OAK RIDGE
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Comparison of Two High-Performance Energy Efficient Homes: Annual Performance Report, December 1, 2010–November 30, 2011

April 2012

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UT-BATTELLE

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Energy and Transportation Science Division

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ACRONYMS

ACH	air changes per hour
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ASHP	air source heat pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building America
CDD	cooling degree day
CFM	cubic feet per minute
COP	coefficient of performance
CWC	clothes washer cycles per year
DHW	domestic hot water
DHWH	domestic hot water heater
DOE	U.S. Department of Energy
DWC	dishwasher cycles per year
ECM	electronically commutated motor
ERV	energy recovery ventilator
HDD	heating degree day
GFX	Gravity Film eXchange
GSHP	ground source heat pump
HERS	Home Energy Rating System
HPWH	heat pump water heater
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air conditioning
IAQ	indoor air quality
IECC	International Energy Conservation Code
ILL	interior lighting load
LCUB	Lenoir City Utility Board
MEL	miscellaneous electric load
OAT	outside air temperature
ORNL	Oak Ridge National Laboratory
Pa	Pascals
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
TMY	typical meteorological year (as in TMY3)
TVA	Tennessee Valley Authority
VOC	volatile organic compounds
WWHP	water-to-water heat pump water heater
XPS	extruded polystyrene

EXECUTIVE SUMMARY

Beginning in 2008, two pairs of energy-saver houses were built at Wolf Creek in Oak Ridge, TN. These houses were designed to maximize energy efficiency using new ultra-high-efficiency components emerging from ORNL's Cooperative Research and Development Agreement (CRADA) partners and others. The first two houses contain 3713 square feet of conditioned area and are designated as WC1 and WC2; the second pair consists of 2721 square feet conditioned area with crawlspace foundation and they're called WC3 and WC4.

This report documents the annual energy performance of WC3 and WC4, and how they compare against a builder standard house (BSH) of a similar footprint. WC3 and WC4 are both designed to be about 55-60% more efficient than traditional new construction. Each house showcases a different envelope system: WC3 is built with advanced framing featuring cellulose insulation partially mixed with phase change materials (PCM); and WC4 has cladding composed of an exterior insulation and finish system (EIFS). The two houses are also equipped with ENERGY STAR rated appliances, or high-efficiency products for categories that are not yet ENERGY STAR certified. WC3 and WC4 are both on crawlspaces with the designs intended to provide a definitive comparison of a vented crawlspace to an insulated and sealed crawlspace in a mixed humid climate.

The builder standard house is a computer model based on a builder house, one of three houses, built at the Campbell Creek subdivision in Knoxville, TN. The Campbell Creek research project supported the retrofit residential housing goals of the Tennessee Valley Authority (TVA) and the U.S. Department of Energy (Christian et al., 2010). The builder house is representative of a standard, IECC 2006 code-certified, all-electric house built around 2005–2008.

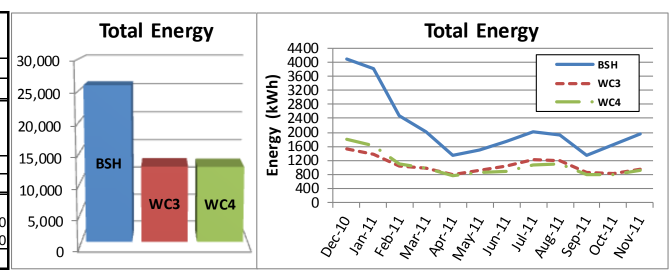
This report presents data collected from WC3 and WC4 from December 1, 2010 to November 30, 2011. The outcome of this research program will contribute to efforts by Tennessee Valley Authority (TVA) to meet their strategic goals of deferring 1,400 MW of additional capacity and reducing growth in energy consumption by 4.3 million MWh per year by 2012, and in the longer term, to transform how homes are built and retrofitted.

Dashboard Report
12/1/10 to 11/30/11

House	Total[1]	Cost	PeakHr[1]	Average[1]	Ld Factor
BSH	25,860	$2,618.47			
WC3	12,658	$1,343.76	7.374	1.499	0.203
WC4	12,605	$1,337.26	7.912	1.556	0.197

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	48.95%	51.32%	1/15/11	1/14/11	9:00
WC4	48.74%	51.07%	1/15/11	12/15/10	20:00

[1] Energy in kWh throughout unless otherwise noted.



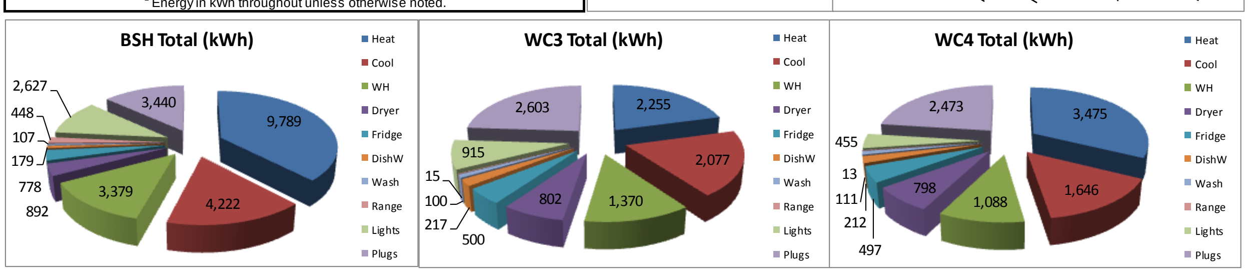


Figure ES.1. BSH, WC3 and WC4 annual energy usage and breakdown, December 2010 – November 2011.

Figure ES.1 shows the annual energy usage of the two test houses and the breakdown among the major appliances and loads in these houses, and compares them to the simulated energy consumption of the builder standard house (BSH). The total annual energy usages of the two houses were similar; 12,685 kWh in WC3 and 12,605 kWh in WC4. The test houses consumed about 51% less energy than the BSH.

The annual energy costs of WC3 and WC4 were $1,344 and $1,337, respectively. Using the same utility rates and service charges, the BSH would have incurred about $2,618. These annual energy costs include about $116/yr hookup charges that are fixed whether the house is energy-efficient or a very large energy consumer. Without the hookup charges, the energy cost of both WC3 and WC4 would be $3.35/day, compared to $6.85/day for the BSH.

Space heating, space cooling and water heating, in that order, were the largest energy consumers in the test houses. The plug loads, which were designed to simulate occupancy following the Building America benchmark protocol, also accounted for a major fraction of the energy consumption.

The WC3 ground source water-to-air heat pump (GSHP or WAHP) performed better than the air source heat pump (ASHP) in WC4 during the heating season. The GSHP had a performance advantage for heating due to its favorable entering water temperature (EWT) compared to the ASHP, whose performance was affected by the low outdoor air temperatures in winter. In summer, the ASHP performed better than the GSHP. These factors are reflected in the higher heating and lower cooling energy consumptions in WC4. The energy consumption of the electric heat pump water heater (HPWH) in WC4 was about 20% less than the water-to-water heat pump (WWHP) in WC3.

Both the GSHP and ASHP were effective in maintaining the indoor temperatures in the respective houses close to the thermostat set points for most of the time during the monitoring period, and especially during the peak heating and cooling months. Major deviations from the mean temperatures were seen primarily during the shoulder months of April and October, when switching of the space conditioning mode and the set points took place. RH levels in both houses were maintained within the human comfort zone throughout the year.

An engineering simulation model, using local TMY3 weather data, was used to compare the two houses' performance with the 2008 Building America (BA) Benchmark. Compared to the BA benchmark, both WC3 and WC4 showed savings of about 55%. The BA benchmark house had a Home Energy Rating System (HERS) score of 111, while WC3 and WC4 had HERS scores of 46 and 51.

The total construction costs of WC3 and WC4 were $445,800 ($164/ft^2) and $422,000 ($155/ft^2). Neutral cash flow analyses, using a 30 year mortgage at 7% interest, were performed to compare the energy cost savings to the incremental cost energy efficiency measures. The neutral cash flow analysis also considered all the federal and state rebates and incentives for the energy efficiency measures. Neither house was cash-flow neutral, i.e. each had a net annual cost for the customer. However, it is important to note that WC3 and WC4 were intended for demonstrations of new and experimental technologies that do not have sufficient market penetration yet. It is expected that with more widespread implementation in the residential building market and additional technical innovations and improvements, these energy efficiency measures will become more cost-effective.

1. PROJECT OVERVIEW

1.1 BACKGROUND

The simulated occupancy research houses provide an opportunity to accelerate progress toward DOE's goal of maximizing cost-effective energy efficiency by investing in a highly leveraged, focused effort to test new high-efficiency components emerging from ORNL's Cooperative Research and Development Agreement (CRADA) partners and others. This effort has integrated efficient components into the construction of seven research houses that will be used as test cases to gauge the integral success of the components and houses. These research houses are the first houses used to field-test several newly emerging products such as ground-source integrated heat pumps, factory assembled ZEHcor walls, innovative waste heat recovery systems and one or more new high-efficiency appliances. When these new components are proven, they will become available to serve regional and national homebuilding markets. Some of these products will impact existing housing retrofit markets as well as new construction.

Beginning in 2008, two pairs of energy-saver houses were built at Wolf Creek in Oak Ridge, TN. The first pair of houses contained 3713 square feet of conditioned area; the second pair consisted of 2721 square feet conditioned area with crawlspace foundation. Table 1 provides the footprint details of the two houses. For ease of discussion the first pair of houses is designated as WC1 and WC2, and the second pair of houses as WC3 and WC4.

Table 1. Footprints of the Energy-Saver Houses

Space	WC1 and WC2	WC3 and WC4
	square feet	
Basement	1518	NA
1st Floor	1518	1802
2nd Floor	677	919
Total	**3713**	**2721**

All four houses demonstrate different strategies for saving energy, but all are about 55-60% more efficient than traditional new construction (based on third party certified HERS evaluations). Each house showcases a different envelope system: Structural insulated panels (SIP) were used as the envelope for WC1; WC2 used optimal value framing (OVF) techniques; WC3 with advanced framing featuring cellulose insulation partially mixed with phase change materials (PCM); and WC4 has cladding composed of an exterior insulation and finish system (EIFS).

The outcome of this research program will contribute to efforts by Tennessee Valley Authority (TVA) to defer 1,400 MW of additional generation and reduce growth in energy consumption by 4.3 million MWh per year by 2012, and in the longer term, transform how homes are built and retrofitted for improved energy efficiency in mixed humid climates.

This report documents the annual performance of the second pair of homes (WC3 and WC4). For comparison, a benchmark builder standard house (BSH) model was created using EnergyGauge software http://www.energygauge.com/usares/). The BSH had the same footprint as WC3 and WC4, and was based on a builder house built at Campbell Creek in Knoxville, TN (Christian et al., 2010). The Campbell Creek research project supported the retrofit residential housing goals of the Tennessee Valley Authority (TVA) and the U.S. Department of Energy. The builder house is representative of a standard, IECC 2006 code-certified, all-electric house built around 2005–2008, is designated as CC1. The BSH model was created using the building technologies and appliances featured in the Campbell Creek builder house. The model was needed because a direct comparison of measured data from the Wolf Creek houses and CC1 was deemed inappropriate due to the differences in the foot print and the geographical location resulting in different orientations of the houses. The orientation of a house impacts the amount of solar heating it receives on its different sides and, hence, the heating and cooling loads.

HERS Index

HERS Index is a rating system based on the International Energy Conservation Code (IECC) for houses. A HERS rating of 100 is close to a new home meeting the 2006 International Energy Conservation Code. A HERS Index of 0 is a house that produces as much energy as it uses. Part of the evaluation includes a blower door test—rated in air-changes-per hour (ACH) at 50 Pascal differential pressures. HERS ratings of the two houses are: WC3 - 46; WC4 - 51.

1.2 ENVELOPE AND TECHNOLOGY SUMMARY

1.2.1 WC3 (PCM house)

Envelope

- Two 2 x 4 walls with offset studs; conventional blown cellulose insulation in the inner cavities and blown cellulose insulation mixed with 20% by weight PCM in the outer cavities.
- Windows – Argon filled triple pane windows; U-factor = 0.22 (Btu/hr-ft^2-°F) and SHGC (solar heat gain coefficient) = 0.17.
- Exterior cladding – fiber cement lap siding and stack stone.
- Roof – stone coated metal roof, with above sheathing ventilation and radiant barriers in the inclined air space.
- Attic – conventional attic with ceiling insulation consisting of 10 inch regular cellulose and 4 inch of 20% by weight PCM enhanced cellulose; added ventilation using solar powered gable ventilators.
- Crawlspace foundation – ventilated crawlspace with R-38 (hr-ft^2-°F/Btu) batt insulation in floor chase cavities.
- HERS index of 46.

HVAC

- High-efficiency, ground-source water-to-air heat pump (GSHP/WAHP) and water-to-water heat pump (WWHP) with a 320 ft vertical well to provide space conditioning and hot water. A back-up 82 gallon standard electric water heater with an energy factor (EF) of 0.92 is used for water storage.
- Ductwork installed in 24 inch truss between first and second floors.
- Zone control separating the first and second floors of the house, with each zone having its own thermostat.
- Programmable air-cycler to control the supply of fresh air.

Electrical and Appliances

- Energy star rated compact fluorescent light bulbs.

- The appliances are Energy Star rated or high-efficiency products for categories that are not yet Energy Star certified.

ZEHcor Wall

- An interior wall assembly with complete rough-ins for hot and cold water plumbing, grey and black water, and HVAC supply.

1.2.2 WC4 (EIFS house)

Envelope

- 16-in on center (O.C.), 2 x 4 framing, with 5 inch expanded polystyrene (EPS) exterior insulation with ½ inch plywood.
- Windows – Argon filled triple pane windows; South facing U-factor = 0.24 (Btu/hr-ft^2-°F) and SHGC = 0.50; North facing U-factor = 0.17 (Btu/hr-ft^2-°F) and SHGC = 0.22.
- Exterior cladding – acrylic stucco and stack stone.
- Roof – conventional shingle roof, with profiled and foil-faced 1 inch EPS insulation installed above roof rafters and covered with foil-faced oriented strand board (OSB).
- Attic – conventional attic with R-50 (hr-ft^2-°F/Btu) blown-fiber ceiling insulation.
- Crawlspace foundation – sealed with R-10 (hr-ft^2-°F/Btu) polyisocyanurate foil faced insulation.
- HERS index of 51.

HVAC

- Dual capacity air source heat pump (ASHP) for space conditioning.
- GE GeoSpring® 50 gallon hybrid electric heat pump water heater (HPWH). The energy factor of this unit is approximately 2.35.
- Ductwork installed in 24 inch truss between first and second floors.
- Zone control separating the first and second floors of the house, with each zone having its own thermostat.
- Programmable air-cycler to control the supply of fresh air.

Electrical and Appliances

- Energy efficient solid state light emitting diodes (LED) for lighting.
- The appliances are Energy Star rated or high-efficiency products for categories that are not yet Energy Star certified.

ZEHcor Wall

- An interior wall assembly with complete rough-ins for hot and cold water plumbing, grey and black water, and HVAC supply.

1.3 OCCUPANCY SIMULATION OVERVIEW

Occupancy in the Wolf Creek houses is simulated by two separate systems, based on BA benchmark 2009. The first is a custom LabVIEW® virtual instrument system that uses a digital USB DAQ device to control relays at the different appliances to turn them on and off and control settings. The other is a ZWave® (WC1 and WC2) or Insteon (WC3 and WC4) based control system which controls the lighting and sensible heat loads.

An ftp server keeps the most current profile. Each night the computers at each house run a scheduled task that downloads the profile and uses this new file the next day. This feature makes it very simple to populate all the houses with the same profile at the same time. In March 2010 an alarm system was also implemented in the Wolf Creek houses which sends emails if data values go out of a user defined range. Some alarms check data every hour and others once a day. The alarms were programmed in RTMC Pro software from Campbell Scientific. The program runs on the computer in WC1 as a server and continuously monitors data from all the houses. Further details of the occupancy simulation in Wolf Creek houses are provided in chapter 7.

2. OVERALL ANNUAL PERFORMANCE OF HOUSES

2.1 OAK RIDGE WEATHER DATA

Table 2 lists the heating and cooling degree days (HDDs & CDDs) for Oak Ridge, TN during the evaluation period, and they are compared to TMY3 data (EnergyPlus, http://www.eere.energy.gov/). Both HDDs and CDDs are based on 65ºF. The actual weather during the evaluation period was colder than average during the heating season and near average during the cooling season.

Table 2. Heating and cooling degree days (HDDs & CDDs) at 65°F compared to TMY3 data

	HDDs at 65°F	TMY3 HDDs at 65°F	Difference	CDDs at 65°F	TMY3 CDDs at 65°F	Difference
Dec-10	1008	772	235.8	0	0	0
Jan-11	922	932	-10.4	0	0	0
Feb-11	585	765	-180	2	0	2
Mar-11	434	437	-3.4	26	0	26
Apr-11	184	232	-48.2	107	65	42
May-11	114	94	20.4	191	182	9
Jun-11	2	0	2	346	403	-57
Jul-11	0	0	0	464	466	-2
Aug-11	5	0	5	423	459	-36
Sep-11	54	0	54	147	209	-62
Oct-11	304	211	93.4	47	4	43
Nov-11	439	410	28.6	4	0	4
Total	**4051**	**3854**	**197**	**1757**	**1787**	**-30**

2.2 INDOOR CONDITIONS DURING EVALUATION PERIOD

Table 3 presents the monthly statistics of the first floor temperature and relative humidity data in WC3 and WC4 and the outdoor temperatures.

Table 3. Monthly temperature and relative humidity (RH) data from the first floors of WC3 and WC4

	Outdoor Temperature (°F)			WC3 Indoor Temperature (°F)			WC4 Indoor Temperature (°F)			Average Indoor RH (%)	
	Min.	**Max.**	**Average**	**Min.**	**Max.**	**Average**	**Min.**	**Max.**	**Average**	**WC3**	**WC4**
Dec-10	9	59	32	70.2	72	71.1	69.5	72.8	71.5	28.3	34.9
Jan-11	13	67	35	68.4	73.5	70.9	69.8	72.6	71.3	26.9	32.5
Feb-11	18	70	44	69.9	72.4	70.9	69.6	73.9	71.1	29.7	34.3
Mar-11	32	82	52	69	79.2	71.8	70.1	74.6	71.2	36.2	41
Apr-11	32	88	63	69.9	84.7	74.2	68.5	80.1	73	42.4	47.7
May-11	37	92	67	67.9	78.5	74	67.5	76.4	73.2	49.7	55.6
Jun-11	60	94	76	74.1	78.2	75.3	73.8	76.5	75.3	56	61.5
Jul-11	62	95	80	74.1	76.2	75.2	73.8	82.7	75.2	57	56
Aug-11	59	96	78	74.1	76.8	75.4	70.7	78.2	74.5	55.3	49.3
Sep-11	51	96	68	73	76.1	75.1	72.3	76.6	75.1	57.4	57.9
Oct-11	32	81	57	67.4	76.1	72.9	67.7	77.2	73.5	49.4	53.2
Nov-11	26	73	51	69	75.4	71.2	65.8	75.1	72	37.9	47.8

During most months, there was very little variation between the minimum and maximum temperatures (<5°F). April and October were expected to be outliers because the space conditioning modes were switched from heating to cooling or vice-versa, with corresponding changes in the temperature set points

(71°F in heating mode and 76ºF in cooling mode). Differences of 6-7°F between the extreme and average temperatures were also observed in March, May, July and November. The average monthly RH in WC4 was about 5-6% higher than WC3 during most months, except July and August, when WC3 had higher RH. The heat pumps in both houses maintained the RH within the human comfort level throughout the year. During July and August, when the cooling demands would have been the highest, the ASHP in WC4 removed more moisture from the conditioned space compared to the GSHP in WC3, resulting in lower RH in WC4.

To investigate how well the space conditioning equipment maintained the temperatures in the different zones in the two houses, the hourly variations of the indoor temperatures from the monthly average are shown in Figure 1 and Figure 2, where the horizontal axis is the day of the year and the vertical axis is the hour of the day.

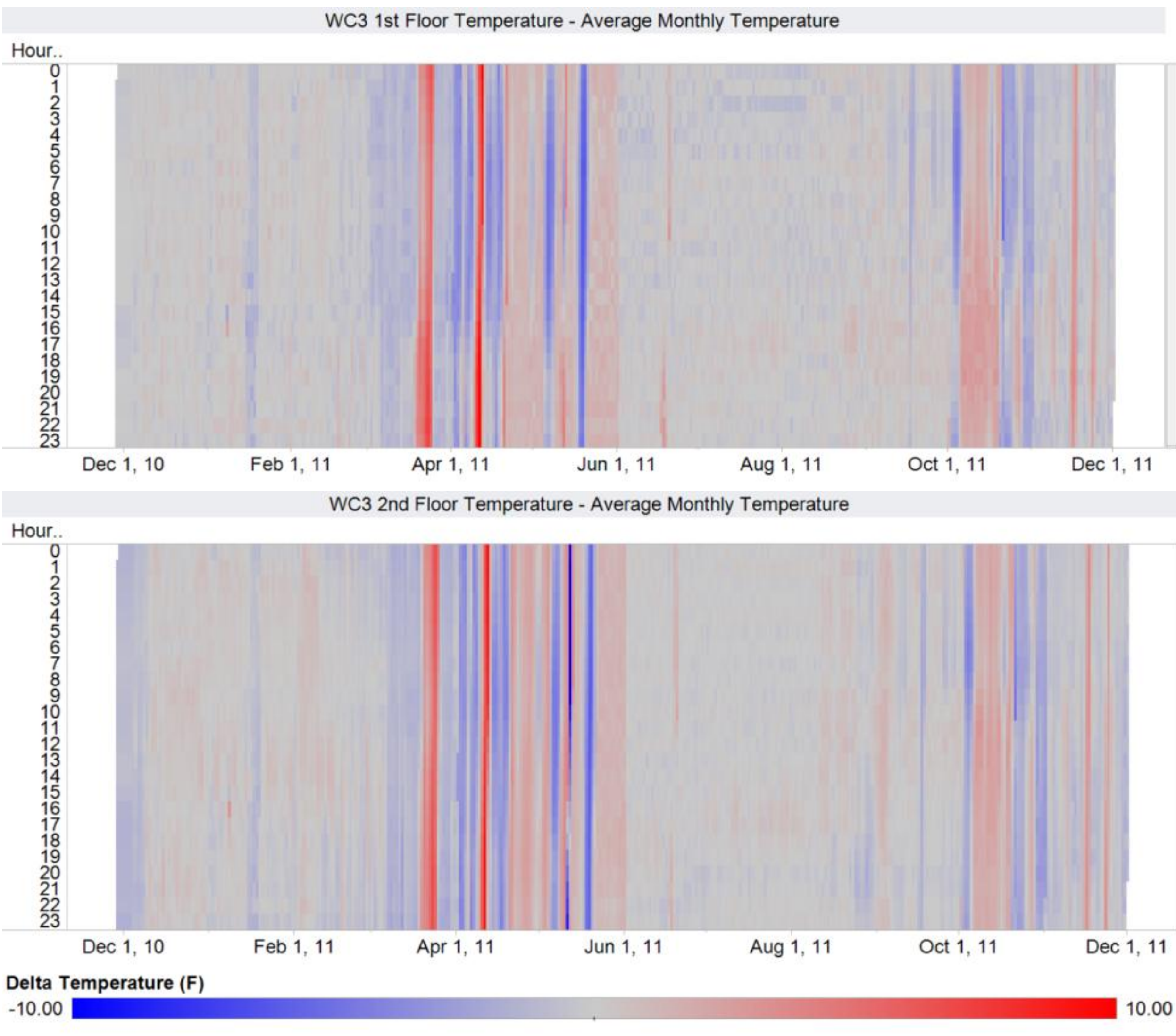


Figure 1. Hourly variation of the WC3 first and second floor temperatures from the monthly averages.

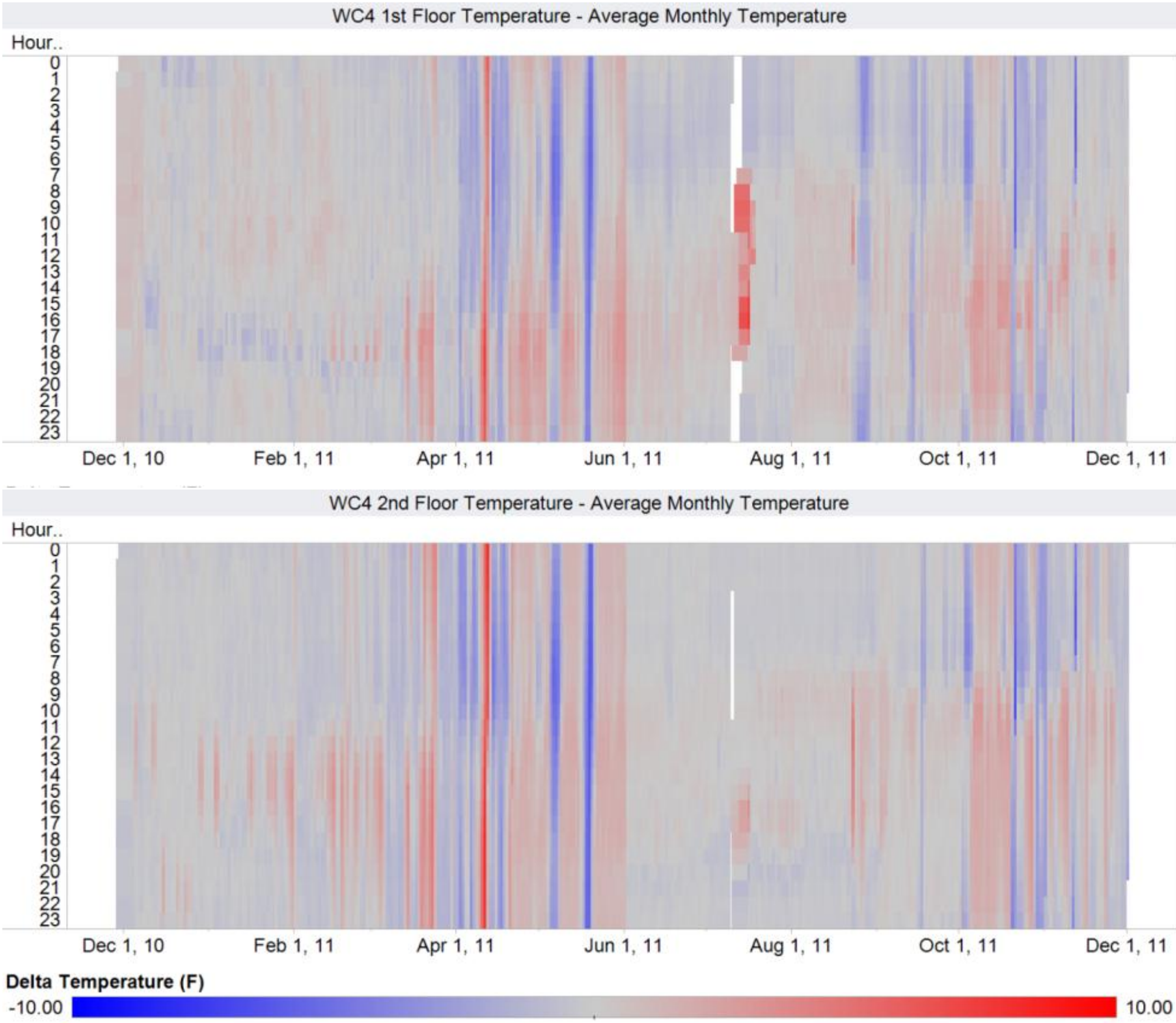


Figure 2. Hourly variation of the WC4 first and second floor temperatures from the monthly averages.

The plots show the differences between the hourly temperatures and the monthly averages in the different zones of the two houses. This view yields a qualitative look at the hourly and daily temperature fluctuations throughout the year. The white spaces in the WC4 plots around July, 2011 resulted from missing data due to faults in the sensors. For most of the time during the monitoring period, the temperatures in both zones of the test houses were held very close to the monthly averages, indicated by the large 'grey' patches in the plots. Major deviations from the mean temperatures were seen primarily during the shoulder months of April and October, when switching of the space conditioning mode and the set points took place. Some deviations were also observed during May. During the peak heating and cooling months, the heat pumps were very effective in maintaining the indoor temperatures close to the thermostat set points, as evidenced by Table 3, Figure 1 and Figure 2.

2.3 ANNUAL CORRECTED ENERGY USAGE DATA

Figure 3 shows the dashboard for a full year of performance from December 1, 2010 to November 30, 2011, comparing the energy consumptions of BSH, WC3 and WC4. The most important performance details can be ascertained from a quick scan of this figure containing concentrated data. The BSH energy usage values were generated by an EnergyGauge model. Complete details of the BSH model are provided in chapter 6. Individual monthly dashboards from December 2010 to November 2011 are shown in Appendix A.

The total annual energy consumptions of BSH, WC3 and WC4 were 25,860 kWh (simulated), 12,658 kWh and 12,605 kWh, respectively; resulting in savings of about 51% for both WC3 and WC4. The pie charts in Figure 3 show the full year energy demands for all the loads in each house. Bar charts are provided to quickly compare energy uses by the heat pumps (space conditioning), lights, plug loads, water heating, washer/dryer combo, refrigerator, dishwasher and range. In BSH, the space heating and cooling energy consumptions made up 38 and 16%, respectively, of the total energy use. WC3 heating and cooling energy consumptions were similar to each other, at 18 and 16% of the total. In WC4, the heating energy consumption was the largest fraction of the total, with 28%; the cooling energy consumption was relatively lower at 13% of the total.

Dashboard Report

12/1/10 to 11/30/11

House	Total[1]	Cost	PeakHr[1]	Average[1]	Ld Factor
BSH	25,860	$2,618.47			
WC3	12,658	$1,343.76	7.374	1.499	0.203
WC4	12,605	$1,337.26	7.912	1.556	0.197

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	48.95%	51.32%	1/15/11	1/14/11	9:00
WC4	48.74%	51.07%	1/15/11	12/15/10	20:00

[1] Energy in kWh throughout unless otherwise noted.

Figure 3. Annual dashboard from December 1, 2010 to November 30, 2011; blue bar = BSH, red = WC3, and green = WC4; units are kWh unless noted otherwise.

In WC3, the ground source water-to-air heat pump (GSHP or WAHP) has a performance advantage for heating due to its favorable entering water temperature (EWT) compared to the outdoor air temperature in winter. The performance of the air source heat pump (ASHP) is dependent on the outside air temperature (OAT) and loses significant capacity as the OAT drops, which requires it to use auxiliary strip heat to make up for lost HP capacity. At temperatures below 40°F, it also needed to defrost the outdoor coil periodically, which requires running the vapor compression cycle in reverse (taking heat from the house and putting it outside). In order to compensate for the heat being removed by the indoor coil, strip heat is also run during defrost cycles. The GSHP also has the advantage, in winter, of having its compressor located in the conditioned space. Any heat loss from the compressor goes towards heating the house. For cooling in summer, the GSHP must reject the heat load of the house as well as the heat load of the compressor to the ground loop. The EWT for WC3 is not as favorable during the summer when compared to the average outside air temperature (OAT) for the ASHP in WC4. These factors are reflected in the higher heating and lower cooling energy consumptions in WC4.

According to Table 2, the number of HDDs and CDDs between the actual evaluation period and a typical TMY3 year were different. To get a better comparison between the BSH model and WC3 and WC4, the heating and cooling energy usages of the BSH model were adjusted to the actual HDDs and CDDs between December 2010 and November 2011. This was done by applying 'least squares' linear regression model to the simulated BSH heating and cooling energy as functions of the TMY3 monthly HDDs and CDDs, respectively. Then the adjusted BSH space conditioning energy consumptions were calculated using the 'best fit' regression function and the actual HDDs and CDDs. Figure 4 shows the regression functions and Table 4 lists the adjusted BSH space conditioning energy consumptions.

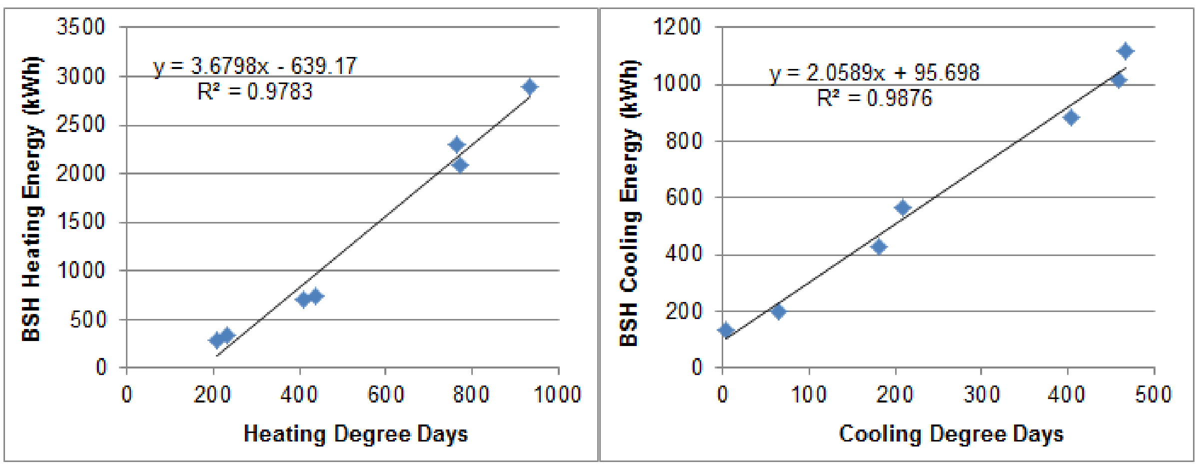


Figure 4. 'Least squares' regression functions for the BSH space conditioning energy.

Table 4. Adjusted heating and cooling energy consumptions for the BSH model

	HDDs at 65°F		Heating Energy (kWh)		CDDs at 65°F		Cooling Energy (kWh)	
	TMY3	Actual	TMY3	Adjusted	TMY3	Actual	TMY3	Adjusted
Dec-10	772	1008	2098	3070	0	0		
Jan-11	932	922	2894	2754	0	0		
Feb-11	765	585	2293	1513	0	2		
Mar-11	437	434	746	958	0	26		
Apr-11	232	184	336	38	65	107	198	316
May-11	94	114			182	191	430	489
Jun-11	0	2			403	346	886	808
Jul-11	0	0			466	464	1117	1051
Aug-11	0	5			459	423	1015	967
Sep-11	0	54			209	147	567	398
Oct-11	211	304	284	479	4	47	138	192
Nov-11	410	439	713	976	0	4		

Water heating energy was 13, 11 and 9% of the total in BSH, WC3 and WC4, respectively. In WC4, the water heater consumption was adjusted to reflect the energy usage if the water heater had been on heat pump mode throughout the year. Since the HPWH in WC4 draws heat from the conditioned space, it also negatively impacts the winter heating load and positively impacts the summer cooling load.

The annual plug loads were 21% of the total in WC3, representing the largest fraction of the total energy usage; in WC4, the plug loads made up 20 % of the total. Lighting energy consumption was higher in WC3, accounting for 7% of the total, compared to 4% in WC4. The washer and dryer combined for 7% of the total in both WC3 and WC4. The refrigerator consumed 4% of the total energy in WC3 and WC4, and the dishwasher energy was 2%. The range was not operated in either WC3 or WC4.

Also included in the WC4 total annual consumption is the energy consumed in dehumidifying the crawlspace at different times of the year. The dehumidifier was set to run on auto mode from April 29, 2011, with a relative humidity (RH) setting of 60%. With the 60% RH setting, the dehumidifier was consuming nearly 3 kWh per day. To reduce the energy consumption the RH setting was raised to 70% and was monitored for a few days, but there was no substantial reduction in the energy usage. The dehumidifier was subsequently turned off and unplugged on May 24, 2011. The RH levels were observed to rise and stabilize at just below 60%, which was deemed low enough not to cause any moisture-related problems. The dehumidifier was again turned on twice between July and September, 2011 for about three days each, after periods of heavy rainfall caused the crawlspace RH to rise above 70%.

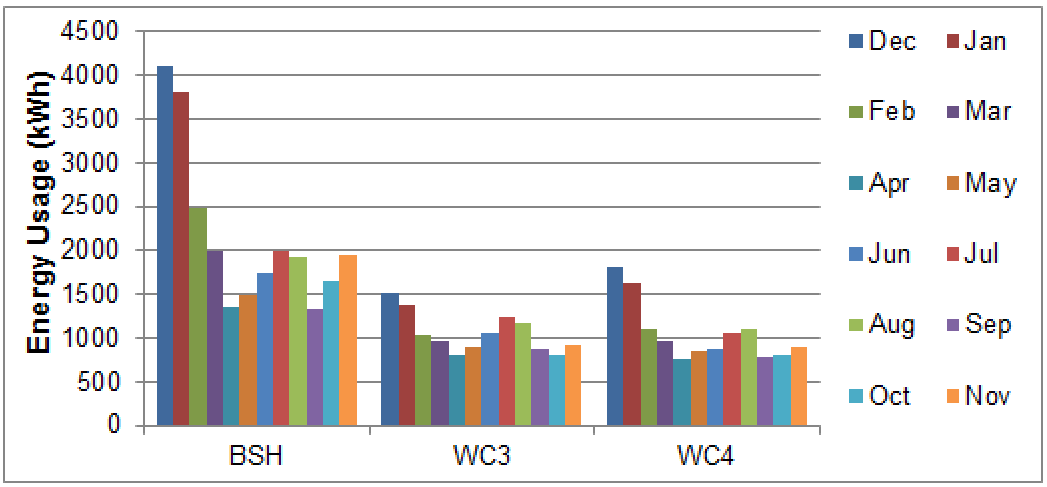


Figure 5. Whole house monthly kilowatt-hour comparisons from December 2010 to November 2011.

The whole house monthly energy usage for each house is shown in Figure 5. The energy usage was highest during the coldest months (December 2010 and January 2011) of the evaluation period for all houses, and showed secondary peaks during the hottest summer months (July and August, 2011).

The monthly heat pump, water heater, lighting, and plug load energy usage in all three houses are shown in Table 5. On an annual basis, the space conditioning energy usage (heat pump) in WC3 and WC4 were 63-69% lower than the simulated BSH heat pump energy. The water heating energy usage was lower in WC3 and WC4 by 60-68% compared to BSH.

There was a major difference in lighting loads, with WC3 consuming about 90% higher than WC4. WC3 is equipped with 100 CFLs compared to LEDs in WC4. Willmorth et al. (2010) reported similar system efficacies for CFL downlights and LED modules, 35 and 30 lumens/W, respectively. However, the WC3 CFL downlights consumed about 20 W, compared to 4.5 W by the LED modules in WC4.

Table 5. Monthly kWh for the heat pumps, water heating, lights, and plug loads

	Heat Pump			Water Heater			Lights			Plugs		
	BSH	WC3	WC4	BSH	WC3	WC4	BSH	WC3	WC4	BSH	WC3	WC4
Dec-10	3070	765	1202	320	156	97	223	84	31	292	221	210
Jan-11	2754	626	1008	339	152	108	223	85	30	292	217	204
Feb-11	1513	370	536	309	139	98	202	82	30	264	192	184
Mar-11	958	213	310	330	144	110	223	88	44	292	214	203
Apr-11	354	126	132	298	117	101	216	67	35	283	203	193
May-11	489	214	151	281	106	91	223	72	36	292	212	199
Jun-11	808	400	285	246	88	79	216	72	36	283	203	188
Jul-11	1051	587	445	237	81	76	223	82	52	292	207	171
Aug-11	967	539	476	233	78	79	223	79	51	292	223	217
Sep-11	398	213	173	236	91	74	216	64	40	283	231	231
Oct-11	672	121	153	266	102	85	223	67	33	292	245	242
Nov-11	976	158	251	284	116	90	216	73	35	283	236	231
Sum	14010	4331	5121	3379	1370	1088	2627	915	455	3440	2603	2473
% Savings		69.1	63.4		59.5	67.8		65.2	82.7		24.3	28.1

Table 6 shows the monthly energy use of the refrigerator, dishwasher, clothes washer and dryer, which are all Energy Star rated appliances. Annually, the refrigerators in WC3 and WC4 used about 35% less energy than BSH. The dishwashers were first programmed to run six times a week, but were later re-programmed to run 4 times a week during July 2011, per the BA Research Benchmark Definition. This is reflected in the dishwasher energy consumption. The clothes washer mode setting was changed from "Normal" to "Heavy Duty" from March to July 2011, resulting in higher energy usage during that period. Dryer energy consumptions in WC3 and WC4 were about 10% less than BSH due to the front loading clothes washers' ability to spin out more water, allowing in shorter dry times than BSH.

Table 6. Monthly kWh for the refrigerator, dishwasher, range, and clothes washer and dryer

	Refrigerater			Dishwasher			Washer			Dryer		
	BSH	WC3	WC4	BSH	WC3	WC4	BSH	WC3	WC4	BSH	WC3	WC4
Dec-10	66	39	39	15	23	23	9	5	5	76	62	59
Jan-11	66	40	39	15	23	23	9	5	5	76	69	69
Feb-11	60	37	35	14	20	20	8	5	6	68	58	58
Mar-11	66	41	40	15	21	21	9	13	13	76	69	68
Apr-11	64	41	40	15	19	19	9	12	13	73	72	70
May-11	66	43	42	15	21	22	9	12	13	76	73	69
Jun-11	64	45	46	15	20	20	9	12	13	73	68	68
Jul-11	66	46	47	15	13	15	9	10	10	76	75	73
Aug-11	66	47	45	15	13	13	9	8	9	76	54	69
Sep-11	64	43	43	15	14	14	9	7	10	73	60	61
Oct-11	66	41	42	15	14	13	9	6	9	76	68	67
Nov-11	64	38	39	15	15	9	9	6	6	73	75	66
Sum	778	500	497	179	217	212	107	100	111	892	802	798
% Savings		35.7	36.1		-21.4	-18.6		6.4	-3.3		10.1	10.6

The data shown in this section, and the rest of the report, were corrected for errors due to data acquisition system, equipment failures and errors in the simulated occupancy protocols. In addition, there were intentional changes made to the occupancy simulation to test their impacts on the house and appliance energy consumptions.

One major change involved the periodic switching of the water heater in WC4 between the heat pump mode and the standard electric resistance mode. This not only impacted the water heater energy consumption, but also the space conditioning load since the heat pump water heater (HPWH) resides inside the conditioned space. When heat pump mode was used it pulled heat from the conditioned space, which is the heat source for the evaporator of the vapor-compression cycle, resulting in a net heat loss from conditioned space (also accounting for the heat loss from the hot water tank); electric mode resulted in heat addition to the conditioned space due to losses from the hot water in the tank. Therefore, corrections were made to both water heater and space conditioning energy consumptions, as explained in chapter 3.

2.4 ENERGY COSTS

Table 7 shows the monthly utility rates during the evaluation period, which were used to generate the costs shown in annual dashboard (Figure 1) and subsequent sections of this report. The monthly costs also took into account monthly hookup fees ('Customer Charge').

Table 7. Monthly residential utility rates in Oak Ridge, TN

	Utility rate ($/kWh)	Customer Charge ($)
Dec-10	0.09548	9.70
Jan-11	0.09625	9.70
Feb-11	0.09505	9.70
Mar-11	0.09694	9.70
Apr-11	0.09600	9.70
May-11	0.09569	9.70
Jun-11	0.09589	9.70
Jul-11	0.09935	9.70
Aug-11	0.09991	9.70
Sep-11	0.09908	9.70
Oct-11	0.09727	9.70
Nov-11	0.09670	9.70

The monthly energy costs for each house are shown in Figure 6, and were calculated using data from Table 7. The full year energy cost for BSH was $2590. In comparison, the energy costs of WC3 and WC4 were $1344 and $1337, respectively. All the cost estimates were obtained after correcting the monthly data for any errors and changes in simulated occupancy protocols.

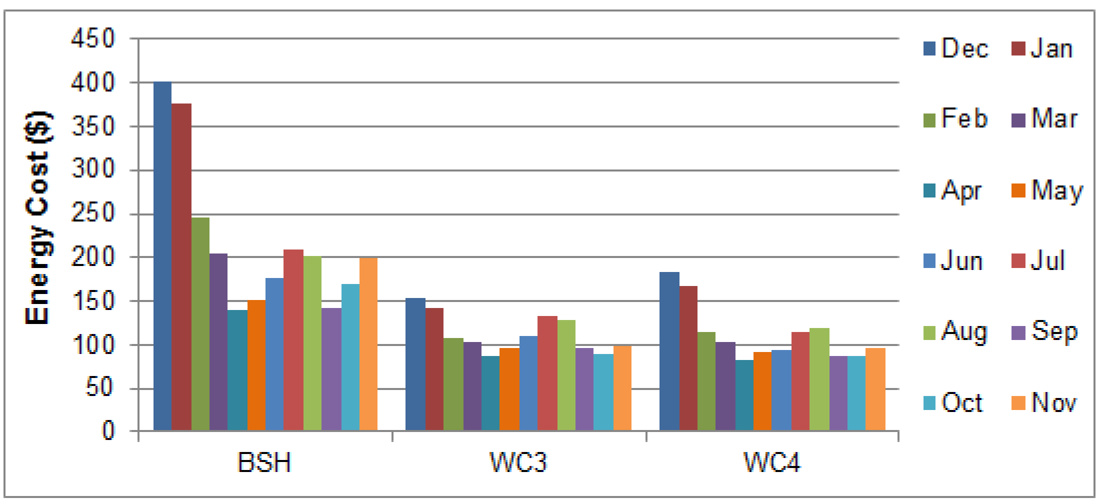


Figure 6. Monthly energy cost for each house, December 2010 – November 2011.

A well-built, typical, “Builder Spec,” new, all-electric, 2512 ft^2 home built in the 2000–2010 time frame in the TVA service territory with average internal homeowner energy usage patterns has daily energy costs of around $5 (Christian et al., 2010). In comparison, with simulated occupancy, the two 2721 ft^2 Wolf Creek houses cost about $3.70 per day in energy use.

2.5 PEAK DEMAND AND AVERAGE DAILY PROFILES

The energy sub metering is collecting watt-hours in 15-minute intervals. Summing the four 15 minute intervals yields the average hourly wattage and can be used to identify the peak wattage each month. Figure 7 shows the hourly WC3 whole house energy for the whole reporting period. This view yields a qualitative look at the daily peak hours as they vary throughout the year.

First, the large energy peaks during December 2010 and January 2011 should be noted. During this time the WWHP was operating in electric resistance mode and caused the daily local peaks. The largest hot water draws programmed into the occupancy simulation profile are observed at 8 AM (20 gallons), 6 PM (10 gallons) and 10 PM (20 gallons). These hot water draws are reflected in the water heater and the whole house energy consumptions. Beyond January 2011, these water heater energy peaks show up as local maxima on some days and global maxima on other days. The local maxima are peaks at various hours of the day, but not the peak during the 24-hour period; global maxima are the highest hourly peaks during the day. Also to be noted are the cyclic peaks at the 11 AM and 8 PM hours. These peaks were caused by the dryer operation. On days when the dryer (8 PM on Wednesday, 11 AM and 1PM on Saturday and Sunday) was operated, the global peak typically occurred during those times.

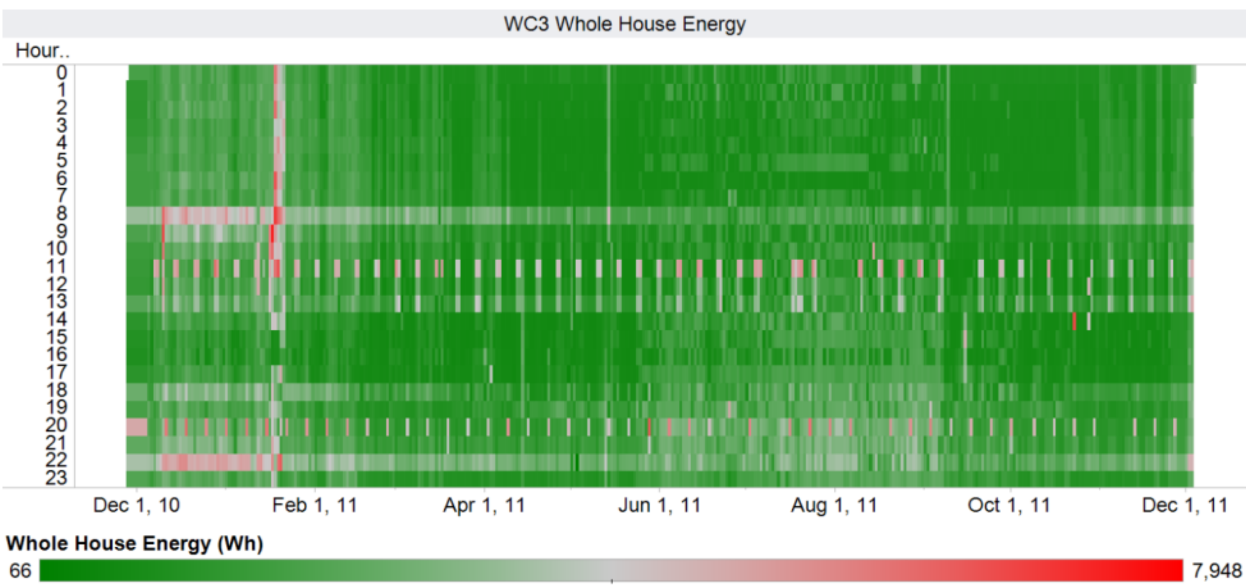


Figure 7. WC3 hourly energy usage profile during the 12-month evaluation period.

Figure 8 and Figure 9 show the whole house energy in WC4 with and without the water heater (HPWH) energy consumption. Similar to WC3, the water heater energy usage can be seen in the peaks at the 8 AM and 10 PM hours. Unlike WC3, however, there is a cyclic nature of the energy usage at these hours throughout the year. This is due to the HPWH being run in resistance mode almost every other week for performance testing. The heat pump water heater energy was subtracted from the whole house energy for investigating peaks without the water heating energy, especially when it was in resistance mode. Similar patterns to WC3 are observed as the two homes are controlled using the same occupancy protocols.

Notice, though, that more energy was consumed in the winter months in early 2011, which was not due to water heating. This was the added space conditioning energy usage due to relatively poorer performance of the ASHP in WC4 compared to the GSHP in WC3 during winter months.

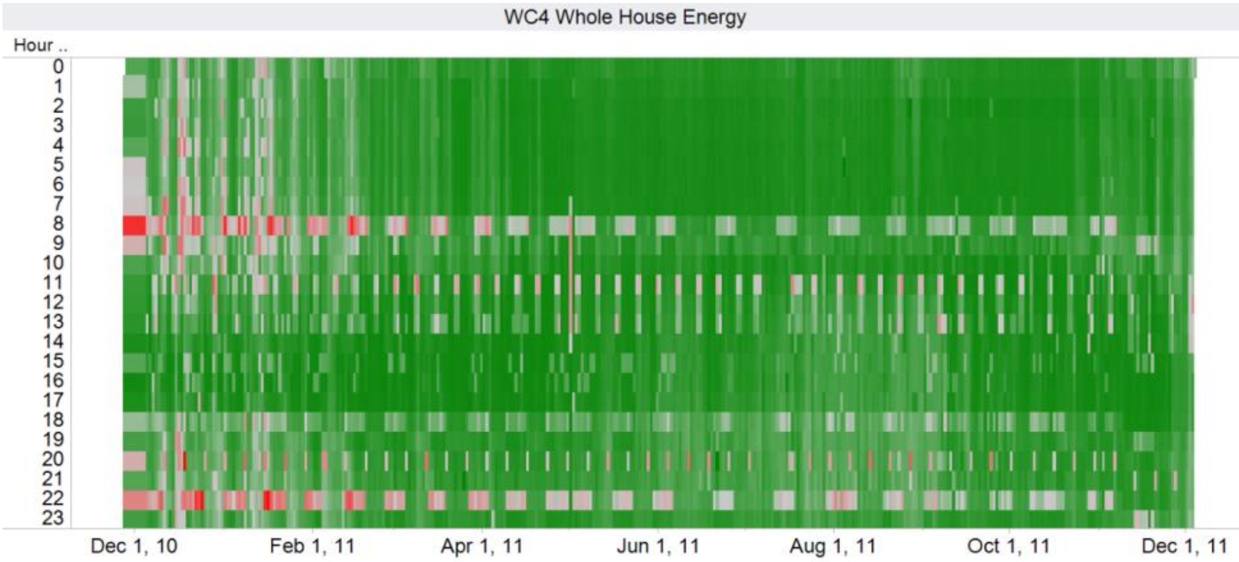


Figure 8. WC4 hourly energy usage profile during the 12-month evaluation period.

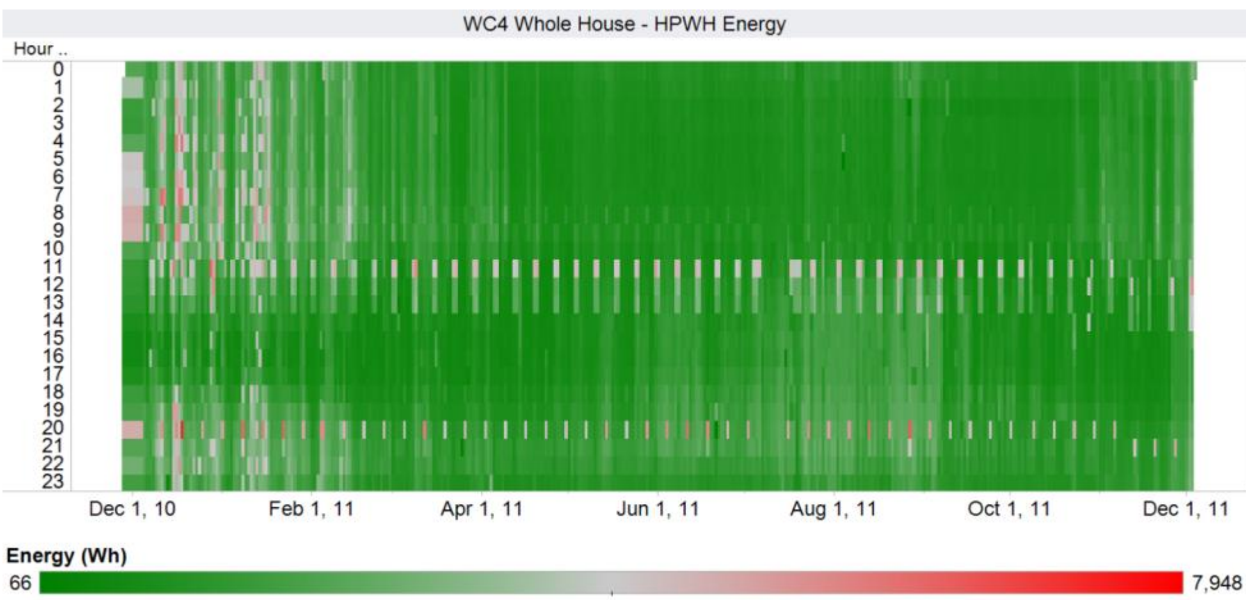


Figure 9. WC4 hourly energy usage profile, without the heat pump water heater, during the 12-month evaluation period.

3. ENERGY USE BREAKDOWNS

This section provides the comparative energy performance of each of the major systems in all three houses for each month from December 2010 until November 2011. The systems covered are heat pump, lights, plug loads, water heater, washer and dryer, refrigerator, dishwasher, and range. The plug load protocols and the appliances operation were designed to be identical in WC3 and WC4, and their energy consumptions were expected to be very similar. This was the case in most months, barring some control related issues. The discussion below also addresses how the raw data were corrected for errors and changes in simulated occupancy protocols.

3.1 DECEMBER 2010

Figure 10 shows a series of bar charts that compare the major energy systems total usage for all three houses in December 2010. All zones in the three houses were kept at 71°F, and the thermostats were in heating mode. The heat pump in WC3 consumed 765 kWh, while the consumption was significantly higher in WC4 (1202 kWh). As explained earlier, the performance of the ASHP in WC4 suffers due to the cold outside temperatures in the heating season.

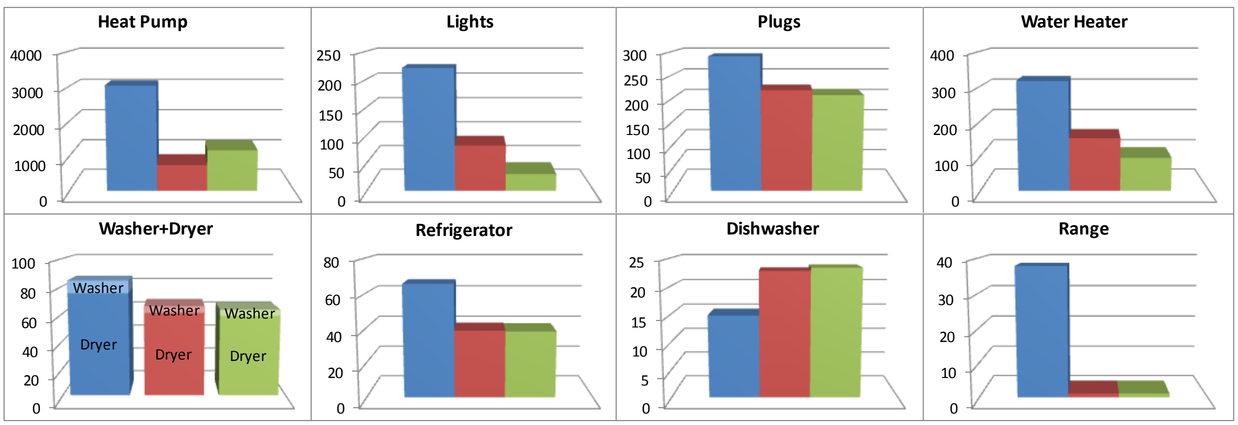


Figure 10. December 2010 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In addition, the water heater in WC4 was on electric resistance mode for 17 days during December and the heating was adjusted to reflect the effect of running the water heater in heat pump mode only. The water heater heat pump draws heat from the conditioned space and the hot water tank loses heat to the conditioned space. The "corrected" heating energy usage ($HP_{Heat,\ Corr}$) of the ASHP was calculated as:

$$HP_{Heat,Corr} = HP + \frac{(Q_{HP}+Q_{Resis})}{COP} * N_{Resis,Heat} \qquad (3.1)$$

In Eqn. (3.1), *HP* is the measured ASHP consumption, Q_{HP} is the net heat transfer per day from the water heater in the heat pump mode, Q_{Resis} is the heat transfer per day from the water heater in the resistance mode, $N_{Resis,Heat}$ is the number of days when the water heater was in resistance mode (with the thermostat on heating mode), and *COP* is the measured coefficient of performance of the ASHP. The Q_{HP} was added to the ASHP heating energy use since this is the energy that should have been removed from the conditioned space and would have increased the heating load. Q_{Resis} was added to conditioned space while the water heater was on resistance mode, reducing the ASHP heating energy use. But that would not have been the case if the water heater was on heat pump mode throughout, therefore, it also was added to heating load of the house.

The heat transfer terms (Q) were calculated using the following energy balance:

$$Q + W_{Electric} + \dot{m} * c_p * (T_{in} - T_{out}) = 0 \qquad (3.2)$$

$W_{Electric}$ is the energy consumed by the water heater, $\dot{m}$ is the measured water flow rate, c_p is the specific heat of water, and T_{in} and T_{out} are the entering and leaving water temperatures.

Figure 11 compares the heat pump energy usages of WC3 and WC4 for the coldest month in the reporting period along with the outdoor air temperature. The WC4 heat pump had higher energy peaks during early mornings compared to the WC3 heat pump. The hourly consumption of the heat pump in WC4 approached 5.5 kWh while the heat pump consumption in WC3 did not rise above 2 kWh.

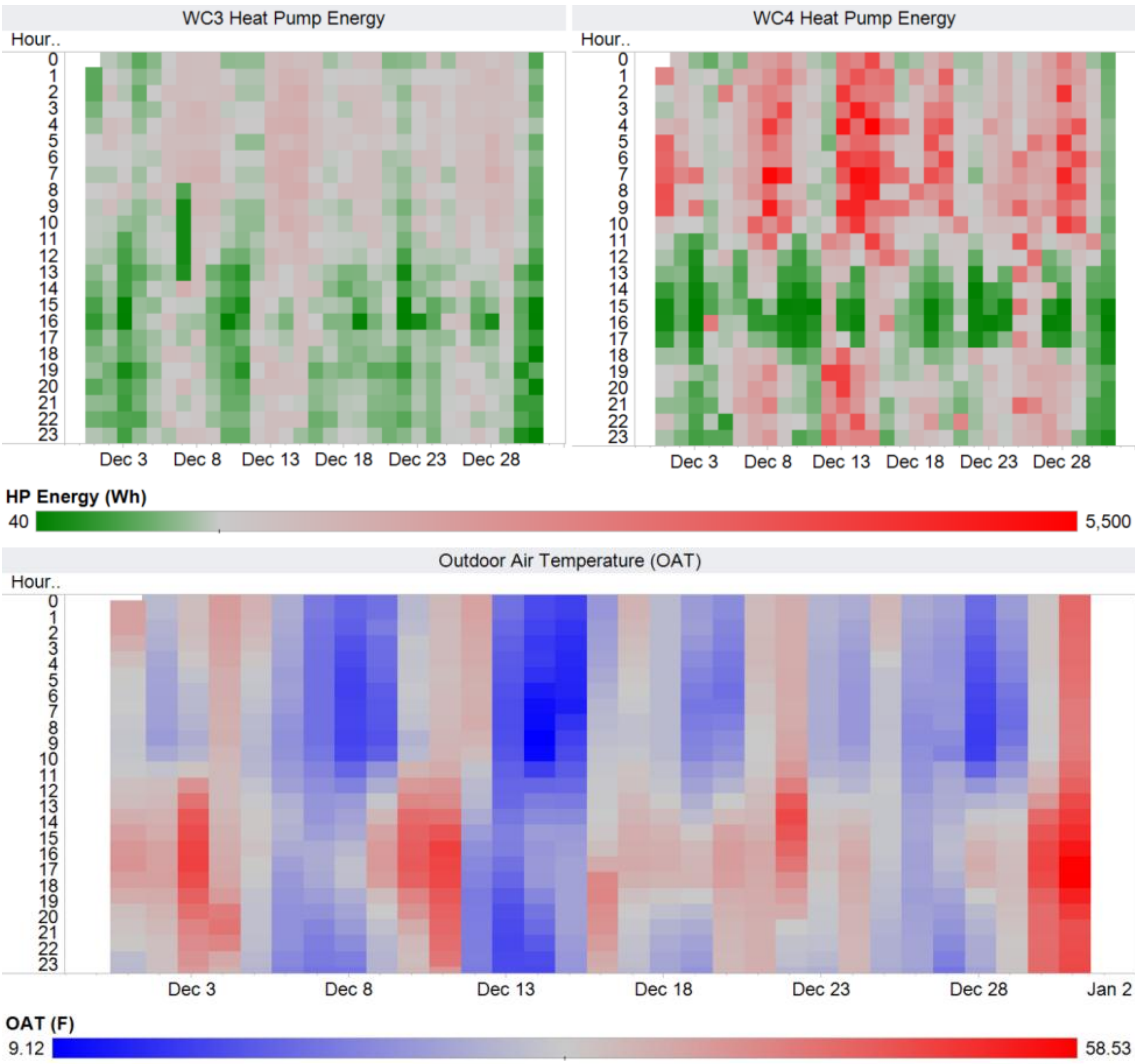


Figure 11. December 2010 heat pump operation in WC3 and WC4, with outdoor air temperatures.

Starting December 7, the water heater in WC3 was also on resistance heating for the remainder of the month. The water energy consumptions in both WC3 and WC4 were adjusted to simulate operation in heat pump mode only. This was done by measuring the water heater consumption and amount of hot water delivered on the days in the heat pump mode and extrapolating the values for the entire month. WC3 and WC4 had estimated water heater energy consumptions 51% and 70% less than BSH (320 kWh).

The LED lighting energy consumption in WC4 (31 kWh) was lower than WC3 with 100% CFLs (84 kWh). The plug loads, as expected, were similar between WC3 (221 kWh) and WC4 (210 kWh). The washer and dryer in WC3 and WC4 consumed 67 and 64 kWh. The refrigerator energy consumption was 39 kWh for both WC3 and WC4. The dishwasher consumed 23 kWh in WC3 and WC4. There is no range control in WC3 and WC4, therefore the measured energy usage was negligible in those houses.

3.2 JANUARY 2011

Figure 12 shows a series of bar charts comparing the major energy systems in January 2011. The heat pump energy consumption was 626 kWh in WC3 and 1008 kWh in WC4. The ASHP performance again suffered due to very cold outside conditions. The heating energy use in WC3 had to be corrected because a ground loop plumbing issue caused the back-up resistance heater to run instead of the WAHP. The correction was made by calculating the average COP of the WAHP when it was operational during January and applying it to the energy use of the resistance heat when the unit was experiencing the plumbing problem. The heating energy use in WC4 was corrected for the water heater operation in resistance mode, according to Eqn. (3.1).

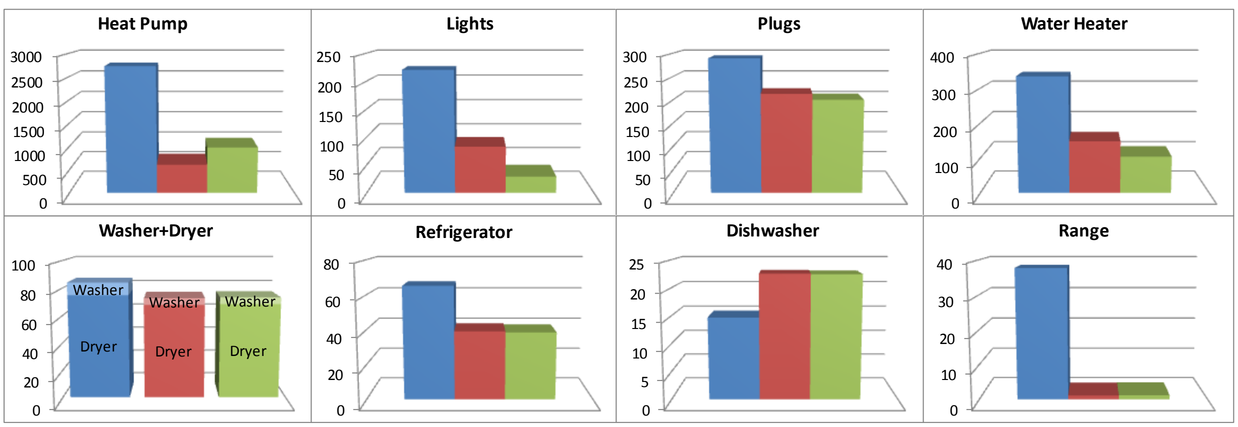


Figure 12. January 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In January, the water heaters in WC3 and WC4 were in the resistance mode for 9 and 19 days, respectively, and the bar chart reflects the corrected values assuming operation in heat pump mode only. The water heater energy usage was 152 and 108 kWh in WC3 and WC4.

3.3 FEBRUARY 2011

Figure 13 shows a series of bar charts comparing the major energy systems in February 2011. The heat pump energy consumption was 370 kWh in WC3 and 536 kWh in WC4. The heating energy use in WC4 was corrected for the water heater operation in resistance mode, according to Eqn. (3.1).

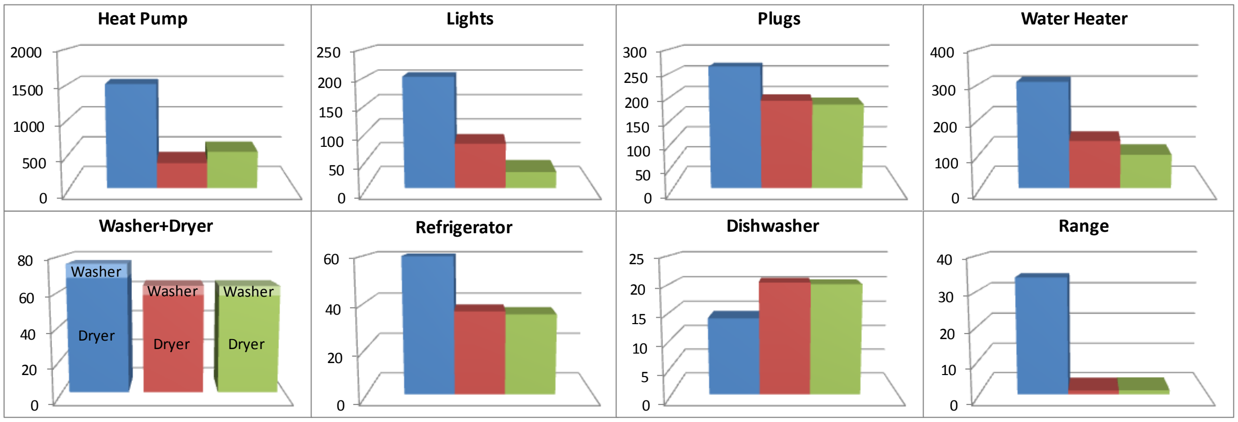


Figure 13. February 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In February, the water heater in WC4 was in the resistance mode for 14 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 139 and 98 kWh in WC3 and WC4.

3.4 MARCH 2011

Figure 14 shows a series of bar charts comparing the major energy systems in March 2011. The heat pump energy consumption was 213 kWh in WC3 and 310 kWh in WC4. The heating energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.1).

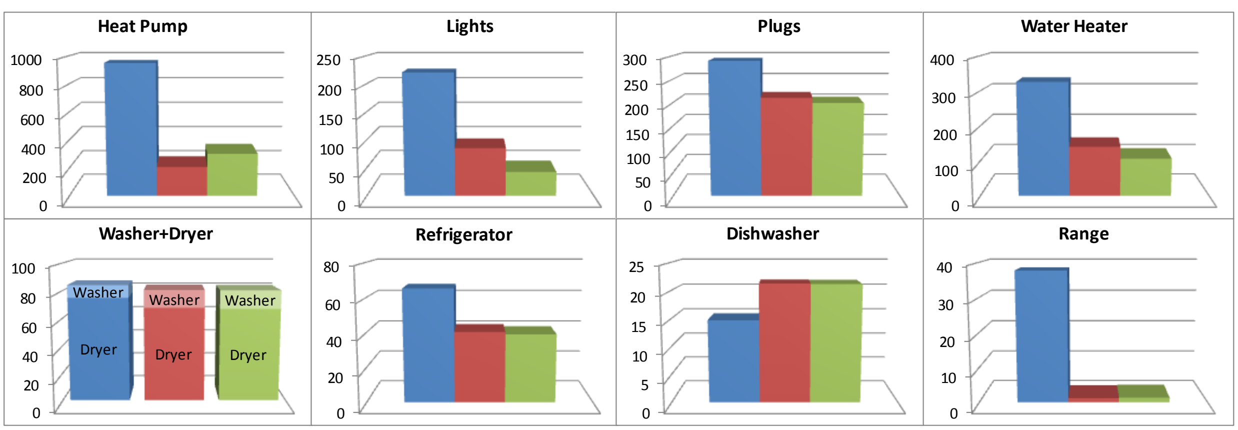


Figure 14. March 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In March, the water heater in WC4 was in resistance mode for 14 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 145 and 110 kWh in WC3 and WC4.

3.5 APRIL 2011

Figure 15 shows a series of bar charts comparing the major energy systems in April 2011. During April, the thermostat modes were changed from heating to cooling; the set points were changed from 71°F to 76ºF. The change was made around April 20, 2011.

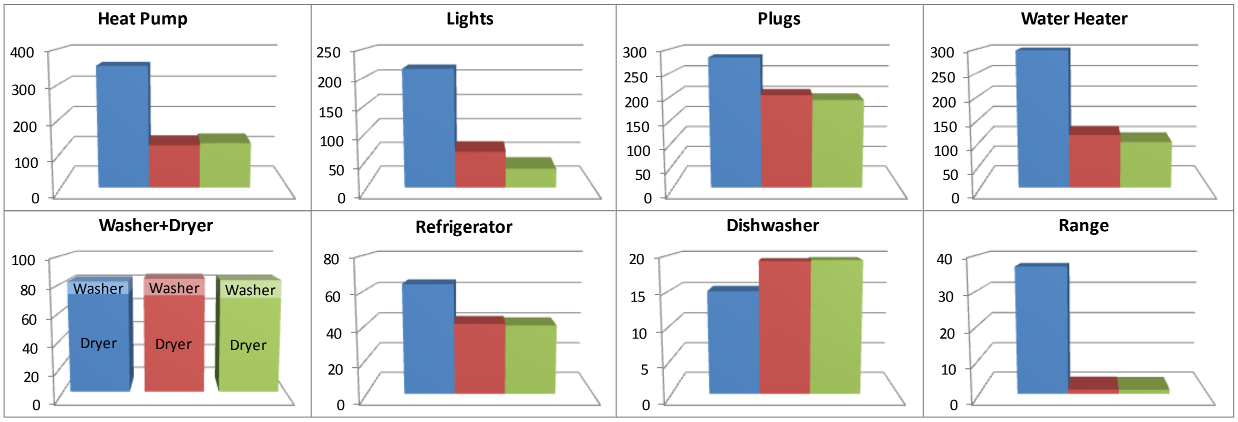


Figure 15. April 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

The heat pump energy consumption, therefore, consists of both heating and cooling loads. The heat pump energy consumptions were 126 kWh in WC3 and 132 kWh in WC4. The heating energy use in WC4 was corrected for water heater operation in resistance mode according to Eqn. (3.1), and the cooling energy use correction was done as follows:

$$HP_{Cool,Corr} = HP - \frac{(Q_{HP}+Q_{Resis})}{COP} \times N_{Resis,Cool} \tag{3.3}$$

Here, $N_{Resis,Cool}$ is the number of days of resistance mode operation of the water heater, coinciding with the days when the thermostat was in cooling mode. For cooling correction, both Q_{HP} and Q_{Resis} are subtracted from the ASHP cooling energy use. Q_{HP} is the energy that should have been removed from the conditioned space, reducing the cooling energy use. Q_{Resis} was added to conditioned space with the water heater on resistance mode, artificially increasing the cooling energy use.

April is a shoulder month with mild ambient temperatures and required minimal space conditioning compared to other months of the year. It was during this time that the thermostat was set from heating to cooling. Around April 11th the thermostat was put into cooling mode and was set to 76°F, because the indoor temperatures were approaching 85°F. A couple days later the thermostat was put back into heating mode. Again, on April 20th the thermostat was set to a 76°F cooling set point. The heat pump energy usages reflect this in both houses, as seen in Figure 16. The peak heat pump energy for WC3 during this month was when the thermostat was switched to cooling mode during April 11th and April 20th. Notice that this peak was not as pronounced in WC4.

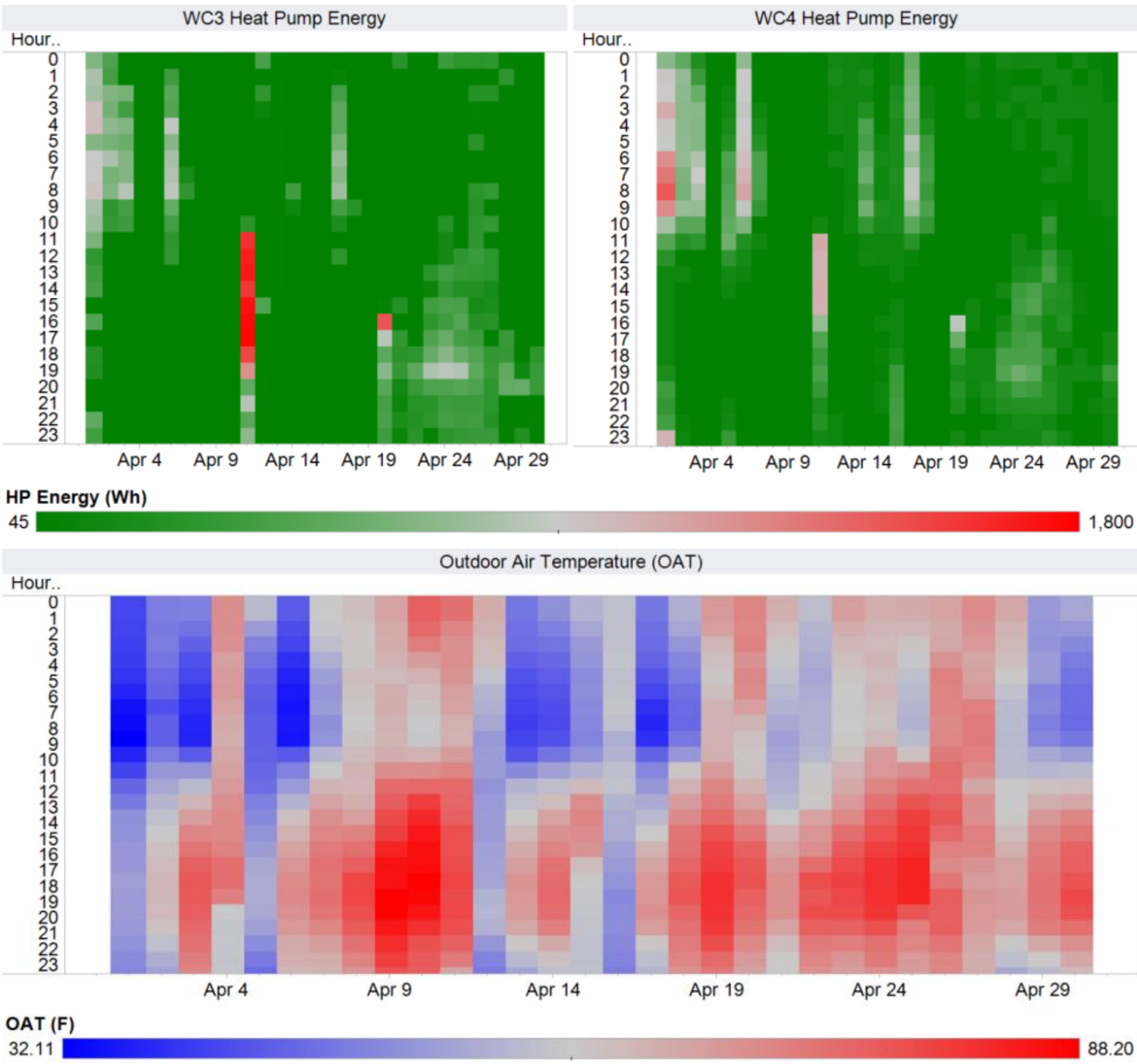


Figure 16. April 2011 heat pump operation in WC3 and WC4, with outdoor air temperatures.

In April, the water heater in WC4 was in resistance mode for 18 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 117 and 101 kWh in WC3 and WC4.

3.6 MAY 2011

Figure 17 shows a series of bar charts comparing the major energy systems in May 2011. The heat pump energy consumption was 214 kWh in WC3 and 151 kWh in WC4. The cooling energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.3).

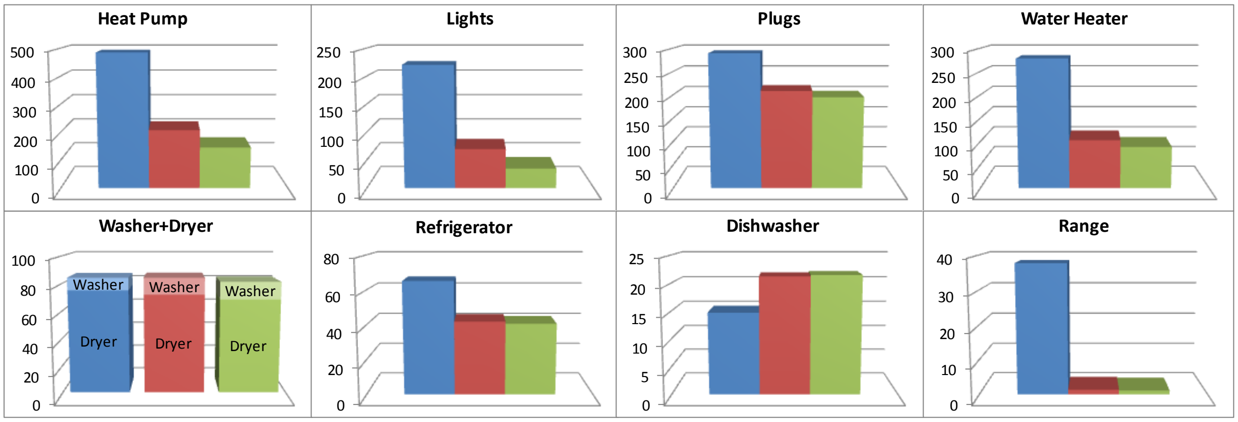


Figure 17. May 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In May, the water heater in WC4 was in resistance mode for 17 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 106 and 91 kWh in WC3 and WC4.

3.7 JUNE 2011

Figure 18 shows a series of bar charts comparing the major energy systems in June 2011. The heat pump energy consumption was 400 kWh in WC3 and 285 kWh in WC4. The cooling energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.3).

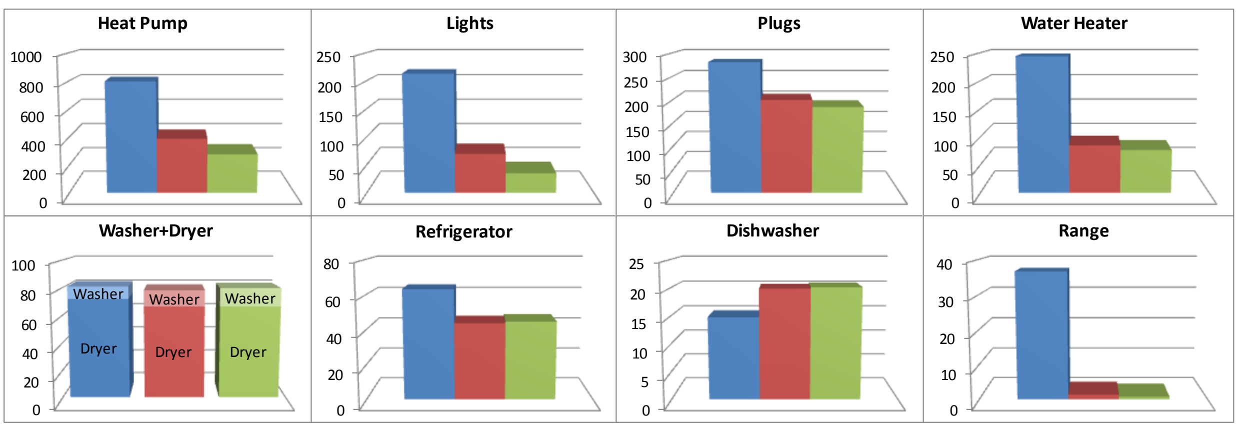


Figure 18. June 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In June, the water heater in WC4 was in resistance mode for 9 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 88 and 79 kWh in WC3 and WC4.

3.8 JULY 2011

Figure 19 shows a series of bar charts comparing the major energy systems in July 2011. The heat pump energy consumption was 587 kWh in WC3 and 445 kWh in WC4. The cooling energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.3).

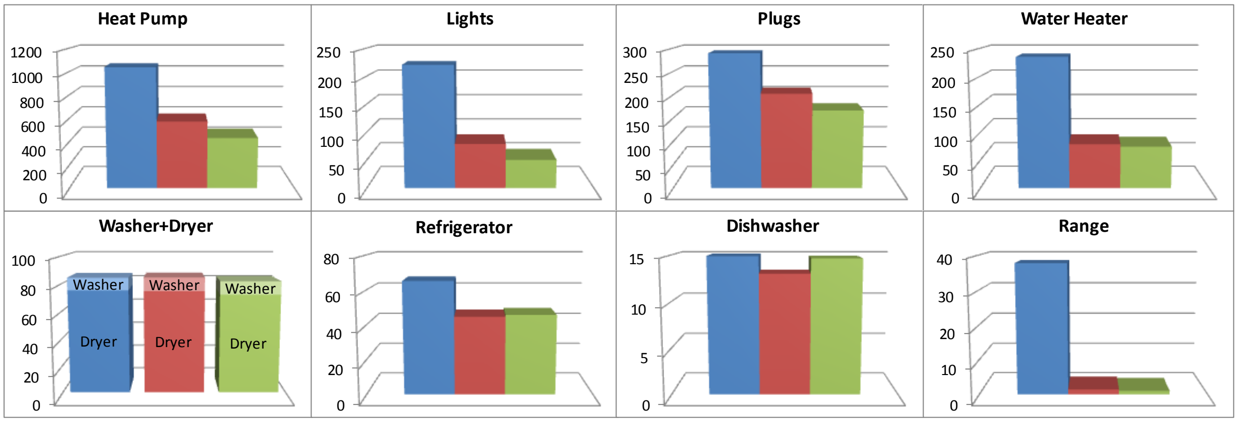


Figure 19. July 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

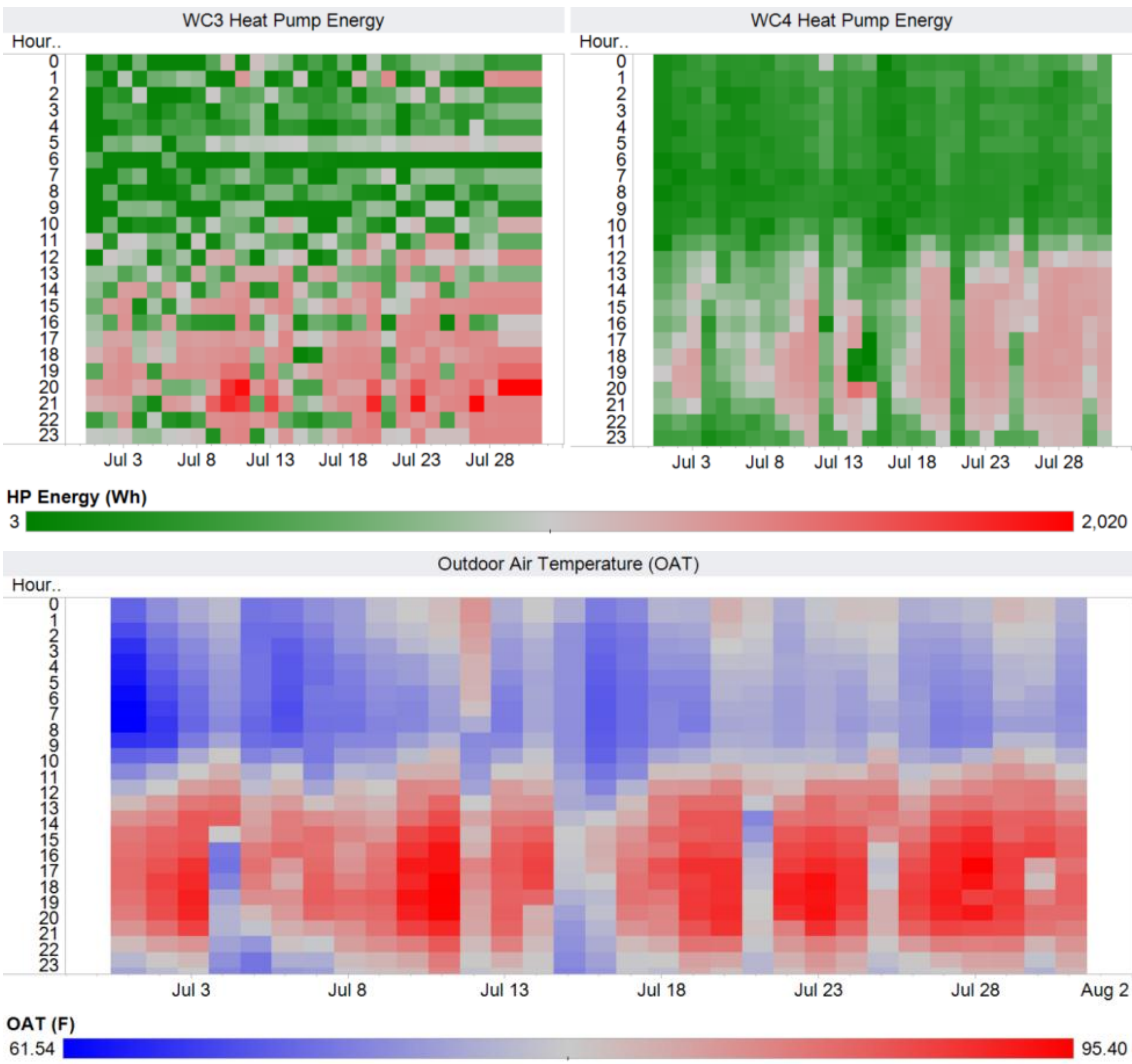


Figure 20. July 2011 heat pump operation in WC3 and WC4, with outdoor air temperatures.

Figure 20 presents the hourly heat pump energy usage and outdoor air temperature during July 2011, the hottest month of the reporting period. Notice that the heat pump energy peaks occurred during the afternoon hours in both homes, as expected. Notice also how the energy peaks were higher in WC3 than in WC4, especially during late afternoons and evenings. This is the opposite of the heating season where the heat pump in WC4 used more overall energy and had higher peak energy during the early morning hours, when the outdoor air temperatures were the lowest.

In July, the water heater in WC4 was in resistance mode for 13 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 81 and 76 kWh in WC3 and WC4.

3.9 AUGUST 2011

Figure 21 shows a series of bar charts comparing the major energy systems in August 2011. The heat pump energy consumption was 539 kWh in WC3 and 476 kWh in WC4. The cooling energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.3).

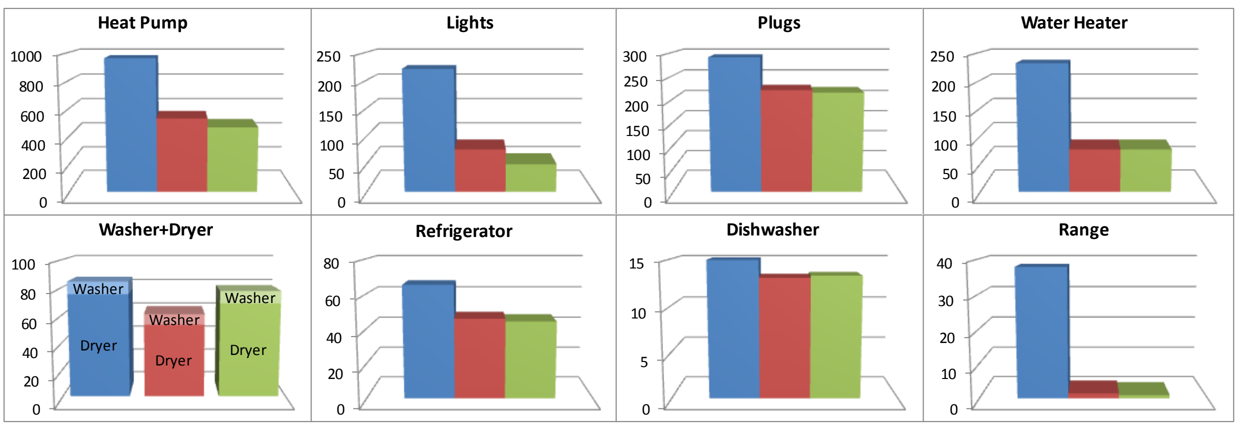


Figure 21. August 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In August, the water heater in WC4 was in resistance mode for 15 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 78 and 79 kWh in WC3 and WC4.

3.10 SEPTEMBER 2011

Figure 22 shows a series of bar charts comparing the major energy systems in September 2011. The heat pump energy consumption was 213 kWh in WC3 and 173 kWh in WC4. The cooling energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.3).

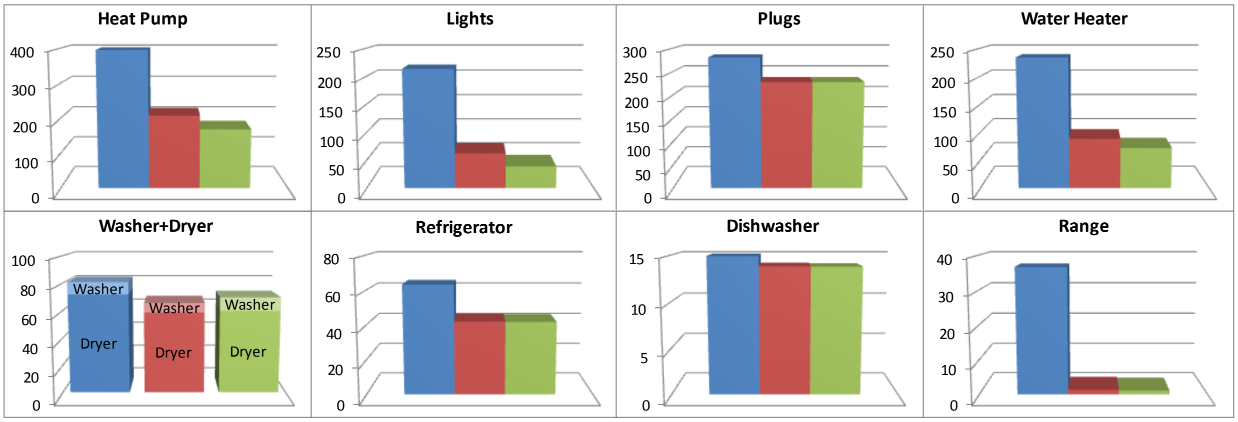


Figure 22. September 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In September, the water heater in WC4 was in resistance mode for 21 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 91 and 74 kWh in WC3 and WC4.

3.11 OCTOBER 2011

Figure 23 shows a series of bar charts comparing the major energy systems in October 2011. During October, the thermostat modes were changed from cooling to heating mode; the set points were changed from 76°F to 71°F. The change was made around October 20, 2011.

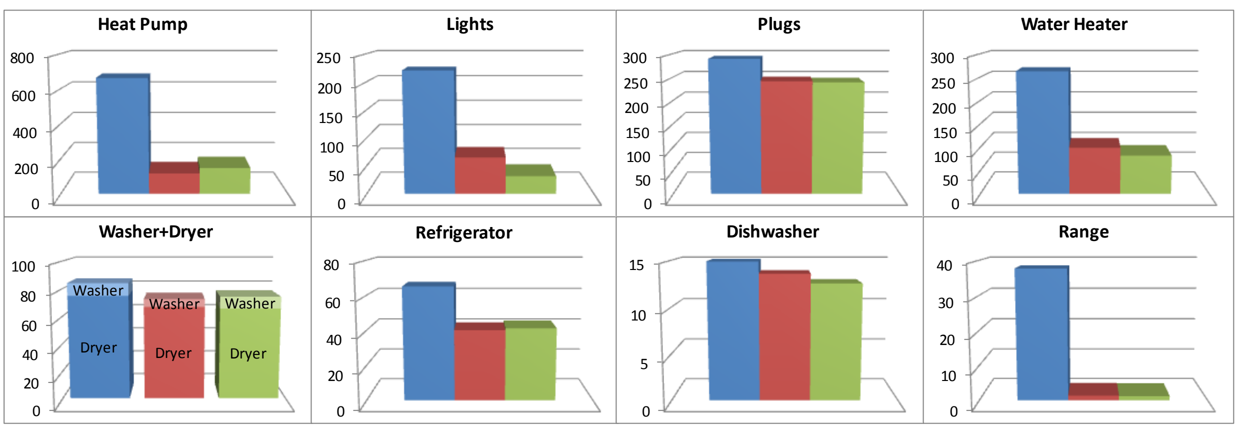


Figure 23. October 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

The heat pump energy consumption, therefore, consists of both heating and cooling loads. The heat pump consumptions were 121 kWh in WC3 and 153 kWh in WC4. The heating and cooling energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqns. (3.1) and (3.3).

In October, the water heater in WC4 was in resistance mode for 21 days and the bar chart reflects the corrected value assuming the operation in heat pump mode only. The energy usage was 102 and 85 kWh in WC3 and WC4.

3.12 NOVEMBER 2011

Figure 24 shows a series of bar charts comparing the major energy systems in November 2011. The heat pump energy consumption was 158 kWh in WC3 and 251 kWh in WC4. The heating energy use in WC4 was corrected for water heater operation in resistance mode, according to Eqn. (3.1).

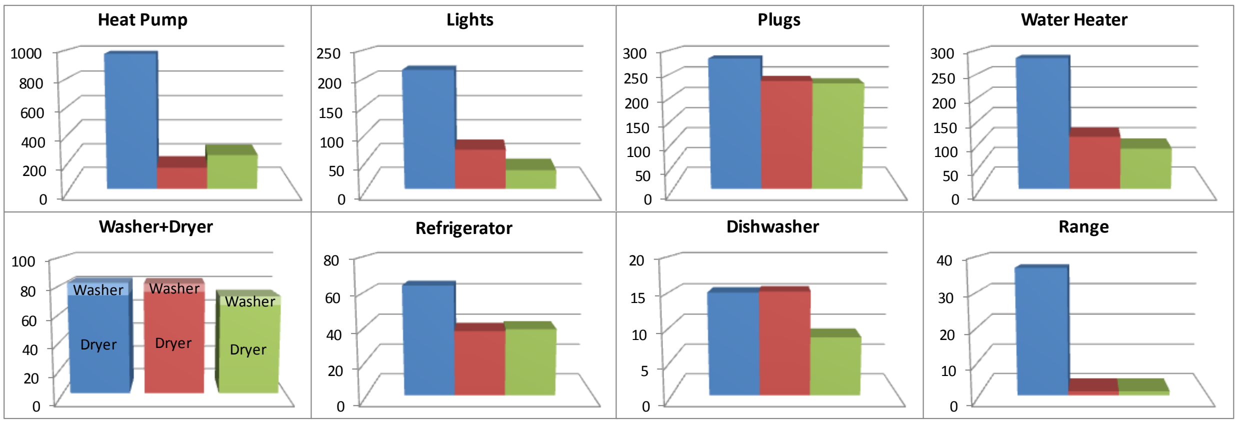


Figure 24. November 2011 comparisons; blue bar = BSH, red = WC3, green = WC4; units are kWh.

In November, the water heater in WC4 was in resistance mode for 9 days and the bar chart reflects the corrected value assuming operation in heat pump mode only. The water heater energy usage was 116 and 90 kWh in BSH, WC3 and WC4.

4. WC3 AND WC4 CONSTRUCTION

4.1 ENVELOPE SPECIFICATIONS

4.1.1 Roof Systems

An infrared reflective (IRR) painted metal shake is installed on WC3. Solar reflectance of the metal shake is 0.34 and its thermal emittance was measured as 0.85 (Miller, 2010). A tapered EPS insulation is inserted under the metal shakes to provide walking support and some resistance (ca. R = 4) to heat transfer across the deck (Figure 25).

Figure 25. Prototype assemblies of WC3 roof (left) and WC4 roof (right).

WC4 has a conventional IRR asphalt shingle roof. Solar reflectance is 0.26 and the thermal emittance of the shingle is 0.88 (Miller, 2010). To mitigate the heat transfer effects of the darker, more heat absorbing shingles, profiled and foil faced 1-in (0.0254-m) EPS insulation was placed over the roof rafters and covered by a foil[*]-faced OSB with the foil facing towards the inclined air space (Figure 25). The assembly provides a radiant barrier facing into the attic plenum, 2 low-e surfaces facing into the inclined 1-in (0.0254-m) air space, and passive ventilation from soffit to ridge. A slot was cut into the roof deck near the eave just above the soffit vent to provide make up air from the soffit vent and attic. As thermally induced airflows move up the inclined air space, cool make up air is pulled from the soffit and attic plenums to enhance thermal performance of the deck. The design puts the air intake of the inclined air space within the enclosure, just above the soffit. A perforated metal soffit vent acts as a fire block to prevent any burning embers from entering the air space.

4.1.2 Attic Systems

WC3 and WC4 were built with conventional attics. WC3 has an OSB deck and the OSB is overlaid with a micro-perforated aluminum foil that faces into the attic. Solar powered gable ventilators were installed on the interior of the attic gables to enhance attic ventilation. At solar noon with clear sky, the fans are designed to induce about 10 air changes per hour from the perforated fiber cement soffit panels and the gable vents. Total soffit and gable-end vent area exceeds the 1:150-code, which mandates that the minimum attic ventilation area be 1/150 of the area of the enclosed attic space.

[*] Thermal emittance of the foils is 0.04 as measured using ASTM C-1371 (ASTM 1997).

Phase change materials (PCMs) were added to the blown fiber insulation on the attic floor of WC3 to absorb the remaining heat that escapes the reflective metal shake roof, the radiant barrier and the solar powered attic ventilation. The attic floor was insulated with 10-in (0.25-m) of regular cellulose insulation and an additional 4-in (0.10-m) of 20% by weight PCM-enhanced cellulose insulation.

A similar arrangement was used for the attic floor of WC4. In addition to the foil faced EPS insulation serving as a radiant barrier (Figure 25, right panel), ceiling insulation of approximately R-50 was included. However, unlike WC3, no PCM was added to the cellulose insulation and R-50 was achieved via increased insulation thickness.

4.1.3 Cladding and Exterior Paint

Plain lap siding and vertical siding are used as the cladding in WC3. A stack stone covers the exposed wall sections from just below grade to the bottom of the 1st floor windows. According to the manufacturer, the siding is composed of a fiber cement material that is fireproof and water resistant; therefore, it will not crack or rot.

WC4 has an exterior insulation finish system (EIFS) covered with a textured acrylic stucco finish. Similar to WC3, a stack stone was placed around the masonry block of the home's crawlspace. However, the stacked stone does not extend as high vertically. Images of the cladding and exterior painting can be seen in Figure 26.

Figure 26. Exterior painting and cladding for WC3 (left) and WC4 (right)

Cladding on the WC3 exterior wall used conventionally pigmented paints because of the expected high R-value resulting from the PCMs in the wall insulation. The solar reflectance (SR) and thermal emittance (ε) values of the exterior paints for WC3 and WC4 are shown in Table 8.

Table 8. Cladding and exterior paint for WC3 and WC4

Description	WC3	WC4
Cladding	Fiber cement lap siding and stack stone	Acrylic stucco and stack stone
Exterior paints		
Gray	SR= 0.30 ε = 0.9 W/m^2	SR=0.23 ε = 0.9 W/m^2
Light Green	SR= 0.37 ε = 0.9 W/m^2	
Yellow	SR= 0.59 ε = 0.9 W/m^2	

4.1.4 Exterior Walls

WC3 has an exterior wall assembly made of two 2 by 4 walls. Wall studs are made of laminated strand lumber and are at 24-in (0.61-m) on-center. The studs from one wall are offset by 12-in (0.3-m) from the other wall's studs (Figure 27). The interior framing is supported by the floor truss while the exterior framing is installed on the sill plate and is fastened to the floor truss. A top plate was used to tie the two walls together for lateral strength. A fabric mesh is stapled between the two sets of 2 by 4 studs to separate and hold two different types of blown fiber insulation. Conventional blown fiber is contained in the interior cavity, while 20% by weight microencapsulated PCMs were added to blown fiber in the exterior framed cavity. Figure 28 shows the PCM enhanced fiber insulation being blown into the exterior framed cavities.

Because of the dynamic nature of the PCM enhanced insulation, a conventional R-value cannot effectively describe the resistance to heat transfer through the wall. However, for reference, the R-value of only the cellulose insulation was estimated as R – 26. Furthermore, in dynamic hot box testing, Kosny et al. (2010) found that PCM induced a 40% reduction in heat flow when blended with cellulose insulation. While this reduction was achieved during thermal ramp-up and cannot be interpreted as reduction in cooling load for all hours during cooling period, it does provide insight into the thermal storage potential of the PCM system.

The exterior wall OSB sheathing (ZIP® Board) has a built-in protective weather resistive barrier (WRB) overlaid at the factory to eliminate the need for house wrap. All joints were taped to maintain the continuity of the sheathing air tightness. A high-density, polyethylene sheet with a ¼-in (6-mm) dimpled profile was also installed on the exterior of the sheathing to ventilate the exterior walls. It provides drainage for transient moisture migrating through the wall and creates two independent air flow streams to dry out both the cladding and the concealed wall cavities. This simultaneously reduces the impact of solar driven moisture problems and the impact of interior moisture loading. It is expected that the combination of phase change insulation, the polyethylene dimpled sheet, and the OSB sheathing will facilitate enhanced charging and discharging of the PCM, while also limiting air infiltration across the sheathing.

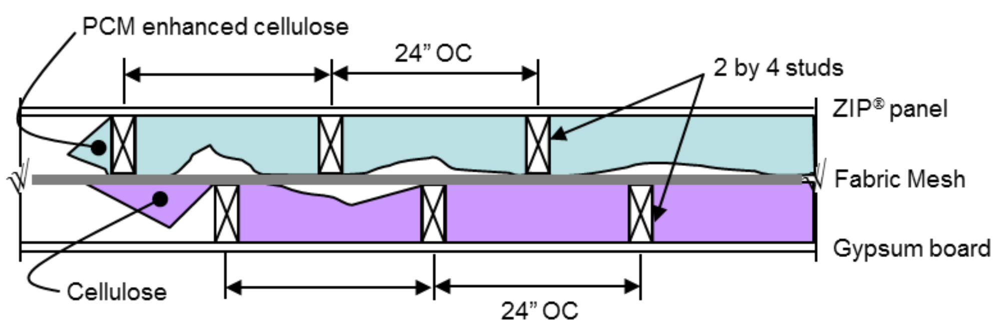


Figure 27. Double-stud wall assembly of WC3

Figure 28. Insulation addition in the double-stud wall assembly of WC3

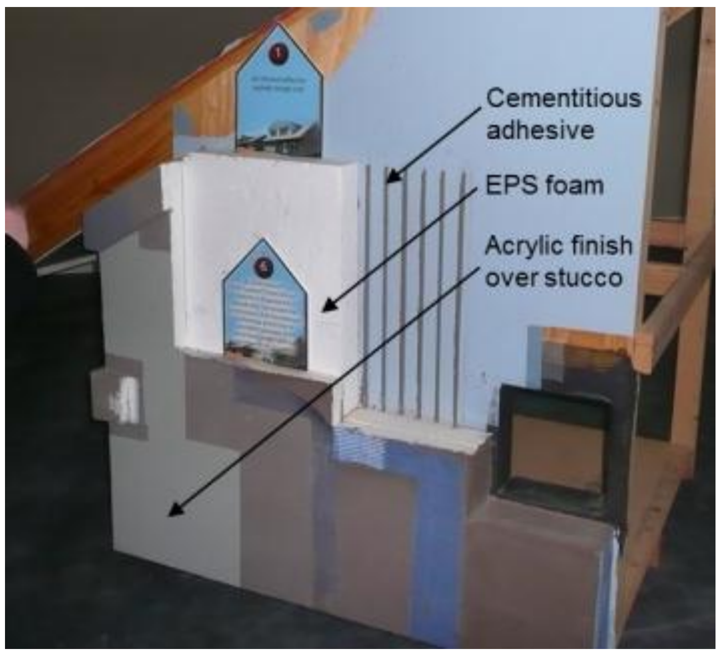


Figure 29. WC4 wall prototype with exterior foam insulation

The WC4 EIFS is an insulated cladding made of 5-in (0.13-m) of EPS insulation outside the exterior wall. The wall was built with studs installed at 16-in (0.61-m) on center; a prototype wall is shown in Figure 29. The 5-in (0.13-m) of EPS insulation is expected to reduce thermal bridging that result in energy losses in high performance wall systems. The system is lightweight, highly energy efficient and vapor permeable. The EPS insulation extends from about 1-ft (0.31-m) above the ground to the soffit of the roof. A flexible polymer-based membrane was manually applied as a liquid over exterior sheathing. The membrane resists water penetration and decreases air infiltration. Next, a fiber-reinforced cementitious adhesive was trowel applied to the weather resistive membrane to attach the EPS insulation. The trowel application formed rows of the adhesive with each row approximately 0.25-in (6-mm) high. The rows provide a small drainage cavity between the WRB and the EPS insulation board through which incidental water can weep to the outdoor ambient. The exterior of WC4 is an acrylic-based coating finish over stucco. The interior has gypsum board fitted with a laminated low-e foil facing (permeated on site with a spike roller to increase the moisture permeability) to reduce radiation exchange across the wall cavity, which was left void of insulation. The thermal resistance of the wall is estimated as R-21.

4.1.5 Windows

Both homes have triple pane windows with insulated glass unit (IGU) air spaces filled with argon gas. Argon gas is denser and less conductive than air. In sealed glass units, argon reduces the convection within the air space, thereby, creating a better IGU. National Fenestration Rating Council (NFRC) ratings for the windows in WC3 consist of a U-factor of 0.22 Btu/h-ft²-ºF and a SHGC of 0.17. Numbering the surfaces of the panes from 1 to 6 with 1 being the outside surface and 6 being the inside surface, the 2^{nd} and the 4^{th} surfaces are low-e surfaces. The three panes of the IGU are equally spaced.

In WC4, the window U-values and SHGC were based on their placement in the home. Southeast and southwest facing windows had U-values of 0.24 Btu/h-ft²-ºF and a SHGC of 0.50. Northeast and northwest facing windows had a U-value of 0.18 Btu/h-ft²-ºF and SHGC of 0.22.

4.1.6 Foundation

WC3 and WC4 are built on crawlspaces. The crawlspace in WC3 is ventilated with two R-19 batts installed in the floor chase cavities above the crawlspace, while the WC4 crawlspace is sealed and insulated on the interior side of the block wall with rigid foam insulation. The masonry block forming the crawlspace in both homes was waterproofed using Tremco's emulsion based asphalt coating. Stack stones were installed on the exterior wall up to the termite barrier between the masonry wall and the base plate in both houses. A 20 mil (0.02-in) liner covers the floor of both crawlspaces. In WC4 the floor liner is taped to a 10 mil (0.01-in) wall liner, which was adhered to the masonry block using a low VOC (volatile organic compound) polyurethane caulk. In WC4, the wall liner stops about 3-in below the sill plate to allow for termite inspections. DOW's Thermax™ rigid polyisocyanurate foam insulation (R -10) was glued to the wall liner using a polyurethane caulk adhesive. R-10 was a local code requirement in October 2010. Photographs of the crawlspaces in WC3 and WC4 are shown in Figure 4; the bare walls in the WC3 crawlspace and the foil-faced insulation on the WC4 crawlspace walls can be seen in the background.

Figure 30. Vented crawlspace in WC3 (left) and walls insulated and sealed in WC4 crawlspace (right)

4.2 SPACE CONDITIONING EQUIPMENT

A 320 ft deep, vertical bore, ground loop provides source energy for a high efficiency water-to-air heat pump (WAHP) in WC3. The WAHP is a ClimateMaster (model TTV026) two-stage (dual capacity) unit with an integral water/brine pump. The nominal low-stage cooling capacity rating ground source heat pump condition is 21.3 kBtu/hr, with a rated EER of 26.0 kBtu/W under present conditions. The rated high stage EER for the unit is 18.5 kBtu/W with a capacity of 26.6 kBtu/hr. The rated coefficients of performance for heating at high and low stages are 4.0 and 4.6, respectively (which only includes pump and fan power to overcome the internal resistance of the unit). The high stage heating capacity is 19.8 kBtu/hr, while the low stage capacity is 16.5 kBtu/hr. Electric heating elements are provided for emergency use. A Duct Blaster test was conducted to measure the total air leakage of the duct system. The results from this test showed 102 CFM (cubic feet per minute) of leakage to the outside at 25 Pascal. Approximately 80% of the supply side ducts are located in the conditioned space while 100% of the return side ducts are in the conditioned space. The remaining 20% of supply side ducts are located in the attic, but were sealed with mastic and wrapped in R-5 insulation.

In WC4, a nominal 2 ton cooling, dual capacity, air-source heat pump donated by Lennox is used for space conditioning (model XP19-024 with a CBX32MV-024/030 air handler unit). The AHRI-rated cooling performance of this unit (high stage operation) is 25 kBtu/hr at 95°F with SEER of 17.6. Rated heating performance (high stage operation) is 22,000 Btu/hr at 47°F and 12,900 Btu/hr at 17°F with HSPF (heating seasonal performance factor) of 8.85. Backup electric elements are provided to supplement the heat pump heating output during periods of low ambient temperature and for emergency heating. The CBX32MV air handler has a continuously variable speed blower with nominal air flow of 540-1320 CFM depending upon the selected speed setting. A Duct Blaster test was conducted to measure the total air leakage of the duct system. The results from this test showed 60 CFM of leakage to the outside of the building at 25 Pascal. Similar to WC3, approximately 80% of the supply side ducts are located in the conditioned space, while 100% of the return side ducts are in the conditioned space. The remaining 20% of supply side ducts are located in the attic, and were sealed in mastic and wrapped in R-5 insulation.

Mechanical ventilation is provided in WC3 and WC4 by running a 6-in duct to the return plenum of the space conditioning heat pump, in line with a motorized damper and a manual damper. The heat pump variable speed indoor fan is used to bring in fresh air, based on the controls in the programmable ventilation system provided by an air cycler. An average ventilation air flow of 30 CFM is maintained in both houses by seasonally adjusting the manual damper. During heavy heating and cooling periods, the air handler runs for more hours on high speed than during the shoulder months. At higher fan speeds, larger volumes of air are drawn into the house compared to lower speeds. Therefore, since the air cycler controls do not monitor the amount of inlet fresh air induced by the variable fan speeds, the manual damper is adjusted to maintain an average air flow.

4.3 WATER HEATING

Water heating is provided in WC3 by a specially built water-to-water heat pump (WWHP) unit of ~1½ ton nominal capacity with integral pumps for both the source and load sides. The source energy is provided by the same ground source brine loop used by the WAHP. With a source entering water temperature of 68°F, the WWHP in WC3 has a COP of 3.7 for 120°F load water temperature. A back-up 82 gallon standard electric water heater with an EF of 0.92 is used for water storage. The storage water heater and the WWHP are both located in the utility room inside the conditioned space. In WC4, water heating is supplied by a donated GE GeoSpring®, 50 gallon hybrid electric heat pump water heater (HPWH). The EF of this unit is approximately 2.35, and it is located inside the conditioned space in the utility room.

4.4 LIGHTING

WC3 is equipped with pin-based, ENERGY STAR-rated, 100 percent fluorescent lighting. In contrast, WC4 has solid state LED lighting. The system efficacy of the LED lighting has been reported to be approximately equivalent to CFL down lights (Willmorth et al., 2010). The LED lighting solution did lead to more down light cans penetrating into the unconditioned attic space. This can lead to a risk of uncontrolled air leakage if not installed to be airtight to the ceiling plane under the insulated attic space.

4.5 APPLIANCES

WC3 and WC4 have equivalent advanced appliances installed. Whirlpool Corporation donated all the appliances for both homes. The appliances are ENERGY STAR rated or high-efficiency products for categories that are not yet ENERGY STAR certified.

Salient appliance features are:

- Refrigerator: 36" wide, 25 cubic feet side-by-side unit. The refrigerator is ENERGY STAR certified; the model number is GS6NVEXV. The manufacturer's suggested retail price is $1,749.
- Clothes Washer & Dryer: Whirlpool donated their high-end, horizontal axis washer and matching dryer because of their potential to reduce energy and water use and because of future enhancements using Whirlpool's load manager. The washer can steam wash and the dryer can steam dry.
- Dishwasher: The dishwasher is ENERGY STAR certified; model GU3600XTV. http://www.whirlpool.com/catalog/product.jsp?categoryId=108&productId=1329&successful_search=gu3600xtv.
- Range: This appliance was just introduced onto the market by Whirlpool. It is a free-standing range with glass cook top featuring an energy saver mode; model GFE471LVQ. http://www.whirlpool.com/catalog/product.jsp?categoryId=76&productId=1293&successful_search=GFE471LVQ.

5. ENERGY USAGE MEASUREMENTS COMPARED TO ENGINEERING MODEL PREDICTIONS

5.1 ENGINEERING MODEL DETAILS

Per the methodology outlined in Hendron and Engebrecht (2010) for Building America (BA) research teams, an analysis of the energy use and potential savings of WC3 and WC4 was conducted using EnergyGauge software. As a first step in this approach, the two houses were modeled using EnergyGauge (http://www.energygauge.com/usares/) with TMY3 weather data.

It is valuable to be able to determine the relative worth of individual energy efficiency features, particularly when trying to determine which ones are cost effective. However, since direct, measured data are only available for the total effect of all the features extant in these houses, the only way to estimate the worth of individual features is through modeling. The approach is to create a computer model that closely matches the overall energy performance of the houses. Particular features can then be added or subtracted from the model to estimate their relative value. This section describes the creation of the models for WC3 and WC4; section 6 will describe how these models are employed to calculate the relative effects of different features."

The model predictions use the Building America (BA) Benchmark modeling procedure (Hendron and Engebrecht, 2010), which is the same source document used to simulate occupancy in the Wolf Creek houses. Some of the newer technologies applied in WC3 and WC4 could not be explicitly modeled in EnergyGauge. In such cases, technologies available in EnergyGauge and corresponding performance specifications were modeled as surrogates. Table 9 summarizes the features of WC3 and WC4 that were used to build the models.

Table 9. Summary of energy efficient technologies and systems

	WC3	WC4
Stories	2	2
Floor (ft^2)	2721	2721
Foundation	Conventional vented crawlspace with R-38 floor joist insulation.	Sealed and insulated crawlspace, with R-10 polyisocyanurate foil faced insulation on the walls.
Exterior Walls	Two 2x4 stud walls; 24-in O.C. with PCM enhanced cellulose.	R-21 wall assembly; 2x4 wood 16-in O.C. 5-in EPS exterior insulation.
Attic	R-50; Conventional attic with PCM enhanced cellulose insulation; Trusses at 24-in O.C.	R-50; Conventional attic with floor filled blown-fiber insulation; Trusses at 24-in O.C.
Windows	Triple pane; U= 0.22 Btu/h-ft²-F, SGHC = 0.17.	Triple pane; Southeast and Southwest facing windows: U = 0.24 Btu/h-ft²-F, SHGC = 0.50. Northeast and Northwest facing windows: U = 0.18 Btu/h-ft²-F, SHGC = 0.22.
Cladding	Fiber cement lap siding and stack stone	Acrylic stucco and stack stone
Exterior Paints	Light Green: SR= 0.37, ε = 0.9 W/m^2; Yellow: SR= 0.59, ε = 0.9 W/m^2.	Light Green: SR=0.23, ε = 0.9 W/m^2.

	WC3	WC4
Space Conditioning	Single ground source HP, dual-speed compressor. Cooling capacity: 26.6 kBtu/hr (high stage), EER: 18.5 kBtu/W (high stage). Heating capacity: 19.8 kBtu/hr (high stage), COP: 4.0 (high stage).	Single air-source HP, dual-speed compressor. Cooling capacity: 25 kBtu/hr (high stage), SEER: 18.4 (high stage). Heating capacity: 22.6 kBtu/hr (high stage), HSPF: 9.1 (high stage).
Mechanical Ventilation	30 CFM	30 CFM
Duct Location	Supply: 80% inside conditioned space, 20% attic; Return: 100% inside conditioned space. R-5 insulation, supply area = 551 ft^2, return area = 306 ft^2, duct air leakage (to the outside) = 15%.	Supply: 80% inside conditioned space, 20% attic. Return: 100% inside conditioned space. R-5 insulation, supply area = 551 ft^2, return area = 306 ft^2, duct air leakage (to the outside) = 8%.
Air Handler Location	Conditioned Space	Conditioned Space
Water Heater	WWHP, COP = 3.1.	Hybrid hot water heat pump, EF = 2.4.
Lighting	100% fluorescent.	LED lighting.

5.2 WC3 MODEL PREDICTIONS

Table 10 shows the comparison of the WC3 modeled monthly energy consumption with the measured data. The modeled WC3 energy consumptions for heating and cooling were adjusted to account for the differences in the actual and TMY3 weather, using a regression model similar to the BSH (described in section 2.3).

Table 10. WC3 model predicted energy use compared to measurements

	Space Heating (kWh)		Space Cooling (kWh)		Hot Water (kWh)		Total (kWh)	
	Measured	Modeled (adjusted)	Measured	Modeled (adjusted)	Measured	Modeled	Measured	Modeled (adjusted)
Dec-10	765	847			156	158	1515	1545
Jan-11	626	757			152	177	1369	1474
Feb-11	370	406			139	157	1039	1053
Mar-11	213	249			144	146	964	935
Apr-11	76	0	50	131	117	124	800	780
May-11			214	225	106	110	902	875
Jun-11			400	399	88	88	1047	1012
Jul-11			587	531	81	80	1232	1151
Aug-11			539	485	78	82	1182	1107
Sep-11			213	176	91	88	864	789
Oct-11	47	113	74	64	102	112	813	829
Nov-11	158	254			116	127	931	906
Total	2255	2627	2077	2010	1370	1449	12658	12455

The specifications in Table 9 for the WC3 technologies needed to be modified for the model results to match the measurements. The heating capacity of the geothermal heat pump in the WC3 model was modified to 24.8 kBtu/hr and the cooling EER was changed to 11.1 kBtu/W. Further modifications made to the WC3 model specifications (described in Table 9) to simulate the annual energy consumption were:

- Water heater: Electric water heater with an energy factor of 0.9 and an add-on heat pump with a COP of 2.65.

- Space Conditioning: Calculated cooling energy use was reduced by 5% to account for the phase change material in the walls and attic. The 5% reduction is based on an analysis of the wall heat flux data from May, 2011 (Shrestha et al., 2011).
- Lighting: The percent of fluorescent lights was changed from 100% to 90.8% to match the annual lighting load.
- Duct location: Fully inside conditioned space.
- Plug loads: In lieu of the measured plug loads, miscellaneous electric loads (MELs) based on the Building American Benchmark (Hendron and Engebrecht, 2010) were included in the house total energy consumption.

5.3 WC4 MODEL PREDICTIONS

Table 11 shows the comparison of the WC4 modeled and measured monthly energy consumptions. The space conditioning energy consumption was again adjusted to account for the differences in the actual and TMY3 weather data. Similar to WC3, following model specifications were modified from the values listed in Table 9:

- Space conditioning: Heating capacity was increased to 40 kBtu/hr.
- Water heater: Electric water heater with an energy factor of 0.9 and an add-on heat pump with a COP of 3.05.
- Lighting: With LED technology not being available in EnergyGauge, WC4 lights were simulated as 100% fluorescent. Because the lighting efficacy of the LED downlight modules of 30 lumens/watt was comparable to similar CFLs (Willmorth et al., 2010), the authors deemed this as an appropriate technology substitute.
- Duct location: Fully inside conditioned space.
- Plug loads: In lieu of the measured plug loads, miscellaneous electric loads (MELs) based on the Building American Benchmark (Hendron and Engebrecht, 2010) were included in the house total energy consumption.

Table 11. WC4 model predicted energy use compared to measurements

	Space Heating (kWh)		Space Cooling (kWh)		Hot Water (kWh)		Total (kWh)	
	Measured	Modeled (adjusted)	Measured	Modeled (adjusted)	Measured	Modeled	Measured	Modeled (adjusted)
Dec-10	1202	1123			97	140	1809	1786
Jan-11	1008	1009			108	157	1632	1689
Feb-11	536	565			98	139	1095	1178
Mar-11	310	366			110	130	975	1019
Apr-11	94	36	70	116	101	110	781	770
May-11			192	193	91	98	887	814
Jun-11			305	336	79	79	897	923
Jul-11			473	445	76	72	1084	1040
Aug-11			511	407	79	74	1127	1004
Sep-11			221	152	74	79	827	739
Oct-11	74	194	95	60	85	100	813	877
Nov-11	251	372			90	113	899	993
Total	3475	3665	1866	1709	1088	1291	12825	12832

6. COST EFFECTIVENESS OF THE ENERGY SAVING FEATURES IN WC3 AND WC4

6.1 WC3

6.1.1 Construction Cost

A detailed breakdown of the cost to construct WC3 is shown in Table 12. The totals costs include construction costs incurred by Schaad Companies and the market value of all donated items by the manufacturing partners. The construction costs were determined from invoices and spreadsheets that Schaad Companies provided. The market value of donated items was estimated by the relevant manufacturing partners. Certain elements of the General Requirements cost section in Table 12 were estimated by Schaad to reflect more accurately the standard costs of building similar homes rather than the actual costs.

Table 12. Detailed costs (estimates) for WC3

Category	($)
Envelope	
Framing	58,290
Roof	30,907
Cladding	25,708
Foundation	28,699
Site Development	5,565
Windows	10,026
Paint (exterior)	10,494
Doors (exterior)	2,140
Garage	4,798
Exterior Décor	1,476
HVAC	
Duct	5,100
Insulation	46,071
Heat Pump/Zone Control	8,400
Geothermal Loop	7,075
Water	
Water Heater	6,200
Plumbing	14,856
Interior Finish	
Appliances	7,590
Floor Covering	19,204
Millwork	15,885
Paint	5,900
Drywall	10,750
Other Interior Décor	25,403
Electrical	
Electrical Systems	9,304
Security	1,000
Lighting	6,530

Category	($)
Utility Services	2,086
Landscaping	
Ornamental	4,000
Yard	6,260
General Requirements	
Labor~	6,750
Supervision/Administration~	27,000
Architectural*	21,227
Engineering°	2,945
Permits/Insurance	5,303
Utilities/Taxes/Dues	1,592
Other General	1,229
Total	**445,800**

6.1.2 Energy Use and Savings Analysis

Per the methodology outlined in Hendron and Engebrecht (2010), an analysis of the energy use and potential savings of WC3 was conducted using EnergyGauge. As a first step in this approach, a Building America Benchmark house (BAB) was defined to facilitate comparison. Once the specifications for the prototype house (i.e. WC3 or WC4) were defined, a BAB model was generated by EnergyGauge.

A model house consistent with current building practices of home builders in the East Tennessee region was also defined in EnergyGauge for comparison and is referenced hereafter as the Builder Standard House (BSH). Common building practices in the Oak Ridge, TN region are described in detail by Christian et al. (2010) and were used in defining the BSH. Table 13 describes the salient details of WC3, BAB, and BSH with respect to energy consumption. As described in chapter 5, certain modifications were made to the WC3 model to better match the measured data.

Table 13. Modeling details of the Building America Benchmark, Builder Standard house and WC3

	BA Benchmark	Builder Standard House (BSH)	WC3
Stories	2	2	2
Floor Area	2721 ft^2	2721 ft^2	2721 ft^2
Foundation	Conventional vented crawlspace; R-18.5 floor joist insulation (U=0.05); Floor framing factor = 13%.	Conventional vented crawlspace; R-19 floor joist insulation (U=0.053); Floor framing factor = 13%.	Conventional vented crawlspace; R-38 floor joist insulation (U=0.035); Floor framing factor = 13%.
Exterior Walls	R-19 wall cavity insulation (Total Wall U =0.061); Wall framing factor = 0.23; Solar absorptance = 0.5.	R-13 wall cavity insulation (Total Wall U = 0.082); Wall framing factor = 0.20; Solar absorptance = 0.62, 0.41.	R-26 wall cavity insulation (Total Wall U = 0.058); Wall framing factor = 0.20 (staggered double wall); Solar absorptance = 0.62, 0.41.
Attic	Conventional attic, R-26 ceiling insulation (U=0.035), ventilation ratio = 1 to 300.	Conventional attic, R-25 ceiling insulation (U=0.037), ventilation ratio = 1 to 300.	Conventional attic, R-50 ceiling insulation (U=0.019), ventilation ratio = 1 to 150.

	BA Benchmark	Builder Standard House (BSH)	WC3
Roofing Material	Composition shingles; Solar absorptance = 0.75; Roof Deck: R-0.	Composition shingles; Solar absorptance = 0.85; Roof Deck: R-0.	Metal; Solar absorptance = 0.66; Roof Deck: R-4.
Windows	Double pane clear windows; U= 0.58, SGHC = 0.58.	Double pane clear windows; U= 0.47, SGHC = 0.58.	Triple pane; U= 0.22, SGHC = 0.17.
Space Conditioning	SEER = 10, SHR= 0.75, cooling capacity = 43.6 kBtu/hr; HSPF = 6.8, heating capacity = 66.4 kBtu/hr.	SEER = 13, SHR= 0.75, cooling capacity = 48 kBtu/hr; HSPF = 7.7, heating capacity = 48.3 kBtu/hr.	Single ground source (vertical well) HP, SHR = 0.72, cooling capacity: 23 kBtu/hr, EER: 16 kBtu/W; Heating capacity: 15 kBtu/hr, COP: 3.85.
Infiltration	ACH(50) = 9.75, SLA = 0.00057 in^2/in^2.	ACH(50) = 8.5, SLA = 0.00050 in^2/in^2.	ACH(50) = 3.49, SLA = 0.00020 in^2/in^2.
Mechanical Ventilation	6 CFM	30 CFM	30 CFM
Duct location	Supply: crawlspace; Return: crawlspace. R-5 insulation, supply area = 353.7 ft^2 , return area = 326.5 ft^2, duct air leakage = 12%.	Supply: crawlspace; Return: crawlspace. R-5 insulation, supply area = 544 ft^2 , return area = 136 ft^2, duct air leakage = 12%.	Supply: interior; Return: interior. R-5 insulation, supply area = 544 ft^2 , return area = 136 ft^2, duct air leakage = 15%.
Air handler location	Crawlspace	Crawlspace	Interior
Water heater	Electric 50 gal capacity, EF = 0.86, usage = 63.5 gal/day, set temp = 120ºF.	Electric 50 gal capacity, EF = 0.86, usage = 60 gal/day, set temp = 120ºF.	Electric 50 gal capacity, EF = 0.92, usage = 60 gal/day, set temp = 120ºF, Add-on heat pump COP = 3.1.
Lighting	14% fluorescent, 86% incandescent.	10.1% fluorescent, 89.9% incandescent.	100% fluorescent.

In order to evaluate the incremental energy savings of each energy efficiency measure, a stepwise progression from the BSH to WC3 was modeled. As each energy efficient measure was added to the BSH model, an EnergyGauge simulation of household energy consumption was run, till the final WC3 model was reached (designated 'BSH ++ R38 Floor Joist Insulation'). The order in which the technologies were added to the BSH model was based on tradeoffs between the ease of retrofitting and cost-effectiveness. For example, changing the household lighting to CFL's was given a higher priority than increasing wall insulation. The model results for this analysis were based on TMY3 weather data and were not adjusted to reflect the actual weather conditions during the evaluation period. This is deemed appropriate since the energy savings and cost analysis should be performed for typical weather conditions, and should not be based on weather conditions during any particular year.

The effects of step-by-step addition of technologies and energy-saving measures on the total, heating, cooling, and hot water heating energy uses are shown in Figure 31. The energy savings from these measures are shown in Table 14. Overall, the WC3 model consumed approximately 56% and 51% less energy than the BA Benchmark and the BSH models, respectively. The annual energy costs savings of each measure was determined by multiplying the decrement in energy consumption by the cost of electricity. With all of the features and equipment used, WC3 saves a total of $1276 per year over the BSH house, based on the average, local utility rate of $0.097/kWh during the evaluation period (see Table 7). Using a national average utility rate of $0.118/kWh during the same period, the reduction in energy cost would be $1548.

Since EnergyGauge cannot simulate the impact of dynamic insulation materials, the steady-state wall insulation was set to R-26. However, as an estimate of the PCM impact, the cooling energy use was reduced by 5% for all simulations after the addition of the 'improved wall insulation'. This reduction is based on an analysis of heat flux data over three days in May 2011 (Shrestha et al., 2011).

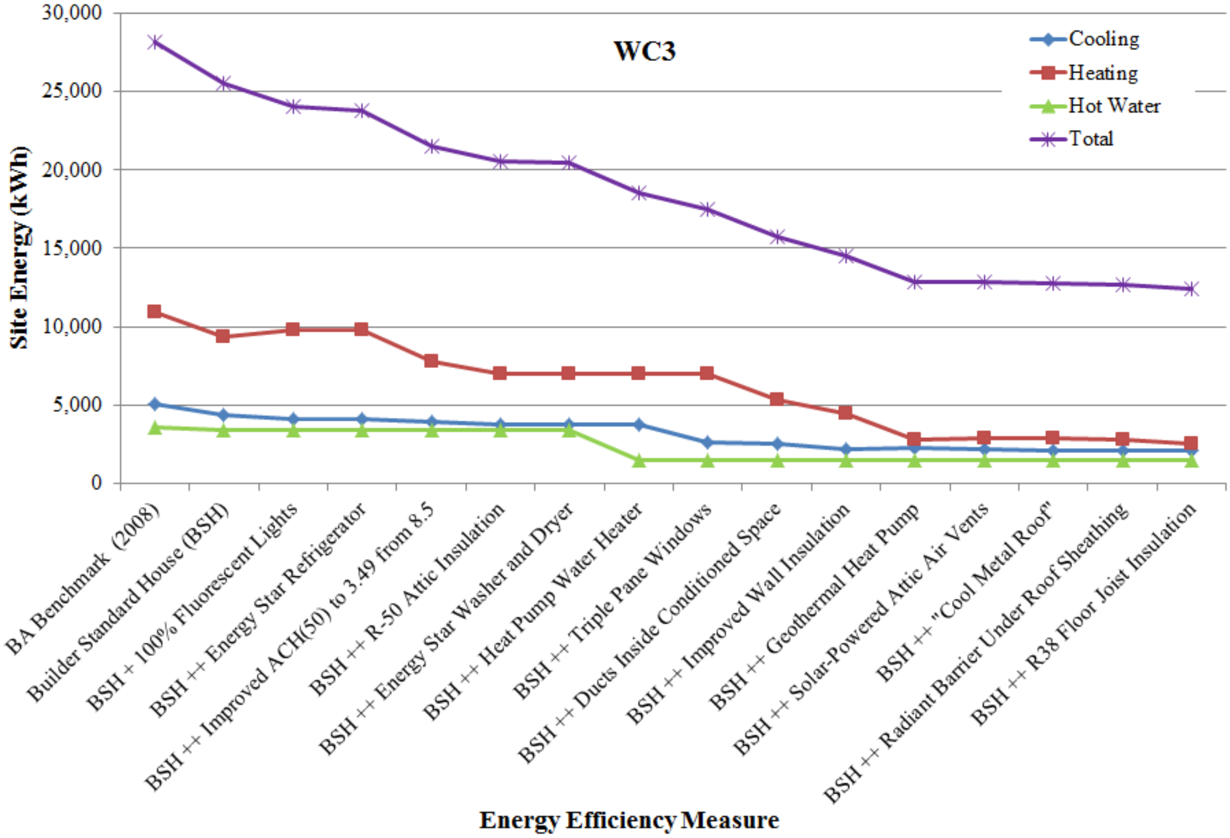


Figure 31. WC3 simulated energy consumption after adding individual energy efficiency measures.

Table 14. Energy savings with incremental energy efficiency measures in WC3

Increment	Site Energy (kWh)	Source Energy (MBtu)	National Energy Cost ($/yr)	Local Energy Cost ($/yr)	Cost Saving	Measure Value ($/yr)	Package Saving ($/yr)
BA Benchmark (2008)	28,167	323	$3,312	$2,731			
Builder Standard House (BSH)	25,569	294	$3,007	$2,479	9%		
BSH + 100% Fluorescent Lights	24,025	276	$2,825	$2,330	15%	$150	$150
BSH ++ Energy Star Refrigerator	23,773	273	$2,796	$2,305	16%	$24	$174
BSH ++ Improved ACH(50) to 3.49 from 8.5	21,499	247	$2,528	$2,085	24%	$221	$395
BSH ++ R-50 Attic Insulation	20,599	237	$2,422	$1,997	27%	$87	$482
BSH ++ Energy Star Washer and Dryer	20,505	235	$2,411	$1,988	27%	$9	$491
BSH ++ Heat Pump Water Heater	18,575	213	$2,184	$1,801	34%	$187	$678
BSH ++ Triple Pane Windows	17,482	201	$2,056	$1,695	38%	$106	$784
BSH ++ Ducts Inside Conditioned Space	15,753	181	$1,853	$1,528	44%	$168	$952
BSH ++ Improved Wall Insulation	14,501	166	$1,705	$1,406	49%	$121	$1,073
BSH ++ Geothermal Heat Pump	12,881	148	$1,515	$1,249	54%	$157	$1,230
BSH ++ Solar-Powered Attic Air Vents	12,857	148	$1,512	$1,247	54%	$2	$1,233
BSH ++ "Cool Metal Roof"	12,767	147	$1,501	$1,238	55%	$9	$1,241
BSH ++ Radiant Barrier Under Roof Sheathing	12,711	146	$1,495	$1,233	55%	$5	$1,247
BSH ++ R38 Floor Joist Insulation	12,405	142	$1,459	$1,203	56%	$30	$1,276

6.1.3 Neutral Cash Flow Analysis

Table 15 shows the neutral-cash-flow analysis for WC3 using the BA Benchmark Definition (Hendron and Engebrecht, 2010). The analysis was conducted by evaluating the incremental investment costs and energy savings of each energy efficient measure against the BSH model. The amortized annual costs are based on a 30 year loan with an interest rate of 7%. All energy costs and savings were estimated based on local utility rates of $0.097/kWh. The net 'annual cost' of each measure was determined by subtracting the energy savings ('Measure Value') from the amortized investment costs; with negative values (in red and within parentheses) indicating better than neutral cash flow. Applicable rebates and incentives were also included in the analysis. A measured HERS rating of 46 makes WC3 eligible for the $2,000 energy efficient house rebate.

The simulated annual energy cost for BSH was $2,479. The total incremental investment for all energy efficient investments in WC3 was $67,894, with an annualized cost of $5,420. Neutral cash flow was not achieved in WC3. When the annual energy costs savings and currently available incentives are considered, the net annual cost of the efficiency measures was $4,144.

Table 15. Neutral cash flow analysis for WC3

Increment	Site Energy (kWh)	Local Energy Cost ($/yr)	Energy Savings (kWh)	Measure Value ($/yr)	Package Savings	Incremental Investment Cost ($)	Amortized Annual Cost (30 year mortgage, 7% interest)	Annual Cost	Cash-flow Neutral?
BA Benchmark (2008)	28,167	$2,731							
Builder Standard House (BSH)	25,569	$2,479	2,598						
BSH + 100% Fluorescent Lights	24,025	$2,330	1,544	$150	$150	$3,330	$266	$116	No
BSH ++ Energy Star Refrigerator	23,773	$2,305	252	$24	$174	$1,127	$90	$66	No
BSH ++ Improved ACH(50) to 3.49 from 8.5	21,499	$2,085	2,274	$221	$395	$2,079	$166	($54)	Yes
BSH ++ R-50 Attic Insulation	20,599	$1,997	900	$87	$482	$17,704	$1,413	$1,326	No
BSH ++ Energy Star Washer and Dryer	20,505	$1,988	94	$9	$491	$1,598	$128	$118	No
BSH ++ Heat Pump Water Heater	18,575	$1,801	1,930	$187	$678	$3,735	$298	$111	No
BSH ++ Triple Pane Windows	17,482	$1,695	1,093	$106	$784	$3,753	$300	$194	No
BSH ++ Ducts Inside Conditioned Space	15,753	$1,528	1,729	$168	$952	$2,095	$167	($0)	Yes
BSH ++ Improved Wall Insulation	14,501	$1,406	1,252	$121	$1,073	$18,955	$1,513	$1,392	No
BSH ++ Geothermal Heat Pump	12,881	$1,249	1,620	$157	$1,230	$5,990	$478	$321	No
BSH ++ Solar-Powered Attic Air Vents	12,857	$1,247	24	$2	$1,233	$949	$76	$73	No
BSH ++ "Cool Metal Roof"	12,767	$1,238	90	$9	$1,241	$13,157	$1,050	$1,042	No
BSH ++ Radiant Barrier Under Roof Sheathing	12,711	$1,233	56	$5	$1,247	$314	$25	$20	No
BSH ++ R38 Floor Joist Insulation	12,405	$1,203	305	$30	$1,276	$904	$72	$43	No
Total Energy Efficiency Investment					$1,276	$75,690	$6,043	$4,766	No
REBATES / INCENTIVES									
Federal energy efficient builder house						$2,000			
State of TN Energy Star heat pump						$250			
TVA high efficiency water heater						$50			
Federal residential renewable energy tax credit						$5,495			
Total Incremental Cost Including Incentives						$67,894	$5,420	$4,144	No

Of all the energy efficiency measures considered, only the improvement in air-tightness (ACH of 3.49 from 8.5) resulted in a reduced annual cost. The incremental cost of improving air infiltration was estimated using BEopt (http://beopt.nrel.gov/). Moving the ducts into the conditioned space was also cost-neutral, with zero net annual cost.

The water-to-water heat pump (WWHP) water heater has a high annualized cost. This is due to the large incremental cost of $3,753 associated with the unit. Because the WWHP water heater uses the same ground source as the geothermal heat pump (GSHP), the excavation costs for the ground loop were split between both units. The proportion of the $6,000 ground loop costs allocated to each unit was based on their estimated retail value. Approximately $2,053 of the ground loop cost was apportioned to the

WWHP water heater while the remaining $3,947 was added to the geothermal heat pump cost. In both cases, the cost of the ground loop was a significant contributor to the annualized costs being greater than zero. A 320 ft deep vertical bore was drilled for this application. However, if novel and more cost-effective drilling techniques could be employed, ground heat exchanger applications could be more appealing from a cost perspective. Such high, cost-prohibitive drilling costs are unfortunate, given that the WWHP water heater achieved the highest energy saving of 1,930 kWh/year, second only to the air-tightness measure.

The radiant barrier located on the underside of the roof sheathing had the lowest incremental cost of all technologies ($314). Therefore, the total annualized costs were also relatively low. However, the EnergyGauge model only predicted an annual energy savings of $5 over the BSH model. This converts to a simple payback of over 62 years. The impact of the radiant barrier is mitigated by the ventilated attic with R-50 insulation over the ceiling joists, in addition to the location of the HVAC equipment in the conditioned space. Similarly, the annualized cost of the additional floor joist insulation is lower than most other technologies due to its lower overall incremental costs.

In contrast to expectation, the ENERGY STAR refrigerator has a positive annual cost. This can be attributed to the fact that the refrigerator donated by Whirlpool is a premium model with amenities superior to the standard refrigerator modeled in the BSH house. Therefore, the incremental cost in the analysis included amenity costs in addition to increased energy efficiency. If an appropriate comparison of refrigerators with similar amenities was done, the refrigerator would likely be cost neutral.

The requirement of 100% fluorescent lights was not cost neutral. The incremental cost of the lights was determined by taking the cost of the lighting package in WC3 and comparing it with the lighting package cost of a similar size house recently built by Schaad Companies. The resulting high incremental cost is mostly attributable to the use of ENERGY STAR rated pin base CFL bulbs in contrast to CFL bulbs with an Edison screw base. Pin based CFL bulbs and fixtures are significantly more expensive than the latter.

The "cool metal roof" had significant annualized costs. This is due in large part to the experimental nature of the technology employed. The IRR painted metal shakes have tapered EPS insulation inserted underneath to provide support when one walks across the roof and to increase the resistance to heat transfer across the deck. The added cost of the total assembly and installation made the roof application cost-prohibitive in WC3. Additionally, because the cooling loads are already significantly reduced by triple pane windows, R-50 insulation, and the placement of the ducts inside the conditioned space, the performance enhancement due to the cool roof application is further mitigated.

The addition of triple pane windows reduced the cooling energy use by approximately 30%. However, Oak Ridge, TN is a heating dominated climate with cooling loads comprising only 44% of the required heating loads in standard residential construction. Therefore, the total annual energy savings were only $106, which are not enough to offset the incremental cost of $3,753 over clear, double pane windows.

The technology measures of R-50 attic insulation and increased exterior wall insulation both employed technologies on the cutting edge of building construction. The retail value of the PCM material was approximately $35,450. These costs are at least 3 to 4 times higher than what would be expected if larger scale production was occurring. The primary cost components are the cost of running the encapsulation reactor and the cost of drying the PCM. It is expected that it will take application in at least 1000 to 5000 houses a year to make a reasonable business case for PCM residential building integration. However, WC3 does provide an opportunity to verify the whole house performance of this material to help inform manufacturers and building contractors.

6.2 WC4

6.2.1 Construction Cost

The cost details of WC4 are shown in Table 16. The total costs include construction costs incurred by Schaad Companies and the market value of all donated items by our manufacturing partners. Certain elements of the General Requirements cost section in Table 16 were estimated by Schaad to reflect more accurately the standard costs of building similar homes rather than the actual costs.

Table 16. Detailed costs (estimates) for WC4

Category	($)
Envelope	
Framing	34,730
Roof	23,859
Cladding	16,976
Foundation	32,591
Site Development	9,260
Windows	10,202
Paint (exterior)	5,100
Doors (exterior)	2,627
Garage	5,054
Exterior Décor	1,811
HVAC	
Duct	9,240
Insulation	44,063
Heat Pump/Zone Control	12,654
Water	
Water Heater	1,500
Plumbing	15,165
Interior Finish	
Appliances	7,590
Floor Covering	20,214
Millwork	17,209
Paint	10,494
Drywall	12,423
Other Interior Décor	24,006
Electrical	
Electrical Systems	11,435
Security	1,000
Lighting	12,000
Utility Services	2,564
Landscaping	
Ornamental	1,600
Yard	11,005
General Requirements	
Labor~	6,750

Category	($)
Supervision/Administration~	27,000
Architectural*	20,094
Engineering°	3,052
Permits/Insurance	5,661
Utilities/Taxes/Dues	1,988
Other General	1,061
Total	**422,000**

6.2.2 Energy Use and Savings Analysis

The modeling and analysis procedure was similar to WC3, as described in the previous section. Table 17 describes the salient details of WC4, BAB, and BSH. As described in chapter 5, certain modifications were made to the WC4 model to better match the measured data.

Table 17. Modeling details of the Building America Benchmark, Builder Standard house and WC4

	BA Benchmark	Builder Standard (BSH)	WC4
Stories	2	2	2
Floor Area	2721 ft^2	2721 ft^2	2721 ft^2
Foundation	Conventional vented crawlspace; R-18.5 floor joist insulation (U=0.05); Floor framing factor = 13%.	Conventional vented crawlspace; R-19 floor joist insulation (U=0.053); Floor framing factor = 13%.	Sealed crawlspace; No floor joist insulation; R-10 wall insulation; Floor framing factor = 13%.
Exterior Walls	R-19 wall cavity insulation (Total Wall U =0.061); Wall framing factor = 23%; Solar absorptance = 0.5.	R-13 wall cavity insulation (Total Wall U = 0.82); Wall framing factor = 23%; Solar absorptance = 0.77.	R-21 whole wall value (Total Wall U = 0.048); Wall framing factor = 23%; Solar absorptance = 0.77
Attic	Conventional attic, R-26 ceiling insulation (U=0.035), ventilation ratio = 1 to 300.	Conventional attic, R-25 ceiling insulation (U=0.037), ventilation ratio = 1 to 300.	Conventional attic, R-50 ceiling insulation (U=0.019), ventilation ratio = 1 to 150.
Roofing Material	Composition shingles, solar absorptance = 0.75, Roof Deck R-0.	Composition shingles, solar absorptance = 0.85, Roof Deck R-0.	Composition shingles, solar absorptance = 0.74, Roof Deck R-4.
Windows	Double pane, clear; U= 0.58, SGHC = 0.58.	Double pane, clear; U= 0.47, SGHC = 0.58.	Triple pane; Southeast and Southwest facing windows: U = 0.24, SHGC = 0.50. Northeast and Northwest facing windows: U = 0.18 SHGC = 0.22.
Space Conditioning	SEER = 10, SHR= 0.75, cooling capacity = 43.6 kBtu/hr; HSPF = 6.8, heating capacity = 66.4 kBtu/hr	SEER = 13, SHR= 0.75, cooling capacity = 48 kBtu/hr; HSPF = 7.7, heating capacity = 48.3 kBtu/hr	Single air-source HP, cooling capacity = 25 kBtu/hr SEER: 18.4; heating capacity: 22.6 kBtu/hr, HSPF: 9.1
Infiltration	ACH(50) = 9.75, SLA = 0.00057 in^2/in^2.	ACH(50) = 8.5, SLA = 0.00050 in^2/in^2.	ACH(50) = 2.3, SLA = 0.00017 in^2/in^2.
Mechanical Ventilation	6 CFM	30 CFM	30 CFM

	BA Benchmark	Builder Standard (BSH)	WC4
Duct location	Supply: crawlspace; Return: crawlspace. R-5 insulation, supply area = 353.7 ft^2 , return area = 326.5 ft^2, duct air leakage (to the outside)= 12%.	Supply: crawlspace; Return: crawlspace. R-5 insulation, supply area = 551 ft^2 , return area = 102 ft^2, duct air leakage (to the outside) = 12%.	Supply: interior; Return: interior. R-5 insulation, supply area = 551 ft^2 , return area = 102 ft^2, duct air leakage (to the outside)= 8%.
Air Handler Location	Crawlspace	Crawlspace	Interior
Water heater	Electric 50 gal capacity, EF = 0.86, usage = 63.5 gal/day, set temp = 120ºF.	Electric 50 gal capacity, EF = 0.86, usage = 60 gal/day, set temp = 120ºF.	Electric 50 gal capacity, EF = 1, usage = 60 gal/day, set temp = 120ºF, Add-on Heat pump COP = 2.4.
Lighting	14% fluorescent, 86% incandescent.	10.1% fluorescent, 89.9% incandescent.	100% fluorescent.

Similar to WC3, simulations were run after each energy efficient measure was added to the BSH model, until the final WC4 model was reached (designated 'BSH ++ Radiant Barrier Under Roof Sheathing'). Also, the model results were based on TMY3 weather data and were not adjusted to reflect the actual weather conditions during the evaluation period. The impact of step-by-step addition of technologies and energy saving measures in WC4 for various energy uses is shown in Figure 32. The energy savings from these measures are shown in Table 18. The WC4 model saved $1,244 and $1,508 per year compared to the BSH model, based on local and national average utility rates of $0.097/kWh and $0.118/kWh, respectively.

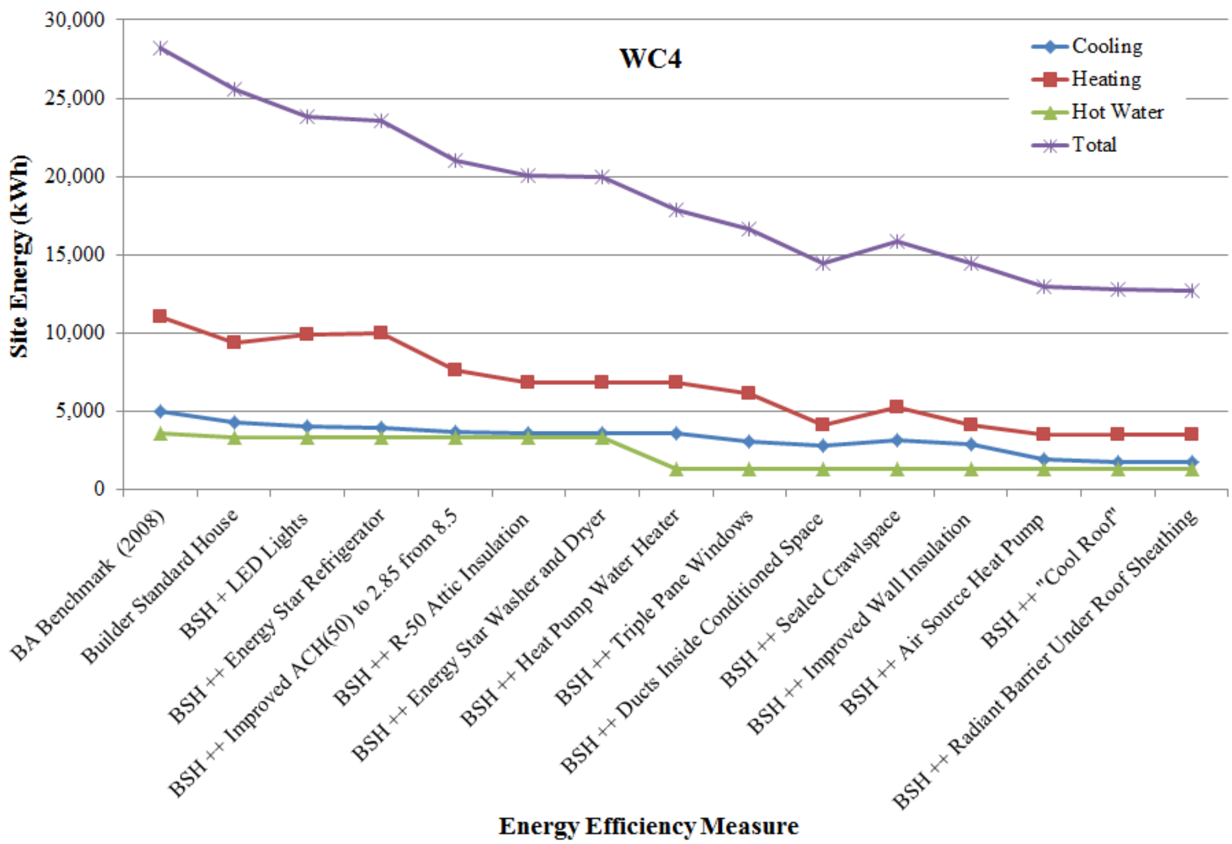


Figure 32. WC4 simulated energy consumption after adding individual energy efficiency measures.

Table 18. Energy savings with incremental energy efficiency measures in WC4

Increment	Site Energy (kWh)	Source energy (Mbtu)	National Energy Cost ($/yr)	Local Energy Cost ($/yr)	Cost Saving	Measure value ($/yr)	Package Saving ($/yr)
BA Benchmark (2008)	28,224	324	$3,319	$2,737			
Builder Standard House (BSH)	25,570	294	$3,007	$2,479	9%		
BSH + LED Lights	23,851	274	$2,805	$2,313	15%	$167	$167
BSH ++ Energy Star Refrigerator	23,599	271	$2,775	$2,288	16%	$24	$191
BSH ++ Improved ACH(50) to 2.85 from 8.5	20,980	241	$2,467	$2,034	26%	$254	$445
BSH ++ R-50 Attic Insulation	20,082	231	$2,362	$1,947	29%	$87	$532
BSH ++ Energy Star Washer and Dryer	19,985	229	$2,350	$1,938	29%	$9	$542
BSH ++ Heat Pump Water Heater	17,897	205	$2,105	$1,735	37%	$202	$744
BSH ++ Triple Pane Windows	16,622	191	$1,955	$1,612	41%	$124	$868
BSH ++ Ducts Inside Conditioned Space	14,412	165	$1,695	$1,397	49%	$214	$1,082
BSH ++ Sealed Crawlspace	15,812	182	$1,859	$1,533	44%	($136)	$946
BSH ++ Improved Wall Insulation	14,498	166	$1,705	$1,406	49%	$127	$1,074
BSH ++ Air Source Heat Pump	12,967	149	$1,525	$1,257	54%	$148	$1,222
BSH ++ "Cool Roof"	12,762	147	$1,501	$1,237	55%	$20	$1,242
BSH ++ Radiant Barrier Under Roof Sheathing	12,745	146	$1,499	$1,236	55%	$2	$1,244

6.2.3 Neutral Cash Flow Analysis

Table 19 shows the neutral-cash-flow analysis for WC4. Similar to WC3, the analysis was conducted by evaluating the incremental investment costs and energy savings of each energy efficient measure against the BSH model. The amortized annual costs are based on a 30 year loan with an interest rate of 7%. All energy costs and savings were estimated using a local utility rate of $0.097/kWh. The net cost of each measure shown was determined by subtracting the energy savings (‘Measure Value’) from the amortized investment costs. Negative annual cost indicates better than neutral cash flow for a particular measure. A HERS rating of 51 makes WC4 eligible for the energy efficient house rebate of $2,000.

Table 19. Neutral cash flow analysis for WC4

Increment	Site Energy (kWh)	Local Energy Cost ($/yr)	Energy Savings (kWh)	Measure Value ($/yr)	Package Savings	Incremental Investment Cost ($)	Amortized Annual Cost (30 year mortgage, 7% interest)	Annual Cost	Cash-flow Neutral?
BA Benchmark (2008)	28,224	$2,737							
Builder Standard House (BSH)	25,570	$2,479	2,654						
BSH + LED Lights	23,851	$2,313	1,719	$167	$167	$8,800	$703	$536	No
BSH ++ Energy Star Refrigerator	23,599	$2,288	252	$24	$191	$1,127	$90	$66	No
BSH ++ Improved ACH(50) to 2.85 from 8.5	20,980	$2,034	2,619	$254	$445	$2,588	$207	($47)	Yes
BSH ++ R-50 Attic Insulation	20,082	$1,947	898	$87	$532	$790	$63	($24)	Yes
BSH ++ Energy Star Washer and Dryer	19,985	$1,938	97	$9	$542	$1,598	$128	$118	No
BSH ++ Heat Pump Water Heater	17,897	$1,735	2,088	$202	$744	$1,282	$102	($100)	Yes
BSH ++ Triple Pane Windows	16,622	$1,612	1,275	$124	$868	$3,929	$314	$190	No
BSH ++ Ducts Inside Conditioned Space	14,412	$1,397	2,210	$214	$1,082	$1,955	$156	($58)	Yes
BSH ++ Sealed Crawlspace	15,812	$1,533	-1,400	($136)	$946	$5,393	$431	$566	No
BSH ++ Improved Wall Insulation	14,498	$1,406	1,314	$127	$1,074	$44,897	$3,584	$3,457	No
BSH ++ Air Source Heat Pump	12,967	$1,257	1,531	$148	$1,222	$4,039	$322	$174	No
BSH ++ "Cool Roof"	12,762	$1,237	205	$20	$1,242	$1,303	$104	$84	No
BSH ++ Radiant Barrier Under Roof Sheathing	12,745	$1,236	17	$2	$1,244	$2,191	$175	$173	No
Total Energy Efficiency Investment					$1,244	$79,892	$6,378	$6,378	No
REBATES / INCENTIVES									
Federal energy efficient builder house						$2,000			
TVA high efficiency water heater						$50			
Total Incremental Cost Including Incentives						$77,842	$6,215	$4,971	No

Overall, WC4 is not cost neutral. The simulated whole-house annual energy cost of the BSH was $2,479. The total incremental investment for all energy efficient investments in WC4, after adding the incentives, was $77,842, with an annualized cost of $6,215. When the annual energy costs savings are considered, the net annual cost of the efficiency measures was $4,971.

The GeoSpring® hybrid heat pump water heater, the placement of the ducts inside the conditioned space, air sealing to improve the ACH (50) to 2.85 and the R-50 attic insulation are the only measures that were better than cost neutral. The costs of improving ACH were estimated using BEopt. BEopt was also used to estimate the cost of placing the ducts inside the conditioned space. The first three measures are also the three largest energy saving measures included in WC4. Out of a total energy savings of 12,825 kWh, these measures comprised 46% of the savings. In contrast to WC3, increasing the attic insulation to R-50 is also better than cost neutral, with a cost reduction of $24/yr. Conventional cellulose insulation was used to achieve R-50 insulation in this case.

The ENERGY STAR refrigerator, clothes washer, and dryer have similar annual costs. These donated models are all premium models and thus include the incremental cost of amenities not included in the builder standard refrigerator. If an appropriate comparison of refrigerators with similar amenities was done, it is expected that the refrigerator would likely be better than cost neutral, while the washer and dryer would be closer to achieving cost neutrality.

The cool roof application applied in WC4 is less costly than the metal shakes used in WC3. However, because the cooling loads are already significantly reduced by triple pane windows, R-50 insulation, and the placement of the ducts inside the conditioned space, the performance enhancement due to the cool roof application is mitigated.

The roof installed on WC4 is an assembly that provides a radiant barrier facing into the attic plenum, 2 low-e surfaces facing into the inclined 1-in high air space, and passive ventilation from soffit to ridge. A slot is cut into the roof deck near the eave just above the soffit vent to provide make up air from the soffit vent and attic. As thermally induced airflows move up the inclined air space, cool make up air is pulled from the soffit and attic plenums to enhance thermal performance of the deck. The incremental cost of this system was $2,191. EnergyGuage does not provide an input option for this type of radiant barrier assembly. Therefore the energy performance is very likely underestimated. However, it is known that the impact of the radiant barrier will be mitigated by the ventilated attic with R-50 insulation over the ceiling joists, in addition to the location of the HVAC equipment in the conditioned space.

The addition of triple pane windows reduces the cooling energy use by approximately 15% and the heating energy use by 10%. With Oak Ridge, TN being in a heating dominated climate with cooling loads comprising on 44% of the required heating loads, the total annual energy savings are only $124, which are not enough to offset the incremental $3,929 over clear, double pane windows.

Interestingly, the model results indicate that sealing and semi-conditioning the crawlspace increases the cooling and heating energy use by 12% and 25% respectively. In the model, no insulation was included in the floor above the crawlspace, only R-10 on the crawlspace walls. The energy penalty attributed to sealing the crawlspace could be attributed to factors such as reduced ground coupling benefits in the summer, additional volumetric space to condition, and greater heat transfer through the floor. A recent ORNL report measured and analyzed the heat flux through the floor in WC3 and WC4 (Biswas et al., 2011). It was found that greater heat was lost through the floor into the crawlspace in WC4 compared to WC3, with a potential for heating penalty in WC4 in the winter. However, in humid climates such as Oak Ridge, TN, sealed crawlspaces are primarily utilized to address moisture management issues and not from an energy savings perspective.

6.3 CASH-FLOW COMPARISON OF THE TEST HOUSES

Cash-flow analysis of the two houses, based on a 30-year mortgage at 7% interest rate, resulted in net positive values, indicating a net annual cost to the customer. The total cost of WC3 was $445,800 ($164/ft^2) and the cost of WC4 was $422,000 ($155/ft^2). The analysis yielded net annual costs of $4144 and $4971 for WC3 and WC4, respectively.

It is important to note that WC3 and WC4 featured high-end flooring, molding, fixtures, etc. that resulted in higher costs. Further, many of the technologies used in WC3 and WC4 are experimental in nature and do not have sufficient market penetration to achieve economies of scale. A major objective of the Wolf Creek test houses was the demonstration of these new technologies. It is expected that with more widespread implementation in the residential building market, these energy efficiency measures will become more cost-effective.

7. WC3 AND WC4 OCCUPANCY SIMULATION

Comparing energy efficiency of houses cannot be done unless energy is being used. An unoccupied house is not sufficient to determine the energy efficiency of envelopes and technologies in the research houses because occupants add sensible and latent heat to the space that put a load on the HVAC system. Appliances, plug loads, and lighting also add sensible heat to the space as well as use energy. Some appliances such as washers, dryers, and dishwashers also add latent heat to the space. Occupants also create a load on the domestic hot water (DHW) system when showers and sink faucets are used.

Putting families in the test houses make the comparison difficult because each family would have different living habits. The answer to this problem is to simulate occupancy. The following sections describe the details of the appliance control and occupancy simulation at WC3 and WC4.

7.1 OCCUPANCY SIMULATION PROTOCOLS

In the Wolf Creek houses, the automated DHW draws, plug load draws, appliance use, and lighting use were based on the Building America Research Benchmark Update December 2009 (Hendron and Engebrecht, 2010). The following information is summarized from an ORNL report (Boudreaux and Gehl, 2011).

Table 20. Appliance Control and Occupancy Simulation Targets

System	Control	WC3 and WC4
Washer Cycles	LabVIEW®	6/week
Dryer Cycles	LabVIEW®	5/week
Dishwasher Cycles	LabVIEW®	6/week
DHW	LabVIEW®	60 gal/day
Lighting Load	ZWave®/Insteon	1958Wh/day (WC3) 1160Wh/day (WC4)
Sensible Heat (Occupants + MELS)	ZWave®/Insteon	10404Wh/weekend day 10910Wh/week day

Table 20 describes the systems that are simulated and the controls used to automate the simulation. Two separate systems are used. The first is a custom LabVIEW® virtual instrument system that uses a digital USB DAQ device to control relays at the different appliances to turn them on and off and control settings. The other is an Insteon (WC3 and WC4) based control system for lighting and sensible heat load control.

An ftp server keeps the most current profile. Each night the computers at each house run a scheduled task that downloads the profile and uses this new file the next day. This feature makes it very simple to populate all the houses with the same profile at the same time.

In March 2010, an alarm system was implemented in the research houses which sends emails if the data values went outside user defined ranges. This was implemented to help catch failures of the simulated occupancy controls in a timely manner. Some alarms check data every hour and others once a day. The alarms were programmed in RTMC Pro software from Campbell Scientific.

Following is a list of the subsystems that are controlled:

1. **Domestic hot water:** This included hot water usage in showers, baths and sinks, and the details are shown in Table 21.

Table 21. Shower Profile

Master Shower Start Time	Master Shower Gallons
7:00	20
8:30	5
12:00	5
17:00	10
21:00	20

2. **Clothes washer and dryer:** Whirlpool donated their high-end horizontal axis washer and matching dryer because of their potential to reduce energy and water use and because of future enhancements using Whirlpool's load manager. The washer can steam wash and the dryer can steam dry.
3. **Dishwasher**
4. **Refrigerator:** The refrigerator and freezer are stocked with bottles of water for thermal mass. The doors are not being opened automatically.
5. **Range:** There is no range control in the Wolf Creek houses.
6. **Lighting load:** To compute the total hard wired lighting load per year, Eqns. (7.1)-(7.3) were used, where FFA is finished floor area. Eq. (7.1) shows the Interior Lighting Load, Eq. (7.2) shows the Garage Lighting Load, and Eq. (7.3) shows the Exterior Lighting Load.

$$ILL = 0.27 * (0.8 * (FFA * 0.737 + 467) kWh / yr \tag{7.1}$$

$$GLL = 0.27 * (GarageArea * 0.3 + 29) kWh / yr \tag{7.2}$$

$$ELL = 0.27 * (FFA * 0.17) kWh / yr \tag{7.3}$$

For WC3 (100% CFL), using values from Table 20 yielded 1958 Wh/day. For WC4 (100% LED) the same schedule was used as WC3, but the daily lighting energy target was less. Using Eqns. (7.1)-(7.3), after replacing the factor 0.27 with 0.16 for LED lighting energy, yielded 1160 Wh/day for WC4. Table 22 shows the light wattages and backgrounds for each circuit used for lighting in WC3 and WC4. The hourly lighting energy consumption is shown in Table 23. The schedule shows the time, in minutes, that each lighting fixture should be on during each hour of the day. Since WC4 has 100% LED lighting, the time on for the lighting is the same as WC3 but the energy targets are less. Note that lighting profile was randomized over an hour so lights will not turn on at the top of an hour but at a random time within the hour.

Table 22. Light wattages and backgrounds for each circuit used for lighting in WC3 and WC4

Light	Net Wattage (WC3)	Watt Node Channel	Measured Wattage (WC3)	Background Wattage (WC3)	Background Wattage (WC4)
Bonus Room Lights	157.175	bath_lts_Tot	159.8	2.625	2.7
Master Bath Fan	34.505	bath_lts_Tot	37.13	2.625	2.7
Master Bath Vanity Lights	81.175	bath_lts_Tot	83.8	2.625	2.7
Upstairs Bath Vanity Lights	52.875	bath_lts_Tot	55.5	2.625	2.7
Bedroom 2 Lights	37.125	bed_tot	38.5	1.375	11.6
Master Bed Lights	111.025	bed_tot	112.4	1.375	11.6
Front Porch Lights	107.375	out_lts	108	0.625	1.5
Dining Room Lights	110.5	lvl1_lts	115.5	5	2
Kitchen Lights	264.9	lvl1_lts	269.9	5	2
Living Room Lights	156.5	lvl1_lts	161.5	5	2

Table 23. WC3 and WC4 Lighting Schedule

	Room	Bonus Room Lights	Master Bath Fan	Master Bath Vanity Lights	Upstairs Bath Vanity Lights	Bedroom 2 Lights	Master Bed Lights	Dining Room Lights	Kitchen Lights	Living Room Lights	Front Porch Lights
	Watt	157.2	34.53	81.2	52.9	37.1	111	112	266.4	158	107.38
Hour of the Day	Needed Watts/hr										
1	16.07						8.68				
2	16.07						8.68				
3	16.07						8.68				
4	16.07						8.68				
5	46.21			17.74			12				
6	96.34	10		20	20.86	10	10				
7	108.48			10	10	5	5	10	12.41		
8	96.34			10	10			10	10	4.15	
9	44.25							10	5.76		
10	31.13									11.82	
11	31.13									11.82	
12	31.13									11.82	
13	31.13									11.82	
14	31.13									11.82	
15	31.13									11.82	
16	50.13								10	2.18	
17	108.48							10.54	20		
18	150.58							20	20	9.28	
19	202.86	18						10	10		51.76
20	243	20			41.7	20			20	20	
21	252.6	30			20	20	35.13			30	
22	172.67			20			20		6.67	30	
23	95.95			30			29.92				
24	39.16						21.17				
Total (WC3)	1958.11	204.36	0	145.81	90.42	34.01	310.72	131.68	509.91	438.57	92.63
Circuit Total (WC3)		474.6				344.73		1080.15			92.63
WC3 Background		63				33		120			15
WC4 Background		64.8				278.4		48			36

7. **Plug loads:** Sensible heat generators were used in WC3 and WC4 as plug loads, to simulate MELS sensible heat, range sensible heat, and sensible heat from occupants. Two space heaters,

one 1500 W ceramic heater in the downstairs great room and one 500 W ceramic heater in the master bath were controlled to generate sensible heat. Table 24 gives the wattages of each heater.

Table 24. Heater wattages

	Downstairs “1500W”	Upstairs “500W”
WC3	1350 W	603 W
WC4	1430 W	648 W

Using the Building America Research Benchmark, the sensible heat output were computed for the whole day for miscellaneous plug loads (includes fixed miscellaneous electric loads, variable miscellaneous electric loads and fixed gas electric loads) plus plug-in lights, and range. The following equations [(7.4)-(7.6)] give the daily total sensible heat from miscellaneous plug loads (MELs), plug-in lighting (PLL), and range (RL).

$$MEL[kWh]=[0.12(469+78N_{br}+0.122FFA)+ 0.83(1281+196N_{br}+0.345FFA)]/365 \quad (7.4)$$

$$PLL[kWh]=0.2(0.737FFA+467)/365 \quad (7.5)$$

$$RL[kWh]=0.4(302+101N_{br})/365 \quad (7.6)$$

The BA Benchmark hourly fractions of total daily use profiles for MELs, plug-in lighting and the range were used in building the final profile. Next, the hourly sensible heat added to the space from people was computed. According to the BA Benchmark, 2.64 occupants were assumed for these homes. Table 25 shows the fraction of total occupants per zone of house (living or bedroom) and time of day, and sensible heat added to the space from occupants per zone and time of day.

Table 25. Sensible heat added to space from occupants (same for all houses)

	Fraction of total people				**Sensible Heat added to Space (Wh)**			
Hour of Day	**Weekday living**	**Weekday bedrooms**	**Weekend living**	**Weekend bedroom**	**Weekday living**	**Weekday bedrooms**	**Weekend living**	**Weekend bedroom**
1	0.000	1.000	0.000	1.000	0	162.5	0.0	162.5
2	0.000	1.000	0.000	1.000	0.0	162.5	0.0	162.5
3	0.000	1.000	0.000	1.000	0.0	162.5	0.0	162.5
4	0.000	1.000	0.000	1.000	0.0	162.5	0.0	162.5
5	0.000	1.000	0.000	1.000	0.0	162.5	0.0	162.5
6	0.000	1.000	0.000	1.000	0.0	162.5	0.0	162.5
7	0.500	0.500	0.000	1.000	89.0	81.2	0.0	162.5
8	0.500	0.330	0.500	0.500	89.0	53.6	89.0	81.2
9	0.290	0.000	0.670	0.000	51.6	0.0	119.2	0.0
10	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0
11	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0
12	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0
13	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0
14	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0
15	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0

16	0.125	0.000	0.500	0.000	22.2	0.0	89.0	0.0
17	0.125	0.000	0.670	0.000	22.2	0.0	119.2	0.0
18	0.500	0.000	0.670	0.000	89.0	0.0	119.2	0.0
19	1.000	0.000	0.670	0.000	178.0	0.0	119.2	0.0
20	1.000	0.000	0.670	0.000	178.0	0.0	119.2	0.0
21	1.000	0.000	0.670	0.000	178.0	0.0	119.2	0.0
22	1.000	0.000	1.000	0.000	178.0	0.0	178.0	0.0
23	0.500	0.500	0.500	0.500	89.0	81.2	89.0	81.2
24	0.000	1.000	0.000	1.000	0.0	162.5	0.0	162.5
Total					**1296.8**	**1353.5**	**1694.2**	**1462.4**

Next, the MELs, plug-in lighting and range were added to the occupants' sensible heat. For these loads, 75% was simulated with the downstairs heater and 25% with the upstairs heater. The results for total sensible heat target per zone and time of day are presented in Table 26. Note that the heater profile was randomized such that the heaters do not turn on at the top of an hour but at a random time within the hour.

Table 26. WC3 and WC4 sensible heat generator profile

	Energy (Wh)				**Time (minutes)**			
Hour of Day	**Weekday living**	**Weekday bedrooms**	**Weekend living**	**Weekend bedroom**	**Weekday living**	**Weekday bedrooms**	**Weekend living**	**Weekend bedroom**
1	192.3	226.6	192.3	226.6	8.55	22.55	8.55	22.55
2	182.2	223.2	182.2	223.2	8.10	22.21	8.10	22.21
3	175.4	221.0	175.4	221.0	7.80	21.99	7.80	21.99
4	175.4	221.0	175.4	221.0	7.80	21.99	7.80	21.99
5	171.5	219.7	171.5	219.7	7.62	21.86	7.62	21.86
6	200.6	229.3	200.6	229.3	8.91	22.82	8.91	22.82
7	328.5	161.1	239.5	242.3	14.60	16.03	10.64	24.11
8	345.7	139.2	345.7	166.8	15.37	13.85	15.37	16.60
9	267.1	71.8	334.7	71.8	11.87	7.15	14.88	7.15
10	211.6	63.1	278.4	63.1	9.40	6.28	12.37	6.28
11	213.8	63.9	280.6	63.9	9.50	6.36	12.47	6.36
12	217.4	65.1	284.2	65.1	9.66	6.47	12.63	6.47
13	215.8	64.5	282.6	64.5	9.59	6.42	12.56	6.42
14	215.6	64.5	282.4	64.5	9.58	6.42	12.55	6.42
15	224.6	67.5	291.4	67.5	9.98	6.71	12.95	6.71
16	244.1	74.0	310.9	74.0	10.85	7.36	13.82	7.36
17	305.2	94.3	402.2	94.3	13.56	9.39	17.88	9.39
18	452.3	121.1	482.5	121.1	20.10	12.05	21.44	12.05
19	557.3	126.5	498.6	126.5	24.77	12.58	22.16	12.58
20	545.0	122.4	486.3	122.4	24.22	12.18	21.61	12.18
21	543.4	121.8	484.6	121.8	24.15	12.12	21.54	12.12
22	517.0	113.0	517.0	113.0	22.98	11.25	22.98	11.25
23	372.4	175.7	372.4	175.7	16.55	17.49	16.55	17.49
24	237.7	241.7	237.7	241.7	10.57	24.05	10.57	24.05
Zone Totals	**7112.2**	**3291.9**	**7509.5**	**3400.8**				
Daily Totals	**10404.1**		**10910.3**					

8. **Latent heat:** There is no latent heat generation in the Wolf Creek houses.

8. MAJOR FINDINGS AND CONCLUSIONS

This report summarizes the annual energy performance of two advanced energy efficient houses and compares them to a builder standard house (BSH) representative of a standard, IECC 2006 code-certified, all-electric house built around 2005–2008. The two houses that were evaluated were designated WC3 and WC4, and were built in Oak Ridge, TN. This report covers data collected from WC3, and WC4 from December 1, 2010 to November 30, 2011.

The total annual energy usages of the two houses were similar; 12,685 kWh in WC3 and 12,605 kWh in WC4. The test houses consumed about 51% less energy than the simulated BSH consumption. The three largest energy consumers in the test houses were space heating, space cooling and water heating, in that order. The plug loads, which were designed to simulate occupancy following the Building America benchmark protocol, also accounted for a major fraction of the energy consumption.

The WC3 ground source water-to-air heat pump (GSHP or WAHP) performed better than the air source heat pump (ASHP) in WC4 during the heating season. The GSHP had a performance advantage for heating due to its favorable entering water temperature (EWT) compared to the ASHP, whose performance was affected by the low outdoor air temperatures in winter. In summer, the ASHP performed better than the GSHP. These factors are reflected in the higher heating and lower cooling energy consumptions in WC4. The energy consumption of the electric heat pump water heater (HPWH) in WC4 was about 20% less than the water-to-water heat pump (WWHP) in WC3.

Both the GSHP and ASHP were effective in maintaining the indoor temperatures in the respective houses close to the thermostat set points for most of the time during the monitoring period, and especially during the peak heating and cooling months. Major deviations from the mean temperatures were seen primarily during the shoulder months of April and October, when switching of the space conditioning mode and the thermostat set points took place. Relative humidity levels in both houses were maintained within the human comfort zone throughout the year.

An engineering simulation model, using local TMY3 weather data, was used to compare the performance of the two houses with 2008 Building America (BA) Benchmark, and to estimate the effectiveness of individual energy efficiency features. Compared to the BA benchmark, both WC3 and WC4 showed energy savings of about 55%. The BA benchmark house had a Home Energy Rating System (HERS) score of 111, while WC3 and WC4 had HERS scores of 46 and 51.

The total construction costs of WC3 and WC4 were \$445,800 (\$164/ft^2) and \$422,000 (\$155/ft^2). Neutral cash flow analyses, using a 30 year mortgage at 7% interest, were performed to compare the energy cost savings to the incremental energy efficiency costs. The neutral cash flow analysis also considered all the federal and state rebates and incentives for the energy efficiency measures. While some specific energy efficiency measures were cost-effective, neither house was cash-flow neutral overall, i.e. each had a net annual cost for the customer. However, it is important to note that WC3 and WC4 were intended for demonstrations of new and experimental technologies, many of which do not yet have sufficient market penetration. It is expected that with more widespread implementation in the residential building market and additional technical innovations and improvements, these energy efficiency measures will become more cost-effective.

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APPENDIX A. MONTHLY DASHBOARDS

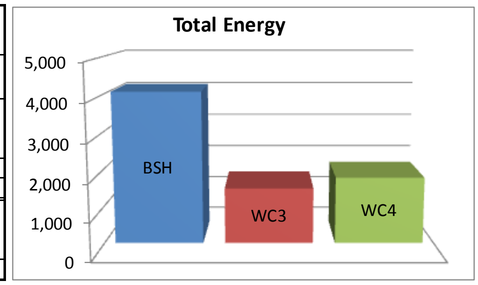
Dashboard Report

12/1/10 to 12/31/10

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	4,109	$402.03					
WC3	1,515	$154.31	6.72	2.26	0.34	0.954	163.10
WC4	1,809	$182.42	7.91	2.52	0.32	0.902	108.09

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	36.86%	38.38%	12/7	12/7	9:00
WC4	44.02%	45.38%	12/15	12/15	20:00

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



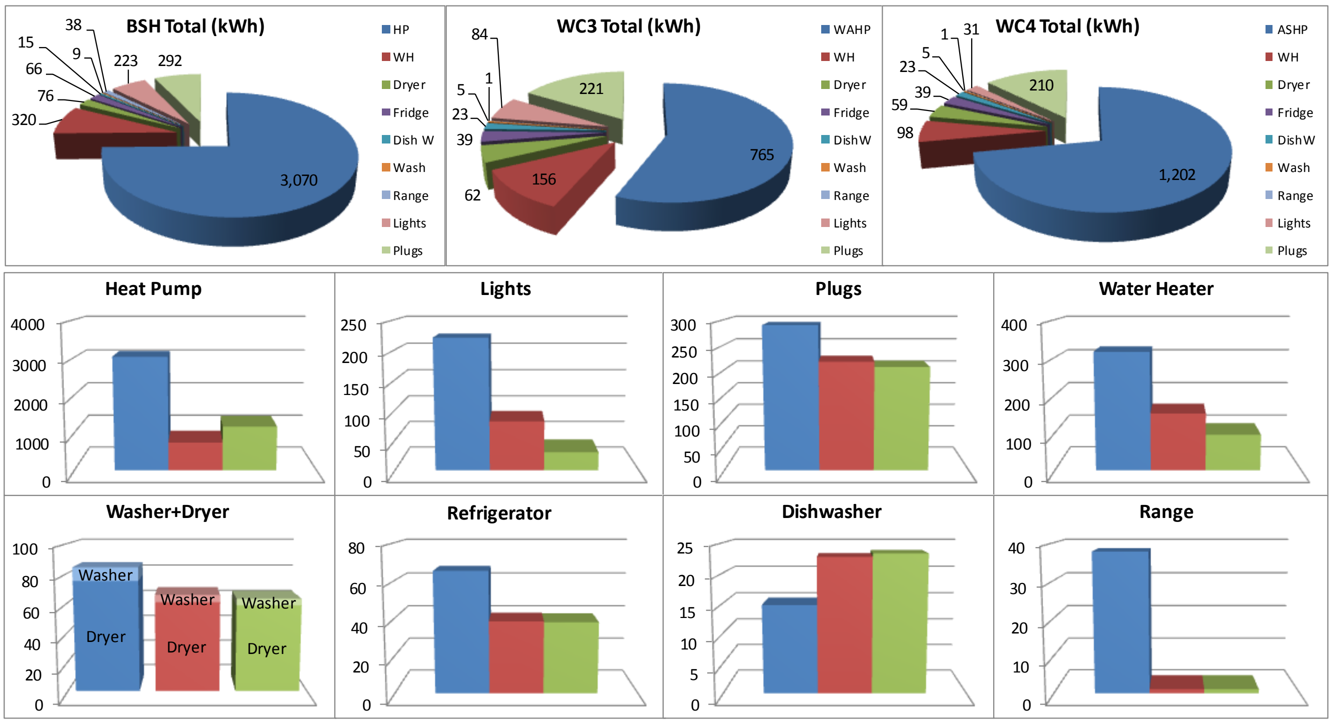


Figure A - 1. December 2010 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

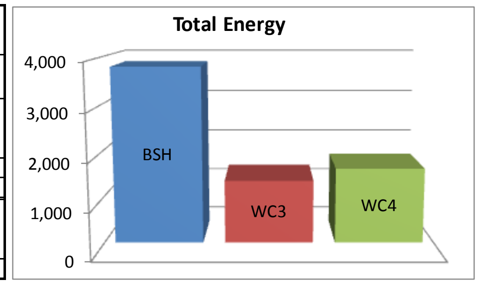
Dashboard Report

1/1/11 to 1/31/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	3,812	$376.56					
WC3	1,369	$141.46	7.37	2.24	0.30	1.058	144.05
WC4	1,632	$166.83	7.72	2.30	0.30	1.013	106.32

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	35.92%	37.57%	1/15	1/14	9:00
WC4	42.83%	44.30%	1/9	1/13	22:00

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



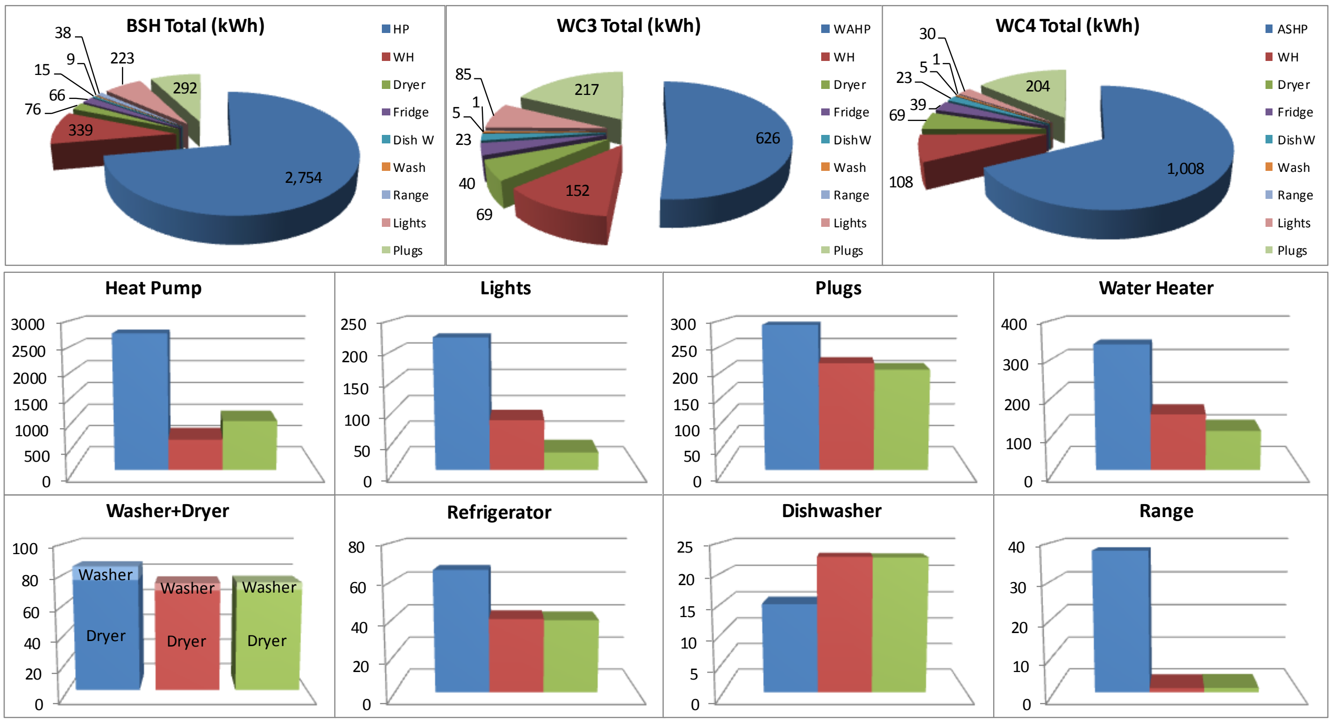


Figure A - 2. January 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

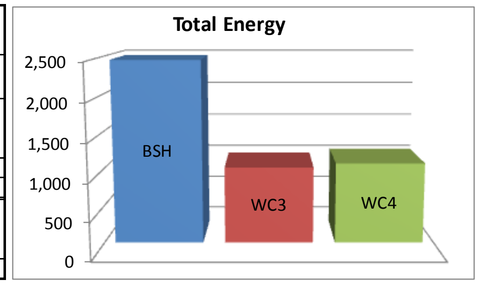
Dashboard Report

2/1/11 to 2/28/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	2,472	$244.71					
WC3	1,039	$108.43	5.44	1.55	0.28	0.986	141.13
WC4	1,095	$113.78	7.34	1.73	0.24	0.915	107.43

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	42.01%	44.31%	2/9	2/2	20:00
WC4	44.29%	46.49%	2/11	2/11	8:00

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



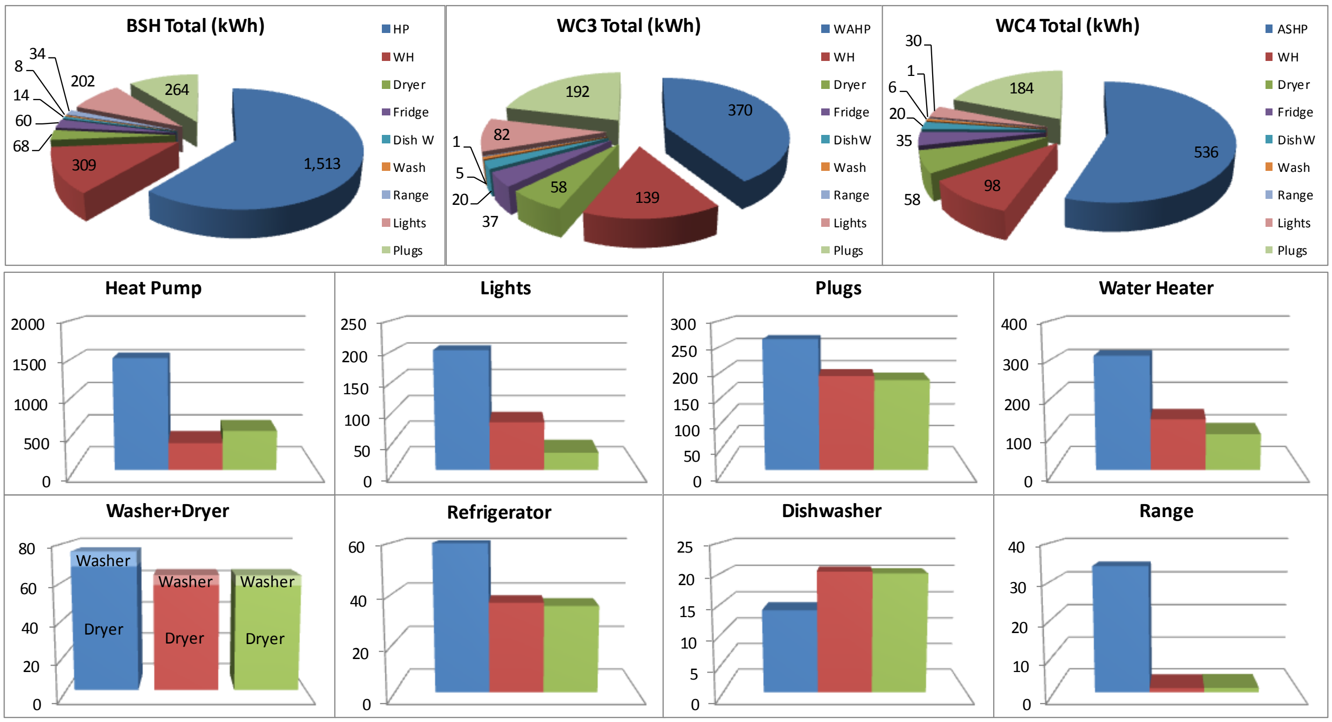


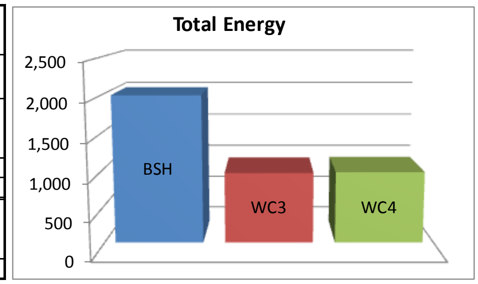
Figure A - 3. February 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

Dashboard Report

3/1/11 to 3/31/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	2,007	$204.24					
WC3	964	$103.13	5.00	1.30	0.26	1.072	134.79
WC4	975	$104.17	6.16	1.41	0.23	1.017	107.75
House	Total	Cost	Peak Day	Peak Hour			
BSH	100.00%	100.00%					
WC3	48.02%	50.49%	3/6	3/12	11:00		
WC4	48.56%	51.00%	3/27	3/2	8:00		

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



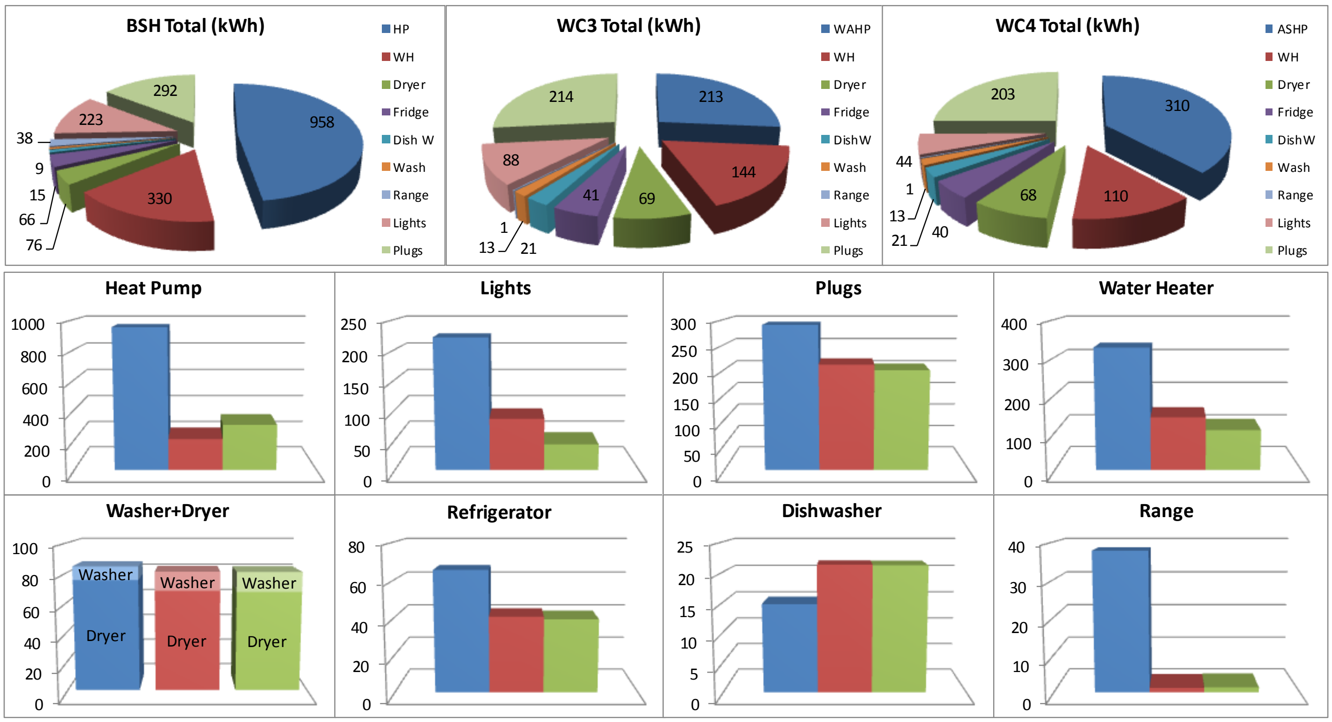


Figure A - 4. March 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

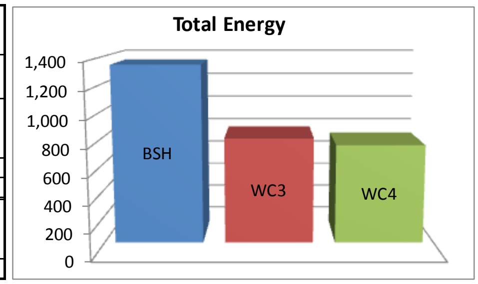
Dashboard Report

4/1/11 to 4/30/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	1,349	$139.20					
WC3	800	$86.53	5.24	1.12	0.21	0.880	132.61
WC4	750	$81.67	5.44	1.23	0.23	0.911	111.09

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	59.33%	62.16%	4/11	4/6	20:00
WC4	55.58%	58.67%	4/28	4/28	8:00

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



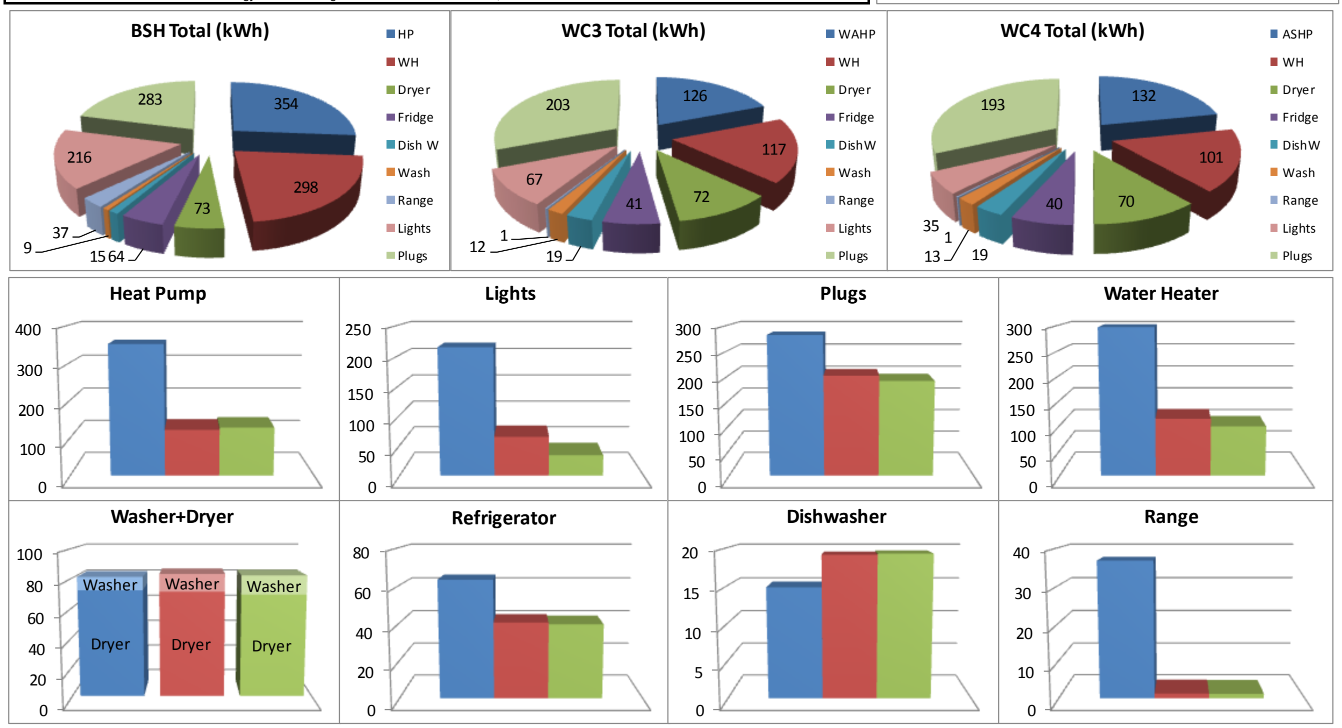


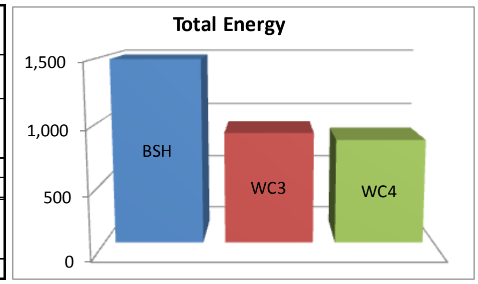
Figure A - 5. April 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

Dashboard Report

5/1/11 to 5/31/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	1,489	$152.18					
WC3	902	$96.04	6.37	1.21	0.19	0.812	130.49
WC4	846	$90.66	5.12	1.30	0.25	0.799	113.89
House	Total	Cost	Peak Day	Peak Hour			
BSH	100.00%	100.00%					
WC3	60.60%	63.11%	5/11	5/25	20:00		
WC4	56.82%	59.58%	5/29	5/25	20:00		

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



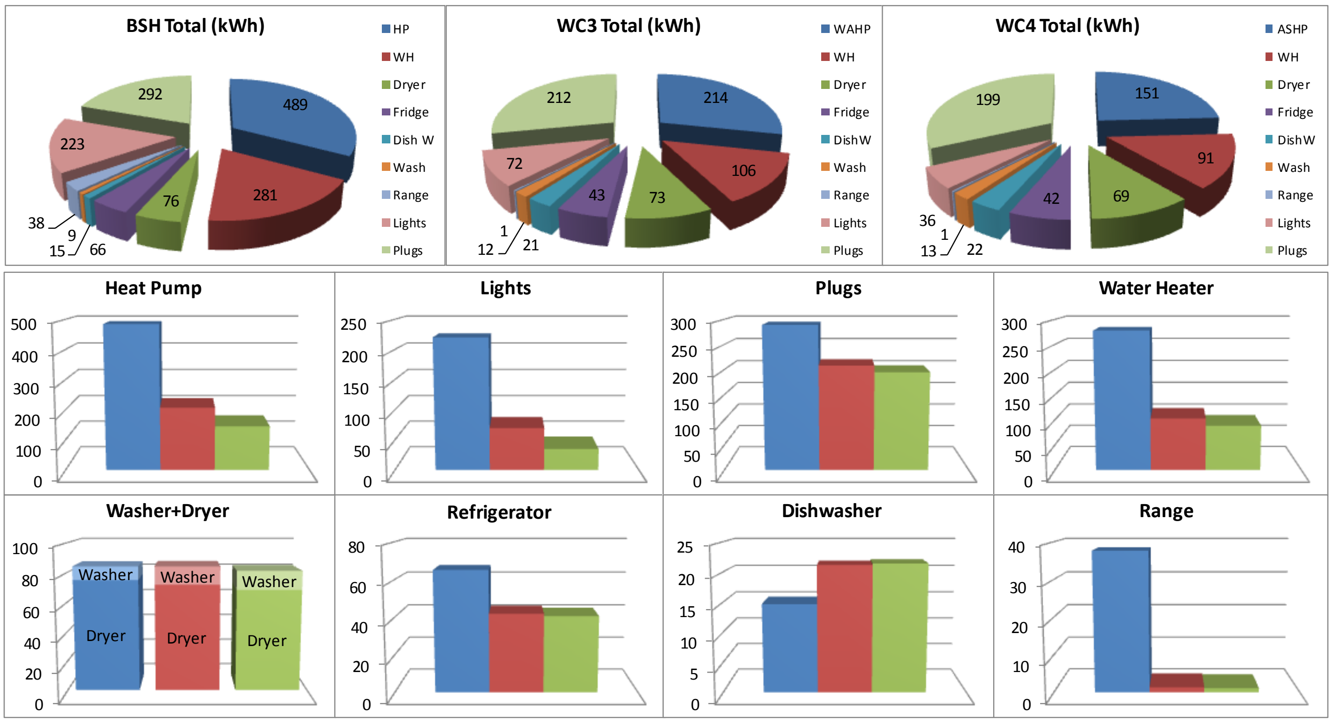
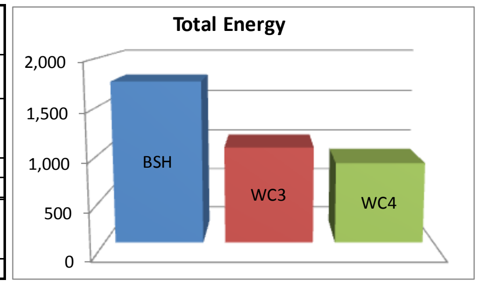


Figure A - 6. May 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

Dashboard Report								
6/1/11			to			6/30/11		
						Water Heater		
House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	
BSH	1,751	$177.61						
WC3	1,047	$110.13	5.53	1.45	0.26	0.703	124.65	
WC4	876	$93.75	5.95	1.30	0.22	0.676	117.01	
House	Total	Cost	Peak Day	Peak Hour				
BSH	100.00%	100.00%						
WC3	59.81%	62.00%	6/11	6/1	20:00			
WC4	50.05%	52.78%	6/1	6/8	20:00			

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



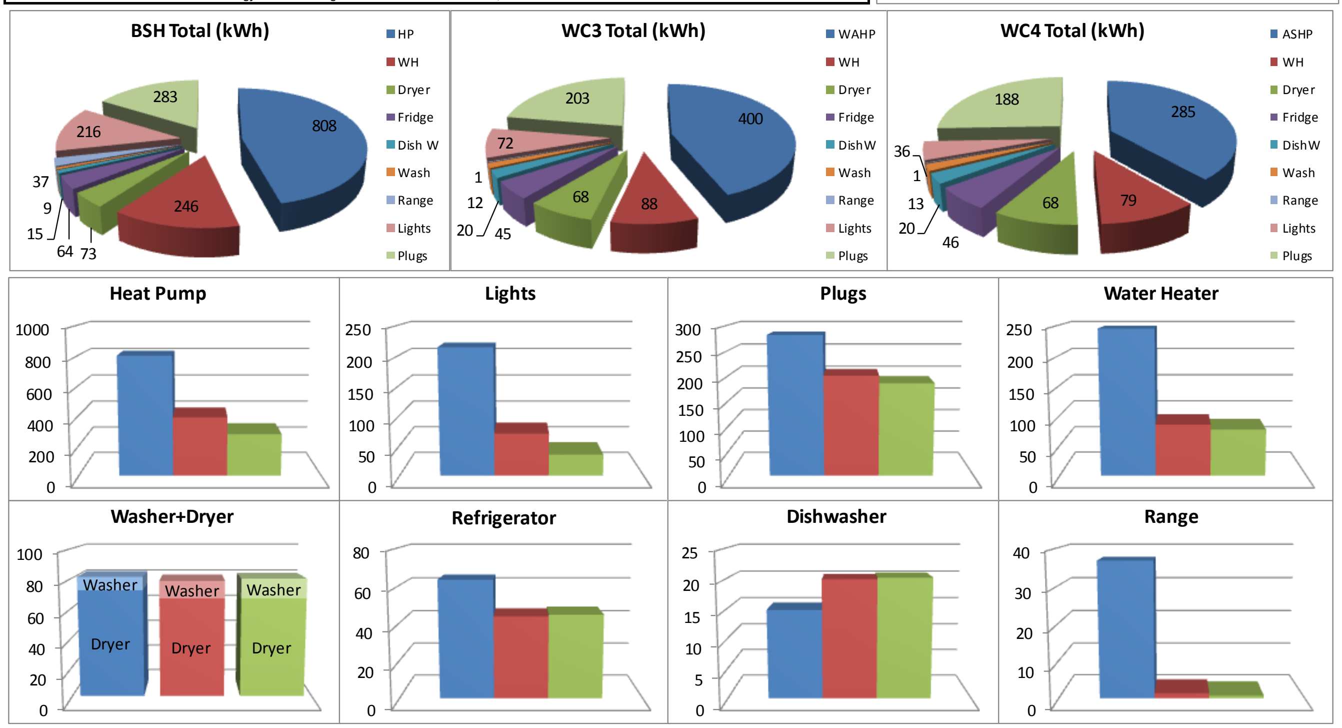
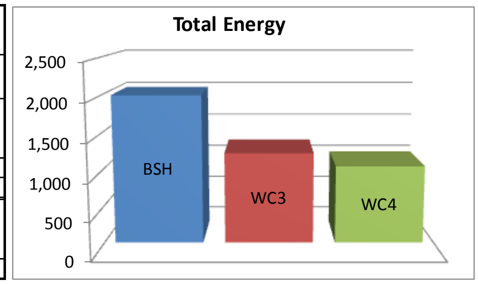


Figure A - 7. June 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

Dashboard Report							
7/1/11		to			7/31/11		
						Water Heater	
House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU
BSH	2,007	$209.10					
WC3	1,232	$132.09	5.77	1.66	0.29	0.658	123.36
WC4	1,055	$114.50	5.56	1.52	0.27	0.638	119.75
House	Total	Cost	Peak Day	Peak Hour			
BSH	100.00%	100.00%					
WC3	61.38%	63.17%	7/14	7/20	20:00		
WC4	52.56%	54.76%	7/31	7/29	22:00		

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



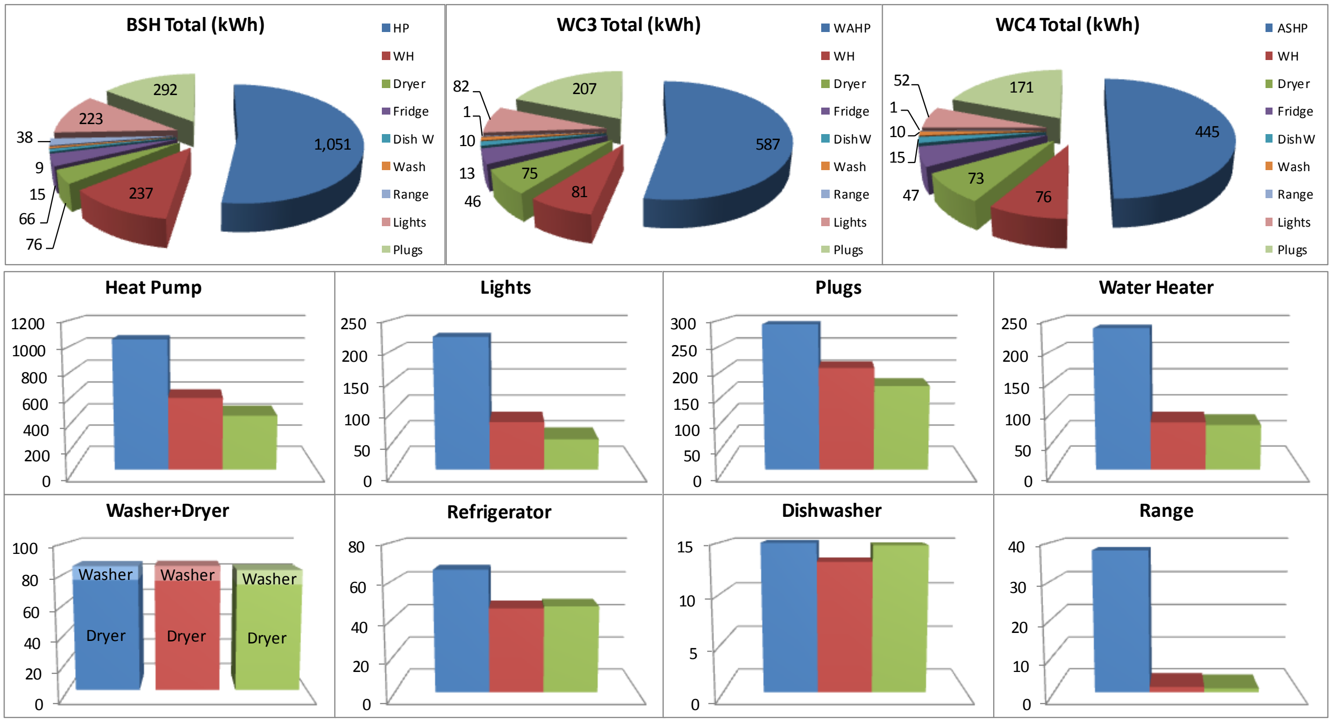


Figure A - 8. July 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

Dashboard Report

8/1/11		to				8/31/11	
						Water Heater	
House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU
BSH	1,919	$201.39					
WC3	1,182	$127.82	5.50	1.59	0.29	0.630	124.43
WC4	1,093	$118.89	6.27	1.59	0.25	0.644	122.05
House	Total	Cost	Peak Day	Peak Hour			
BSH	100.00%	100.00%					
WC3	61.62%	63.47%	8/21	8/31	20:00		
WC4	56.96%	59.03%	8/20	8/24	20:00		

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load

Figure A - 9. August 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

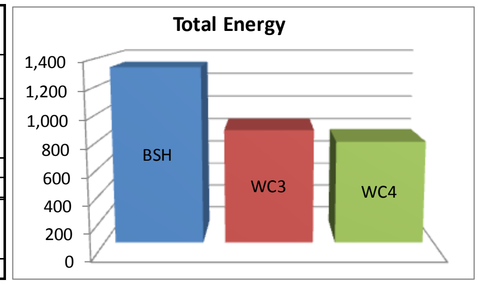
Dashboard Report

9/1/11	to	9/30/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	1,331	$141.61					
WC3	864	$95.34	5.33	1.20	0.23	0.767	118.59
WC4	778	$86.79	5.74	1.28	0.22	0.648	114.66

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	64.92%	67.32%	9/3	9/3	11:00
WC4	58.44%	61.29%	9/3	9/21	20:00

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



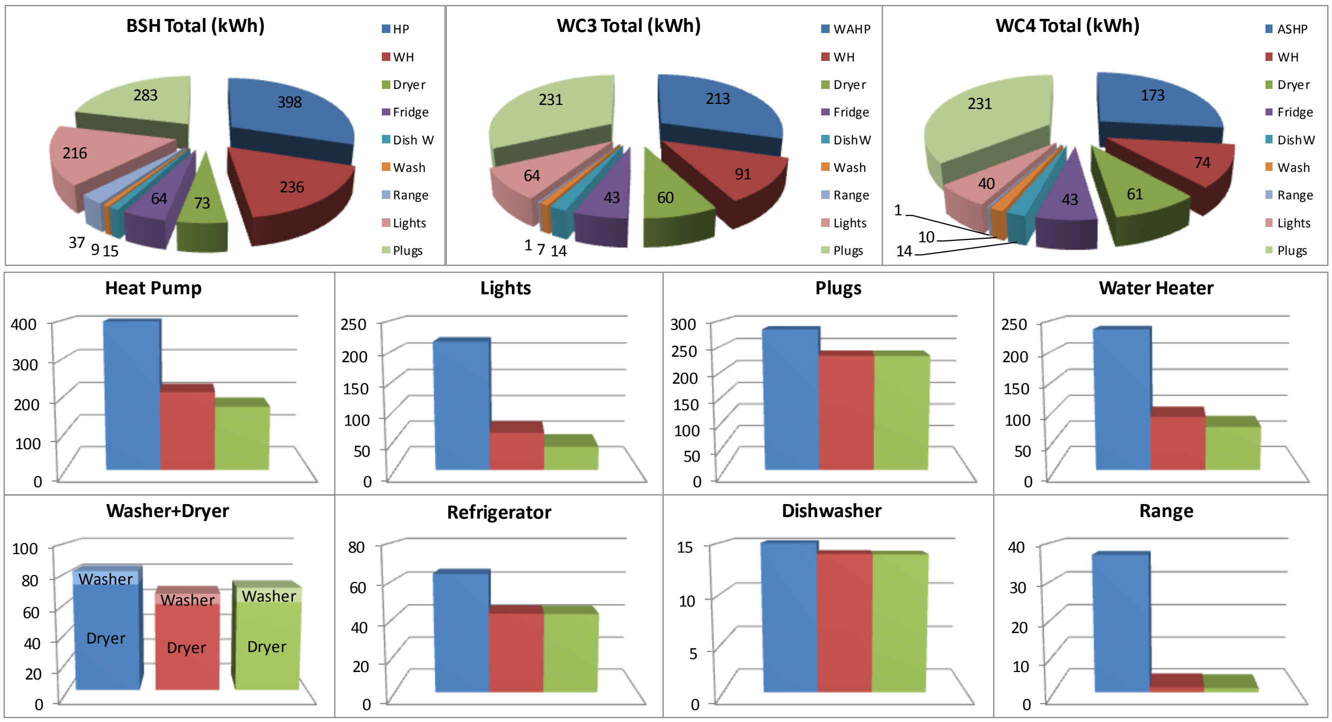


Figure A - 10. September 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

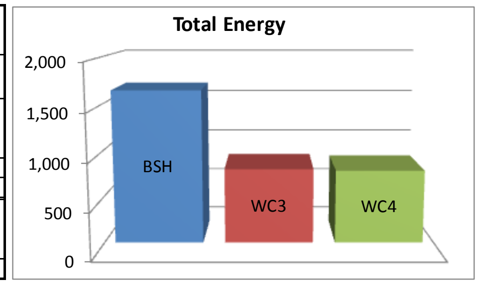
Dashboard Report

10/1/11 to 10/31/11

House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU
BSH	1,657	$170.87					
WC3	813	$88.75	6.66	1.09	0.16	0.758	134.59
WC4	797	$87.18	4.50	1.18	0.26	0.728	116.48

House	Total	Cost	Peak Day	Peak Hour	
BSH	100.00%	100.00%			
WC3	49.05%	51.94%	10/20	10/20	14:00
WC4	48.07%	51.02%	10/20	10/20	20:00

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



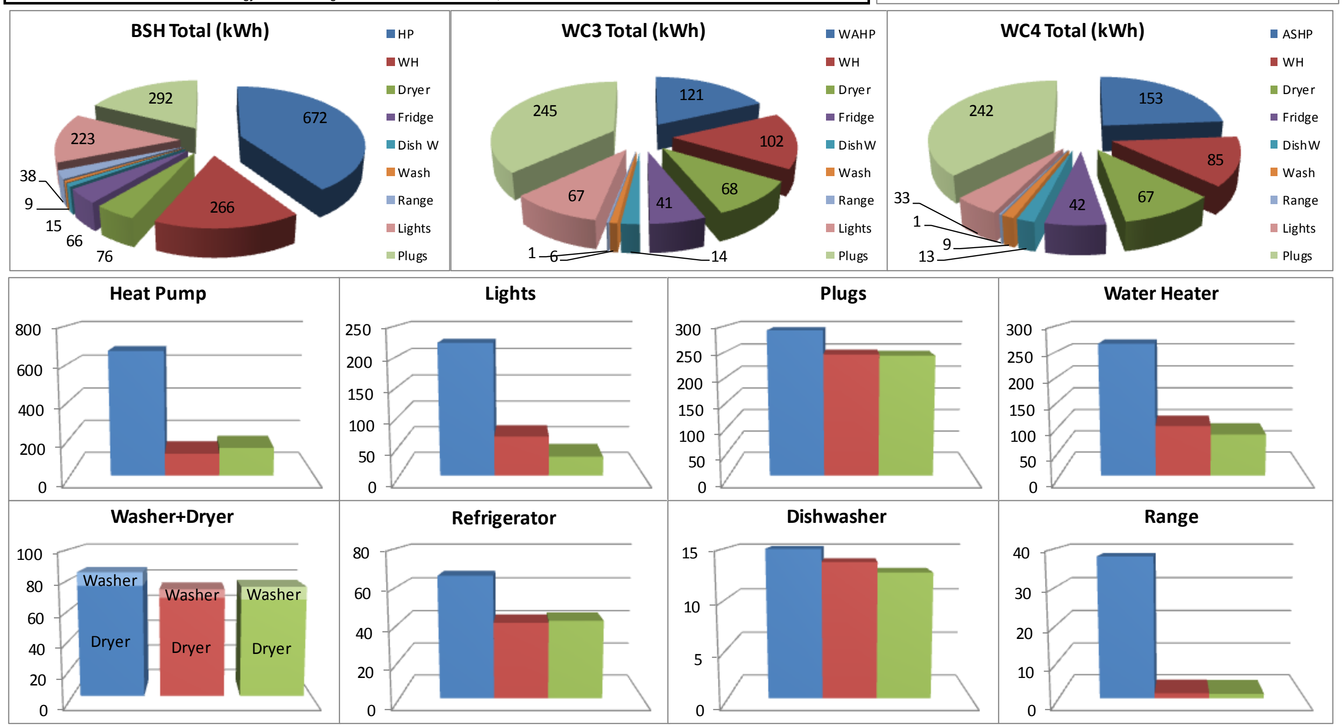
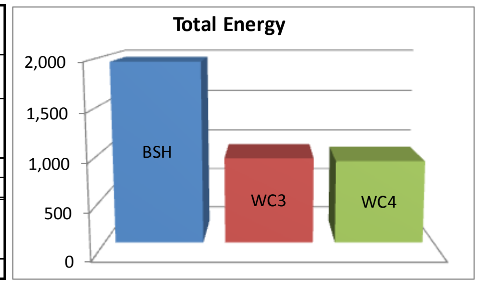


Figure A - 11. October 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.

Dashboard Report

11/1/11				to			11/30/11
						Water Heater	
House	Total[1,2]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU
BSH	1,957	$198.97					
WC3	931	$99.74	4.56	1.29	0.28	0.842	137.31
WC4	899	$96.65	4.97	1.30	0.26	0.781	114.72
House	Total	Cost	Peak Day	Peak Hour			
BSH	100.00%	100.00%					
WC3	47.57%	50.13%	11/30	11/30	13:00		
WC4	45.94%	48.58%	11/30	11/30	12:00		

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load



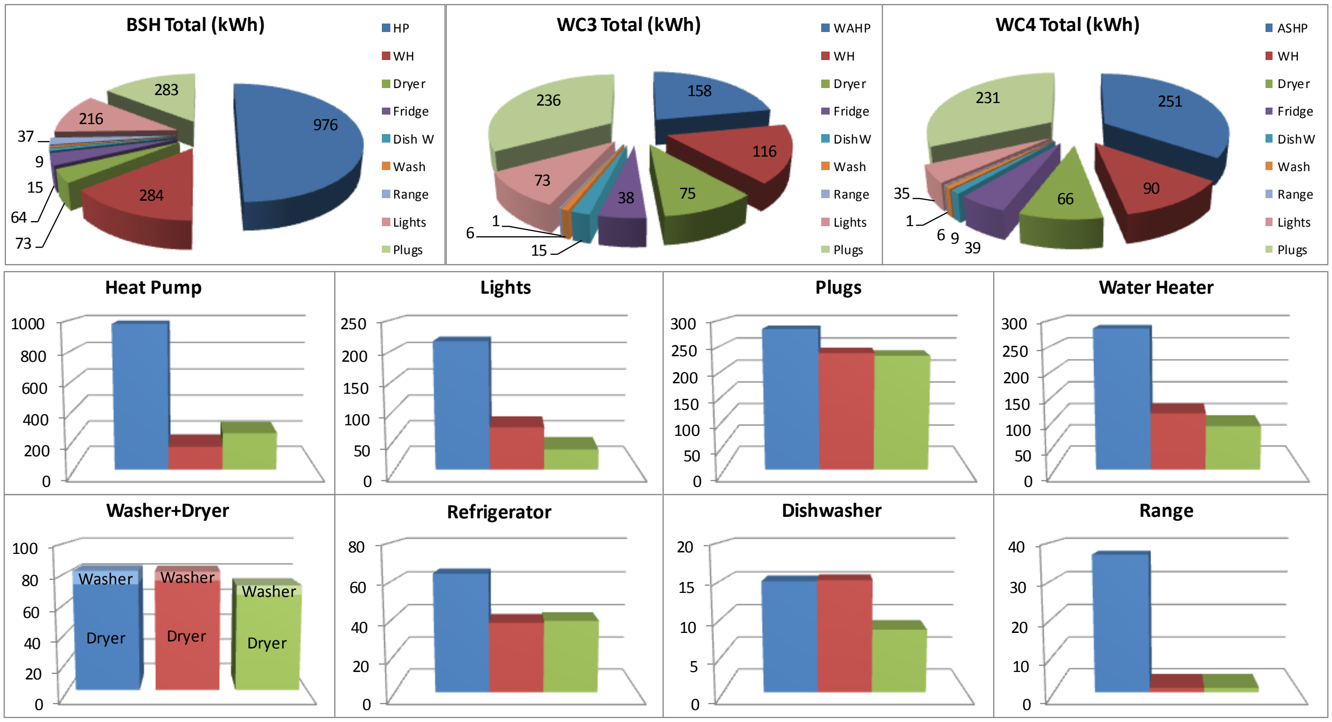


Figure A - 12. November 2011 dashboard; blue bar = BSH, red = WC3, and green = WC4; units = kWh.