comfort.
- **Heat storm precooling.** The same precooling schedule as "advanced precooling" was used during a heat storm, which is defined as three consecutive days that reach 100°F (38°C). Heat storms place enormous stress on electricity supplies because the homes never have a chance to cool down, so air conditioners have to work harder and longer to counteract the extreme heat. Shifting peak cooling load during a heat storm would help the utility manage the electricity demand. Note that the shades were drawn during the heat storm precooling test (but not during the other precooling tests).
- **Shade control.** All the windows on the west side of the house had externally mounted semitransparent shades. The sliding glass door in the living room was shaded by a retractable awning. All the shades (and the awning) were drawn (covering the windows) during the shade control test for all hours of the day. The thermostat was set to maintain a constant temperature of 78°F (25.5°C) at all times.
- **Whole-house fan.** A short-term test of the whole-house fan was conducted over four days. The shades remained down during the whole-house fan test. The fan was operated between 8:00 p.m. and 10:00 p.m. with a few windows in the house open. The windows were closed after the fan was turned off. The fan was run later in the evening to ensure that the outdoor temperature was cooler than the interior temperature.

3.4.3 Results

The tests spanned several months (July through September), so weather conditions varied. Average outdoor temperature and insolation were used to find days with similar weather conditions. These days were then used to compare results. In the following section, a graph comparing hourly combined energy consumption of the heat pump and air handler is shown for each test (see Figures 23 through 33). All tests are compared to the baseline schedule. The two precooling schedules are also compared to each other. The total HVAC energy consumption for each test day is summarized in a table following each graph (see Tables 8 through 14). The HVAC energy consumption during the summer peak hours (4:00 p.m. to 7:00 p.m.) is also shown in each table. All the data come from a single day of testing and are not averaged with any other days.

Simple Precooling

The first of two precooling strategies tested was the simple precooling schedule. This strategy allows the heat pump to cool the house only six hours of the day; nonetheless, the indoor air temperature did not exceed 79°F (26°C). This spartan cooling schedule would likely not produce the same results in homes that are not as well sealed or insulated as the Greenbuilt house. The strategy relies on the home's ability to maintain a cool indoor air temperature without being affected by leaks and heat transfer from the warmer outdoor air. Even though the application for this scenario is limited, it provides a means of shifting summer peak loads and reducing overall HVAC energy use in high performance homes without sacrificing comfort.

The simple precooling strategy effectively shifts the peak to earlier in the day and reduces total daily HVAC energy use. The living room temperature is also displayed in Figure 22 to show that the simple precooling strategy results in an increase in indoor temperature during peak hours. It does not, however, deviate outside the bounds of the summer comfort zone as defined by ASHRAE, which has an upper temperature limit of 80°–83°F (27°–28°C), depending on the RH (ASHRAE, 2005). Figure 23 shows the outdoor air temperature and insolation on the days compared in Figure 22. The outdoor air temperature matches well between the two days, but the total insolation on the simple precooling day was about 30% lower than the day of the baseline schedule. This is primarily due to the timing of the tests: the baseline schedule was run in mid-July and the simple precooling test occurred in mid-September.

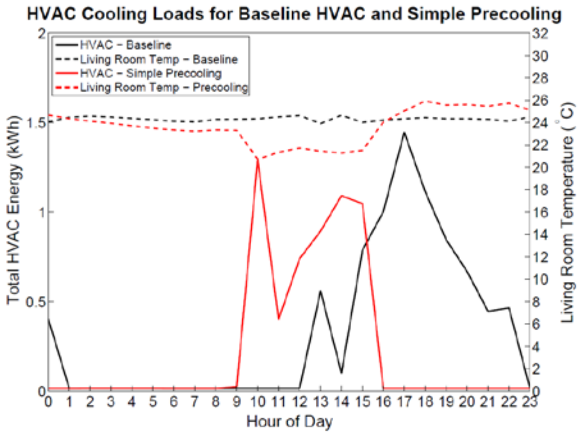

Figure 22. HVAC energy use for the baseline case and the simple precooling schedule

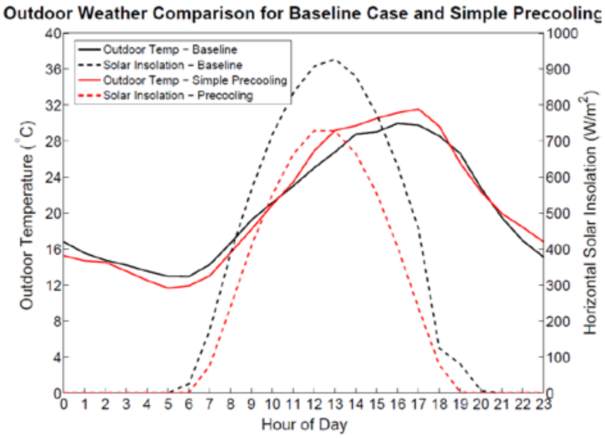

Figure 23. Weather comparison for baseline case and simple precooling days

Table 9 shows the daily and peak HVAC energy use for the days compared in Figure 22. The simple precooling schedule virtually eliminates the peak HVAC energy use and reduces the overall daily HVAC use by nearly 30%. Despite the success of this strategy, it may not be suitable for the warmest summer days. The outdoor temperature reached a maximum of 93°F (34°C) while this schedule was running. However, if a heat storm occurred, the home would hold more thermal energy through the warm nights and the time allowed for cooling may not be enough. The advanced precooling schedule may be a better option for the hottest days.

Table 9. Total Daily HVAC Energy Consumption for Baseline and Basic Precooling

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Baseline	6.68	1.34	**8.02**	**3.56**
Simple precooling	4.69	1.03	**5.72**	**0.04**

Advanced Precooling

The second precooling schedule, advanced precooling, is more typical. It has a cooler set point (74°F [23.3°C]) in the hours preceding the peak hours, a warmer set point (80°F [26.7°C]) during the peak time, and a standard set point (78°F [25.5°C]) for the rest of the day. Compared to the baseline case, the advanced precooling strategy succeeds in shifting the peak load, but does not save energy. In fact, for the two days compared in Figure 24, the daily HVAC energy use increased by 28% under the advanced precooling schedule. Figures 24 and 25 show the hourly HVAC energy use profile for the baseline schedule and the advanced precooling case, along with a comparison of the weather on those days.

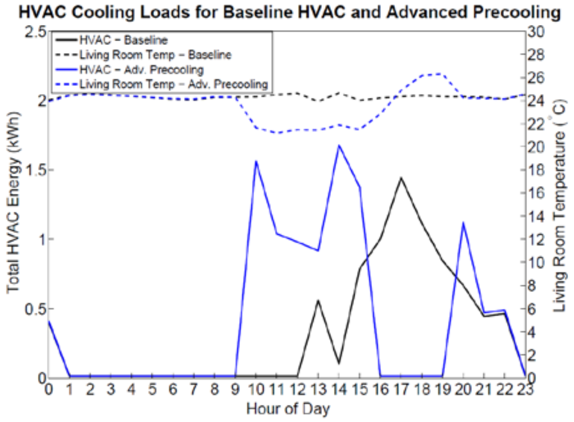

Figure 24. HVAC energy use for baseline case and advanced precooling schedule

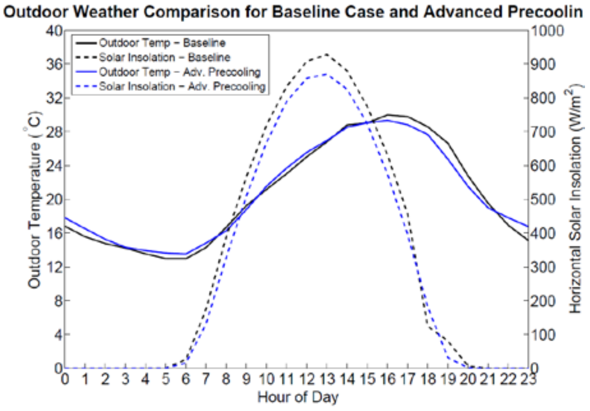

Figure 25. Weather comparison for baseline case and advanced precooling days

Table 10. Total Daily HVAC Energy Consumption for the Baseline and Advanced Precooling Cases

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Baseline	6.68	1.34	**8.02**	**3.56**
Advanced precooling	8.60	1.64	**10.24**	**0.04**

Advanced Precooling Versus Simple Precooling

Figure 26 and Figure 27 compare the hourly cooling energy used during simple precooling and advanced precooling and show the indoor temperature as measured in the living room. The weather on the days of comparison is also shown. By turning off the heat pump between 4:00 p.m. and 10:00 a.m., the simple precooling scenario reduces the total daily consumption by about 35% relative to the advanced precooling schedule. During that interval, the energy use and indoor temperature look very similar. During the peak hours, the indoor temperature in both situations reaches a maximum of about 79°F (26°C). The advanced precooling schedule turns the heat pump back on for cooling at 8:00 p.m. and the interior temperature drops a couple of degrees. Even though the simple precooling maintains a "comfortable" temperature (as defined by ASHRAE), slightly cooler overnight temperatures may be preferred, making the advanced precooling schedule more attractive, despite the higher energy use. Both schedules effectively eliminate peak HVAC energy use.

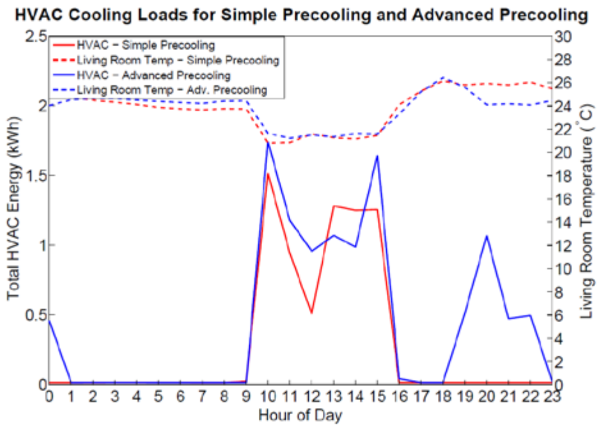

Figure 26. HVAC energy use for the simple precooling and advanced precooling schedules

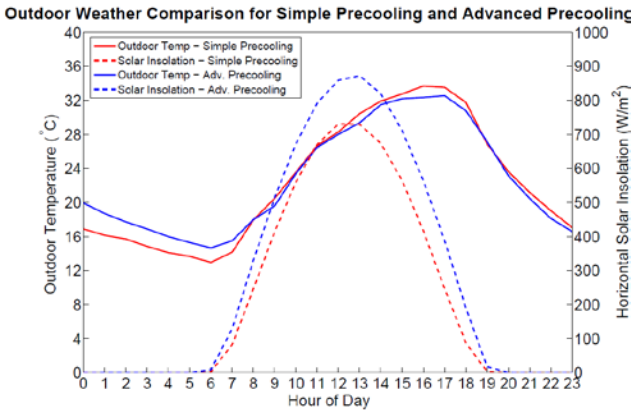

Figure 27. Weather comparison for simple precooling and advanced precooling days

Table 11. Total Daily HVAC Energy Consumption for Simple Precooling and Advanced Precooling

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Simple precooling	5.83	1.17	**7.01**	**0.04**
Advanced precooling	9.09	1.69	**10.78**	**0.07**

Heat Storm Precooling

The baseline case on a hot day is compared to one day during a heat storm with the advanced precooling strategy enabled and the shades drawn. The day from the baseline case also occurred during a heat storm. The outdoor temperature and the insolation for the days of comparison are also shown. The precooling effectively shifts the peak HVAC energy use, but does not reduce overall energy consumption. Also, the shades were drawn during the heat storm advanced precooling test, which could explain why cooling energy did not increase more as a result, as was seen when the baseline case and the advanced precooling schedule were compared under more typical conditions (see Table 10). This combination of the advanced precooling schedule and closed shades during a heat storm may be an effective way for homeowners to deal with extremely hot summer weather. The added stress on the utility during heat storms is difficult to keep up with, especially during peak hours, and this strategy effectively shifts the peak load with only a slight increase in overall HVAC energy use.

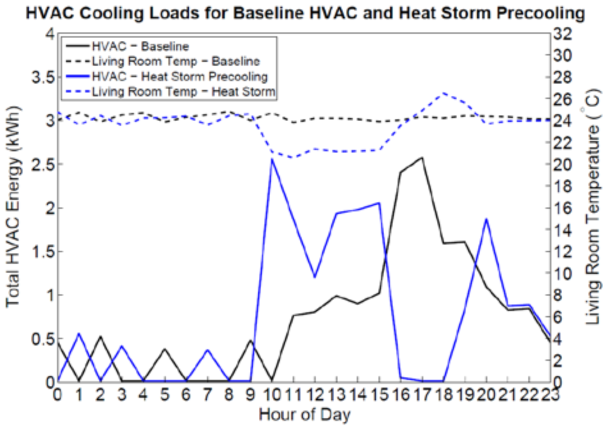

Figure 28. HVAC energy use comparison between baseline case and advanced precooling (with shades) during a heat storm

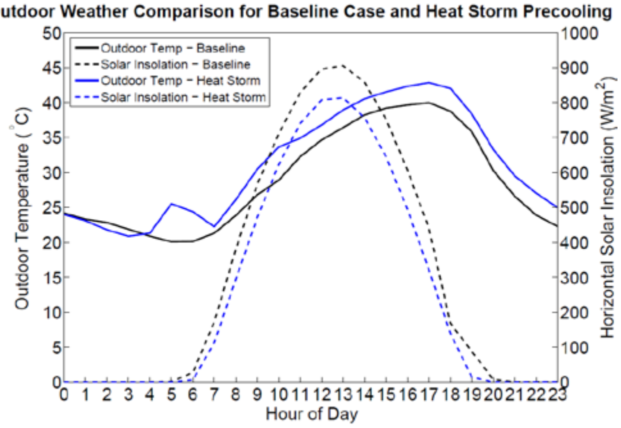

Figure 29. Weather comparison for baseline case and advanced precooling (with shades) during a heat storm

Table 12. Total Daily Energy Consumption for Baseline Case and Heat Storm Precooling (With Shades)

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Baseline	15.47	2.34	**17.81**	**6.57**
Heat storm precooling	15.73	2.38	**18.11**	**0.08**

Shade Control Test

The shades for the windows on the west side of the house and the awning were drawn (see Figure 4a) during all hours of the day for the shade control test. The motorized shades were drawn all day because they were not remotely controllable. A large percentage of the west wall is composed of windows (see Figure 6), which introduced a large solar heat gain. Blocking that heat gain dramatically reduces the required cooling energy on a summer day. For the two days compared in Figure 30, the shades reduced the HVAC energy consumption by 34%. These shades were externally mounted; internally mounted shades would likely have a smaller effect on energy savings because they do not block radiation. Even though the external shades do not reduce the peak HVAC energy use as dramatically as the precooling schedules, the shades can cut the peak load by nearly 40% and reduce the overall daily HVAC energy use. This is by far the simplest strategy tested, so it is likely the most attractive to homeowners.

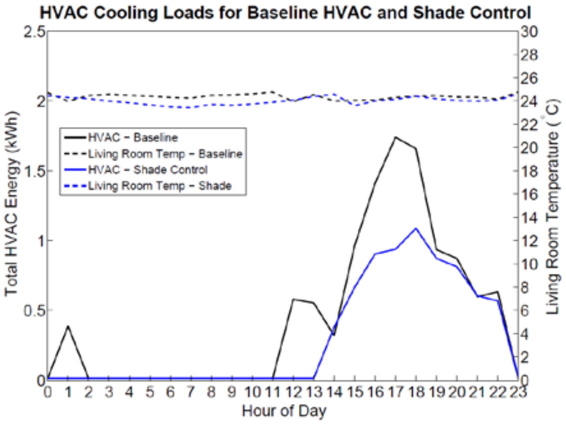

Figure 30. HVAC energy use for the baseline case and shade control tests

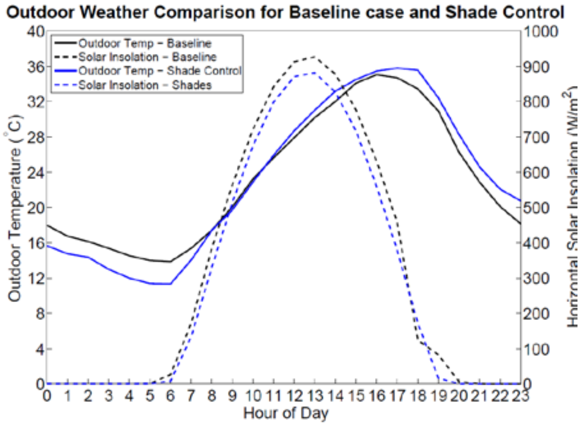

Figure 31. Weather comparison for baseline case and shade control tests

Table 13. Total Daily HVAC Energy Consumption for Baseline Case and Shade Control Tests

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Baseline	9.20	1.63	**10.82**	**4.81**
Shade control	5.91	1.14	**7.05**	**2.93**

Whole-House Fan Test

The whole-house fan test was performed over the course of four days while the shades and awning were still drawn. Energy consumption was reduced slightly by using the whole-house fan with the shades drawn relative to the shade control test, as seen when comparing the total HVAC energy consumptions in Table 13 and Table 14. (Note: The days shown in Tables 13 and 14 were comparable in terms of outdoor air temperature and insolation.) The HVAC energy use shown in Figure 32 and Table 14, however, does not include the energy used by the whole-house fan. This will add about 300 W during operation. Because the whole-house fan was run for two hours each day, an additional 0.6 kWh should be added to the daily HVAC energy total, making the shade control test and whole-house fan test nearly identical. For this situation, running the whole-house fan does not reduce energy consumption, but if the whole-house fan had been run without shades, a more noticeable benefit might have been be apparent. In terms of peak HVAC use reduction, the whole-house fan test with shades decreased peak use by 46%, which is similar to the reduction seen with the shades alone.

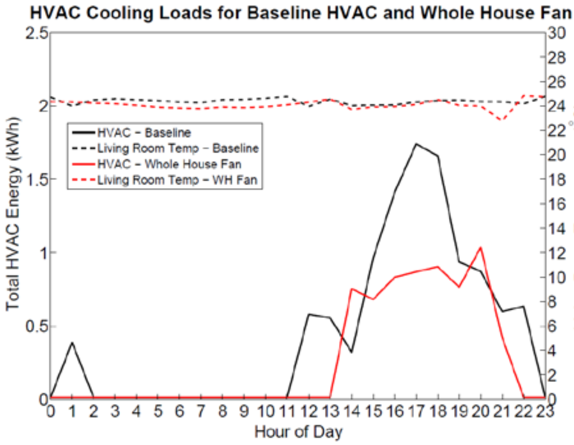

Figure 32. HVAC energy use for the baseline case and whole-house fan tests

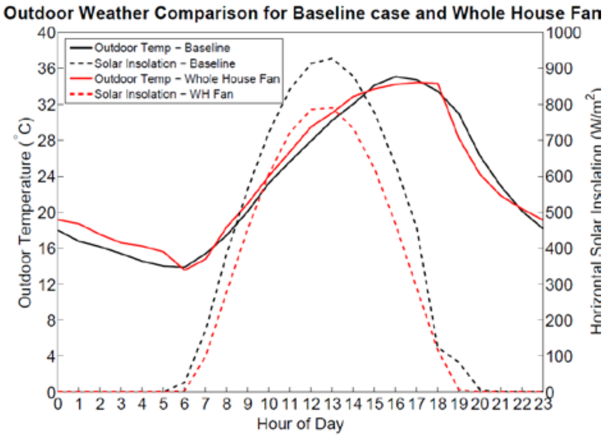

Figure 33. Weather comparison for baseline case and whole-house tan test

Table 14. Total Daily HVAC Energy Consumption for Baseline Case and Whole-House Fan Tests

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	Summer Peak 4:00 p.m.–7:00 p.m. (kWh)
Baseline	9.20	1.63	**10.82**	**4.81**
Whole-house fan	5.39	1.10	**6.49**	**2.60**

3.4.4 Time-of-Use Pricing Comparison

Peak energy use puts a large strain on utilities. One way they can encourage lower peak use is to institute a time-of-use (TOU) billing plan. These plans charge a higher rate for electricity during peak hours and a lower rate during off-peak hours. Smart meters enable utilities to implement TOU pricing schedules, although this is still at an early stage. Currently, most TOU billing plans are optional for residential customers, but will likely become more common and cease to be optional in the future. For illustration, the various space conditioning schedules are compared with a hypothetical TOU pricing scheme.

The peak price used for this rate plan is $0.24/kWh and the off-peak price is $0.0997/kWh. The peak hours are 4:00 p.m. to 7:00 p.m.; all other hours are off-peak (most TOU programs define a much longer peak period). This rate schedule is not taken from a real utility price plan but the rates are. This schedule is being imposed on the results for various HVAC tests only to illustrate the motivation for shifting peak HVAC use. Table 15 shows the price for each HVAC schedule for a single day. The percent savings are also shown for each pair of tests.

Table 15. Time-of-Use Pricing Comparison for Various HVAC Schedules

	Off-Peak Energy Use (kWh)	Peak Energy Use (kWh)	Total HVAC Cost ($)	Savings Relative to Baseline
Baseline	4.45	3.56	1.31	–
Simple precooling	5.68	0.04	0.58	56%
Baseline	4.45	3.56	1.31	–
Advanced precooling	10.20	0.04	1.03	21%
Baseline—heat storm	11.23	6.57	2.71	–
Heat storm precooling	18.03	0.08	1.82	33%
Baseline	6.02	4.81	1.77	
Shade control	4.12	2.93	1.12	36%

This TOU pricing plan is not expected to be perfectly realistic, but it does illustrate the monetary advantage to tailoring a precooling schedule to fit with a TOU billing schedule. The three precooling schedules, simple precooling, advanced precooling, and advanced precooling with shades (during a heat storm), eliminate HVAC energy use during the peak hours and shift all the cooling energy to the off-peak hours, which results in cost savings even when the overall energy use is higher than the baseline case. The shade control test does not involve any peak shifting, but the reduction in total daily energy is enhanced by the TOU pricing. Most utility TOU programs have a much longer peak period, such as from 2:00 p.m. to 8:00 p.m., but our precooling schedules were designed around a 4:00 p.m. to 7:00 p.m. peak period. These cooling schedules would not produce such dramatic results when used with real TOU schedules, but a precooling schedule tailored specifically for the TOU pricing schedule could be as effective. As new pricing schedules become more common, creating heating and cooling schedules to take advantage of the off-peak prices can be a worthwhile effort.

Additional Tests

With more time, a few additional tests would have been performed. The highest priority tests would have been to repeat the whole-house fan test and the heat storm precooling test without the shades drawn. Having the shades drawn for both tests gives the best case scenario, especially for the heat storm precooling, but decoupling the effects is preferred.

Another test that would be interesting to implement would be the pairing of the simple precooling schedule with the whole-house fan test. This combination may bring the interior temperatures in the evening into a more comfortable range without requiring as much energy as running the heat pump. The power to the whole-house fan should also be measured to capture the total HVAC load.

The shade control test was done with external shades, which were very effective but are not as common as internal shades. It would be useful to repeat the shade control test with internal shades to see how effective they are relative to the external type. A variety of types of internal shades could also be tested.

A nighttime setup test was originally planned, where the thermostat set point is raised from the standard 78°F (25.5°C) set point overnight. This will likely have minimal impact on energy use, as the heat pump usually turned off by 11:00 p.m. and did not turn on again until 9:00 a.m. This also may be uncomfortable to the residents, but may still be worth trying in the future.

3.5 Domestic Hot Water

3.5.1 Introduction

The DHW system in the Greenbuilt house consists of two parts, a CopperHeart ICS system and an AirTap HPWH. The ICS is a solar collector with a 40-gallon capacity that provides hot water to the system when the solar radiation is sufficient. It was mounted on the west-facing roof, as shown in Figure 34. The ICS preheats water before it enters a (formerly) conventional electric resistance water heater in the garage. The electric resistance elements in the tank were disabled and an add-on HPWH unit was attached to the top of the storage tank to provide supplemental heating when the ICS SWH could not meet the hot water demand. The AirTap A7 add-on HPWH used for this application is shown in Figure 35. Appendix A includes further details about these systems.

Figure 34. CopperHeart 40-gal ICS

NREL/PIX 19617, Credit: Lieko Earle

Figure 35. AirTap add-on HPWH

NREL/PIX 19618, Credit: Lieko Earle

3.5.2 Test Setup

The DHW system was designed to be operated in two ways:

- Connect the mains water to the ICS, where it is heated by solar radiation and then sent to the storage tank in the garage for additional heating by the heat pump, if needed.
- Bypass the ICS system and send the mains water directly to the storage tank, where it is heated exclusively by the add-on HPWH.

A schematic of the DHW system is shown in Figure 36. This system was designed with the bypass option so that the pipes leading to and from the ICS can be drained. This is ideal for maintenance or when weather conditions are not optimal and the ICS needs to be disabled. This schematic also shows a pressure relief valve, which is installed for safety reasons and is similar to pressure relief valves found on conventional hot water storage tanks.

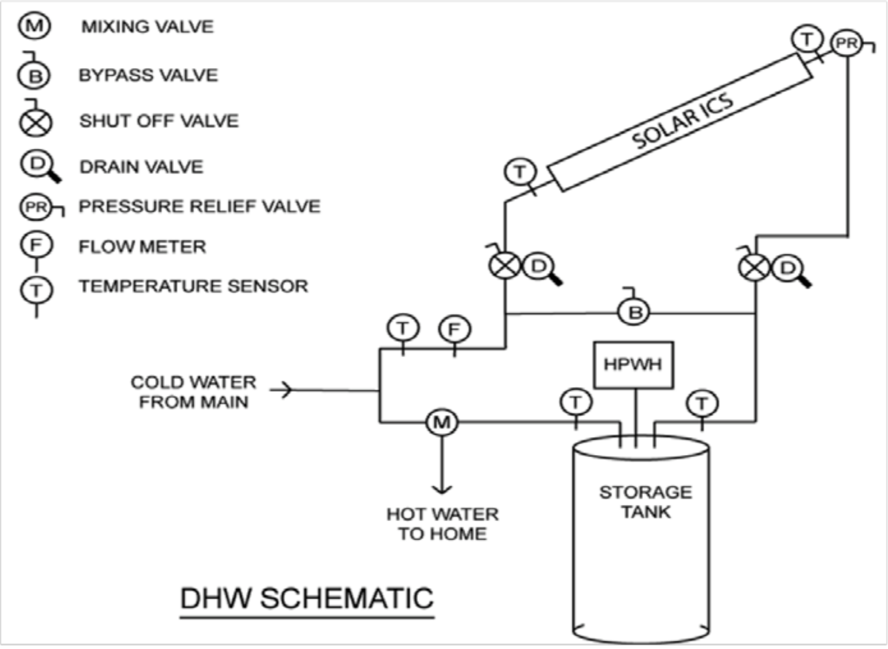

Figure 36. Schematic showing the DHW system. This includes an ICS solar panel, an add-on HPWH, and a storage tank.

Figure 36 shows some of the sensors that were used to quantify the performance of the ICS and HPWH. The water temperature is measured as it exits the water heater, and at the inlet and outlet of the ICS and water storage tank, as well as at the fixture in the house. These temperatures were measured using immersion thermocouples installed in the pipes. A thermostatic mixing valve is located before the hot water enters the house, primarily to ensure that extremely hot water from the ICS is tempered before reaching the fixtures. A flow meter was also installed to measure the flow rate of the water being drawn from the tank.

The delivered water temperature was measured at the hot water connection in the laundry closet. This faucet was used to simulate all water draws during this experiment (see Figure 37). The hot water supply valve for the laundry room was fully opened and attached to a solenoid valve that opened and closed to generate hot water draws. Downstream of the solenoid valve, a rotometer with a needle valve was installed (after this picture was taken) that allowed the flow rate to be measured and controlled. As long as the system water pressure remained relatively constant, the flow rate was held at 3 gpm for all draws. After the rotometer, a thermocouple was installed to measure the temperature of the water as it went down the drain, as shown in Figure 38. This measurement was intended to represent the water temperature delivered to the end user.

Figure 37. Water draw configuration in laundry closet

NREL/PIX 19619, Credit: Lieko Earle

Figure 38. Thermocouple to measure end-use temperature of hot water

NREL/PIX 19620, Credit: Lieko Earle

In addition to the sensors shown in Figure 36, air temperature was measured at the exhaust of the heat pump and in a central location in the garage. These measurements, along with some data provided by the manufacturer, are essential for determining the cooling effect of the add-on HPWH on its surroundings. Other important measurements include the solar irradiance in the plane of the ICS and the electric energy use of the HPWH. The solar irradiance was measured using a pyranometer installed on the roof. The electric energy use of the HPWH was measured using a WattNode power transducer. Appendix B includes a detailed list of this instrumentation.

3.5.3 Research Questions

The DHW system was installed at the Greenbuilt house to optimize the energy savings of the hot water system. The ICS was chosen because Sacramento has a temperate climate and does not typically see air temperatures below freezing; therefore, a direct solar system can be used. Sacramento also has ample solar radiation throughout most of the year. The add-on HPWH unit was installed to supplement the water heating in the most efficient way possible for an all-electric home. The AirTap unit has a manufacturer's quoted EF value of 2.11, meaning that it should be more than twice as efficient as electric resistance heating elements. Tests were performed that simulated hot water use of a typical household to determine the performance of this system. The data collected were intended to answer the following research questions:

- How much thermal energy was collected by the ICS system during winter and summer testing, and how does this compare to the amount of thermal energy needed to satisfy the hot water demand?
- What time of day is the ICS most effective at providing hot water? How effective is the use of the ICS and HPWH at reducing peak energy loads? How effective is the ICS and HPWH at reducing daily energy consumption?
- What is the COP of the system in the summer and how does that compare to the COP of the system in the winter?
- How do different draw profiles affect the system COP?

- How much is the temperature of the air in the garage affected by the operation of the heat pump?
- Was the outlet water temperature maintained for all profiles?

To answer these questions, six daily draw profiles were tested during the winter and summer seasons of 2010. Each was run across a span of about four to six days for both system configurations: the ICS and HPWH operating as a combined system and the HPWH operating independently. The temperature set point for the HPWH was 130°F (54°C) throughout testing. The flow rate was held constant at 3 gpm for all draw profiles. The data were averaged hourly across the multiple days of testing to reduce the impact of weather variations. Figures 13 through 16 provide graphical representations of the draw profiles and each profile is described here.

- **Hourly benchmark**. Draws are intended to simulate the hot water use of an average American family. These draws occur at the top of the hour throughout the course of the day. The total daily volume of water drawn for the benchmark profile is 64.5 gallons (240 liters). This is the baseline draw profile and will be used to answer most of the DHW research questions.
- **Discrete benchmark**. Similar to the hourly benchmark in terms of volume drawn each hour, but the profile comprises many smaller, more realistic draws.
- **Double volume benchmark**. Similar to the hourly benchmark in terms of profile shape, but differs because the volume drawn is doubled. Draws still occurred at the top of the hour.
- **Quarter volume benchmark**. Similar to the hourly benchmark in terms of profile shape, but the volume drawn at the beginning of each hour is reduced by 75%.
- **Morning dominated**. Draws simulate a real-life situation where most of the hot water is used in the mornings.
- **Evening dominated**. Draws simulate a real-life situation where most of the hot water is used in the evenings.

3.5.4 Results

Integrated Collector Storage Thermal Energy Analysis

The thermal energy collected by the ICS is determined by the amount of solar radiation that reaches its surface. Figure 39 shows the average solar irradiance that was measured by the pyranometer during February and August, which represent the winter and summer seasons, respectively. The dashed lines show the averaged values across the month and the solid lines show the averaged values during the hourly benchmark test. This graph shows that the solar irradiances during the August and February tests of the hourly benchmark are representative of the monthly averages. This plot also shows that the solar irradiance in the summer is more than double that in winter. (the irradiance was measured in the plane of the ICS, which faced west with an angle of 27° from horizontal).

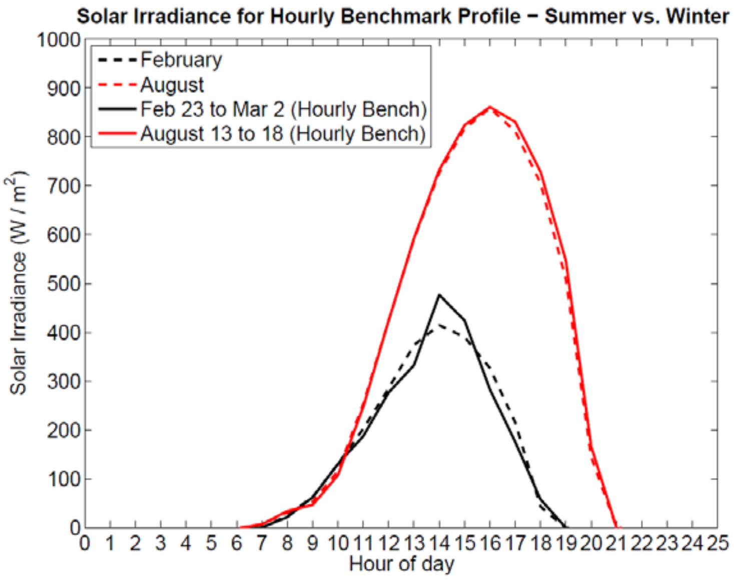

Figure 39. Solar irradiance measurements for the months of February and August are compared to measurements taken during the hourly benchmark test

To assess the performance of the ICS system, the thermal energy collected by the ICS solar panel was calculated for the hourly benchmark test and compared to the thermal energy needed to meet the hot water demand (see Eq. 3.1):

$$Q_{thermal} = m \cdot C_p \cdot \Delta T \qquad (3.1)$$

Where:

m = the mass of the water drawn from the ICS solar panel

C_p = the specific heat of water

ΔT = the difference between the temperature of the water exiting the solar panel and the temperature of the water entering the solar panel.

A similar calculation was performed to determine the thermal energy associated with the pipes running to and from the ICS solar panel. This energy can be either positive or negative, because sometimes the pipes experience thermal gains and other times thermal losses. The thermal energy of the ICS as a system, which includes the solar panel and its piping, is discussed in the remainder of this section.

The amount of thermal energy collected by the ICS during the summer hourly benchmark test is shown in Figure 40. The results show that the ICS can provide all the hot water demand from 4:00 p.m. through midnight. For morning hot water draws, some of the load was met by the ICS but the HPWH had to supplement it. The HPWH shows a negative thermal energy in the afternoon because the average inlet water temperatures were higher than the average temperature of the water in the storage tank. This results in a negative calculated thermal energy for the

HPWH. Overall, for the summer hourly benchmark test, the ICS provided 81% of the energy for water heating.

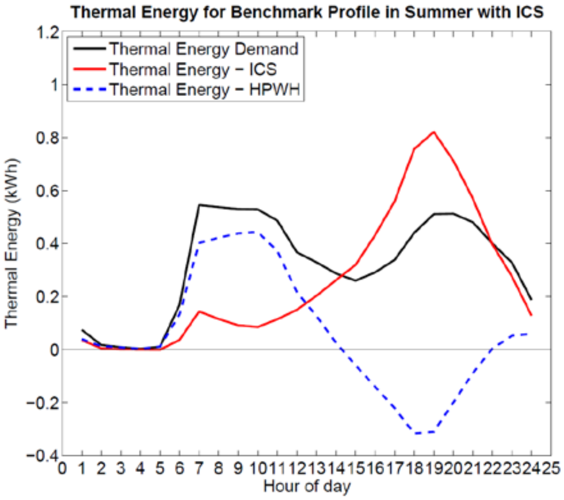

Figure 40. Thermal energy of the ICS and HPWH during the summer hourly benchmark test

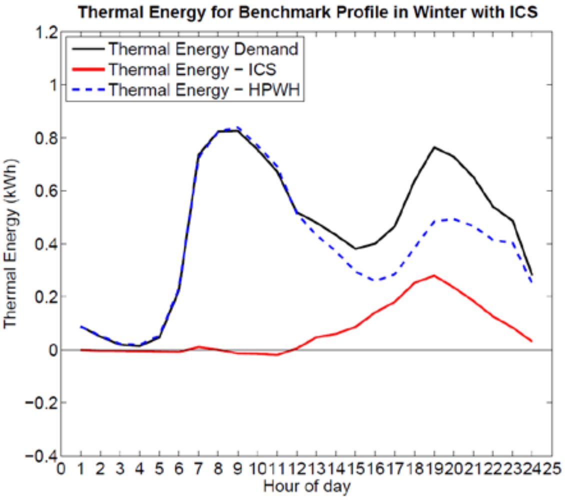

Figure 41. Thermal energy of the ICS and HPWH during the winter hourly benchmark test

For winter testing, the hourly benchmark draw profile produced the thermal energy profile shown in Figure 41. The thermal energy requirement is greater in the winter because the mains water temperature is colder and therefore more energy is needed to heat the incoming water to set point temperature. These data show that the heat pump was used almost exclusively because much less solar energy was available during February. Also, the thermal energy for the ICS system went slightly negative during part of the day, meaning the thermal losses to the environment outweighed the gains. This implies that sometimes in the winter using the ICS is detrimental to the DHW system. For the winter portion of testing, the hot water provided by the ICS made up only 15% of the hot water demand, all of which was in the second half of the day.

Table 16 summarizes these results. These numbers imply a solar fraction of approximately 48% for this system, which is estimated as the average of the summer and winter hot water contributions made by the ICS. This is in line with expectations, because a 50% solar fraction was expected. The solar fraction represents the net energy savings associated with an SWH system and is the measure of the amount of solar energy collected divided by the total amount of energy required to meet the system demand. The solar fraction of an SWH system depends on the quality of the solar resource, the technical characteristics of the individual system, and water use patterns (Denholm, 2007).

Table 16. Summary of DHW Daily Thermal Energy Generation Versus Requirement for Hourly Benchmark

	Thermal Energy Requirement (kWh)	Thermal Energy From ICS (kWh)	ICS Contribution (%)
Summer	7.6	6.2	**81**
Winter	11.0	1.6	**15**

Performance and Relationship to Time of Day

The ICS contributes most effectively to the hot water demand in the afternoon and evening hours. This makes an ICS system an attractive option for reducing demand during periods of peak energy use, which is between 4:00 p.m. and 7:00 p.m. during the summer in Sacramento. Figure 42 shows the energy used during the summer hourly benchmark test for the ICS and HPWH combined system and the HPWH alone. Also shown is the predicted energy use for a typical electric resistance water heater assuming the same draw profile. The peak energy hours are highlighted in light blue. When the ICS and HPWH were used together, the energy used during peak demand was reduced to zero. In fact, the ICS was able to provide all hot water from 2:00 p.m. to midnight, a period that accounts for nearly half the daily hot water use. The HPWH operating alone reduced the energy use during peak demand by 56% on average.

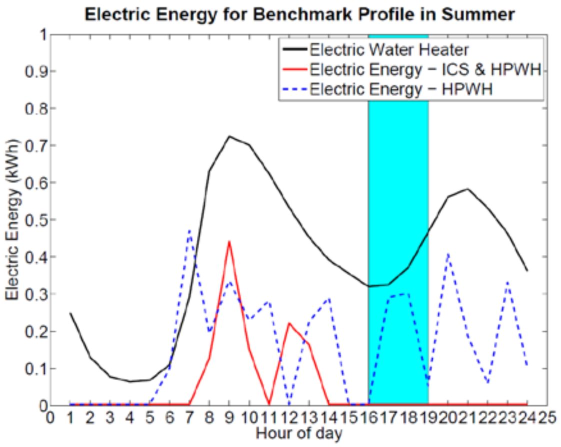

Figure 42. Electric energy use during the summer benchmark test

The peak energy hours are highlighted in blue.

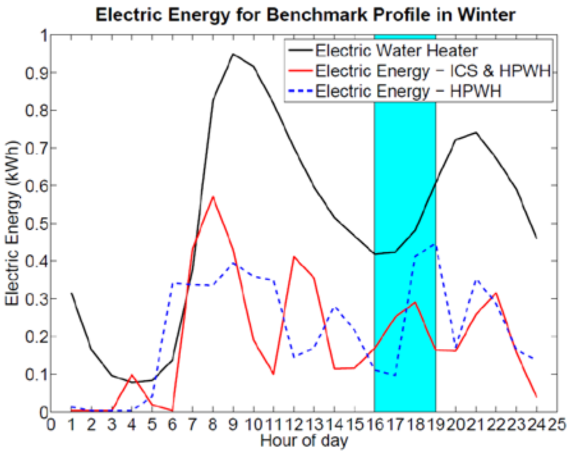

Figure 43. Electric energy use during the winter benchmark test

The summer peak energy hours (4:00 p.m.–7:00 p.m.) are highlighted in blue.

Figure 43 shows the energy used during the winter hourly benchmark test. There is not a peak period during the winter time, but summer peak hours (4:00 p.m. to 7:00 p.m.) are shown on the graph for comparison. The ICS was not able to provide enough hot water to meet the demand in the evening, but the combined HPWH and ICS system was able to reduce the load between 4:00 p.m. and 7:00 p.m. by 55% on average. The HPWH operating alone reduced the energy use from 4:00 p.m. to 7:00 p.m. by 45% on average.

In general, it is difficult to predict the energy reduction during hours of peak electricity demand because HPWH use is tied to hot water use and is not necessarily coincident with times of peak demand. For most homeowners, total electricity use is more important than peak energy use, so the results from Figures 42 and 43 are compared based on the daily energy savings. Tables 17 and 18 show the daily average energy savings for the two configurations compared to an electric resistance water heater. These results clearly show that the combined ICS and HPWH system has an energy savings advantage over the HPWH operating alone and that the greatest benefit is seen in the summer. Both configurations achieved greater than 50% daily energy savings for the summer and winter hourly benchmark tests relative to a standard electric water heater.

Table 17. Daily Energy Use for Summer Hourly Benchmark

	Daily Energy Use (kWh)	Energy Reduction (%)
Electric resistance	9.0	–
HPWH and ICS	1.2	**87.1**
HPWH alone	3.9	**56.9**

Table 18. Daily Energy Use for Winter Hourly Benchmark

	Daily Energy Use (kWh)	Energy Reduction (%)
Electric resistance	11.8	–
HPWH and ICS	4.7	**60.7**
HPWH alone	5.2	**56.3**

Domestic Hot Water System Coefficient of Performance

Another way to compare the performance of the DHW systems is to calculate a COP for each configuration. COP is the measure of the useful energy transferred to the water divided by the input energy to the system. Equation 3.2 was used to calculate system COP for the DHW system:

$$COP = \frac{Q_{thermal}}{W_{hpwh}} = \frac{m \cdot C_p \cdot \Delta T}{W_{hpwh}} \qquad (3.2)$$

Where:

m = the mass of the water drawn from the tank

C_p = the specific heat of water

ΔT = the difference between the temperature of the water exiting the tank and the temperature of the water entering the tank

W_{hpwh} = the electric energy consumed by the heat pump.

When evaluating the ICS and HPWH as a system, the inlet water temperature to the ICS was used instead of the inlet temperature to the tank. The mass of the water entering the tank is calculated by knowing the volume of water drawn (which is measured by a volumetric flow meter) and the density of water.

Daily averages of thermal and electric energy were used to calculate the COPs for the two configurations during summer and winter testing. The calculated COPs are listed in Tables 19 and 20. The results show that the COP of the ICS and HPWH as a combined system is significantly better than the HPWH alone in the summer. The results during winter testing show a slight advantage of using the ICS and HPWH as a combined system, but do not show a significant advantage over operating the HPWH alone. If these values are assumed to be representative of the best- and worst-case scenarios for the year, the average annual COP for the ICS and HPWH combined system can be estimated as the average of these values at 4.5. For the HPWH alone, the average annual COP can be estimated at 2.0.

Table 19. System COP for Summer Hourly Benchmark

	Daily Electric Energy (kWh)	Daily Thermal Energy (kWh)	Average Daily System COP
ICS and HPWH	1.16	7.64	**6.58**
HPWH alone	3.88	8.27	**2.13**

Table 20. System COP for Winter Hourly Benchmark

	Daily Electric Energy (kWh)	Daily Thermal Energy (kWh)	Average Daily System COP
ICS and HPWH	4.66	11.02	**2.37**
HPWH alone	5.17	10.08	**1.95**

Effect of Integrated Collector Storage on Heat Pump Water Heater Performance

One concern with a DHW configuration consisting of an ICS and HPWH is that the ICS could reduce the performance of the HPWH to the point where the purchase of an HPWH cannot be justified. Tables 21 and 22 compare the results of the HPWH COP when the HPWH is operating alone and with the ICS in the summer and winter, respectively. The results in Table 21 show that, in the summer, the average reduction in HPWH performance for a typical daily hot water load is 32%. For the quarter benchmark profile, most of the hot water load can be met with the ICS, so HPWH performance drops significantly. This is because the HPWH operates for shorter periods and when it does run, the inlet water is preheated by the ICS. In contrast, the double benchmark profile shows that the ICS has a small impact on performance. Also, for evening-dominated profiles, the ICS will likely have a more significant impact on HPWH performance. As with the quarter benchmark, this is because most of the hot water demand for this profile can be met by the ICS. In general, these results show that HPWH performance in a HPWH and ICS combined system depends on how much hot water load is supplied by the ICS. When the ICS is used to meet a significant part of the demand, the HPWH performance will decrease.

Table 21. Effect of ICS on HPWH Performance During the Summer

Draw Profile	HPWH COP (HPWH Operating Alone)	HPWH COP (HPWH Operating With ICS)	Percent Reduction (%)
Hourly benchmark	2.14	1.19	**44**
Discrete benchmark	2.27	1.52	**33**
Double benchmark	2.28	2.26	**1**
Quarter benchmark	1.53	0.34	**78**
Morning dominated	2.21	1.91	**14**
Evening dominated	2.36	1.50	**36**

The results in Table 22 show that the performance impact in the winter is less than in the summer, primarily because of the lower winter solar resource. The results similarly vary between –22% and 12%. In general, when the ICS can meet most of the demand, the HPWH performance decreases. However, the HPWH will still save energy in this configuration and should be considered when a significant portion of the annual hot water load cannot be met with solar.

Table 22. Effect of ICS on HPWH Performance During the Winter

Draw Profile	HPWH COP (HPWH Operating Alone)	HPWH COP (HPWH Operating With ICS)	Percent Reduction (%)
Hourly benchmark	1.95	2.37	**–22**
Discrete benchmark	1.86	1.72	**8**
Double benchmark	2.11	2.17	**–3**
Quarter benchmark	1.29	1.21	**6**
Morning dominated	1.44	1.45	**–1**
Evening dominated	1.61	1.41	**12**

Annual Energy Use and Cost Effectiveness

Table 23 shows the annual energy savings that would be associated with these systems compared to a conventional electric resistance water heater. The combined ICS and HPWH system would save 78% and the HPWH alone would save 51% energy annually.

Table 23. Annual Energy Savings Compared to an Electric Resistance Water Heater

	Annual Estimated COP	Annual Estimated Energy Use (kWh)	Energy Savings %
Electric resistance	1.0	3805	**–**
ICS and HPWH	4.5	851	**78**
HPWH alone	2.0	1865	**51**

Although using the ICS with the HPWH reduces the efficiency of the HPWH, the combined assembly still further reduces energy use relative to the HPWH alone. However, the combined system may not save enough energy to justify the additional cost. A simple payback period was calculated to investigate that question. The initial costs (provided by SMUD) for the HPWH and ICS were used, without taking into account rebates and incentives or installation costs. The 40-gallon CopperHeart ICS cost $4000 and the add-on AirTap HPWH cost $700. The estimates for annual energy use given in Table 23 were used to calculate annual operating costs for each scenario. Sacramento has a winter electricity rate of $0.0967/kWh and a summer rate of $0.1045/kWh. A very crude estimate on annual operating cost was done by dividing the annual energy use by 2 (6 months each) and using the summer energy rate for half the year and the winter energy rate for the other half. The cost savings for the HPWH alone and ICS + HPWH system were used to find the simple payback period for each. The electric water heater cost is not considered, as it is necessary for all scenarios.

Table 24. Simple Payback Period Relative to an Electric Resistance Water Heater

	Initial Cost ($)	Annual Estimated Energy Use (kWh)	Annual Estimated Operating Cost ($)	Payback Period (Years)
Electric resistance	–	3805	383	**–**
ICS and HPWH	4700	851	84	**15.7**
HPWH alone	700	1865	188	**3.6**

From this simple analysis, the additional cost of the add-on HPWH would be recouped in less than 4 years; in contrast to nearly 16 years that would take to break even on the cost of the ICS + HPWH combined system. This is still within the expected lifetime of the ICS (estimated around 20 years) but is a few years beyond the expected lifetime for HPWHs (approximately 13 years).

Effect of Specific Draw Profiles on System Coefficient of Performance

The average daily COP values in Tables 19 and 20 imply that the DHW system worked well for this application. These numbers, however, represent only the performance during the hourly benchmark draw profile. Additional draw profiles were tested as previously mentioned and the calculated COP values for each of these profiles are listed in Table 25. The COP values are also shown graphically in Figure 44.

Table 25. Summary of COP Values for All Draw Profiles

Draw Profile	DHW Configuration	Average Daily Winter COP	Average Daily Summer COP
Hourly benchmark	HPWH alone	**1.95**	**2.14**
Discrete benchmark	HPWH alone	**1.86**	**2.27**
Double benchmark	HPWH alone	**2.11**	**2.28**
Quarter benchmark	HPWH alone	**1.29**	**1.53**
Morning dominated	HPWH alone	**1.44**	**2.21**
Evening dominated	HPWH alone	**1.61**	**2.36**
Hourly benchmark	ICS and HPWH	**2.59**	**6.37**

Discrete benchmark	ICS and HPWH	**3.02**	**4.92**
Double benchmark	ICS and HPWH	**2.37**	**4.96**
Quarter benchmark	ICS and HPWH	**1.58**	**2.78**
Morning dominated	ICS and HPWH	**2.08**	**3.79**
Evening dominated	ICS and HPWH	**2.35**	**3.89**

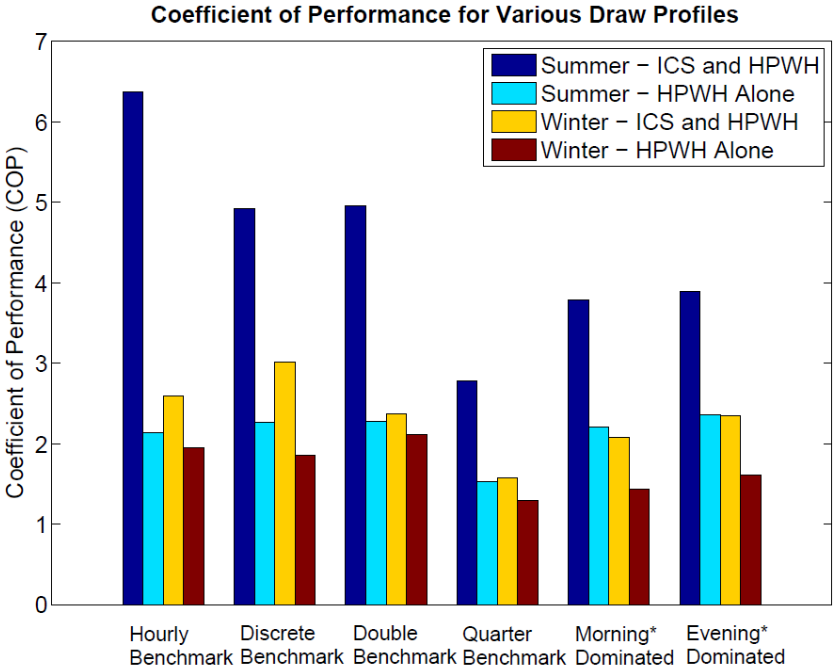

Figure 44. Calculated COP values for all draw profiles

Note: Draw volumes during the winter were inadvertently less than during the summer.

These results show that the COP of the ICS and HPWH combined system is higher for all draw profiles compared to the HPWH alone; the greatest benefit of the ICS is seen in the summer. The hourly and discrete benchmark tests performed on the HPWH alone are almost the same, showing that the method of drawing water from the top of the hour is a good estimate of actual hot water use. The double benchmark performed slightly better than the hourly benchmark for the HPWH alone, and the quarter benchmark performed noticeably worse than the other draw profiles. This verifies that the COP of the system depends on the volume of water drawn. This can be attributed to increased tank losses and reduced heat pump performance. When small volumes of water are drawn, the water temperature near the heat pump's condenser remains high, which reduces the performance of the direct expansion system.

Figure 45 shows the correlation between the volume of water drawn and the COP. The data shown in this graph are for the HPWH operating alone. Clearly, air temperature also affects this correlation, as the correlation curves shift according to season. Despite the sparse dataset, the data fits are good, with R^2 values of 0.9114 and 0.9834 for the summer and winter tests, respectively. The lower R^2 value for the summer correlation is partly due to a low COP calculated for the double volume test. The air temperature in the garage was lower than average during this part of the test, which likely caused this low COP value.

The correlation of COP and average daily temperature in the garage is shown in Figure 46. As with the previous graph, the data shown here are for the HPWH operating alone. Only days with similar draw volumes were used to reduce the variation of results. The correlation to average daily air temperature is not strong, but clearly the COP increases with increased air temperature. The inlet water temperature is not the same for all data points and tank losses were not removed. Although this would change the correlation slightly, the data presented here show how an HPWH is likely to perform in an installed situation.

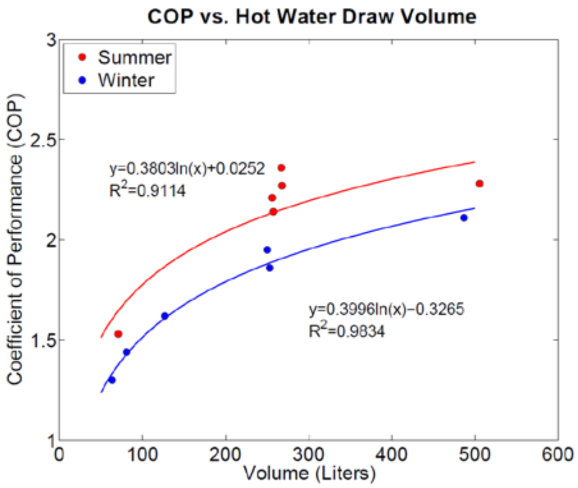

Figure 45. Correlation between COP and volume of water drawn for HPWH operating alone

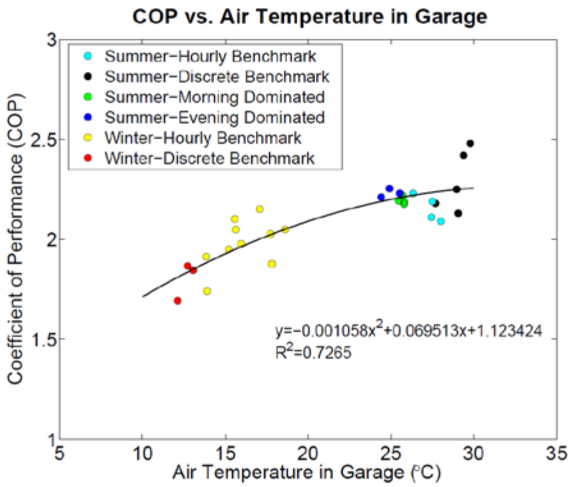

Figure 46. Correlation between COP and average daily air temperature in the garage for HPWH operating alone

Annual COP values were estimated for each draw profile by averaging the COPs for the summer and winter tests. Table 26 and Figure 47 show the annual estimated COPs. The results clearly show that the ICS and HPWH combined system is more efficient than operating the HPWH alone. On average, the ICS and HPWH together are more efficient than the HPWH alone by 42%, but range from 35% to 54% depending on the draw profile. Compared to a typical electric resistance water heater, low water use households with only an HPWH save about 29% energy and households with average hot water use and a combined ICS and HPWH system save about 78%.

Table 26. Annual Estimated COP Values and Energy Savings Compared to an Electric Resistance Water Heater for All Draw Profiles

Draw Profile	DHW Configuration	Annual Estimated COP	Annual Energy Savings Versus Electric (%)
Hourly benchmark	HPWH alone	**2.05**	51
Discrete benchmark	HPWH alone	**2.07**	52
Double benchmark	HPWH alone	**2.19**	54
Quarter benchmark	HPWH alone	**1.41**	29

Morning dominated	HPWH alone	**1.83**	45
Evening dominated	HPWH alone	**1.99**	50
Hourly benchmark	ICS and HPWH	**4.48**	78
Discrete benchmark	ICS and HPWH	**3.97**	75
Double benchmark	ICS and HPWH	**3.66**	73
Quarter benchmark	ICS and HPWH	**2.18**	54
Morning dominated	ICS and HPWH	**2.94**	66
Evening dominated	ICS and HPWH	**3.12**	68

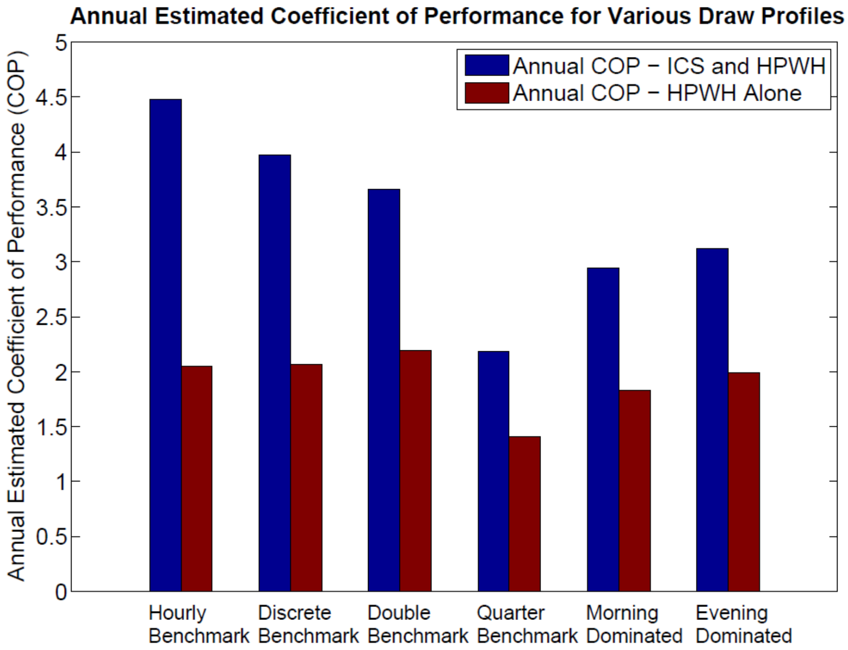

Figure 47. Annual estimated COP values for all draw profiles

Cooling Effect on Garage

The add-on HPWH provides cooling to the garage when the heat pump is operating. Figure 48 shows how the operation of the heat pump affected the air temperature immediately downstream of the heat pump and in the middle of the garage. The temperature at the exit of the heat pump dropped 39°–41°F (4°–5°C) and the average temperature in the garage dropped 33°–34°F (0.5°–1°C) when the heat pump was on. Based on information provided by the manufacturer, the approximate airflow rate of the heat pump is 400 CFM. With this information, the sensible cooling capacity of the heat pump can be calculated using Eq. 3.3:

$$Q_{thermal} = m \cdot C_p \cdot \Delta T \tag{3.3}$$

Where:

m = the mass flow rate of the air
Cp = the specific heat of air

ΔT = the difference between the temperature of the air at the inlet and outlet of the heat pump.

The sensible cooling capacity of this unit was calculated to be approximately 4000 Btu/h. However, this cooling effect can be observed only when the heat pump is operating, which varies depending on hot water use.

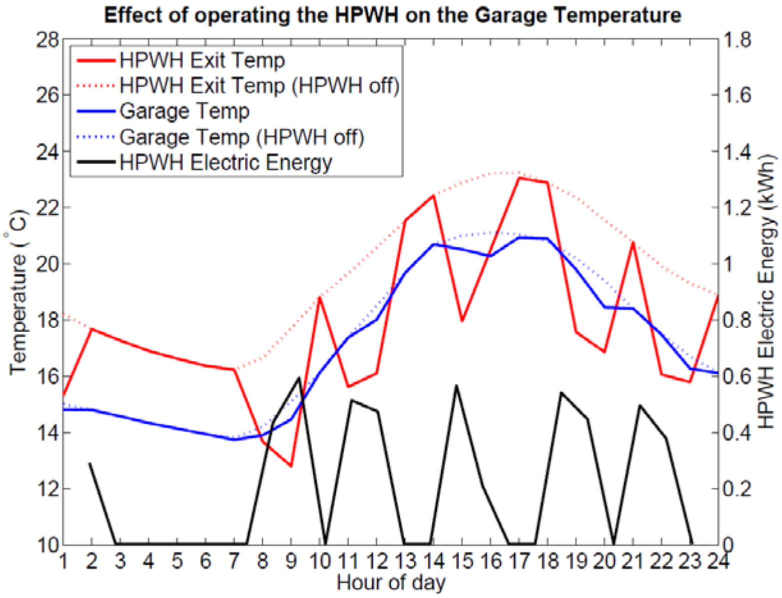

Figure 48. Air temperature variations when HPWH is operating

Outlet Temperature

One concern about HPWH technology is its slower recovery rate compared to a conventional electric resistance water heater. Using the results from the EF test discussed in Section 2.6, the recovery rate was determined to be 41.4°F/h (5.2°C/h). This number is an approximation, as the average tank temperature is unknown and the outlet temperature was used for this calculation instead. This can be compared to an electric resistance water heater, which has a recovery rate of about 72°F/h (22°C/h), which was determined based on an annual simulation run with the benchmark draw profile.

A slower recovery rate results in higher energy efficiency but can have a negative impact on the temperature of the water that is delivered to the end user. Integrated HPWHs are available that have larger storage tanks to mitigate this problem. In the case of the Greenbuilt house, the add-on unit was installed on top of a 50-gallon storage tank, which may not be able to provide sufficient hot water, depending on household size and water needs. Figure 49 shows the water temperature at the outlet of the water heater for the summer and winter discrete benchmark tests. In this figure, the spikes in outlet temperature indicate when water draws occurred. These spikes drop from the set point temperature (at around 126°F [52°C]) to about 118°F (48°C) before the heat pump turns on. This is well above the temperature considered by most people to be “hot” water, which is marked on the graph as 104.9°F (40.5°C).

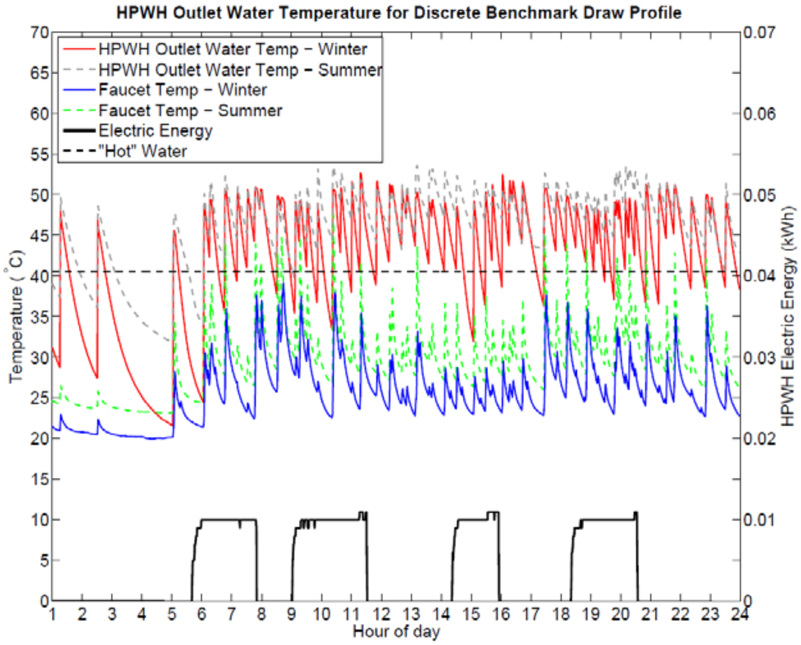

Figure 49. End-use water temperature—discrete benchmark profile

This figure also shows the water temperature measured at the faucet in the laundry room. The temperature is plotted for a day during both the summer and winter tests and shows that during the winter, the temperature at the faucet never reaches 104.9°F (40.5°C). During the summer, the temperature at the faucet exceeds 104.9°F (40.5°C) during most draws. The house had no other hot water uses, so this is quite a significant temperature drop between the water heater and the faucet. One explanation could be heat lost when the pipes travel through the unconditioned attic to the laundry room faucet on the other side of the house. Also, a mixing valve, which is used to protect the house against extremely hot water coming from the SWH, is located between the water heater outlet and the end uses in the house. Usually a temperature range is set with the mixing valve, but the colder mains temperature during the winter may have produced slightly colder delivered water. The colder water temperature may still be within the set point range, even though it causes the actual delivered temperature to be below the expected "hot water" temperature. End-use hot water is a potential concern, so the electric resistance elements should not be disabled for future installations of this add-on HPWH. Also, when the ICS is installed with the thermostatic mixing valve, final hot water temperature around the house should be measured to ensure that the set point on the mixing valve is high enough to deliver hot water in all seasons.

4 Whole-House Simulation Model

Whole-house building models can be used to determine energy use impacts or cost effectiveness of new building features or retrofit measures for a particular house and climate. This is the primary use for the BEopt software developed by NREL's Residential Buildings Group, but it can also be used for a variety of other purposes. A whole-house model can be compared to actual energy bills to verify that systems are working properly or to help identify problems if the home is performing below expectations. A whole-house model of the Greenbuilt house was used to estimate the energy savings achieved through the deep energy retrofit, described in the next section. The rest of the modeling analysis was used to predict energy savings using various space conditioning strategies over extended periods. Short-term tests were performed on the space conditioning system to capture data points for cooling energy consumption and indoor temperature, as described in Section 3.4. Representative days are presented as validation for the EnergyPlus model, which was then used to compare energy consumption for various cooling strategies over a cooling season, from June through September.

4.1 Annual Retrofit Analysis

A project goal was to verify the success of the deep energy retrofit. Part of that process included evaluating the whole-house retrofit energy savings using whole-house BEopt models for the pre- and post-retrofit house. This analysis also looked at the cost effectiveness of the implemented retrofit measures.

The geometry of the Greenbuilt house was modeled in BEopt, including wall construction and insulation, window area and orientation, and attic and roof construction. Figure 50 shows the model of the Greenbuilt house as it appears in BEopt. After the physical layout was defined, the characteristics of the house, HVAC equipment, and appliances were added as inputs to the model. Local weather data as collected by the weather station on the roof were also incorporated into the simulation. The specific input parameters are nearly identical to the list of pre- and post-retrofit characteristics listed in Table 35 in Appendix A. However, some features required by the model, such as the orientation of the house, did not change during the retrofit (see Table 27).

Figure 50. Greenbuilt house model in BEopt

Table 27. Additional Model Inputs

Model Parameter	Greenbuilt Input
Front of house orientation	East
Proximity of neighbors	15 ft from house
Total floor area	1748 ft^2
Garage characteristics	Attached, 2 car capacity
Exterior finish	Light-colored wood siding
Foundation type	Uninsulated slab
Exposed floor	20% exposed flooring
Window area	290 ft^2 total window area
Size of eaves	2 ft. width

The general building model was developed using BEopt because of its straightforward user interface and seamless generation of the EnergyPlus input file. The more complicated features, such as the heat pump model, varying wall insulation levels, and exterior shades on the west wall and finished garage were implemented directly in EnergyPlus v7.0 input files. Two separate models of the Greenbuilt house were created that incorporate its pre- and post-retrofit characteristics. Figure 51 shows the annual energy use results from the pre- and post-retrofit models. The heating and cooling set points used in both models are consistent the Building America recommendations: 71°F (21.7°C) heating set point and 76°F (24.4°C) cooling set point (Hendron & Engebrecht, 2010). The simulated annual net energy use (total use minus generation from PV) is displayed in Figure 51 in terms of site energy use, the same quantity that is shown on utility bills. The net annual electricity consumption is 9400 kWh, down from the pre-retrofit annual energy use of approximately 22000 kWh. Based on these results, the retrofit measures and PV generation reduced net annual energy consumption by 57%.

The properties of the original house were used to create the pre-retrofit model. A home energy audit was performed before the retrofit began, which yielded information on infiltration, insulation levels, and the efficiency of the installed appliances. This information was used to define many of the pre-retrofit model input parameters. Utility bills from before the retrofit were unavailable because the house was vacant for an extended period before Greenbuilt Construction bought it. The post-retrofit model was created based on post-retrofit audit information and data collected. The annual simulation used TMY3 weather data so the modeled annual energy use corresponds to a typical year in Sacramento.

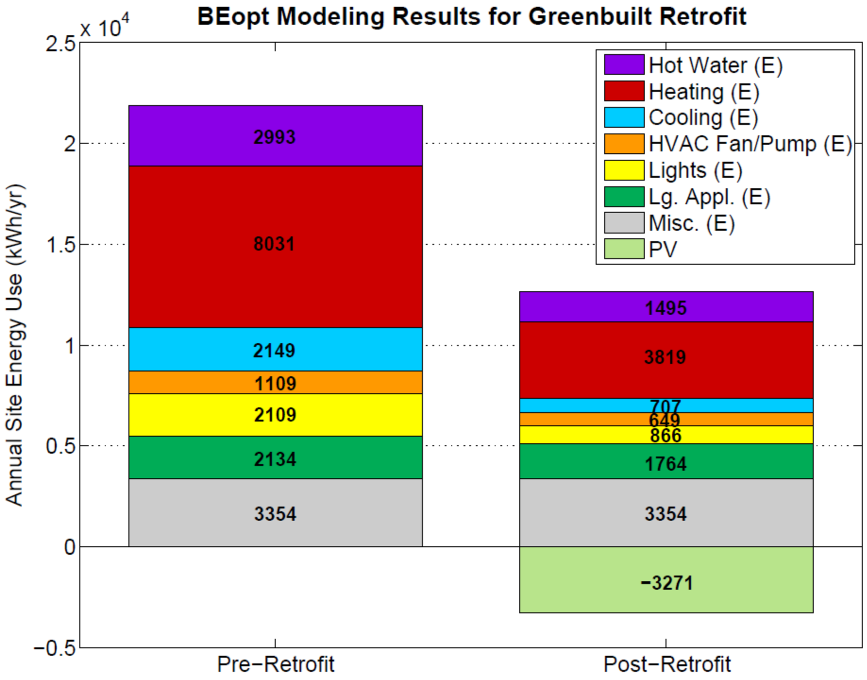

Figure 51. BEopt results for annual site energy use, before and after the retrofit

Although other energy efficiency research and development projects have made cost effectiveness a top priority, the Greenbuilt house was intended to showcase new efficiency measures. As a result, the project did not constitute the least-cost option for the net energy savings. Figure 52, generated by BEopt, shows many retrofit packages that vary in cost and net energy savings. The energy costs shown on the vertical axis include the cost of the retrofit measures and the cost of energy bills over the course of the year. The cost of the retrofit is assumed to be financed with a 5-year, 7% interest rate loan (the default loan option in BEopt) with an analysis period of 30 years (Polly & al, 2011). The variables include the amount of insulation in the walls, ceiling, and attic, the inclusion of a radiant barrier, the type of windows, infiltration level or sealing, amount of ventilation, duct sealing and insulation, appliance efficiency, percentage of fluorescent lighting, space conditioning heat pump efficiency, inclusion of the HPWH, inclusion of the ICS water heater, and the PV system. The cost and energy savings associated with the various combinations of these options are shown as red dots. The original house is represented by the pink diamond on the left side of the graph and the post-retrofit house is depicted by the green circle in the upper right portion of the graph. The blue curve shows minimum energy-related costs achieved by cost-optimal packages.

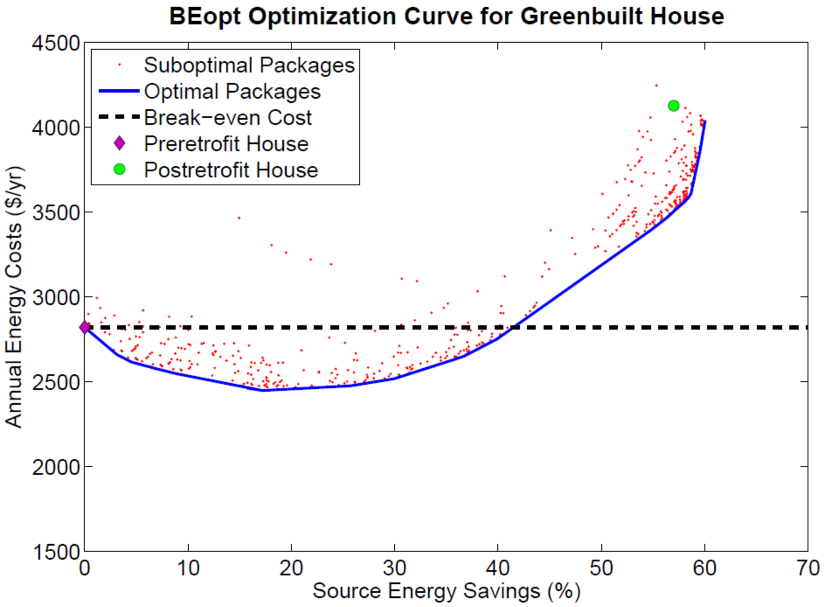

Figure 52. BEopt optimization curve based on energy saving and annual energy cost

The final package of energy efficiency measures at the Greenbuilt house produced good energy savings results, but the same energy savings may have been achieved at a reduced cost. Based on the optimization curve, the lowest annual cost required at 57% energy savings is about $3500, rather than $4130, the actual annual cost of the retrofit at the Greenbuilt house, meaning that the retrofit could have cost 15% less without reducing the energy savings. Relative to the actual retrofit measures, the least-cost option to achieve 57% energy savings included a reduction in insulation, removal of the HPWH, and use of a less efficient space conditioning heat pump. However, demonstrating technology such as the HPWH and a high-efficiency heat pump to the building community and public was more important than ensuring that the minimum cost point was achieved.

This curve shows that energy-related costs can be reduced and energy savings up to 40% achieved. For the Greenbuilt house and the set of variables considered in this optimization, the break-even point occurs around 40% energy savings. To further increase the energy savings, the overall energy-related costs are higher than if the house was not improved at all. Much of the additional cost comes from the renewable energy generation: the ICS SWH and the PV panels. Generally, the most cost-effective way to improve energy efficiency is to reduce overall energy use as much as is reasonable before implementing renewable energy measures. That strategy allows the renewable energy to make a big impact on final energy use or allows for a smaller and less expensive renewable energy system, while keeping the energy savings goal unchanged.

4.2 Comparison of Cooling Strategies

One goal for creating a simulation model for the Greenbuilt house was to enable a comparison of energy consumption for the various cooling strategies over an entire cooling season. A field test in a single house cannot be used to compare multiple cooling schedules simultaneously. The data collected during the space conditioning tests at the Greenbuilt house were used to guide the development of a detailed EnergyPlus model. The model from BEopt was further developed in

EnergyPlus v7.0 directly, which allowed more customization of the ventilation and occupancy schedules and individual characteristics for items such as specific walls, ceiling areas, and equipment. Only the HVAC energy use—the sum of the heat pump and air handler energy consumption—was used to compare the modeling results to the field data. For each cooling strategy, the house was modeled for several days before the day used for data comparison to allow for thermal and other transient simulation effects to diminish, as recommended by (Ellis, Liesen, & Pedersen, 2003). Each cooling strategy was then modeled over an entire cooling season to produce comprehensive and more broadly useful results.

Weather data collected during the space conditioning tests were used to inform the model, which used weather data that were collected on the roof, including outdoor dry bulb temperature, RH, wind speed, and insolation. Other required weather data, including sky radiation, precipitation, and wind speed, were taken from the TMY3 weather data for the Sacramento International Airport. This hybrid simulated weather file closely reproduced experimental conditions.

The thermostat set points used in the model deviated slightly from the schedules described in Section 3.4 because the measured indoor temperatures were always lower than the set points. The set points for the model were based on the actual indoor temperature to model the cooling energy. There was no temperature sensor next to the thermostat and the EnergyPlus model treated the living space as a single thermal zone, so the measured living room temperature was used to determine the modeled thermostat set point as it was the closest temperature sensor to the thermostat. The set point was chosen to be equal to the average living room temperature during the first two hours that the heat pump was actively cooling the space. If cooling occurred over a shorter period, such as with the advanced precooling schedule, the average living room temperature during that time was used as the set point. Figures 53 through 56 compare the temperature measured in the living room to the indoor temperature from the EnergyPlus simulation, which is assumed to the same throughout the entire living space.

4.2.1 Validation of EnergyPlus Model

Five of the six space conditioning strategies tested were modeled: baseline, simple precooling, advanced precooling, advanced precooling + shades (the schedule used during the heat storm), and shade control. The shades on the west side of the house remained closed during the whole-house fan test and the fan did not appear to improve the results from the shade control scenario, so the whole-house fan test was not modeled. The details for each schedule are given in Section 3.4. To verify the EnergyPlus model, each simulated cooling schedule was compared to the data from the Greenbuilt house for at least five days (more if possible). Each strategy was then modeled over the entire summer to compare afternoon HVAC energy consumption and peak demand. The modeling results and field test data presented here include the living room temperature and hourly HVAC energy (heat pump and air handler energy use). The same representative day used in the experimental results (Section 3.4) was also used when comparing data to the modeling results. All the other days of data in each schedule are similarly matched by the model.

An hourly comparison of cooling energy consumption data and modeled energy consumption was used to ensure that the model was reliable before comparing the modeled schedules over the cooling season. This process allowed the NREL researchers to identify and correct internal loads and ventilation schedules that deviated from the Building America Simulation Protocols and building envelope characterizes that are not allowed in BEopt. Examples of modifications made to the EnergyPlus model include:

- West wall insulation increased to R-15.
- 1 in. of expanded polystyrene and radiant barrier added to knee wall.
- Ceiling and drywalls added to garage.
- Exterior shades added to the windows on the west wall for the shade test.
- Exhaust fans, natural ventilation and vacation periods were eliminated.
- Latent loads were eliminated.
- Internal gain (lights and heaters) schedules were modified to represent the simulated occupancy schedule used at the Greenbuilt house.

Baseline Schedule

Figure 53 shows the hourly energy use and living room temperature for the baseline cooling strategy for a representative day in July. The predicted hourly profile captures the important characteristics for the cooling energy. The daily cooling energy uses were well matched, with the model coming within 1% of data for this day (see summary in Table 28). The simulated peak energy use was within 3.5% of the actual peak load (peak hours highlighted in light blue in Figure 53. Some physical properties, including internal thermal mass, ground coupling, and airflow patterns, may not be accurately represented in the model, leading to these discrepancies. Some assumptions for these are built into the EnergyPlus model and we did not have sufficient data to properly specify these properties. Any of these complex effects could impact the modeled indoor air temperature, which is the primary driver for heat pump operation. Overall, despite some small differences, the model for the baseline cooling schedule is a good representation of the data gathered at the Greenbuilt house.

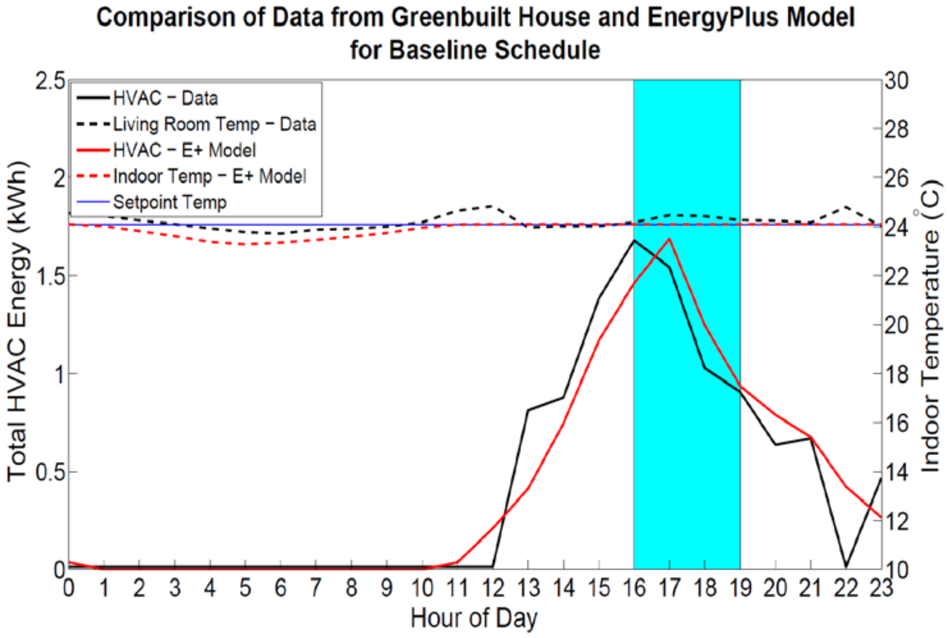

Figure 53. Baseline HVAC energy and living room temperature comparison between data from the Greenbuilt house and the EnergyPlus model

Peak hours are indicated by the blue band.

Table 28. Single Day Comparison of Baseline HVAC Energy Consumption for Data from the Greenbuilt House and the EnergyPlus Simulation

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	On Peak 4:00 p.m.–7:00 p.m. (kWh)
Field data	8.68	1.52	**10.20**	**4.25**
EnergyPlus results	8.50	1.60	**10.10**	**4.40**
% error in model	–2.1	5.2	**–1.0**	**3.5**

Simple Precooling

Figure 54 and Table 29 compare the representative day of data from the simple precooling schedule to the same simulation day in terms of HVAC energy use and indoor temperature. The important features in the total HVAC energy use data are the large spike in energy use when the heat pump is initially turned on in the morning followed by a large decrease in energy use after the new set point temperature has been reached and the subsequent increase in cooling energy in early afternoon as the outdoor temperature and cooling load increase. EnergyPlus captures these features qualitatively but does not quite match peak power. When the measured temperature exceeds the predicted temperature, the measured energy use is lower than the predicted use and vice versa. The difference between the measured and simulated temperatures from 10:00 a.m. to 11:00 a.m. is consistent with the difference in cooling energy use in Figure 54. Overall, the total daily HVAC energy predicted by the simulation matches the data within 3.5%, so even though the shape of the hourly energy consumption is slightly different, the model is a good surrogate for the data from the Greenbuilt house.

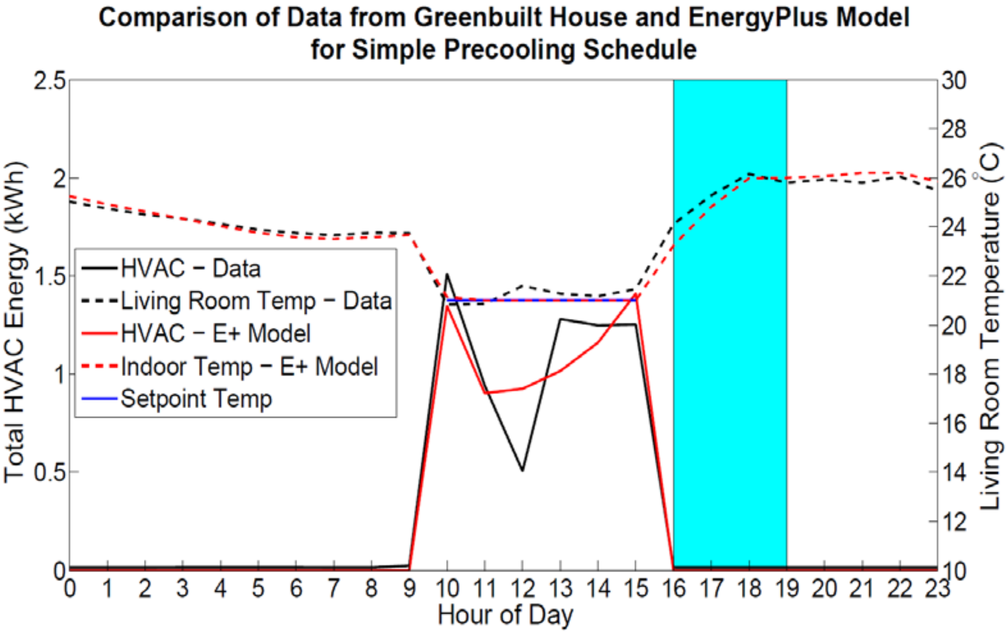

Figure 54. Simple precooling HVAC energy and living room temperature comparison between data from the Greenbuilt house and the EnergyPlus model

Peak hours are indicated by the blue band.

Table 29. Single Day Comparison of Simple Precooling HVAC Energy Consumption for Data from the Greenbuilt House and the EnergyPlus Simulation

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	On Peak 4:00 p.m.–7:00 p.m. (kWh)
Field data	5.84	1.17	**7.00**	**0.04**
EnergyPlus results	5.63	1.13	**6.76**	**0.00**
% error in model	-3.6	–3.4	**–3.4**	**–**[1]

[1] Peak energy use is nearly 0, so reporting model error would be misleading.

Advanced Precooling

Figure 55 and Table 30 compare a day of the EnergyPlus simulation for the advanced precooling schedule to a day of data collected at the Greenbuilt house. This cooling strategy is similar to the simple precooling but with an additional cooling period in the evening. The heat pump is also allowed to run overnight, if needed. The multiple rapid changes in the temperature set points and the associated thermal transients seen in living room temperature profile in Figure 55 make this a challenging schedule to model accurately. The important characteristics of the measured data are reflected in EnergyPlus simulation results, but the predicted energy use at the peaks (10:00 a.m. and 3:00 p.m.) do not match the magnitude seen in the actual data. The total daily energy use (as predicted by the model) matches the data within 1%. The cooling load during peak hours is slightly higher than was seen in the data, but the peak load is still essentially eliminated.

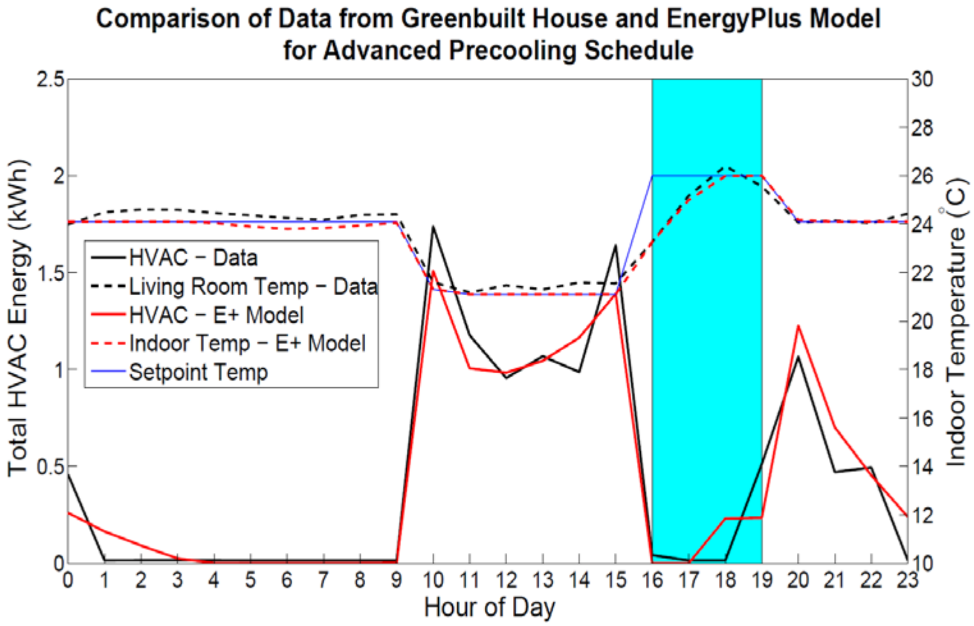

Figure 55. Advanced precooling HVAC energy and living room temperature comparison between data from the Greenbuilt house and the EnergyPlus model

Peak hours are indicated by the blue band.

Table 30. Single Day Comparison of Advanced Precooling HVAC Energy Consumption for Data from the Greenbuilt House and the EnergyPlus Simulation

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	On Peak 4:00 p.m.–7:00 p.m. (kWh)
Field data	9.09	1.69	**10.78**	**0.07**
EnergyPlus results	8.89	1.83	**10.72**	**0.23**
% error in model	−2.2	8.3	**-0.6**	**–**[1]

[1] Peak energy use is nearly 0, so reporting model error would be misleading.

Advanced Precooling + Shade Control

During a heat storm, the advanced precooling schedule was implemented while all the west-facing windows were shaded by the external shades. The initial peak in cooling energy at 10:00 a.m. is about 20% smaller in the model relative to the data, which is consistent with the previous cooling strategies tests. Overall, the daily cooling load is still well predicted by the model. A small cooling load is predicted during the afternoon peak period, but the schedule still achieves an 85% reduction from the baseline peak cooling load.

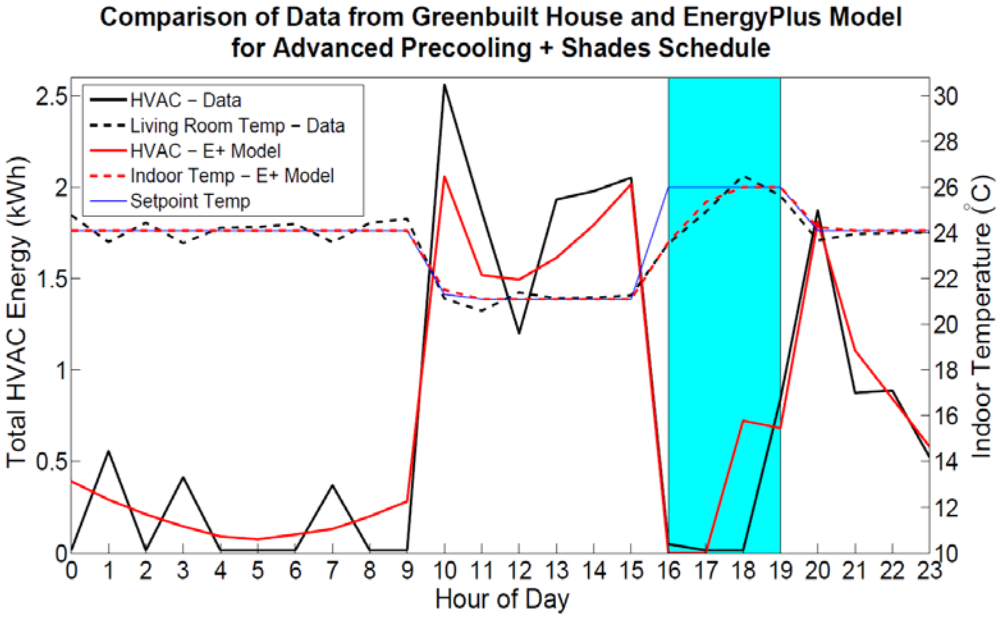

Figure 56. Advanced precooling + shade control HVAC energy and living room temperature comparison between data from the Greenbuilt house and the EnergyPlus model

Peak hours are indicated by the blue band.

Table 31. Single Day Comparison of Advanced Precooling + Shade Control HVAC Energy Consumption for Data from the Greenbuilt House and the EnergyPlus Simulation

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	On Peak 4:00 p.m.–7:00 p.m. (kWh)
Field data	15.73	2.38	**18.11**	**0.08**
EnergyPlus results	15.34	2.82	**18.16**	**0.72**
% error in model	-2.5	18.5	**0.3**	**–**[1]

[1] Peak energy use is nearly 0, so reporting model error would be misleading.

Shade Control

The shade control test was performed with all the west-facing windows and glass doors shaded with externally mounted shades and an external awning. The shades in the EnergyPlus simulation were set at 24% solar transmittance, based on the specifications for the installed shades. The cooling set point was constant throughout the day and was the same as the baseline cooling schedule. Even though the maximum simulated and actual cooling loads at 6:00 p.m. are well matched (within 6%), the shape of the predicted hourly cooling load is much sharper than the data collected at the Greenbuilt house. The simulated energy use for the shade control test is similar to the baseline schedule simulation. The only difference between these two schedules is the external, west-facing shades in the shade control test, which should cut the magnitude of the cooling load. However, the actual cooling load during the shade control test had a different shape than the baseline schedule, with a lower, wider energy use profile. The model did not capture this shape, and the cause is not well understood. Thus, the simulation underpredicts the daily cooling load and the afternoon peak load by nearly 15%.

EnergyPlus needs several shade properties besides solar transmittance, including reflectance, transmittance, and reflectance in the visible range, thermal emissivity, thermal transmittance, thickness, and conductivity. The manufacturer specified none of these, so reasonable values were used, but considerable uncertainty remains. The energy use predictions were highly sensitive to the shade properties and because they were not known, the model for this cooling schedule has the largest error relative to the data collected at the Greenbuilt house.

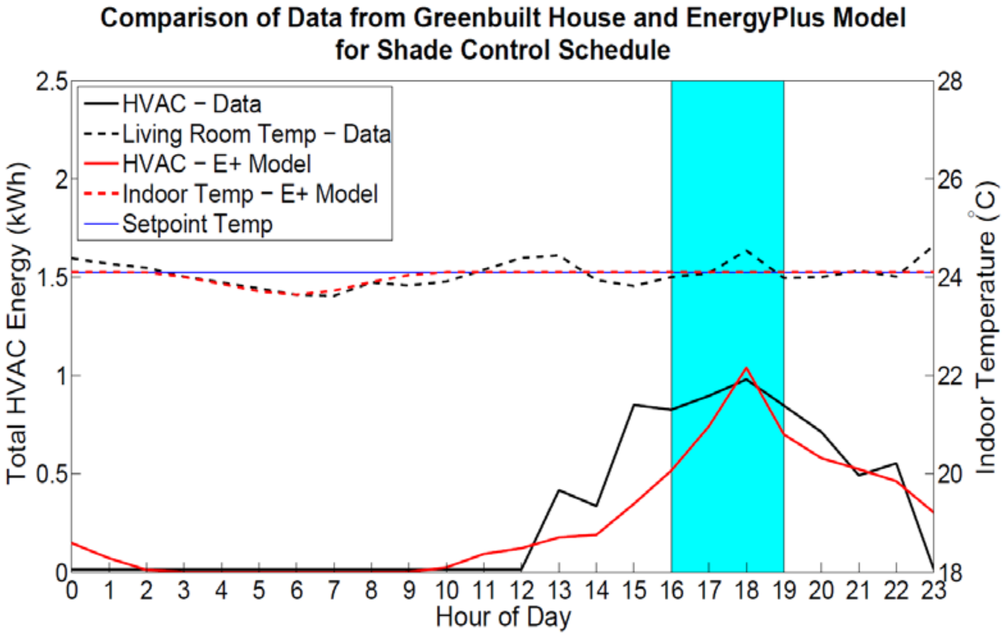

Figure 57. Shade control HVAC energy and living room temperature comparison between data from the Greenbuilt house and the EnergyPlus model

Peak hours are indicated by the blue band.

Table 32. Single Day Comparison of Shade Control HVAC Energy Consumption for Data from the Greenbuilt House and the EnergyPlus Simulation

	Heat Pump Energy (kWh)	Air Handler Energy (kWh)	Total HVAC Energy (kWh)	On Peak 4:00 p.m.–7:00 p.m. (kWh)
Field data	5.95	1.16	**7.11**	**2.70**
EnergyPlus results	5.19	0.86	**6.05**	**2.30**
% error in model	–12.8	–25.9	**–14.9**	**–14.8**

4.2.2 Whole Summer Comparisons

NREL researchers compared measured data to the EnergyPlus model for representative days to demonstrate the model’s ability to accurately predict cooling energy use. All the simulated cooling schedules matched the corresponding data within 3.5%, except for the shade control simulation, which underpredicted the HVAC load by 15%.

The main goal for the validated EnergyPlus model was to extrapolate the cooling schedules over an entire cooling season (June through September) and determine how the modeled HVAC energy consumption and peak cooling load compare. This is an important step to ensure that the limited results from the Greenbuilt house can be more broadly applied. Each cooling schedule was modeled over an entire summer; all cases used the same weather file. The simulated summer-long HVAC energy uses are compared in Table 33. The baseline strategy is used as a reference to compare summer-long energy savings (or gains) for the other strategies. Based on the simulation results, the shade control and simple precooling strategies resulted in the lowest energy use. In contrast, advanced precooling increased the HVAC energy use by 22% relative to the baseline case and the advanced precooling + shades schedule resulted in about a 5% increase. However, there is more uncertainty in the energy savings predicted for the shade control simulation because the single day comparison between the model and the data was not as well matched.

Table 33. June through September Total Cooling Energy Comparison Using EnergyPlus Model for Five Cooling Strategies

Cooling Schedule	Total Summer Cooling Energy (kWh)	Difference From Baseline (%)
Baseline	943.4	**–**
Simple precooling	886.4	**–6.0**
Advanced precooling	1152.5	**22.2**
Advanced precooling + shades	986.7	**4.6**
Shade control	880.3	**–6.7**

Finding ways to shift peak cooling energy is a priority for utilities, especially during the hottest days of the year. The three-day heat storm in late August was the hottest series of days during the summer of 2010; thus, these should represent the days with the highest peak cooling load. The peak cooling energy predicted by the EnergyPlus model for each schedule during those days is summarized in Table 34. The sum of the cooling energy between 4:00 p.m. and 7:00 p.m. for those three days is presented; the baseline schedule is used for comparison with the other strategies.

Table 34. On Peak Cooling Energy Comparison During August Heat Storm Using EnergyPlus Model for Five Cooling Strategies

Cooling Schedule	On Peak Energy 4:00 p.m.–7:00 p.m. (kWh)	Difference From Baseline (%)
Baseline	16.1	**–**
Simple precooling	0.0	**–100**
Advanced precooling	2.5	**–84.2**
Advanced precooling + shades	1.1	**–93.0**
Shade control	13.8	**–14.2**

All the schedules that included precooling nearly eliminated any peak cooling load during the heat storm. Even though the advanced precooling schedule and the advanced precooling + shade control strategy both increased summer-long cooling energy use, a TOU pricing schedule could make these schedules cost effective for homeowners. Overall, the advanced precooling + shade control schedule increases the total cooling load by only about 5% and successfully shifts the peak cooling load to earlier in the day, making it potentially the best strategy for homeowners under TOU pricing. The simple precooling also eliminates the peak cooling load and reduces the overall cooling load, but the cooling schedule is so severe that it may not be comfortable for an entire summer.

4.3 Modeling Conclusions

An EnergyPlus model was developed to compare five cooling strategies over an entire summer; each schedule was applied to the same summer-long weather file. The same cooling schedules were first tested in the Greenbuilt house and the data from those tests were used to validate the EnergyPlus model. Several days of data were compared to the same days of the EnergyPlus model for all the cooling schedules to ensure good agreement. The daily cooling energy predicted by the models matched the actual data within 4% for all schedules except for the shade control model, which underpredicted the cooling load by 15%.

The summer-long modeling results for total cooling load and peak cooling load were compared to the same results for the baseline schedule. The shade control schedule resulted in the largest overall HVAC energy reduction, nearly 7%, and reduced the peak cooling load during the heat storm by 14%. The simple precooling schedule reduced the total summer cooling load by about 6% and completely eliminated the peak cooling load. The advanced precooling + shade control strategy increased the overall cooling load by 5% and shifted nearly the entire peak load out of the peak time during the heat storm. The advanced precooling schedule resulted in the largest increase (22%) in overall HVAC energy use, but like the other precooling schedules, also significantly reduced the peak cooling load.

The ability to model these complex space conditioning schedules is important for maximizing the benefit of TOU pricing for the utility and the customers. As TOU pricing becomes more common, this type of modeling could be used to find the optimal precooling schedule for a specific house. A specific TOU pricing schedule saves money, and the utility keeps its peak loads manageable. However, further work is needed to determine the data and modeling needs before that type of optimization can easily be implemented. Rapid changes in cooling load, such as large changes in thermostat set point, are difficult to accurately reproduce in a model even though the steady-state periods can consistently be simulated. Determining all the physical properties for internal or external shades is nearly impossible without additional information from the manufacturer. It is unclear which properties are the most important to know fully. Further work is needed to understand the sensitivity of the model to difficult-to-measure parameters such as thermal mass, ground coupling, interior temperature variations, and room-to-room airflow patterns.

5 Conclusions

5.1 Lessons Learned and Future Work

This project was successful in many ways, but there is room to improve similar future projects. Recommendations follow, grouped by topic.

5.1.1 Retrofit Project

One critical piece of information missing from this project was the pre-retrofit utility bills. Modeling was done based on the characteristics of the house, the initial energy audit, and the blower door test done before the retrofit, but it would have been better to have actual utility bills (and thus, actual electricity use). Pre-retrofit data should be collected for any retrofit project, regardless of whether it will be used as a laboratory house. If pre-retrofit utility bills cannot be collected, pre-retrofit monitoring should be performed to ensure that the impact of the retrofit can be well characterized. Because the Greenbuilt house was empty for some time before the retrofit, pre-retrofit monitoring would have required simulated occupancy during the monitoring period.

NREL's involvement with the Greenbuilt house began after the retrofit construction was complete. Modeling the home in BEopt to determine the most cost-effective retrofit measures before starting the project may have produced even better construction cost and whole-house energy saving results.

5.1.2 Laboratory House Implementation

The Greenbuilt house is about 1000 miles from NREL, so researchers had difficulty making changes to equipment settings or sensor locations. Everything that was installed had to operate autonomously for an indefinite period, which was limiting. Having a closer laboratory house would be optimal, but having a dedicated local assistant would have been useful. Ideally, the assistant would be familiar with the house and all the monitoring and control systems installed by NREL and would make regularly scheduled and impromptu trips to the house.

One consequence of the distance between NREL and the Greenbuilt house was that latent loads were not included in the simulated occupancy schedule. People, appliances, and hot water draws contribute to latent loads, and have an impact on the cooling load requirements. However, despite several attempts, NREL researchers were not able to install a reliable and safe means of introducing latent heat to the house. With additional testing time, it should be possible to reliably deliver latent loads remotely, but it was not feasible in the project time frame. Future laboratory house projects should include latent loads in their occupancy simulation schedule as a priority if space conditioning is a focus of the project.

5.1.3 Enhancing Results through Modeling

Creating a robust simulation model for a home used in a field test, especially when the home contains extensive monitoring equipment, is critical to ensuring that the results are more broadly applicable. If development of the model had started at the beginning of the project, the initial results could have been compared to energy consumption data while the project was ongoing, allowing the model to be perfected before the tests were complete. This would have highlighted some additional sensor needs, such a temperature sensor next to the thermostat and more heat flux sensors around the house, possibly before any space conditioning experiments had been conducted. Even simple information, such as the height of the cathedral ceilings in the living room, would have been helpful when building the EnergyPlus model and could not be obtained months after the house was sold.

The difference in temperature measurements taken in five rooms around the house (living room, den, master bedroom, bedroom 2, and bedroom 3) revealed that treating the house as a single zone with a constant temperature is not accurate. The temperature variation between rooms was as high as 5.4°F (3°C) and the predicted HVAC cooling loads were sensitive to even smaller temperature differences. The Greenbuilt house had many large west-facing windows that probably caused the large temperature variation between the rooms on the west side and those on the east and north sides. Especially when the variation between rooms appears to have an obvious cause, the ability to include multiple zones in an EnergyPlus model should improve the agreement between data and modeling results for future projects.

5.2 Summary of Results

The Greenbuilt house underwent extensive renovations as a part of SMUD's EERD project and was used to show builders and homeowners what is possible with an energy efficiency renovation. Greenbuilt Construction was the contractor for the design and completion of all the retrofit measures. After the renovation was complete, NREL performed several short-term tests to ensure that the major systems installed during the retrofit were performing as expected. The systems evaluated included the space conditioning heat pump, the air handler and ducts, the HPWH, the ICS SWH, and the PV array. The duct system required attention after the test revealed that the master bedroom and bathroom were receiving insufficient airflow. Some small modifications to the ducts in the attic corrected the problem. Otherwise, all major systems performed within an acceptable range.

NREL was also given the opportunity to use the Greenbuilt house as a laboratory house for a year. The two main systems of interest were the space conditioning system (in cooling mode, specifically) and the DHW system. SMUD and NREL worked together to develop a mutually beneficial test plan. Experiments done on the HVAC system during the summer were aimed at finding ways to shift the peak cooling load and reduce the overall cooling load during a summer day. Of the scenarios tested, the use of external shades was the most effective means for cutting the daily cooling load. The simple precooling schedule was the most effective way of shifting the peak load and reduced the total cooling load relative to the baseline HVAC schedule. However, the advanced precooling + shades schedule may be a better way to shift peak cooling load and maintain indoor comfort during very hot days.

A similar trend was observed when the EnergyPlus model was used to compare the cooling strategies over the entire summer. The shade control test produced the largest total HVAC energy savings relative to the baseline schedule, followed closely by the simple precooling case. All schedules that included precooling nearly eliminated the peak cooling load, but the advanced precooling + shades and the advanced precooling schedules increased the summer-long cooling energy by 5% and 22%, respectively.

In the end, the "best" cooling strategy will likely depend heavily on a utility's pricing schedule. If a TOU price schedule is implemented that dramatically increases the cost of peak electricity, the precooling schedules will likely produce the best results. The advanced precooling + shades scenario slightly increases the total HVAC use, but eliminates the peak load. Coupled with pricing that makes midday electricity use cheaper, this schedule should reduce energy bills for consumers and decrease the stress on the utility during peak hours. The advanced precooling + shades schedule may be a better option than the simple precooling schedule because the home receives additional cooling in the evening, which should make the occupants more comfortable, especially on very hot days. If TOU pricing is not in place, simply drawing shades during the day appears to be the most effective way of reducing cooling energy use, though it is unclear how these results would translate to homes with internal shades. Only the west-facing windows were shaded at the Greenbuilt house because it has no south-facing windows. In most houses, east, south, and west-facing windows should be shaded during the day to reduce the cooling load. Anyone with a programmable thermostat can implement a precooling schedule, but switching between cooling schedules is often cumbersome. However, most homes have some form of window shades (though most are internal), so it would be feasible for a homeowner to close the shades during summer days.

The hot water system was tested in two configurations: the HPWH alone and the ICS SWH paired with the HPWH. Six hot water draw profiles were imposed on the hot water system to test their effects on performance. In both configurations, the standard Building America benchmark draw profile, the benchmark profile segregated into smaller draws, double benchmark profile, quarter benchmark profile, and morning- and evening-dominated profiles were tested. With the HPWH operating alone in the summer, all profiles produced a COP around 2.2, except the quarter benchmark that had a COP of 1.6. During the summer, the combination of ICS and HPWH resulted in a greater COP variability in the draw profiles. The standard benchmark profile had the highest COP (6.4), followed by the discrete benchmark and the double benchmark, which both had COPs of 4.9. The morning- and evening-dominated profiles were actually very similar for the ICS + HPWH system, with COPs of 3.8 and 3.9, respectively. Just as with the HPWH operating alone, the quarter benchmark profile produced the lowest COP (2.8) for the combined system. In terms of impact on summer peak load, the ICS + HPWH combined system reduced the peak load to zero and the HPWH alone reduced the peak load by 56% relative to a standard electric water heater running the hourly benchmark profile. Other interesting observations from the DHW tests include the ICS system performance during summer and winter. In the summer, as previously stated, adding the ICS to the HPWH had a large impact on system efficiency. However, during the winter, the increase in COP due to the addition of the ICS was much less significant. In fact, the ICS had a negative impact on the hot water system at some times during the winter. However, over the course of the year, either configuration of the DHW system would save homeowners at least 50% of their water heating electricity, compared to a standard electric resistance water heater.

5.3 Future Work

The results of these experiments performed on the space conditioning and DHW systems should be incorporated into future field tests in similar climates. The most effective cooling schedules should be used in other homes and compared to other cooling strategies. The schedules tested here cannot be considered comprehensive, so other innovative cooling schedules should also be considered. It will be important to verify that the conclusions drawn from this research are not unique. This same process should be repeated in other climate regions to determine viable cooling strategies. The EnergyPlus model effectively represented the results seen in the Greenbuilt house, but a great deal of time was needed to create a model with the required detail. The model was built with EnergyPlus because BEopt does not allow some of the complex geometries seen in the Greenbuilt house, such as one wall having more insulation than the others. BEopt also has some built-in assumptions that control schedules for internal loads, occupancy, lighting, and ventilation, all of which had to be adjusted to fit the simulated occupancy schedule. Modeling could play a large role in optimizing cooling schedules that can reduce overall cooling loads and shift the peak to earlier in the day, but more complex space conditioning schedules require detailed home models to ensure accurate results.

On the DHW side, the Greenbuilt house results could be used for future research in a number of ways. HPWH technology has moved away from the add-on type of system used here toward integrated HPWHs with backup electric resistance elements that are built as a single unit. The performance of HPWHs in various climates and in conditioned and unconditioned spaces is currently being investigated by a number of field tests. Additionally, ducting the outlet air to either put it to better use when cooling is required or rejecting the cold air to the outside during the heating season could maximize the benefits of HPWHs, but the cost and feasibility of that configuration are not well understood. A field test to investigate that question would be a valuable addition to HPWH research. The developmental focus for solar thermal systems is reducing costs for colder climate systems. As new products enter the marketplace to address this need, field tests should be conducted in cold climates. These systems will likely be paired with gas water heaters for backup water heating. The work done at the Greenbuilt house will hopefully be used to advance the performance and acceptance of deep energy retrofits and the advanced energy efficiency technologies installed in the process.

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Appendix A: Summary of Retrofit Measures

Table 35. List of Retrofit Measures at the Greenbuilt House and the Systems That Were Replaced

System	Pre-Retrofit	Post-Retrofit
Thermal Envelope		
Ceilings	R-19 insulation	R-42 blown-in cellulose
Roofing	Asphalt shingles	Asphalt shingles with radiant barrier
Band joist areas and attic perimeter	No insulation	Rake and "pack" insulation to perimeter
Knee walls	R-11 insulation	1-in. metallic-reflective face rigid foam (R-6) over R-15 batts
West wall	R-11 insulation	R-15 blown-in cellulose insulation
Infiltration	3280 CFM @ 50 Pa 15.5 ACH @ 50 Pa	946 CFM @ 50 Pa 3.6 ACH @ 50 Pa
Windows		
Windows and sliding glass doors	Al. frame, single pane U-value ≈ 1.07, SHGC ≈ 0.7	Vinyl frame, dual pane Argon filled, low-emittance coating U-value = 0.28 - 0.29, SHGC = 0.19 - 0.22
Air sealing	None	Air Sealing to comply with ENERGY STAR thermal bypass checklist
Mechanical Systems		
Space conditioning heat pump	HSPF 7.75 SEER 13/EER 10	HSPF 9.75 SEER 16/EER 13
Ducts	R-2 insulation	R-6 insulation, "tight" - 4.5% leakage @ 25 Pa
Thermostat	Manual	Programmable, communicating
Whole-house fan	None	2-speed AirScape 2.5 whole-house fan
Water heating	Electric Storage Tank EF ~ 0.97	Storage tank with add-on HPWH, COP of 2.11
Ventilation		
Spot ventilation	None	ENERGY STAR bathroom low sone fans with timer controls
Lighting and Appliances		
Lighting	Incandescent bulbs	100% hardwired ENERGY STAR CFL bulbs, LED fixtures in master bath
Ceiling fans	Incandescent bulbs	ENERGY STAR rated with CFL bulbs
Solar tubes	None	ENERGY STAR rated, in bathrooms
Refrigerator	Existing	Tier 2 ENERGY STAR
Dishwasher	Existing	Tier 2 ENERGY STAR (EF = .69)
West-facing shades	None	Motorized awning and shades

System	Pre-Retrofit	Post-Retrofit
Whole-house controls	None	Control4 home area network
Renewable Energy		
SWH	None	40-gal ICS 50% solar fraction
PV	None	2.3 kW AC PV
Home Energy Rating		
HERS Index	181.5	77.9 (57% improvement)
Green Point Rating	Unknown	134

Appendix B: List of Instrumentation

Table 36. List of Data Logger Equipment and Accessories Used at the Greenbuilt House

Data Logger and Accessories		
Equipment Purpose	**Make and Model**	**Notes**
Measurement and controls data logger	Campbell Scientific CR1000	All other peripherals connect to CR1000
Solid-state multiplexer	Campbell Scientific AM25T	Used to read thermocouples
Voltage pulse count module	Campbell Scientific SDM-SW8A	Used to collect all power measurements
Relay controller	Campbell Scientific SDM-CD16AC	On/off control for relays
Remote data collection	Campbell Scientific CR206	Two of these modules were used to collect data from rooftop sensors
Backup power supply for CR1000	Campbell Scientific PS12	12-volt battery
Radio receiver for CR206 modules	Campbell Scientific RF 401 Radio	
Wireless modem	Sierra Wireless Raven XT	Used for remote access to data logger
Antenna for wireless modem	Campbell Scientific Cellular Antenna 800 MZ	

Table 37. List of Sensors and Controls Equipment Used at Greenbuilt

Sensors and Controls Equipment		
Measured Quantity	**Make and Model**	**Notes**
Air temperature sensors (center of room)	Omega TT-T-24S-TWSH-SLE T type thermocouple wire	Twisted, shielded wire and rated for special limits of error
Air temperature sensors (wall-mounted)	Omega EWS-TC-T Environmental Wall Mount Sensor	T-type thermocouple in housing
Surface-mounted thermistors	Omega SA1-TH-44006-120-T	Surface-mounted thermistors for PV surface temperature measurements
Water temperature sensors	Omega TMQSS-062U-6	T type thermocouples, rated for special limits of error.
Humidity sensors	Vaisala Intercap HMP50	Three were installed inside and one outside for humidity measurement
Pulse output flow meter	Omega FTB4605	Used to measure flow rate of hot water drawn from water heater tank
Ultra sensitive heat flux plates	Hukseflux HFP03	Four were installed in house to measure heat flux through the slab
Pulse output power transducers	Continental Control Systems WNB-3Y-208-P3	Used to measure power consumption of appliances, PV and whole-house
Current transformers	Continental Control Systems CTS-075-030, CTS-075-100	100 A CT used for whole-house power 30 A CTs used for everything else
Pyranometers for Irradiance measurements	Campbell Scientific CS300-L50	Two were installed on roof: Horizontal irradiance and irradiance in plane of PV and ICS systems
Pyrgeometer for Infrared measurement	Eppley model PIR	One installed on roof in plane of PV and ICS systems
Barometric pressure sensor	Vaisala PTB110	Outdoor pressure measurement
Anemometer	R M Young 03002-L Wind Sentry Anemometer	Rooftop Wind speed measurement
Solenoid valves	Asco Redhat II 8210G002 1/2” pipe, normally closed	Controlled water flow out of water heater
Space heaters	930 W each	Used to introduce sensible load to building
Solid-state relays	Crydom CSD2425	Relays for space heaters and solenoid valves

Table 38. List of Control4 Equipment at the Greenbuilt House

Control4 Equipment		
Equipment Description	Control4 Product ID	Notes
Home controller	C4-HC200-E-B	Main controller for all other components
Composer software	C4-CHE-XXX	Used to program control system remotely
System remote control	C4-SR150-Z-B	Remote used with TV to program controller on site
Wireless thermostat	CCZ-RCR1-B	Programmable thermostat
Wireless 3 button keypad	KPZ-3B1-W	Installed at the front door: Home, Green, and Away buttons
Wireless outlet switch	LOZ-5S1-W	Able to control power to plug loads
Wireless switch	LSZ-102-W	Allows for remote control of light switches
Wireless dimmer switch	LDZ-102-W	Allows for remote control of dimmer switches

Appendix C: Air Temperature Measurement Location

Wall-Mounted Versus Center of Room Thermocouples

Historically, interior air temperature measurements have been made with thermocouples that are housed in an aspirated radiant barrier enclosure that is suspended in the middle of each room. (See Figure 58 for an example of this type of installation.) This has been established as the best practice for interior temperature measurements, but the installation is labor intensive and too awkward for field tests involving occupied homes. When instrumenting an occupied house, thermocouples are mounted on the walls instead of hung in the center of the room (also shown in Figure 58). However, the two sensor locations have never been compared to see if there are significant benefits to the center of the room location or if the wall-mounted thermocouples are adequate.

Greenbuilt provided an opportunity to investigate this question. Another motivation for this comparison comes from the structure of our modeling software. The internal temperature used by BEopt is air temperature, rather than wall temperature. The center of the room measurement is the ideal data source for the model, but occupied field tests are more common and so most often, the wall temperatures are used to inform the model. Another more practical consideration is that thermostats for space conditioning control are wall mounted, but occupants feel the air temperature rather than wall temperature. Are there large enough differences to justify the thermostat manufacturers making specific changes to their product to address the difference?

Figure 58. Thermocouples for interior temperature measurements

NREL/PIX 19621, Credit: Lieko Earle

Each of the five rooms where air temperature was measured had thermocouples installed in the center of the room and on a wall. The thermocouples were simple welded T-type thermocouple wire, taken from the same spool of wire, meaning that there should be ≤0.2°F (0.1°C) difference between the temperature signals if they were next to each other. In reality, a larger difference in temperature was measured between the wall-mounted and center of the room thermocouples of 0.4°–0.7°F (0.2°–0.4°C) on average, depending on the room and whether heating or cooling was occurring. The thermal mass of the walls appears to be the main source of the discrepancy. The center of the room thermocouple is more sensitive to temperature changes, especially when cooling or heating are actively occurring. As expected, the wall-mounted thermocouples are slower to respond to temperature changes because the thermal mass of the wall cannot change as fast as the air temperature. An example of this is shown in Figure 59, which shows the wall-mounted thermocouple and the thermocouple suspended in the center of the room for the living room during one day of the advanced precooling schedule.

Because this example features a thermostat set point that changes several times throughout the day, the differences between the center and wall temperature measurements are amplified. When the precooling period begins, the difference between the two thermocouples jumps to 1.3°F (0.7°C), but over the course of the day, the average temperature difference is only 32.5°F (0.45°C). For tests that maintained a steady set point through the day, both the maximum and daily average temperature differences were smaller.

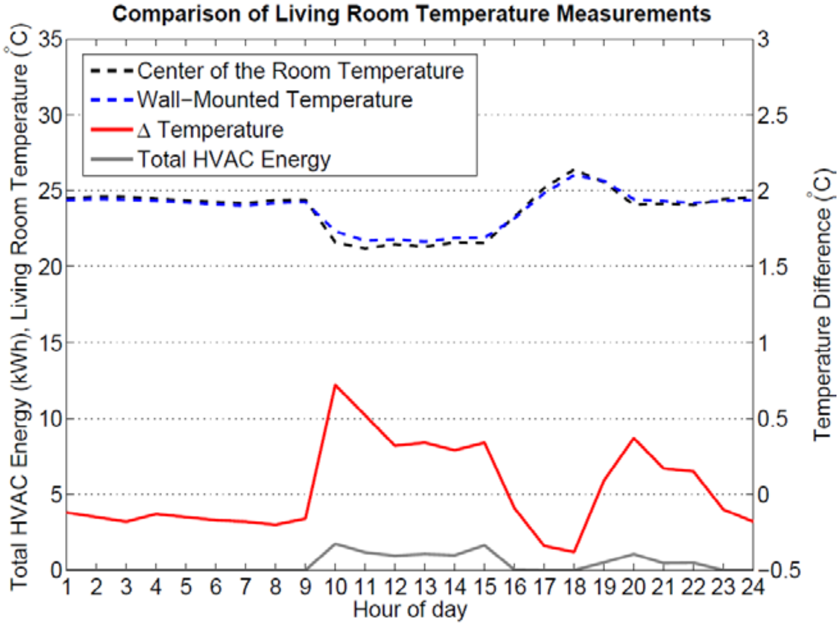

Figure 59. Temperature differences between wall-mounted thermocouple and center of the room thermocouple during the advanced precooling schedule. The heat pump energy is shown to indicate when cooling is actively occurring.

For some perspective on these temperature differences, over the same day shown in Figure 59, the average temperature difference between rooms during the day was 2°F (1.1°C), with a maximum temperature difference of 4°F (2.2°C). BEopt assumes a constant temperature throughout the house and it is not currently possible to specify multiple thermal zones. Therefore, wall-mounted temperature sensors introduce a smaller error to the simulation than assuming a constant temperature throughout the house.