ORNL/TM-2012/591

Campbell Creek Research Homes

FY 2012 Annual Performance Report
Test Results October 1, 2011—September 30, 2012

VA Contract No. 0035916

December 2012

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Energy and Transportation Science Division

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ABBREVIATIONS, ACRONYMS, and INITIALISMS

CC1	Builder House
CC2	Retrofit House
CC3	High-performance House
CDD	cooling degree days
COP	coefficient of performance
DHW	domestic hot water
EF	energy factor
EPRI	Electric Power Research Institute
ERV	energy recovery ventilators
GFX	gravity-film heat exchanger
HDD	heating degree days
HP	heat pump
HPWH	heat pump water heater
HVAC	heating, ventilation, and air-conditioning
HSPF	heating seasonal performance factor
kWh	kilowatt-hour
LCUB	Lenoir City Utilities Board
LED	light-emitting diode
NOAA	National Oceanic and Atmospheric Administration
OAT	outdoor air temperature
ORNL	Oak Ridge National Laboratory
PV	photovoltaic
RH	relative humidity
SEER	seasonal energy efficiency ratio
SHR	sensible heating ratio
TMY	typical meteorological year
TVA	Tennessee Valley Authority

1. INTRODUCTION AND PROJECT OVERVIEW

The Campbell Creek project is funded and managed by the Tennessee Valley Authority (TVA) Technology Innovation, Energy Efficiency, Power Delivery and Utilization Office. Technical support is provided under contract by the Oak Ridge National Laboratory (ORNL) and the Electric Power Research Institute (EPRI). The project was designed to determine the relative energy efficiency of typical new home construction, energy efficiency retrofitting of existing homes, and high-performance new homes built from the ground up for energy efficiency.

This project will compare three houses that represented the current construction practices: a base case (Builder House—CC1); a modified house that could represent a major energy-efficient retrofit (Retrofit House—CC2); and a house constructed from the ground up to be a high-performance home (High Performance House—CC3). To enable a valid comparison, it was necessary to simulate occupancy in all three houses and heavily monitor the structural components and the energy usage by component.

All three houses are two story, slab on grade, framed construction. CC1 and CC2 are approximately 2,400 ft^2. CC3 has a pantry option, primarily used as a mechanical equipment room, that adds approximately 100 ft^2. All three houses are all-electric (with the exception of a gas log fireplace that is not used during the testing) and use air-source heat pumps for heating and cooling. The three homes are located in Knoxville in the Campbell Creek Subdivision. CC1 and CC2 are next door to each other and CC3 is across the street and a couple of houses down.

The energy data collected will be used to determine the benefits of retrofit packages and high-performance new home packages. There are over 300 channels of continuous energy performance and thermal comfort data collection in the houses (100 for each house). The data will also be used to evaluate the impact of energy-efficient upgrades on the envelope, mechanical equipment, and demand-response options. Each retrofit will be evaluated incrementally, by both short-term measurements and computer modeling, using a calibrated model.

This report is intended to document the comprehensive testing, data analysis, research, and findings within the January 2011 through October 2012 timeframe at the Campbell Creek research houses. The following sections will provide an in-depth assessment of the technology progression in each of the three research houses. A detailed assessment and evaluation of the energy performance of technologies tested will also be provided. Finally, lessons learned and concluding remarks will be highlighted.

2. REVIEW OF THE TECHNOLOGY PROGRESSION

The following is a description of changes to equipment and technologies used in the three homes from the initial design and construction.

Fig. 1. GE Geospring HPWH at CC2.

Furniture was moved into the homes on March 31, 2009, to provide a thermal mass more appropriate for testing than an empty house.

A prototype GE heat pump water heater (HPWH) was installed at CC2 on April 15, 2009, replacing the original standard electric model (Fig. 1).

The dryer at CC1 was changed by GE on December 2009 to one of the same model used at the other two houses (because of issues with the control board in the originally installed dryer).

The prototype GE HPWH in CC2 was taken out of service on March 22, 2010, and replaced with a commercially-available version that had a more efficient compressor. The change resulted in a unit with a higher field coefficient of performance (COP) than the prototype.

A light-emitting diode (LED) lighting upgrade package was installed on September 30, 2010, at CC3, an operation that involved replacing several of the compact fluorescent light fixtures in the home with more efficient LED fixtures (The equipment and the cost of this package were detailed in the May 2011 TVA Progress Report).

Fig. 2. Mitsubishi multi-split HVAC lines and compressor at CC2.

A Moen thermostatic shower control valve was installed in the master bath of CC3 on November 16, 2011, to reduce variation in the shower temperatures (caused by inconsistent delivery temperatures from the solar thermal system). In addition, a new Taco mixing valve was installed on the solar thermal hot water system at CC3 a week later, November 22, 2011, to provide a more consistent hot water delivery temperature to the home.

On December 21, 2010, a Mitsubishi multi-split heating, ventilation, and air-conditioning (HVAC) system with one 4-ton outdoor unit and eight indoor units began operation at CC2 (Fig. 2). Refrigerant lines for the individual units were run through exterior walls and along either the garage or the backside of the house to the branch boxes on the back wall of the garage. The unit remained in service until January 2012, when it was shut down (a Carrier Greenspeed system was installed - see related item later in this section). The Mitsubishi equipment was removed from the home in May of 2012 and salvaged by TVA.


Fig. 3. The Daikin inverter compressor at CC3.

On November 19, 2010, a Daikin ducted inverter HVAC system was installed at CC3 to replace the baseline two-stage zoned system (Fig. 3). On January 12, 2011, a 5 kW electric heat unit was installed; and on January 28, 2012, that 5 kW unit was replaced with a 3 kW heat unit.

Televisions were added to each house on March 8, 2011. At CC1, a 50 inch plasma TV was added that had an average daily energy consumption of 1.04 kilowatt-hours (kWh) (with 8.5 hours per day of on time). At CC2, a 55 inch liquid crystal diode (LCD) TV was installed that had an average daily energy consumption of 0.77 kWh. At CC3, a 55 inch LED/LCD TV was added with an average daily kWh consumption of 0.46 kWh.

A Mitsubishi Lossnay energy recovery ventilator (ERV) went into service at CC2 on March 25, 2011, to provide the required fresh air to that house. The Lossnay unit replaced the original Air Cycler fresh air system initially installed at CC2.

Human emulators were installed in each house by the EPRI in 2011 and began running on May 12, 2011. There are two in each house: one in the kitchen provides sensible and latent load to represent people spending time and cooking in the living space, and a second one in the master bathroom represents the load from occupants in the bedroom space. The profile used is based on the DOE Building America benchmark.

A heat recovery system was installed at CC3 in May 2011 to allow evaluation of a system designed to capture waste heat from the shower, clothes washer, and dryer, and to use this waste heat to offset some of the hot water energy needs of the house. The system included a gravity-film heat exchanger (GFX) installed on a vertical section of drain line, a dryer exhaust heat exchanger, a preheat tank for storing the captured heat, and a recirculation pump with associated controls. After the 6-week test period concluded, the equipment remained in place; however, the dryer heat exchanger and the recirculating pump use were discontinued and only the GFX remains in use. Currently, only waste heat from the shower is still being captured.

On December 31, 2011, an attempt was made to drill for a potential geothermal system in CC2; however, problems with geology forced the attempt to be aborted after only about a third of the required depth was reached. The hole was grouted and capped according to code in January 2012.

On January 16, 2012, a Carrier Greenspeed heat pump HVAC system with an inverter compressor and variable-speed indoor blower went into service in CC2 to replace the Mitsubishi multi-split system. The Carrier system uses the existing zoned ductwork installed for the baseline system.

A Sanden Integrated EcoCute CO_2 HPWH was installed at CC2 on June 14, 2012, but it failed because of damage incurred in shipping the unit from France. A replacement installed on August 10, 2012, was successfully tested. That unit was put into service heating the water for the house on August 28, 2012.

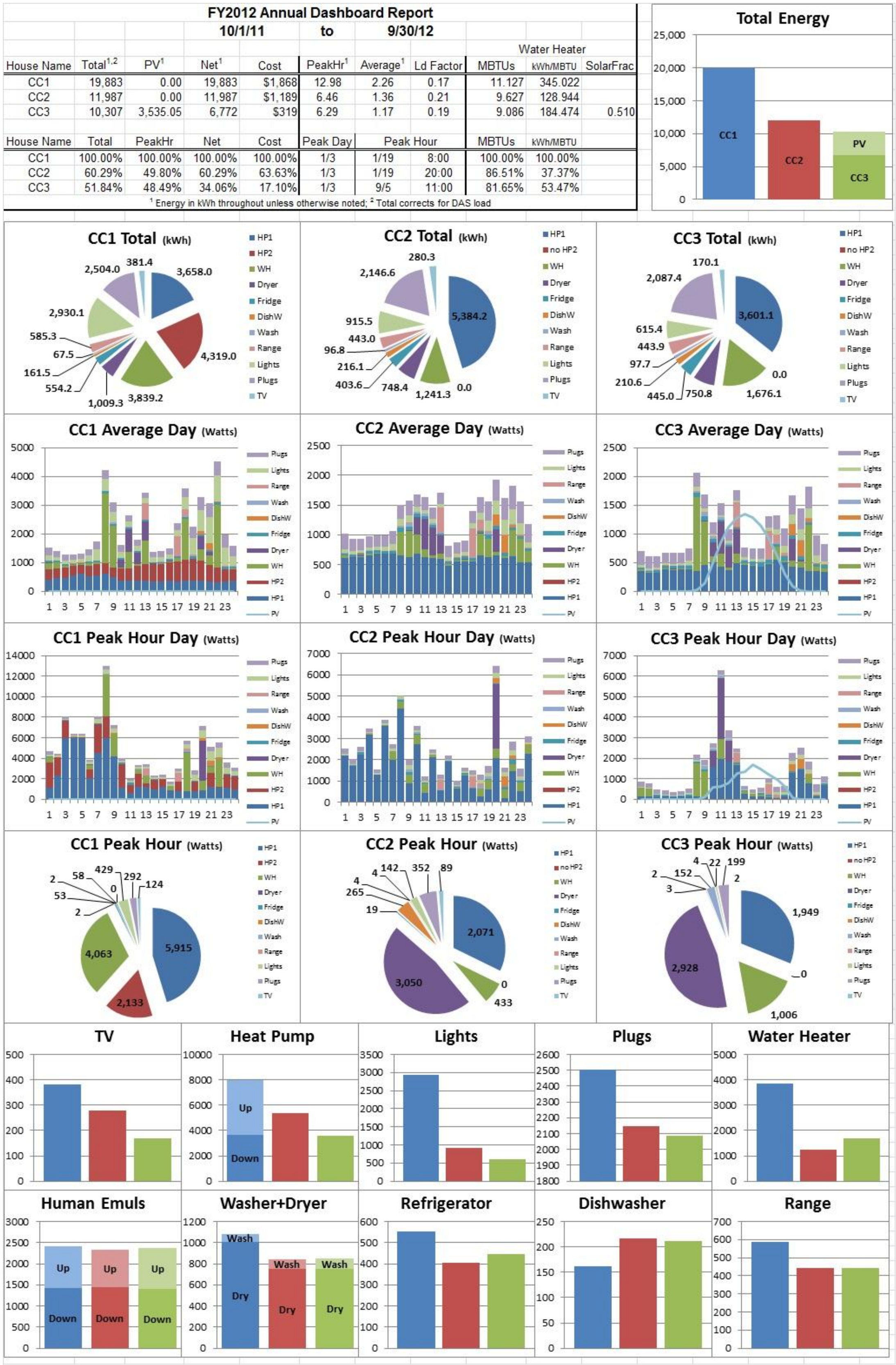
3. OVERALL PERFORMANCE OF HOUSES FROM OCTOBER 1, 2011, THROUGH SEPTEMBER 30, 2012

3.1 ANNUAL DASHBOARDS

Figure 4 shows the dashboard for a full year of performance from October 1, 2011, through September 30, 2012. The annual energy consumption savings of CC2 and CC3 compared with CC1 are 40% and 48%, respectively. The net energy savings of CC3 over CC1, accounting for photovoltaics (PV) generation, is 66%. The peak hourly demand occurred on January 19, 2012, at CC1 and CC2 and on September 5 at CC3. The peak demand in September was due to the precooling study that occurred during that month. CC2 had a 50% lower absolute peak and CC3 a 51% lower peak. The load factors for the entire year are 0.17, 0.21, and 0.19 for CC1, CC2, and CC3, respectively. The pie charts in Fig. 4 show the full-year energy demands for various loads in each of the houses. Bar charts are provided to show the relative energy uses in all three houses of the heat pumps, lights, plug loads, water heating, washer/dryer (combined), refrigerator, dishwasher, human emulators, television, and range. The actual Lenoir City Utilities Board (LCUB) residential rates and monthly hookup fee were used to calculate the costs.

Figure 4 also contains a pie chart showing the pieces that make up the total annual kilowatt-hours used in the builder, retrofit, and high-performance house. In the builder house, the space heating load makes up the largest fraction of energy usage, 21% of the total. The cooling load was 19% and water heating energy another 19% of the total. The annual plug loads (including TV) represent 15% and the lights also represent 15%. The dryer was 5% of the total builder house load. In the retro house, heating is the largest piece at 32%, followed by plug loads 20%, cooling 13%, water heating 10%, lights 8%, and dryer 6%. In CC3, plug load were the largest piece at 22%, cooling 20%, heating 15%, water heating 15%, and the electric dryer 7%.

The FY 2012 annual energy consumption for the heat pump, water heater, lights, plug loads, refrigerator, dishwasher, range, clothes washer, and dryer for all three houses is shown in Table 1. The rightmost column shows the percentage of annual energy savings resulting from each major energy user. The heat pump in CC2 used 33% less energy and the heat pump in CC3 used 55% less than the one in CC1 over the entire one year period. The energy savings for water heating reflect not only the more efficient HPWH in CC2 and the solar water heater in CC3 but also the measured 14 gallon reduction in hot water needed to wash clothes and dishes with the ENERGY STAR® appliances in CC2 and CC3 that are not in CC1. The more efficient lighting in CC2 and CC3 saved 69% and 79%, respectively, compared with the 100% incandescent lighting installed by the builder in CC1. The energy for the ERVs that provide fresh air ventilation in CC2 and in CC3 is included in the “HP” energy columns.



FY2012 Annual Dashboard Report

10/1/11 to 9/30/12

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	19,883	0.00	19,883	$1,868	12.98	2.26	0.17	11.127	345.022	
CC2	11,987	0.00	11,987	$1,189	6.46	1.36	0.21	9.627	128.944	
CC3	10,307	3,535.05	6,772	$319	6.29	1.17	0.19	9.086	184.474	0.510

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	1/3	1/19	8:00	100.00%	100.00%
CC2	60.29%	49.80%	60.29%	63.63%	1/3	1/19	20:00	86.51%	37.37%
CC3	51.84%	48.49%	34.06%	17.10%	1/3	9/5	11:00	81.65%	53.47%

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

Fig. 4. FY 2012 dashboard for a full year from October 1, 2011, until September 30, 2012.

Table 1. FY 2012 annual kilowatt-hour usage by equipment for the three houses

Equipment/ appliances	House	Total	% Savings
HP	CC1	7977	
	CC2	5384	33%
	CC3	3601	55%
Water heater	CC1	3839	
	CC2	1241	68%
	CC3	1528	60%
Lights	CC1	2930	
	CC2	916	69%
	CC3	615	79%
Plug load	CC1	2504	
	CC2	2147	14%
	CC3	2087	17%
Refrigerator	CC1	554	
	CC2	404	27%
	CC3	445	20%
Dishwasher	CC1	162	
	CC2	211	–30%
	CC3	216	–34%
Range	CC1	585	
	CC2	443	24%
	CC3	444	24%
Washer	CC1	68	
	CC2	97	–43%
	CC3	98	–45%
Dryer	CC1	1009	
	CC2	748	26%
	CC3	751	26%

The refrigerators in CC2 and CC3 used 27% and 20% less energy than the refrigerator in CC1 over the one year period. The electric ranges in CC2 and CC3 used the smaller of the two ovens available in the installed models, which led to a 26% percent energy savings compared with the single larger oven in CC1 under the same simulated cooking load in all three houses.

The ENERGY STAR dishwasher in CC2 and CC3 actually used over 30% more energy than the standard (non-ENERGY STAR) model in CC1. The ENERGY STAR model did save on hot water consumption: CC2 used 113 fewer gallons and CC3 used 139 fewer gallons of hot water. Based on 157 Wh/gal, the measured electrical energy required to heat water with the standard electric water heater in CC1, the ENERGY STAR dishwashers realized an annual hot water energy savings of only 15 and 18.5 kWh, respectively, for CC2 and CC3. Adjusting the numbers in Table 1 to account for the energy used to heat the water supplied, the three dishwashers used 335, 367, and 368 kWh, respectively, in CC1, CC2, and CC3. Thus even with hot water savings, the ENERGY STAR model used ~10% more energy annually than the non-ENERGY STAR dishwasher model in CC1.

The ENERGY STAR front-load clothes washers in CC2 and CC3, which have a much higher-speed spin cycle, used more energy than the conventional top-load clothes washer in CC1, as shown in Table 1. However, the savings from reduced hot water demand and their capability to force more water from the washed clothes resulted in dryer energy savings. The annual hot water use by the CC1, CC2, and CC3 clothes washers was 4784, 1499, and 1558 gallons, respectively. That is a savings of over 3200 gallons of hot water per year for the ENERGY STAR models. The total kilowatt-hours required for washing clothes when energy to heat water is included is 819, 332, and 342 kWh respectively, a ~58% savings for the ENERGY STAR front-load machine over the top-load machine. Considering both washer and dryer loads and the electrical energy to heat water gives a combined savings of about 40% for laundry in CC2 and CC3 compared with CC1.

Table 2 illustrates the savings potential for different appliance “suites” paired with different WH systems and provides an interesting comparison of the energy use given any of the three WH systems and any of the appliance “suites”. The months of August and September 2012 were excluded from the CC2 efficiency averages due to installation of the Sanden water heater in that house. Those values were replaced with linearly interpolated values from the July and November data; and, since the performance of the HPWH didn’t vary too much from month to month, this method provides a reasonable estimate. Estimated values are shaded in Table 2.

Table 2. Comparison of Appliance and WH System Energy Savings Potential in kWh.

	HW Energy Delivered	**CC1 Standard Electric**	**CC2 HPWH**	**CC3 Solar Thermal**
	kWh (thermal)	157 Wh/gal	55 Wh/gal	84 Wh/gal
CC1 **Standard Appliances**	3261	3839	1358	2053
CC2 **Energy Star Appliances**	2862	3369	1192	1801
CC3 **Energy Star Appliances + GFX Shower Heat Recovery**	2663	3135	1109	1676
	▨	Shaded areas denotes estimated values		

Figure 5 shows the monthly whole house energy data. The annual whole house energy savings for CC3 after accounting for onsite solar PV generation is 66%. The 2.5 kW peak solar PV fraction is about 31% of the total kilowatt-hour demand of CC3.

A Carrier Greenspeed system was installed in CC2 on January 16 to replace the Mitsubishi multi-split system. Since the Carrier system has a higher heating seasonal performance factor (HSPF) and seasonal energy efficiency ratio (SEER) than the multi-split system, a reduction in the total energy consumption of CC2 was expected. The impact of this retrofit can be seen in Fig. 5. In January, CC2 energy use was 66% relative to CC1. However, in February CC2, energy use dropped to only 54% relative to CC1. This drop in energy use is mainly attributed to the installation of the Carrier Greenspeed.

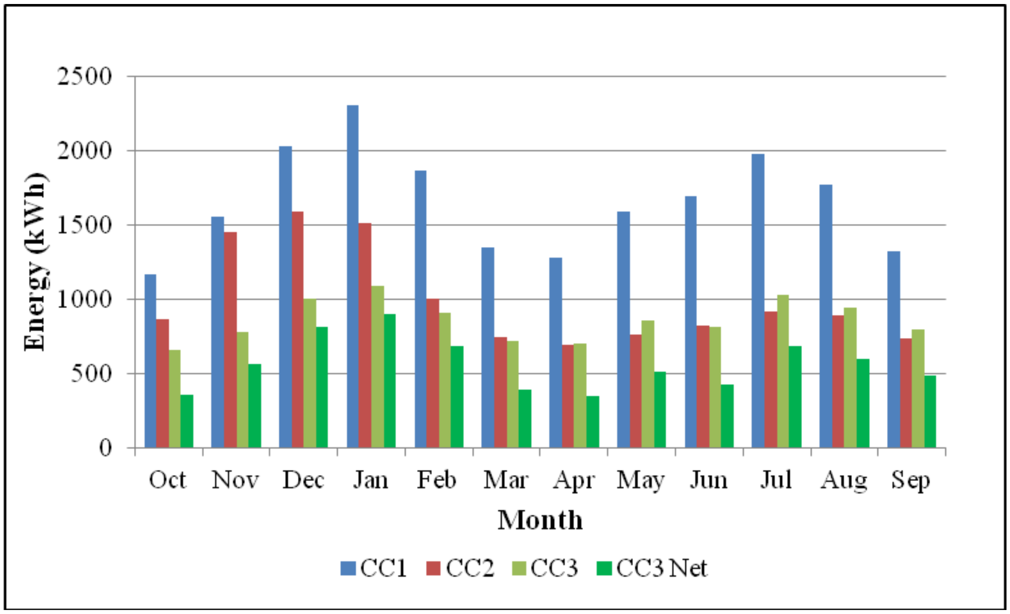


Fig. 5. Monthly energy totals from October 2011 until September 2012.
CC3 net accounts for solar generation.

3.2 ENERGY USE

Heating degree days (HDD) and cooling degree days (CDD) were calculated for the entire year using 60 minute data and a base of 65°F. They are compared in Table 3 with the 30 year normal data for the Knoxville area published by the National Oceanic and Atmospheric Administration (Comparative Climatic Data–NOAA). Although the weather was cooler than normal in October 2011 and September 2012, the 12 month period of this report was the hottest October–September period on record for the contiguous United States (NOAA, 2012). June and July, particularly, were hotter than average, with July being the 10th warmest July recorded for Knoxville (*Knoxville New Sentinel*, 2012). The period overall had 6.5% fewer HDDs at 65° and 11.7% more CDDs than has been normal over the past 30 years.

Table 3. Heating degree days at 65° and departure from normal

	HDD at 65°	Normal HDD at 65°	Departure from normal	CDD at 65°	Normal CDD at 65°	Departure from normal
Oct 11	344	210	134	44	28	16
Nov 11	463	470	–7	4	3	1
Dec 11	679	732	–53	1	0	1
Jan 12	734	841	–107	0	0	0
Feb 12	577	652	–75	6	1	5
Mar 12	258	467	–209	69	5	64
Apr 12	222	223	–1	75	27	48
May 12	49	65	–16	205	110	95
Jun 12	26	3	23	316	282	34
Jul 12	0	0	0	429	408	21
Aug 12	15	0	15	295	381	–86
Sep 12	76	22	54	176	205	–29
Totals	3445	3685	–240	1620	1450	170

3.3 ENERGY COSTS

The monthly energy costs for each house are shown in Fig. 6. All three houses have simulated occupancy energy demands embedded in the costs, as well as exterior lighting. The energy for data collection and occupancy simulation equipment is not included in the energy costs. The costs shown are based on the LCUB actual monthly residential rates shown in Table 1. The full-year energy cost for CC1 (builder house) was $1,868, compared with a net cost for CC3 (high performance house) of $320 (less than $1 per day). The annual energy cost for CC2 (retrofit house) was $1,189, a 36% whole house energy cost savings compared with CC1.

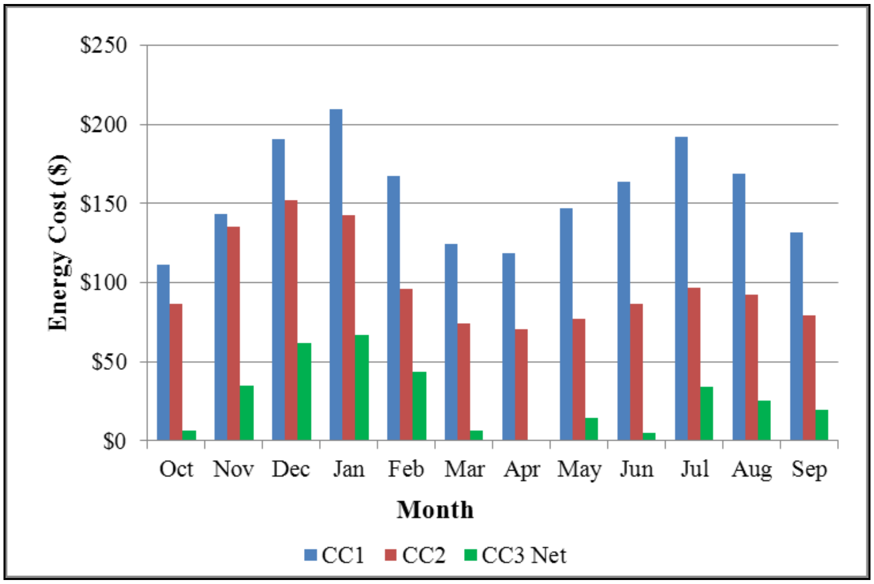


Fig. 6. Monthly energy cost for each house (including generation partners credit).

3.4 SOLAR AND GENERATION PARTNER CREDIT

The 2.5 kW peak solar system on CC3 generated 9.7 kWh/day average for the complete one year test period. Generation averaged 11.4 kWh per day for the 6 month period of April through September. The total annual energy cost savings for CC2 compared with CC1 is $1,549, an 83% whole house energy cost savings compared with CC1. Savings from solar generation accounted for $727, or 47% of the $1,549. The balance of the savings, $821 (53%), is due to energy efficiency improvements. Figure 7 shows the monthly generation from the PV system, which averaged 29 kWh/month. Figure 8 shows the monthly credit from solar energy production. The monthly average for the complete year is $61, an average daily solar credit of $1.99.

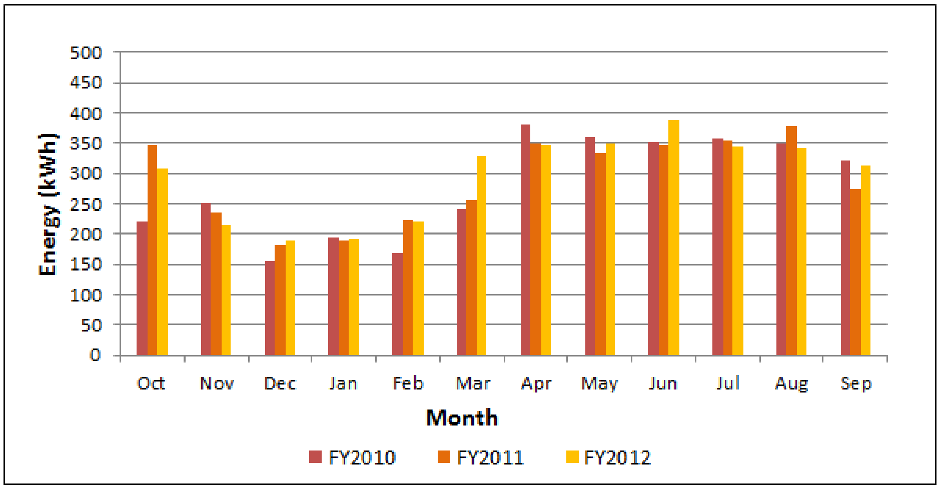


Fig. 7. Solar generation under TVA's generation partners program.

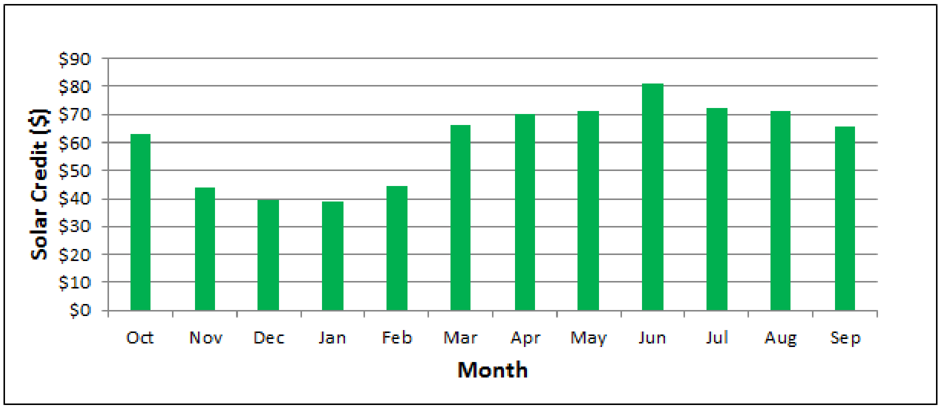


Fig. 8. Monthly generation partner credit for solar generation at CC3.

4. PERFORMANCE EVALUATION

4.1 HVAC COMPARISON—RETROFIT HOUSE CC2

In January 2012, a Carrier Greenspeed ducted inverter heat pump with zoning was installed in CC2. The system is rated at 3-tons of cooling with an Air-Conditioning, Heating, and Refrigeration Institute rated SEER of 20.5 and HSPF of 13.0. The fan coil was installed in the sealed attic and connected to the existing ductwork. The system was split into two zones, with one serving the upstairs and the other the downstairs.

Two prior systems have been installed at CC2, a single-stage, 16 SEER, 9.75 HSPF 3-ton heat pump (which will be referred to as the baseline system) and a multi-split heat pump consisting of a 15 SEER, 8.7 HSPF, 4-ton outdoor unit with an inverter-driven compressor and 8 high-wall indoor units rated at either 0.75 ton (3 units) or 0.5 ton (5 units).

4.1.1 Heating Data

Previous reports (Munk, 2012) have detailed the performance of the Mitsubishi multi-split heat pump. For this report, only the heating season performance of the Greenspeed system is discussed; therefore, energy use prior to January 18, 2012, is not included in the following analysis. The winter was fairly mild, but the system still did a very good job of minimizing the need for resistance heat. In Fig. 9, the daily energy use is plotted against the average outdoor air temperature (OAT). Because the Carrier system has a variable-speed compressor that can run at higher speeds when the OAT is lower, it can significantly reduce the need for resistance heat as supplemental heat. Most of the resistance heat use for the Carrier system was during defrost cycles, when the resistance heat was used to prevent cold air from being blown into the house. Figure 10 shows the resistance heat usage, in terms of energy and runtime, of the Carrier system and the baseline system. Because of the mild winter, the data do not provide a complete picture of the very-low-temperature resistance heat use of the Carrier system, but curve fits imply that there would be roughly a 75–80% reduction compared with the baseline system. Figure 10 shows the total energy use of the Carrier ducted inverter system compared with the baseline system; the Carrier system shows significant energy savings. When these data are normalized by applying them to typical meteorological year (TMY) data for Knoxville, Tennessee, the ducted inverter system is predicted to save 1519 kWh (32%) compared with the baseline heat pump over a typical heating season (Fig. 11). This is slightly more than the 25% savings than the HSPF ratings would indicate.

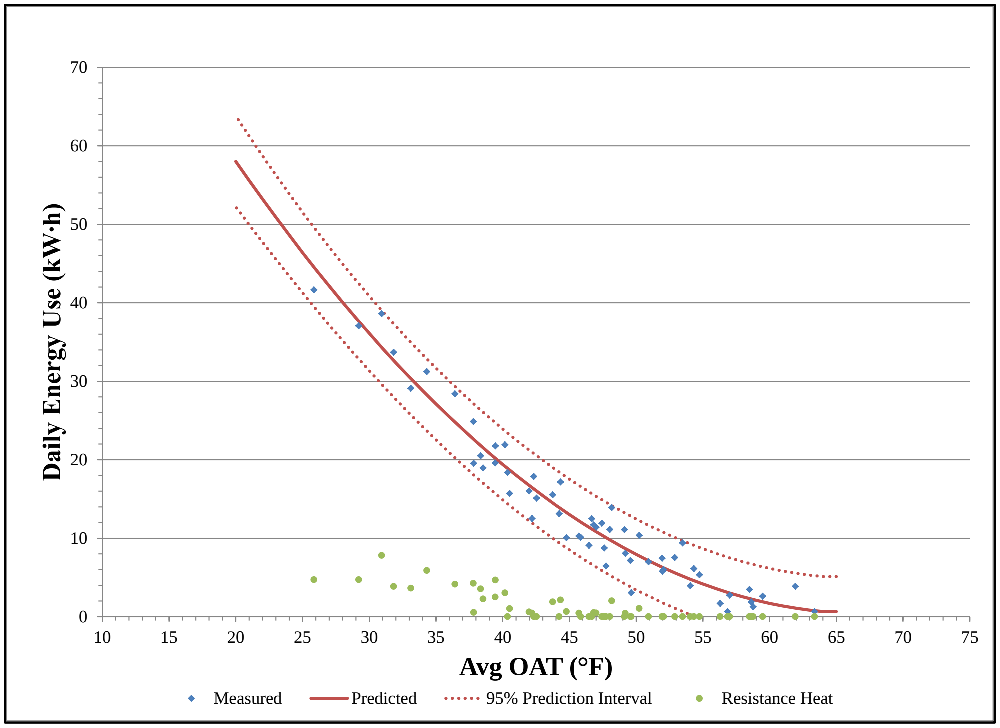


Fig. 9. CC2 Carrier heating data.

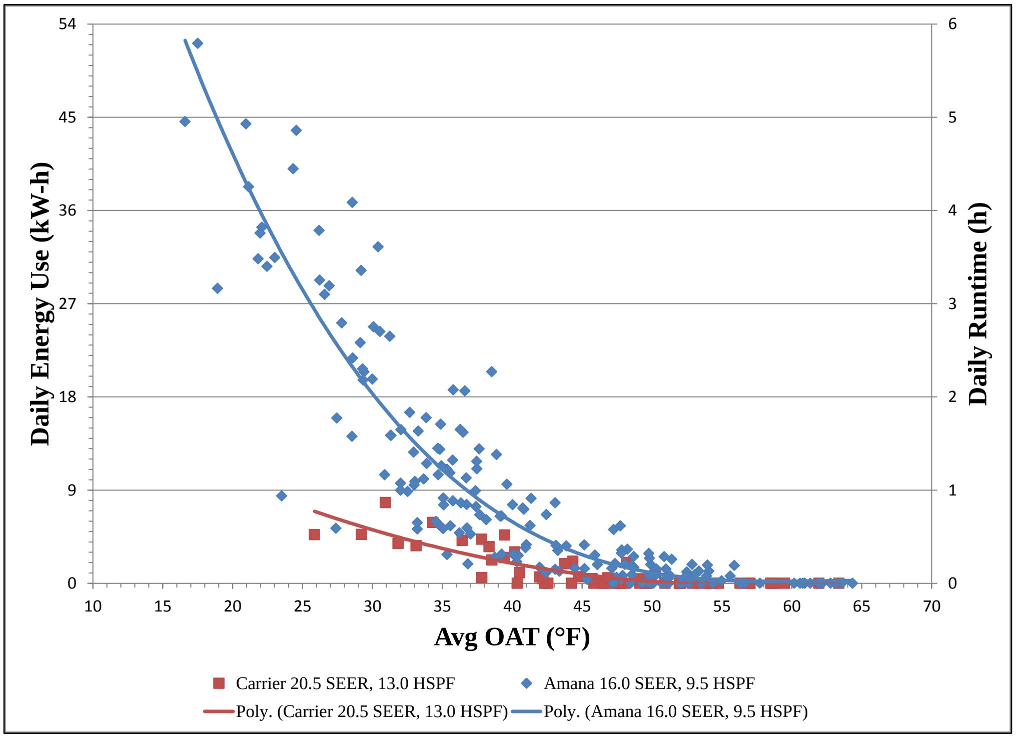


Fig. 10. CC2 resistance heat usage.

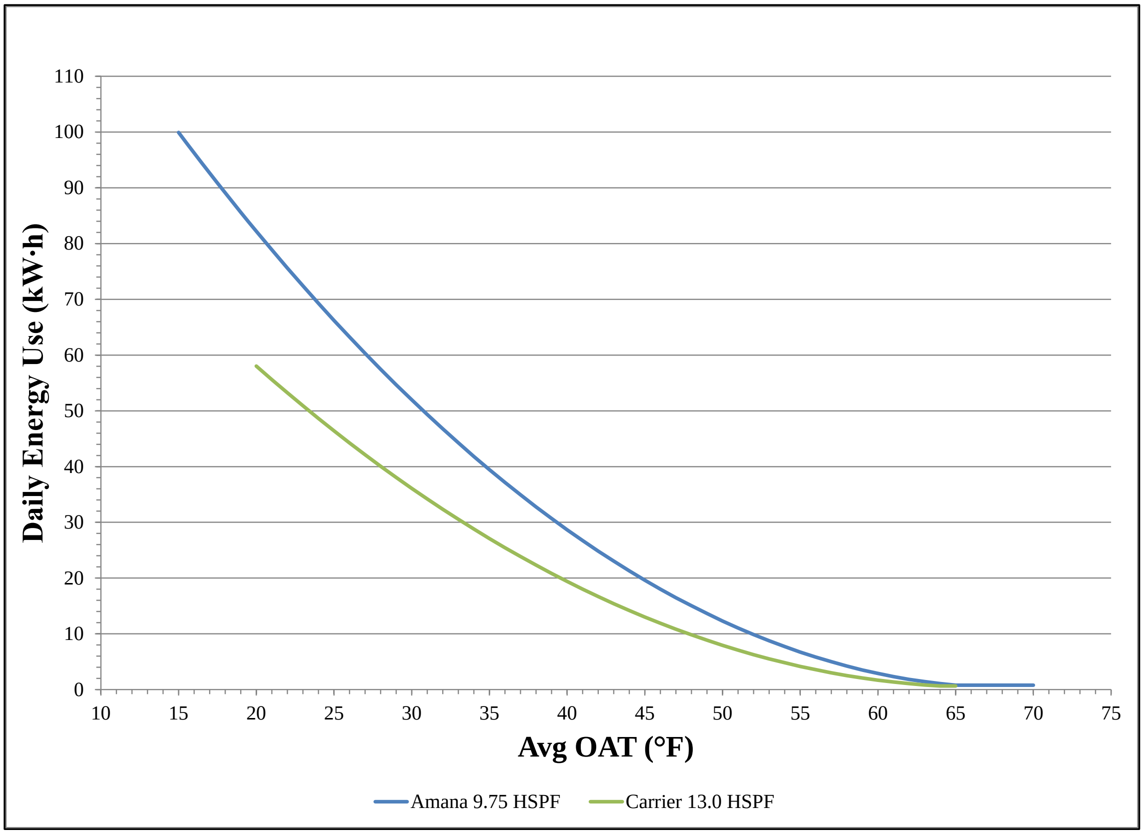


Fig. 11. CC2 heating mode predictions.

4.1.2 Cooling Data

The cooling energy use through September 30, 2012, is plotted in Fig. 12. The cooling data show very low energy use, with about a $2/day energy cost for cooling at $0.10/kWh during the hottest days. Figure 13 shows the energy use compared with the two prior systems. The new ducted inverter system also showed significant energy savings during the cooling season. Normalizing the data to the TMY data for Knoxville predicts that the ducted inverter system will save 681 kWh (36%) compared with the baseline system. This is significantly more than the 22% savings predicted by comparing the SEER ratings of the two units.

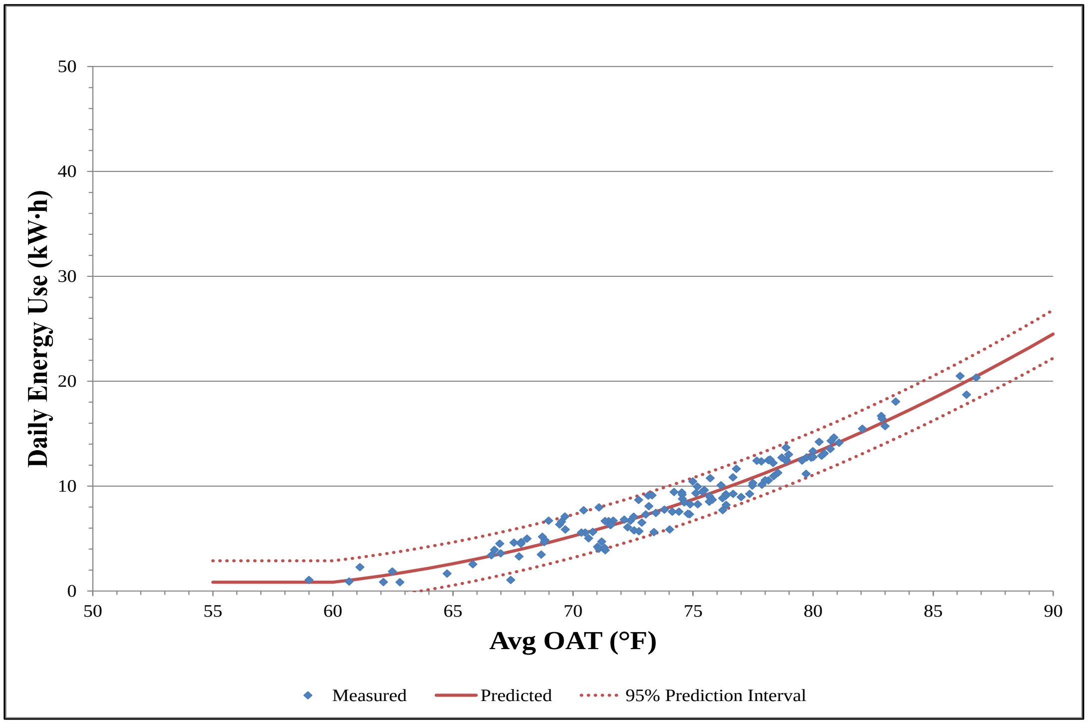


Fig. 12. CC2 Carrier ducted inverter cooling season data.

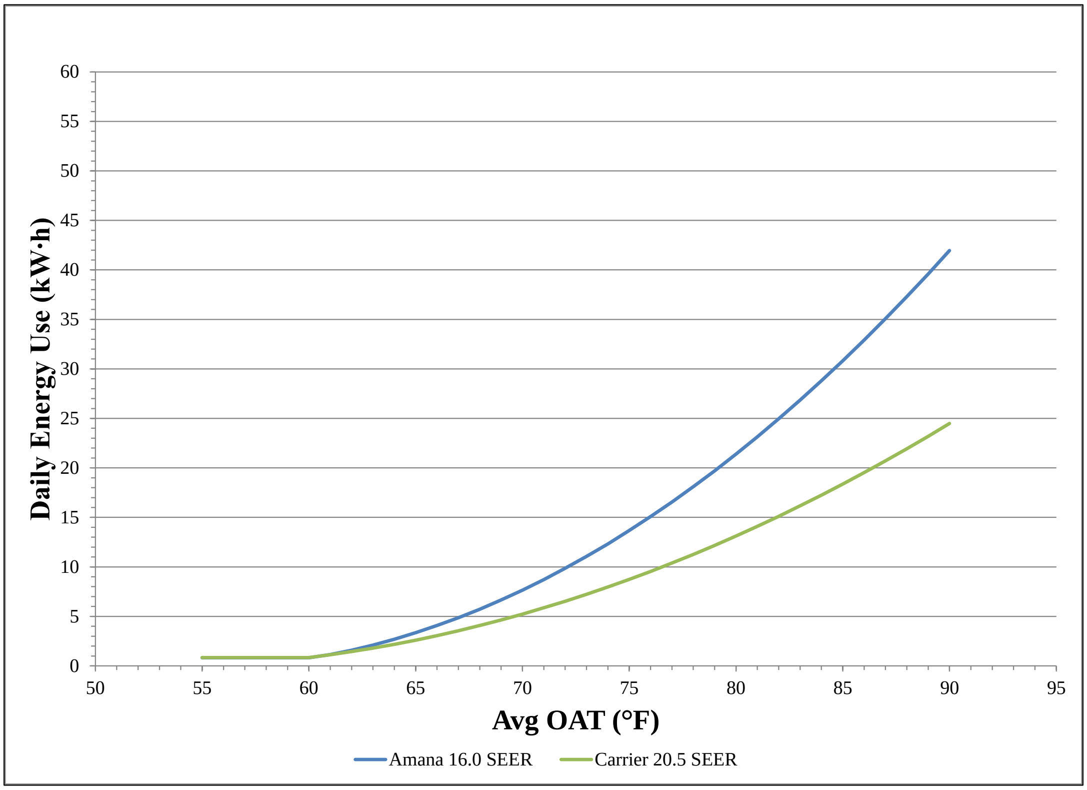


Fig. 13. CC2 cooling mode predictions.

4.1.3 Annual Performance

The TMY predictions for the heating and cooling season energy use are combined for an annual energy use comparison in Fig. 14. Heating energy use was between 2.5 and 3 times more than the cooling season energy use for all systems. The ducted inverter system shows an annual savings of 2200 ±144 kWh, or 33%, over the baseline system.

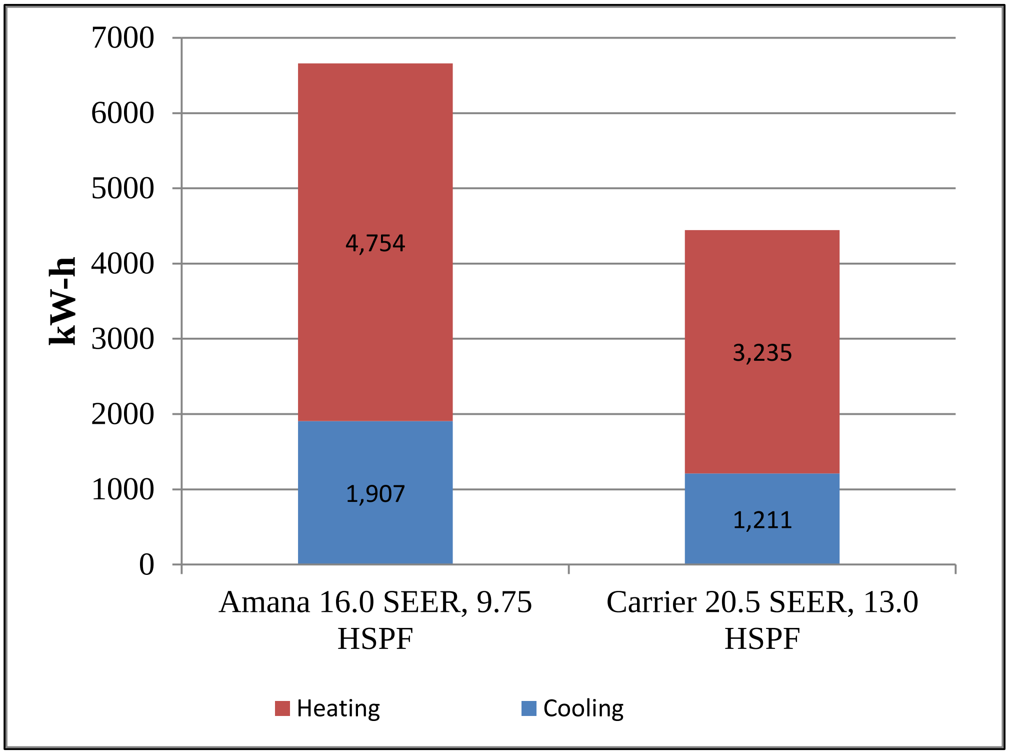


Fig. 14. CC2 predicted TMY energy use for Knoxville, Tennessee.

4.1.4 Hourly Peak Power

Of particular interest to utilities is reducing the peak power consumption of HVAC systems. The ducted inverter system is capable of providing much higher heating capacities at lower temperatures compared with traditional single- or two-speed heat pumps. This can allow the heat pump to avoid the use of inefficient resistance heat and reduce the peak power draw. Figure 15 is a plot of hourly power consumption regressions of the baseline system from 2010 and the ducted inverter system for 2012. Because 2012 had such a mild winter, there is little very cold weather data for the ducted inverter system; but at an OAT of 20°F, the system shows about a 25% reduction in peak power draw while heating. The peak power reduction in cooling is more significant, with the data showing an average 47% reduction at an OAT of 95°F.

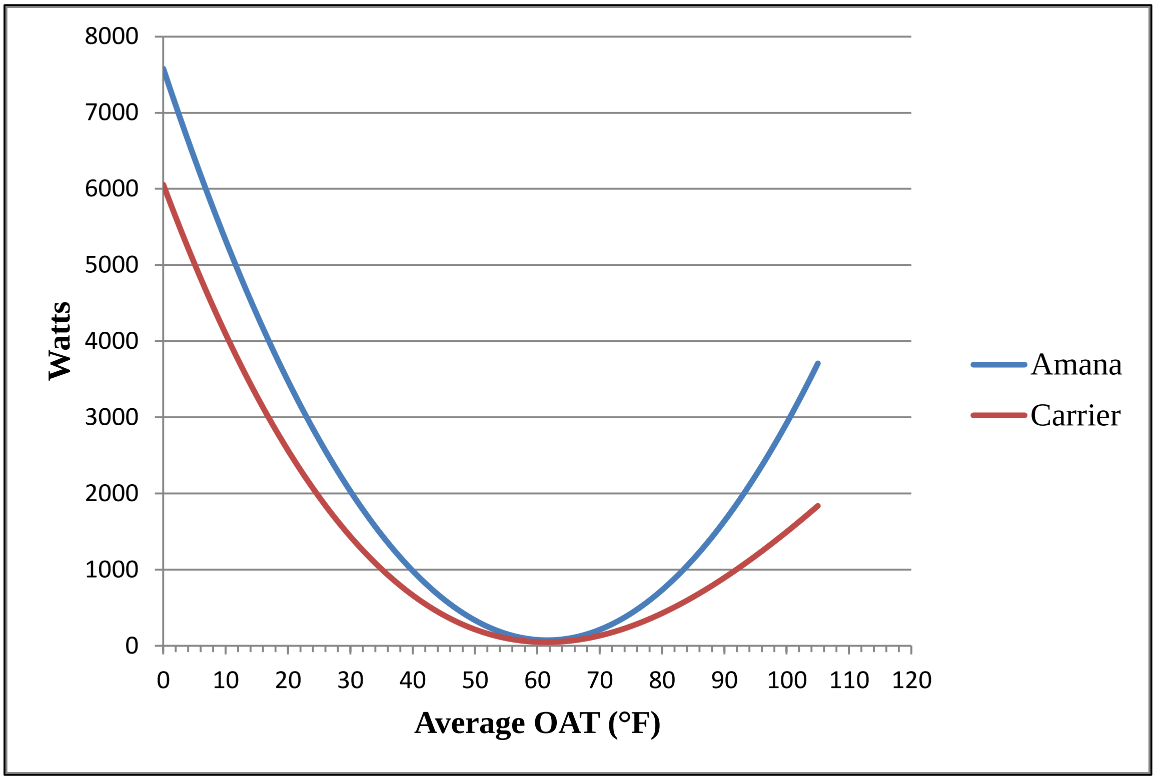


Fig. 15. CC2 baseline hourly average power draw.

4.2 HVAC COMPARISON—HIGH-PERFORMANCE HOUSE CC3

The Daikin ducted inverter 18.0 SEER, 8.89 HSPF, 2-ton heat pump has been installed since December 2010. The fan coil in CC3 is installed in a utility closet on the first floor instead of in the attic as in CC2. There was no compatible zone control for the Daikin system, so it is set up as a single zone with the thermostat located centrally on the first floor. The baseline system in this house was an Amana two-stage, 15.0 SEER, 9.5 HSPF, 2-ton heat pump with zoning.

4.2.1 Heating Data

The heating energy use for the Daikin system from 2011 and 2012 is plotted in Fig. 16. The new data match very well with the older data and indicate that the unit performance has not changed significantly. Late in February, representatives from Daikin visited to investigate concerns that the unit was not modulating as expected. This concern was documented in a prior report (Munk 2012), in which the unit was shown to run at near constant power throughout each cycle. During the visit, the refrigerant charge was checked and an additional 14 ounces was added to the system. No other issues were discovered during the visit. Given the limited heating data following the visit, there was not sufficient data to determine if the charge adjustment had any impact on the heating performance. Unlike the Carrier system at CC2, the Daikin system does not use resistance heat during defrost cycles. Therefore, the Daikin system did not use any resistance heat between October 2011 and September 2012.

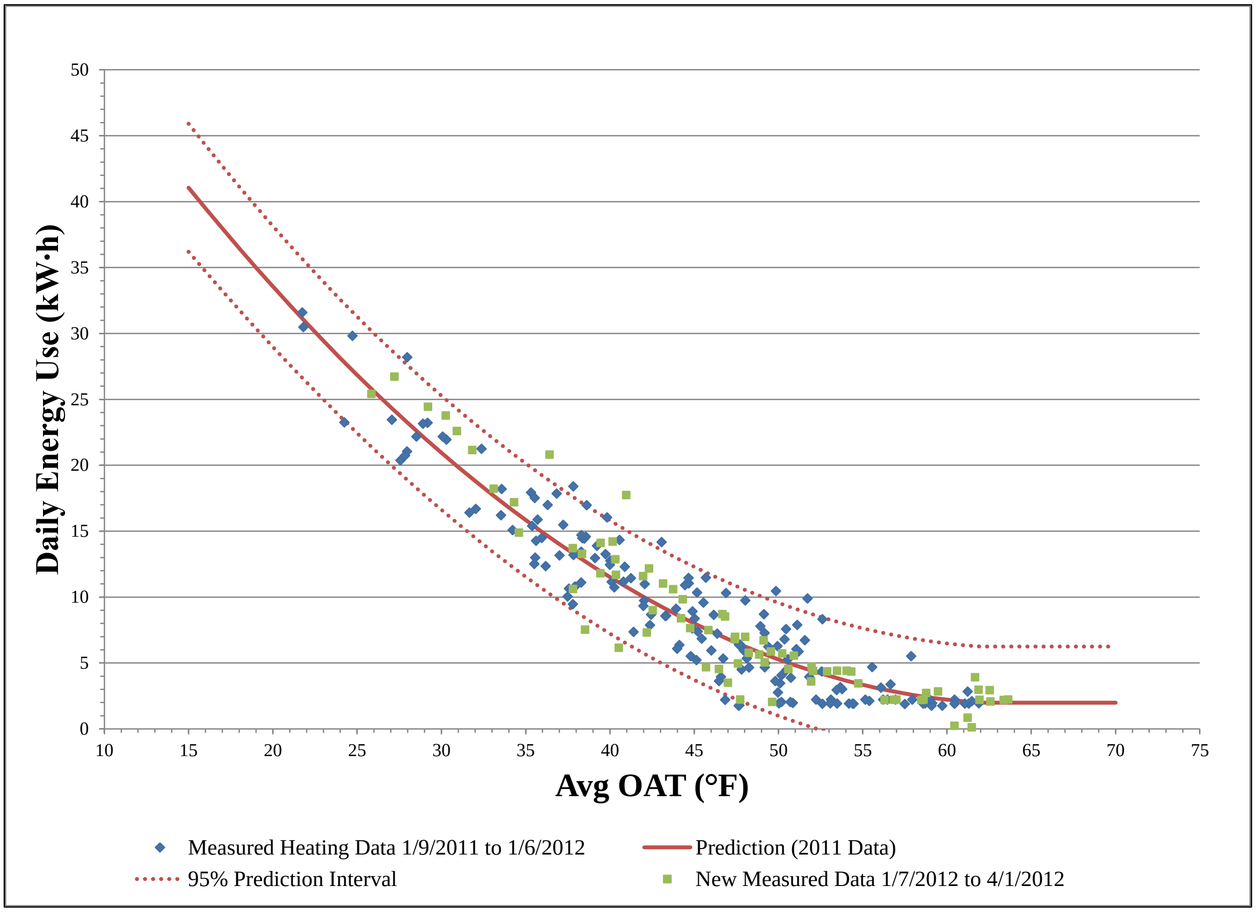


Fig. 16. CC3 Daikin ducted inverter heating season.

4.2.2 Cooling Season

Since the Daikin system does not have zoning capability, the existing zoning dampers and room registers are adjusted seasonally to maintain similar temperatures on the first and second levels. During the summer, the downstairs requires significantly less cooling than the upstairs; so to achieve a reasonable temperature balance, the downstairs damper was closed completely. Although the arrangement provided consistent temperatures, it had the unintended effect of reducing the system airflow. The fan coil does have a variable-speed brushless permanent magnet motor; however, closing the downstairs damper increased the external static pressure enough that the motor was no longer able to maintain the desired airflow. When the issue was discovered, the reduced airflow was measured and the damper was opened enough to allow the motor to reach the target airflow. For analysis, the data were separated into two sets, one with the downstairs damper partially open and the other with the downstairs damper closed, as seen in Fig. 17. These two data sets from the 2012 cooling season were compared with the data from the 2011 heating season. The 2012 data indicate slightly worse performance at lower average OATs and slightly better performance at higher OATs. The data do all fall within the 95% confidence prediction intervals that were generated from the 2011 data.

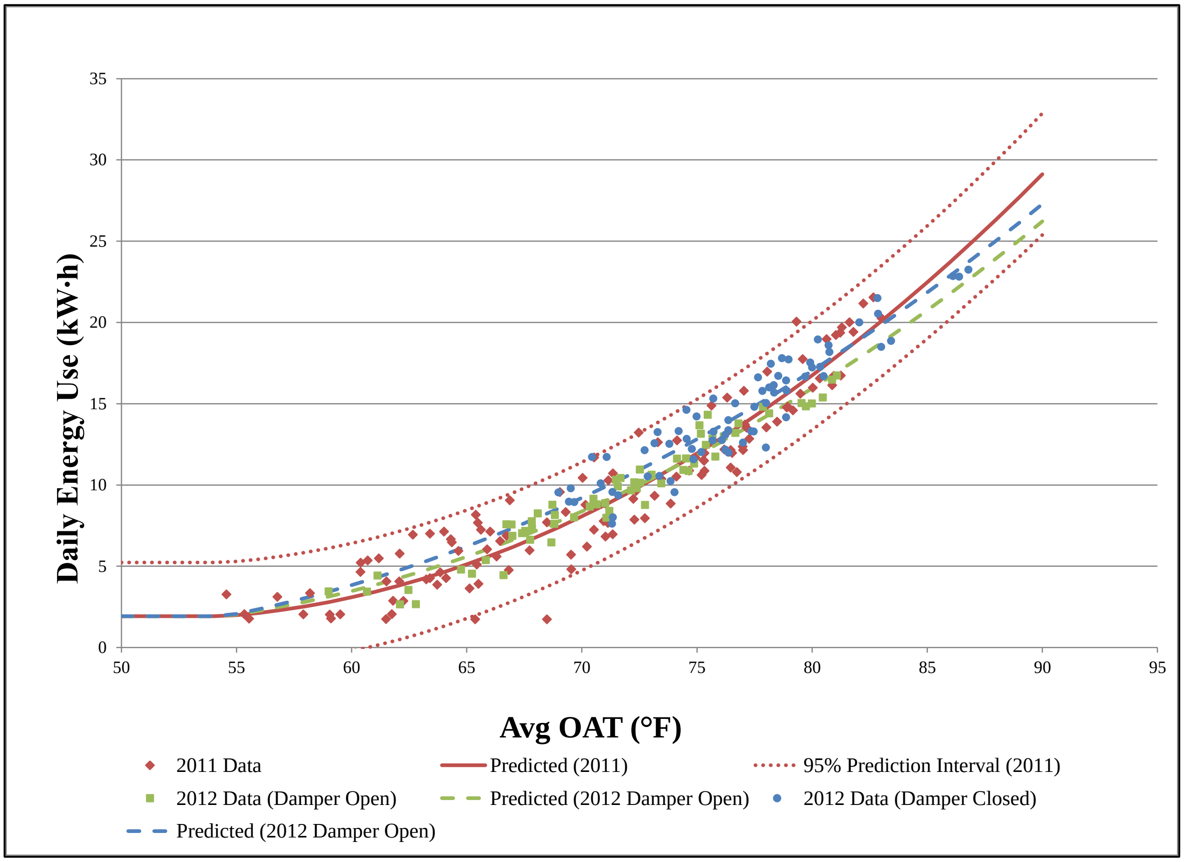


Fig. 17. CC3 Daikin ducted inverter cooling season data.

The damper-open and damper-closed data sets were analyzed and predictions were generated for the entire 2012 cooling season for both sets. These were compared in order to determine if the difference in the data sets was statistically significant and, if so, the magnitude of the difference. The predicted energy difference indicated that with the downstairs damper closed, the system would have used 137 ± 40 kWh more energy (with 95% confidence) than if the damper was only partially open and the blower could reach the target airflow. This translates into a 7.6% ± 2.2% increase in energy use. This is only a modest penalty for what was a significant, ~38%, reduction in airflow. Figures 18 and 19 show a comparison between the compressor power and sensible heat ratio (SHR) plotted versus OAT for periods when the downstairs damper was partially open and periods when it was fully closed. The plots show a significant decrease in compressor power when the damper was closed, but the SHR was virtually the same. For the SHR to be the same, the total cooling capacity had to have been reduced by approximately the same percentage that the airflow was reduced. The drop in compressor power indicates that the reduced capacity was likely a result of the variable-speed compressor running at lower speeds. It is likely that the system reduced the compressor operating speed in response to the reduced airflow caused by the downstairs damper being closed. The net result was reduced capacity and only slightly reduced performance.

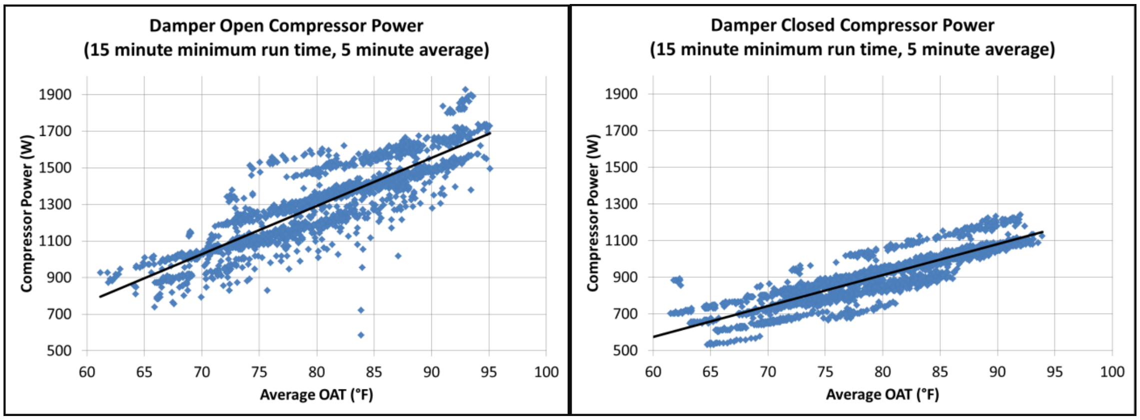


Fig. 18. CC3 compressor power comparison.

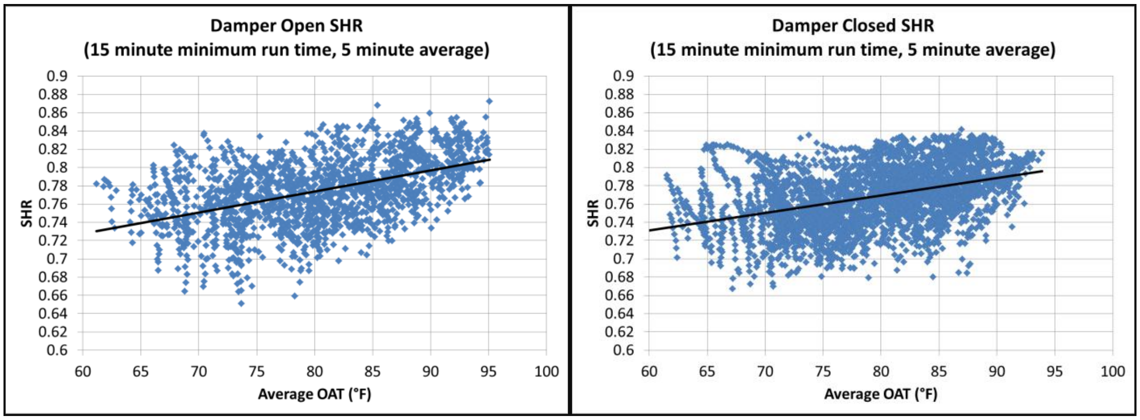


Fig. 19. CC3 SHR comparison.

4.3 WATER HEATER COMPARISON

Three types of water heating systems have been installed at the Campbell Creek homes. CC1 has a 0.9 energy factor (EF), 40 gallon electric water heater installed in the garage. CC2 had an R-134a HPWH with a 2.35 EF rating installed until August 2012. In September 2012, a CO_2 HPWH was installed, and it operated for the remaining timeframe studied in this report. Both units were installed in the garage. CC3 has a solar thermal water heating system. This system uses a secondary fluid to pick up heat from the solar absorbers and a brazed plate heat exchanger to transfer the heat to the domestic hot water. An 80 gallon storage tank with backup resistance heat installed in a utility room is used to store the heated water, and a mixing valve is used to temper the water down to a target temperature of 120°F.

The past 12 months of energy use for water heating at all three homes is plotted in Fig. 20. As expected, the standard electric water heating in CC1 used the most energy for all months and had higher use in the winter months when the incoming water temperature was lower. The water heating energy use for CC2 is more consistent throughout the year and is a quarter to a third of the energy use at CC1. The energy use of the solar system at CC3 follows a similar trend but deviates from past energy use data. The next section presents an in-depth look at these deviations.

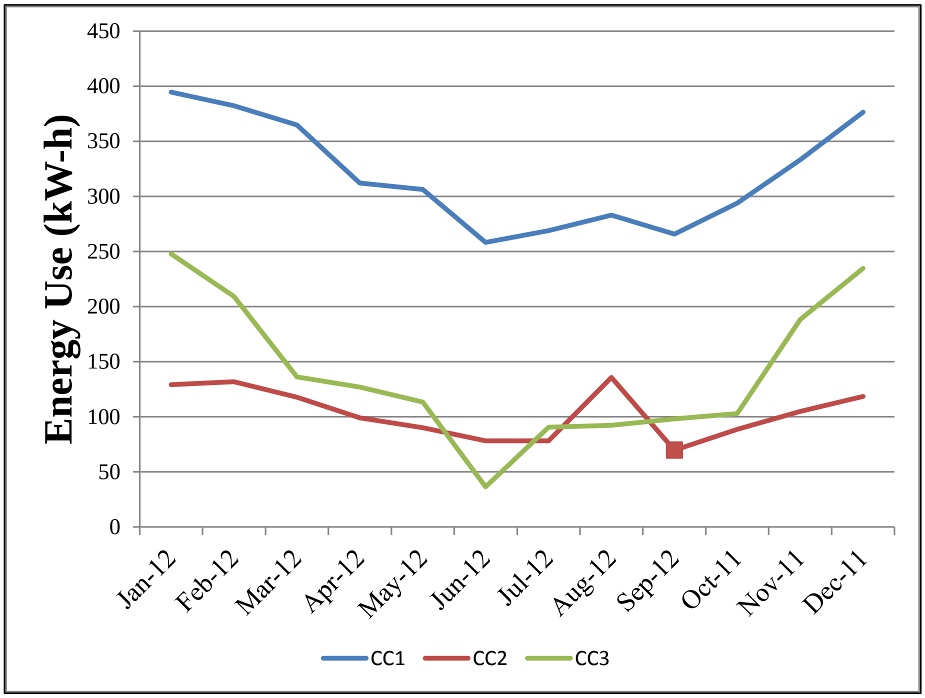


Fig. 20. Water heating energy use (October 2011 to September 2012).

Since the solar system draws water from the bottom of the tank for water heating, adjusting the lower element thermostat also increased the temperature of the water entering the solar system's heat exchanger (Fig. 21). This reduced the opportunities for solar heating and reduced the efficiency of the heat transfer. Although the tank temperature sensor was moved to a better position, the more frequent use of the bottom element also led to more cycles in which the solar system was not actually capable of heating the water, as can be seen in Fig. 22.

The water heating COP has been calculated for the system by dividing the amount of heat delivered from the storage tank by the total energy use of the system Fig. 23. Therefore, this number includes the effect of heat loss from the storage tank. The COP of the standard electric water heater in CC1 is very consistent and varied only between 0.84 and 0.86. This indicates that the seasonal difference in tank losses have minimal impact on the system efficiency, despite the fact that the average garage temperature varied by more than 20°F between winter and summer months. The R-134a HPWH installed in CC2 showed very good performance throughout the year with COPs ranging from 2.2 to 2.6. The installation of the CO_2 HPWH was taking place in August, and there were some operational issues at startup that caused the low COP. September was a whole month of good data for the CO_2 HPWH though, and it showed very promising performance with a COP of 2.7.

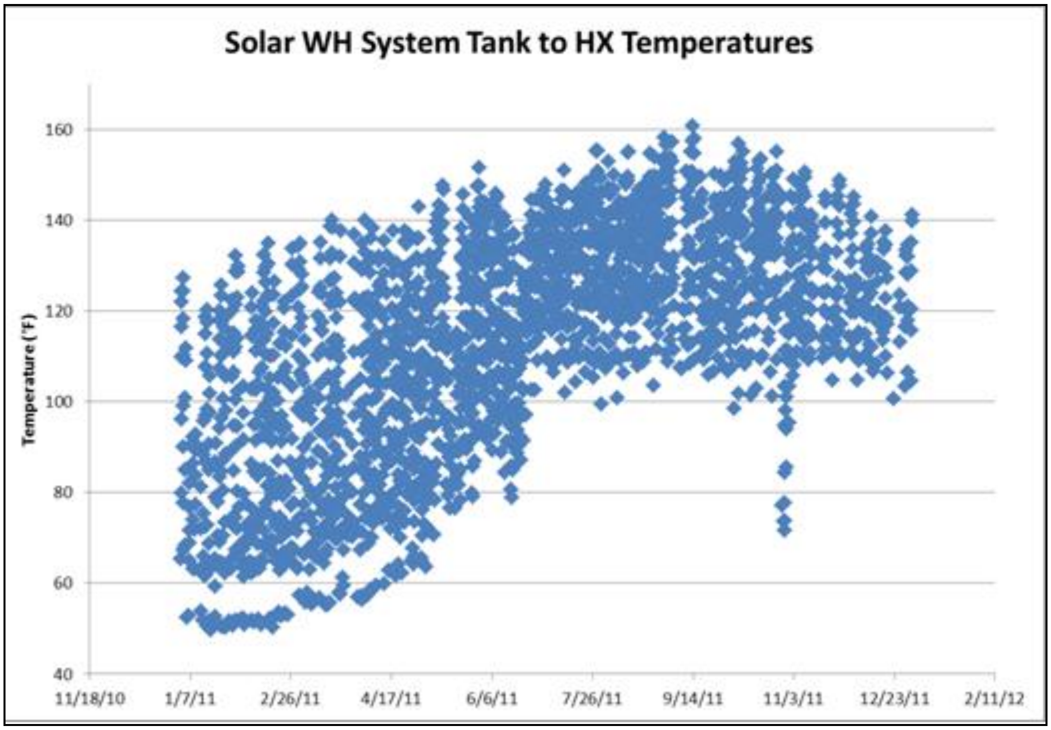


Fig. 21. Solar water heater system tank–to-heat–exchanger temperatures.

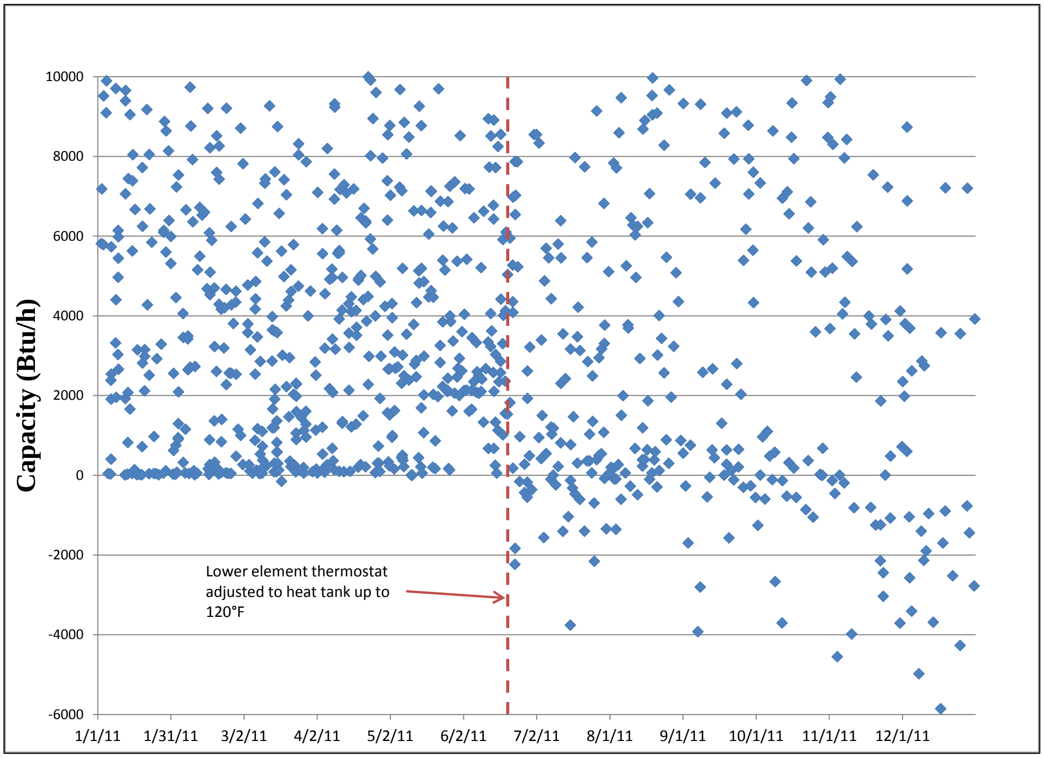


Fig. 22. Solar water heater capacity.

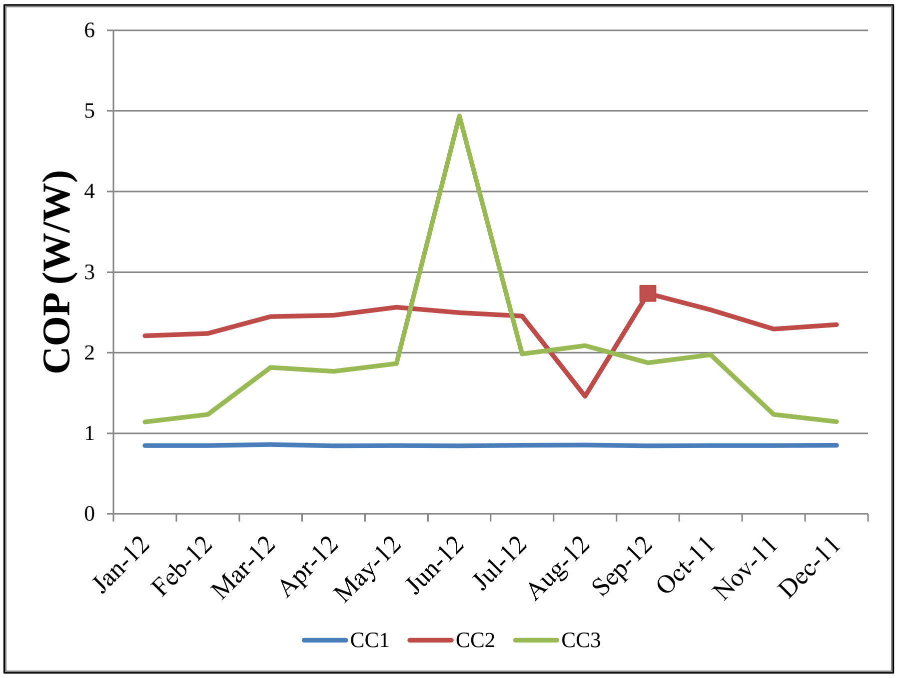


Fig. 23. Water heating COP (October 2011 to September 2012).

The solar thermal system in CC3 shows a wide range of COPs throughout the year. To fully explain the operational performance of the system, the COP of the unit was plotted from data over the last three years in Fig. 24. As seen in the plot, the performance was significantly higher in 2010 than in most of the corresponding months in later years. It was observed in June 2011 that the resistance heating element in the storage tank was not heating the water up to the 120°F setpoint. This was being masked by the fact that the tempering valve was set too high, causing the system to supply water hotter than 120°F to the house soon after the solar system had run and water cooler than 120°F when the solar system had not been running. This phenomenon can be seen in Fig. 25, which plots the hot water temperature to the house during water draws for the year of 2011. In June 2011 the water heater thermostats were adjusted to heat the tank to the desired 120°F set point, and the tempering valve was adjusted downward to limit the hot water supply temperature to 120°F. The result was a much tighter band of hot water supply temperatures.

In June 2011, the temperature sensor for the solar system was securely attached to the lower element nut. Previously, it was sitting loosely in the lower element/thermostat compartment. The solar system compares the temperature at the solar collector with the tank temperature; when a 12°F temperature difference is sensed, the solar system turns on. With the tank temperature sensor more securely attached to the lower element nut, it probably read a higher temperature than before; therefore, a comparatively higher temperature at the solar collector would be required to turn the solar system on.

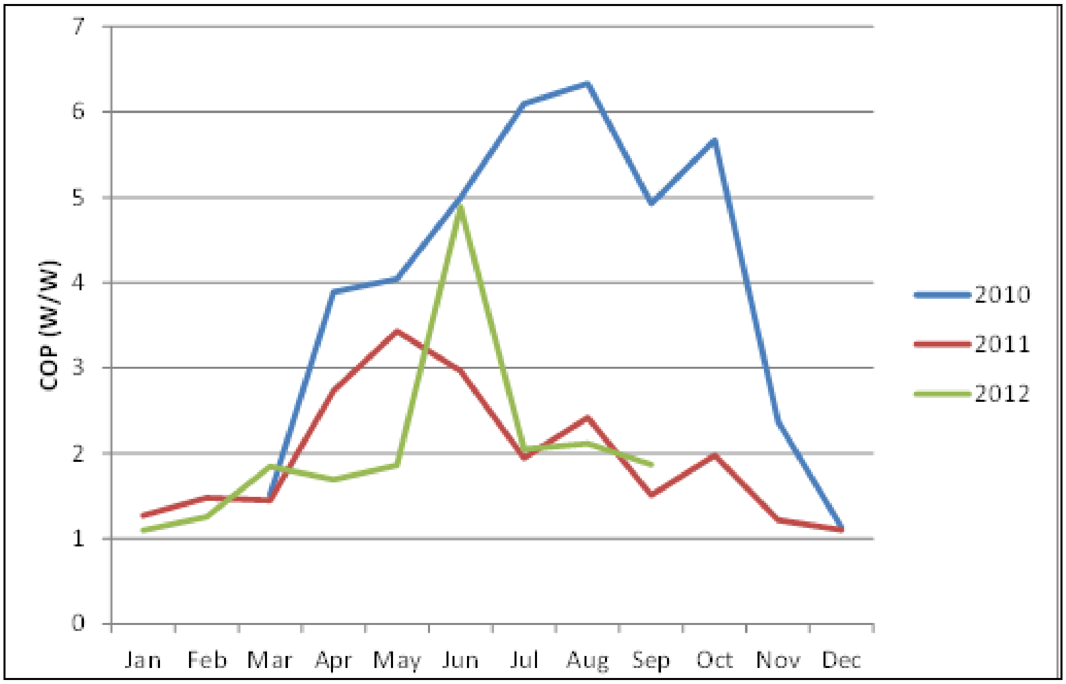


Fig. 24. CC3 water heating COP.

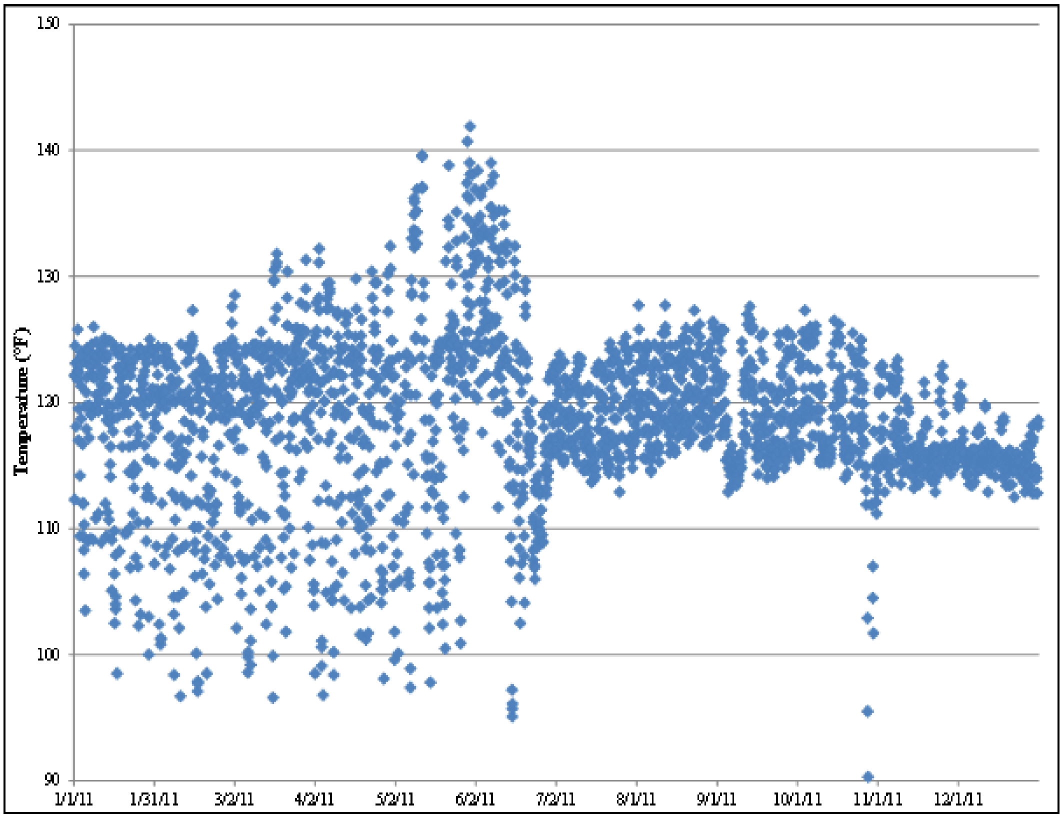


Fig. 25. CC3 hot water supply temperature.

In February 2012 it was observed that the solar system was shutting off even while the domestic hot water was still picking up significant heat from the heat exchanger. The temperature differential was adjusted downward to force the solar thermal system to run longer before shutting off. The net effect of this change is not fully apparent in the data, however, because the May 2012 data seem to be on the low end, whereas the June 2012 data are quite good when compared with the 2011 data. In June 2011 the flow rate on the source side was adjusted to match the sink side in the heat exchanger in an attempt to increase the efficiency. June had a period when the power to the resistance heat was removed, which allowed the lower tank temperature to drop below the typical level. This allowed the solar thermal system to run more and at higher efficiencies. The July to September 2012 data indicate that the adjustment did not have a significant impact on the water heating energy use.

The lower element thermostat setting from 2010 to June 2011 was not high enough to guarantee that the water leaving the tank was kept near 120°F; however, this typically was not an issue because of the higher degree of stratification seen in the tank as a result of the solar system. A typical electric water heater may see only a 15°F difference between the upper tank temperature and lower tank temperature before the lower element turns on. Since the solar system can heat the water in the tank to temperatures well above the 120°F setpoint, the tank may still have plenty of hot water in the upper half when the lower half drops below the thermostat close temperature.

There is great potential for savings by optimizing the resistance heat use of a solar thermal system, as shown by the performance difference between the system in 2010 compared with that in the latter half of 2011 and 2012. With the current control mechanism for the resistance heating element, a compromise must be made between ensuring the availability of hot water and increased efficiency.

5. LESSONS LEARNED AND CONCLUSIONS

CC1 consumed 19,883 kWh of total energy during FY 2012; CC2 used approximately 40% less and CC3 approximately 48% less. However, since PV supplied 3,535 kWh of the total load, CC3 required 66% less energy from the grid for FY 2012. In addition to the valuable insight provided by the reduction in energy consumption afforded by the various combinations of energy conservation measures in the three homes, other key points of interests and lessons gleaned from over the past year are described below.

HVAC: It is very difficult to maintain consistent temperature levels between the first and second levels of a home without some sort of zoning. If zoning is employed, then the ducts should be sized with this in mind. Zoning will likely require that the ducts be larger in order to handle additional airflow when the other damper(s) are closed while avoiding performance penalties due to reduced airflow or increased blower power.

A system with a variable-speed compressor is more likely to mask inherent system problems unless it has a sufficiently sophisticated control system to communicate issues with the homeowner. In trying to balance the temperatures of the first and second floors, we had to close the downstairs damper completely. Doing so increased the external static pressure of the duct system enough to reduce indoor cooling airflow by 37%, which in a typical system would probably lead to a frozen evaporator coil. However, the variable-speed compressor was able to compensate for the reduced airflow with only a minor penalty in performance. It is good that the system can stay running with only a minor efficiency penalty; however, its ability to do so could lead to problems going undiagnosed and result in systems running at less than peak efficiencies.

Water Heater: The method of controlling the backup heat in a solar thermal system can have large impacts on energy consumption. There is a balance between guaranteeing enough hot water and unnecessarily using resistance heat. The solar system is attached to an 80 gallon storage tank, whereas the other houses have only 40–50 gallon tanks. In the future, we may be able to disable the lower element thermostat on the solar system and set the upper element to come on at around 120°F and still ensure that there is hot water available without using the resistance heat excessively. This will allow the water in the bottom of the tank to get much colder, which will provide more favorable temperatures for the solar water heating system.

The HPWH has provided very consistent COPs, between 2.2 and 2.6, compared with the solar water heating system. This is particularly true in light of the variability possible as a result of the different backup heating control methods in solar water heating systems. The solar system definitely has the potential to provide higher efficiencies, but it will probably require some tweaking and experimentation to reach optimal performance. The performance of the solar system will also be more dependent on the hot water use patterns of the occupants. Water draws late in the evening and early in the morning often deplete the hot water generated during the day and require the use of backup heat. If occupants could tailor their hot water use to better coincide with the availability of solar heating, then performance would be improved further.

High Relative Humidity (RH) at CC2: Higher indoor RH at CC2 compared with CC1 was observed during the summers of 2010, 2011, and 2012 (Fig. 26). A different HVAC unit was used in CC2 during each summer. Although some of the RH difference between the summers

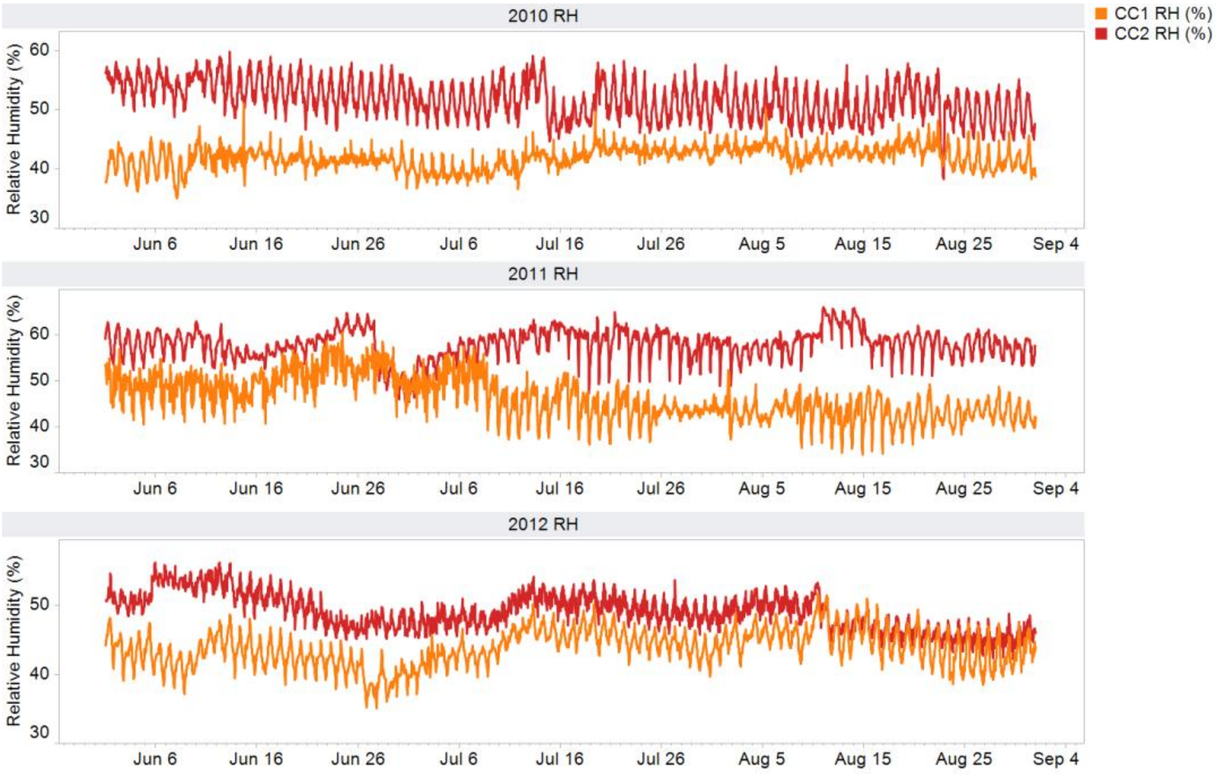


Fig. 26. Relative in humidity CC2 compared with CC1.

might be due to the difference in HVAC units at CC2, that does not explain the consistent higher level of summer RH at CC2 than at CC1.

Based on analysis of temperature/RH sensors on the roof deck, in the attic air, on the attic floor, and in the second level of the retrofit home, it is possible that the source of moisture in the conditioned space might be the attic. Experiments are ongoing, focused on the roof as a possible moisture infiltration point, to understand the high RH levels in CC2.

Precooling for Peak Energy Shaving: ORNL investigated the impact of precooling a home and letting it coast through the on-peak time (12–8 p.m.) using a calibrated model of CC1. Model analysis showed that precooling used 13% more cooling energy than a flat 78°F schedule for the whole summer. However, on sunny days with high outdoor temperatures, the on-peak (12–8 p.m.) energy savings resulting from a precooling schedule compared with a flat 78°F schedule were as high as 60%. The precooling schedule that was modeled was programmed in the thermostats at all the Campbell Creek homes on September 4 and continued until September 25; it can be used for further analysis of precooling strategies.

6. PUBLICATIONS

Biswas, Kaushik, Anthony Gehl, Roderick Jackson, Philip Boudreaux, and Jeffrey Christian. 2012. *Comparison of Two High-Performance Energy Efficient Homes: Annual Performance Report, December 1, 2010–November 30, 2011*, ORNL/TM-2011/539. Oak Ridge, TN: Oak Ridge National Laboratory.

Boudreaux, Philip, Anthony Gehl, and Jeffrey Christian. 2012. *Occupancy Simulation in Three Residential Research Houses, ASHRAE Transactions*, vol. 118. Pt. 2.

Boudreaux, Philip, Timothy Hendrick, Jeffrey Christian, and Roderick Jackson. 2012. *Deep Residential Retrofits in East Tennessee,* ORNL/TM-2012/109. Oak Ridge, TN: Oak Ridge National Laboratory.

Munk, Jeffrey D., Anthony C.Gehl, and Roderick K. Jackson. 2012. *Performance of Variable Capacity Heat Pumps in Mixed Humid Climates*, ORNL/TM-2012/17. Oak Ridge, TN: Oak Ridge National Laboratory.

Tomlinson, John, Jeffrey Christian, and Anthony Gehl. 2012. *Evaluation of Waste Heat Recovery and Utilization from Residential Appliances and Fixtures*, ORNL/TM-2012/243, Oak Ridge, TN: Oak Ridge National Laboratory.

Christian, Jeffrey, Anthony Gehl, Philip Boudreaux, Joshua New, and Rex Dockery. 2010. *Tennessee Valley Authority's Campbell Creek Energy Efficient Homes Project: 2010 First Year Performance Report July 1, 2009–August 31, 2010,* ORNL/TM-2010/206. Oak Ridge, TN: Oak Ridge National Laboratory.

7. REFERENCES

Knoxville News Sentinel. 2012, "Ouch! July in US was hottest ever in history books," (August 8, 2012), retrieved November 11, 2012, from Knoxnews.com, http://www.knoxnews.com/news/2012/aug/08/ouch-july-in-us-was-hottest-ever-in-history/?print=1.

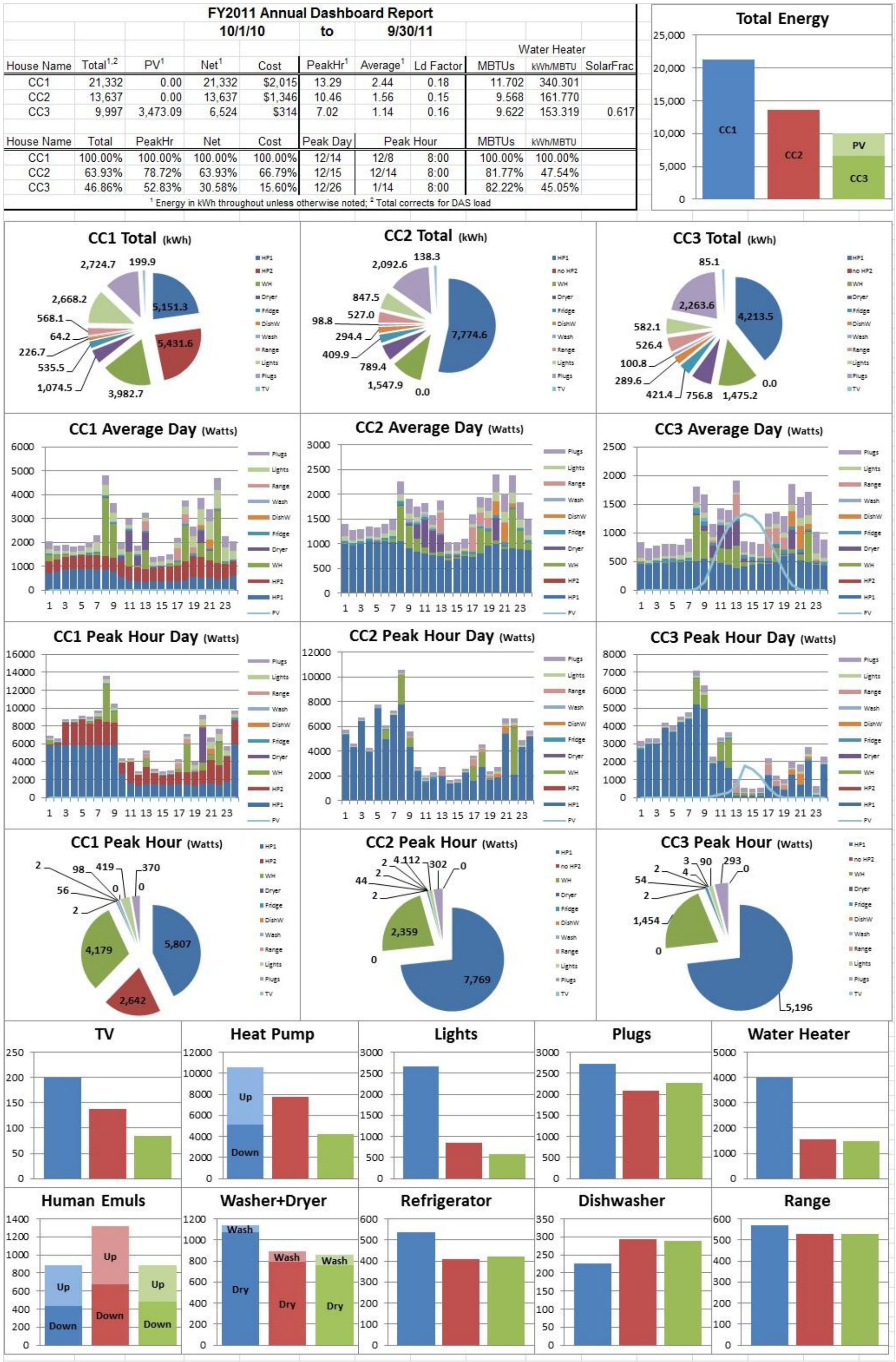
"Comparative Climatic Data (n.d.)," retrieved November 1, 2012, from National Climatic Data Center, "Normal Monthly Heating Degree Days (Base 65)," http://www.ncdc.noaa.gov/oa/climate/online/ccd/nrmhdd.html

Munk, J. D. 2012. *Performance of Variable Capacity Heat Pumps in Mixed Humid Climates.* Oak Ridge National Laboratory, April.

NOAA (National Oceanographic and Atmospheric Administration. 2012, *NOAA National Climatic Data Center, State of the Climate: National Overview for September 2012*, published online October 2012, retrieved on November 2, 2012, http://www.ncdc.noaa.gov/sotc/national/2012/9.

APPENDIX A

PAST ANNUAL DASHBOARDS



FY2011 Annual Dashboard Report

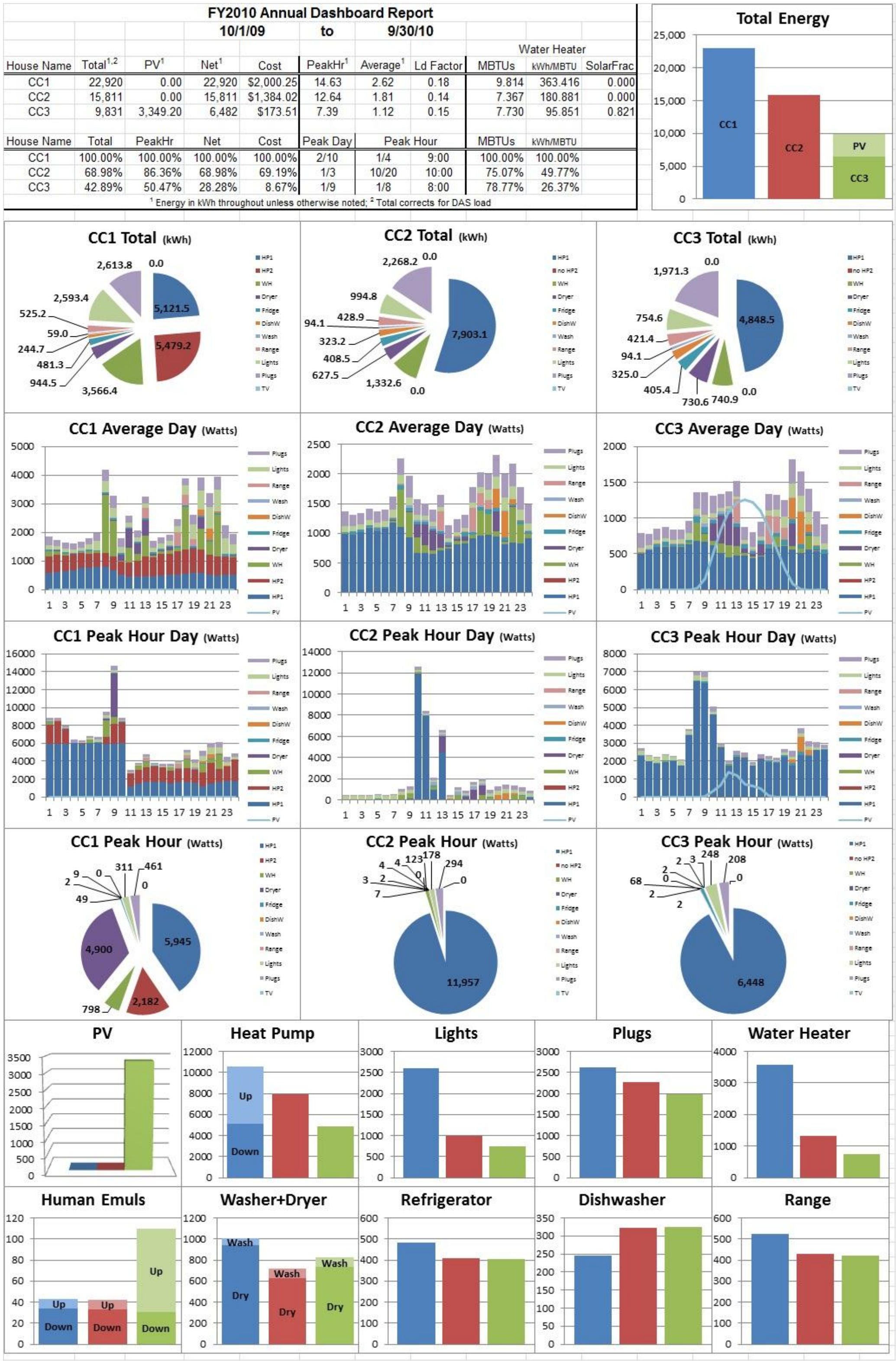
10/1/10 to 9/30/11

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	21,332	0.00	21,332	$2,015	13.29	2.44	0.18	11.702	340.301	
CC2	13,637	0.00	13,637	$1,346	10.46	1.56	0.15	9.568	161.770	
CC3	9,997	3,473.09	6,524	$314	7.02	1.14	0.16	9.622	153.319	0.617

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	12/14	12/8	8:00	100.00%	100.00%
CC2	63.93%	78.72%	63.93%	66.79%	12/15	12/14	8:00	81.77%	47.54%
CC3	46.86%	52.83%	30.58%	15.60%	12/26	1/14	8:00	82.22%	45.05%

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

Fig. A.27. FY 2010 dashboard.



FY2010 Annual Dashboard Report

10/1/09 to 9/30/10

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	22,920	0.00	22,920	$2,000.25	14.63	2.62	0.18	9.814	363.416	0.000
CC2	15,811	0.00	15,811	$1,384.02	12.64	1.81	0.14	7.367	180.881	0.000
CC3	9,831	3,349.20	6,482	$173.51	7.39	1.12	0.15	7.730	95.851	0.821

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	2/10	1/4	9:00	100.00%	100.00%
CC2	68.98%	86.36%	68.98%	69.19%	1/3	10/20	10:00	75.07%	49.77%
CC3	42.89%	50.47%	28.28%	8.67%	1/9	1/8	8:00	78.77%	26.37%

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

Fig. A.28. FY 2011 dashboard.

MONTHLY DASHBOARDS

Dashboard Report

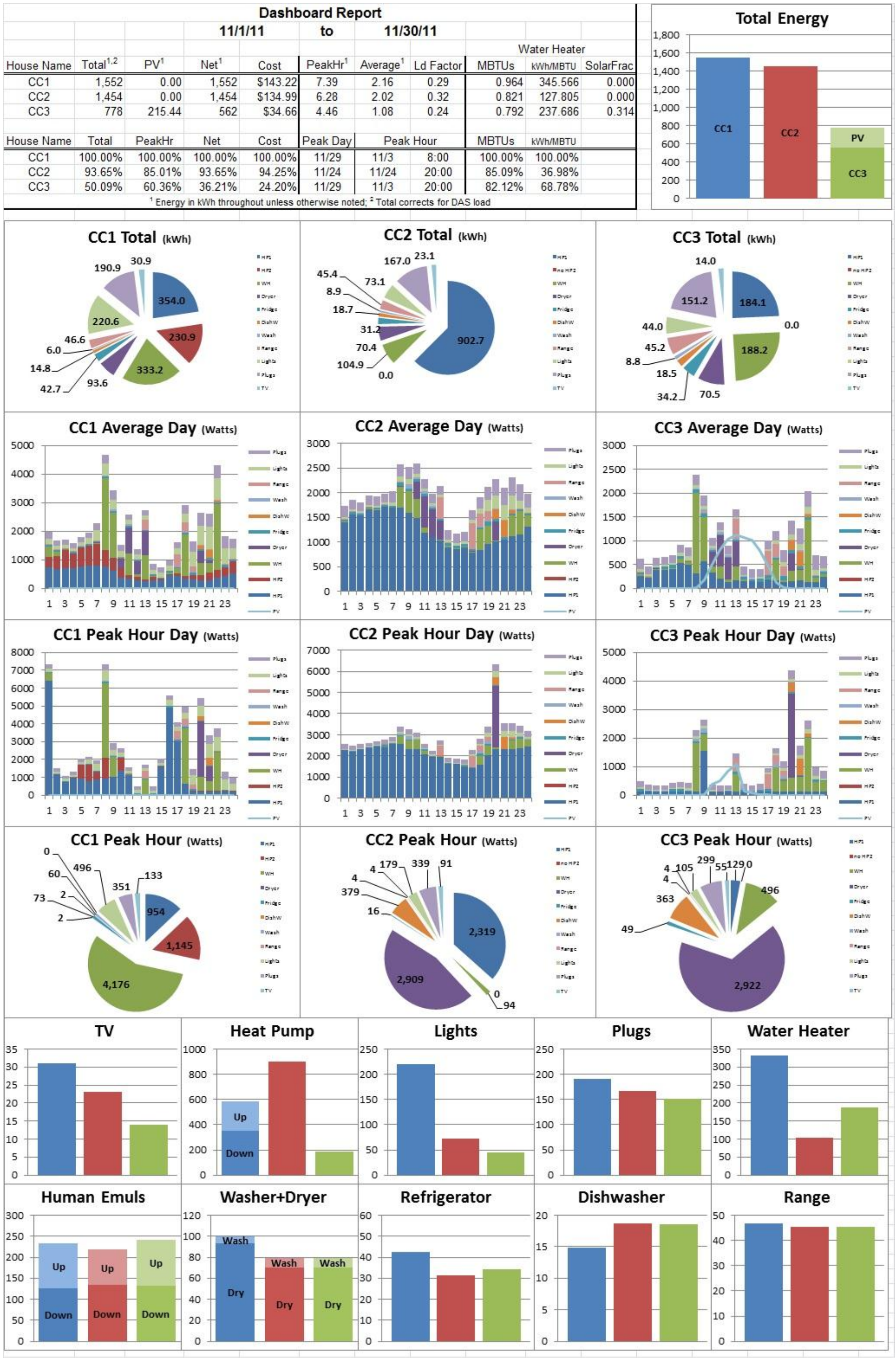
10/1/11 to 10/31/11

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,166	0.00	1,166	$111.58	6.74	1.57	0.23	0.851	345.241	0.000
CC2	856	0.00	856	$85.51	5.19	1.16	0.22	0.757	117.059	0.000
CC3	651	308.49	343	$5.35	4.36	0.89	0.20	0.692	148.499	0.629

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	10/20	10/6	20:00	100.00%	100.00%
CC2	73.41%	77.05%	73.41%	76.64%	10/30	10/20	20:00	88.92%	33.91%
CC3	55.86%	64.69%	29.40%	4.79%	10/12	10/13	20:00	81.36%	43.01%

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

Fig. A.29. October 2011 dashboard.



Dashboard Report

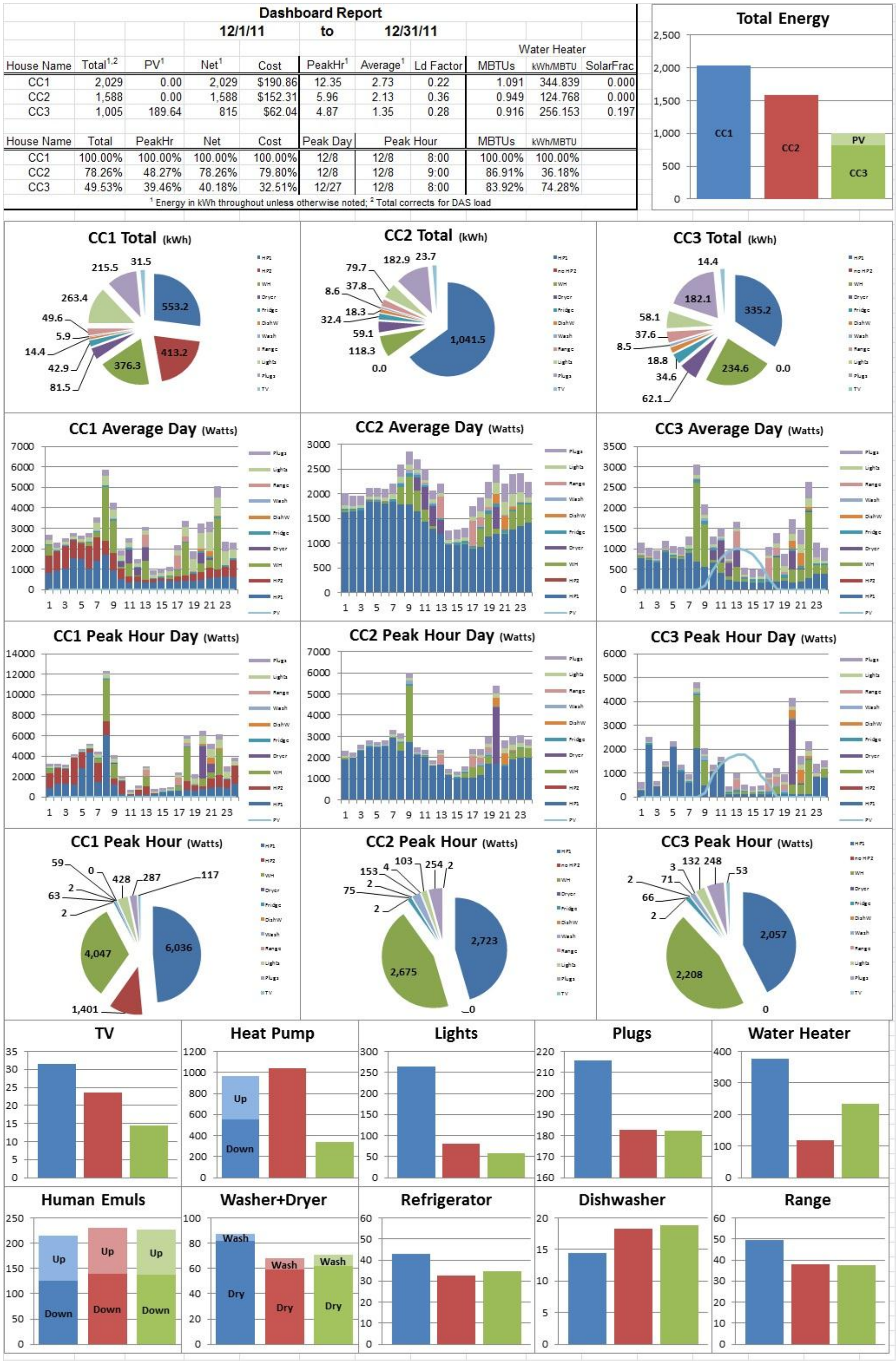
11/1/11 to 11/30/11

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,552	0.00	1,552	$143.22	7.39	2.16	0.29	0.964	345.566	0.000
CC2	1,454	0.00	1,454	$134.99	6.28	2.02	0.32	0.821	127.805	0.000
CC3	778	215.44	562	$34.66	4.46	1.08	0.24	0.792	237.686	0.314

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	11/29	11/3	8:00	100.00%	100.00%
CC2	93.65%	85.01%	93.65%	94.25%	11/24	11/24	20:00	85.09%	36.98%
CC3	50.09%	60.36%	36.21%	24.20%	11/29	11/3	20:00	82.12%	68.78%

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

Fig. A.30. November 2011 dashboard.



Dashboard Report

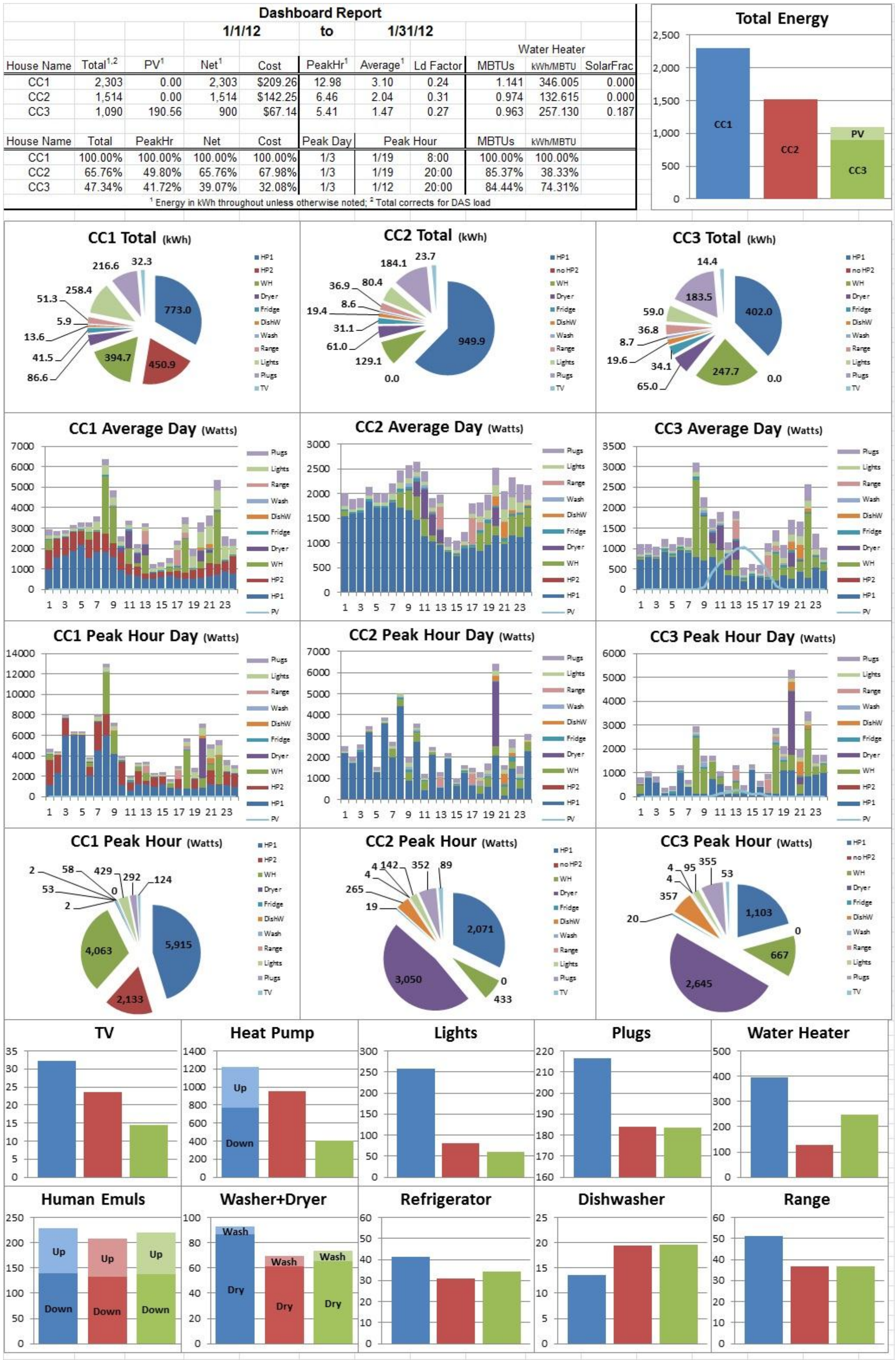
12/1/11 to 12/31/11

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	2,029	0.00	2,029	$190.86	12.35	2.73	0.22	1.091	344.839	0.000
CC2	1,588	0.00	1,588	$152.31	5.96	2.13	0.36	0.949	124.768	0.000
CC3	1,005	189.64	815	$62.04	4.87	1.35	0.28	0.916	256.153	0.197

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	12/8	12/8	8:00	100.00%	100.00%
CC2	78.26%	48.27%	78.26%	79.80%	12/8	12/8	9:00	86.91%	36.18%
CC3	49.53%	39.46%	40.18%	32.51%	12/27	12/8	8:00	83.92%	74.28%

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

Fig. A.31. December 2011 dashboard.



Dashboard Report

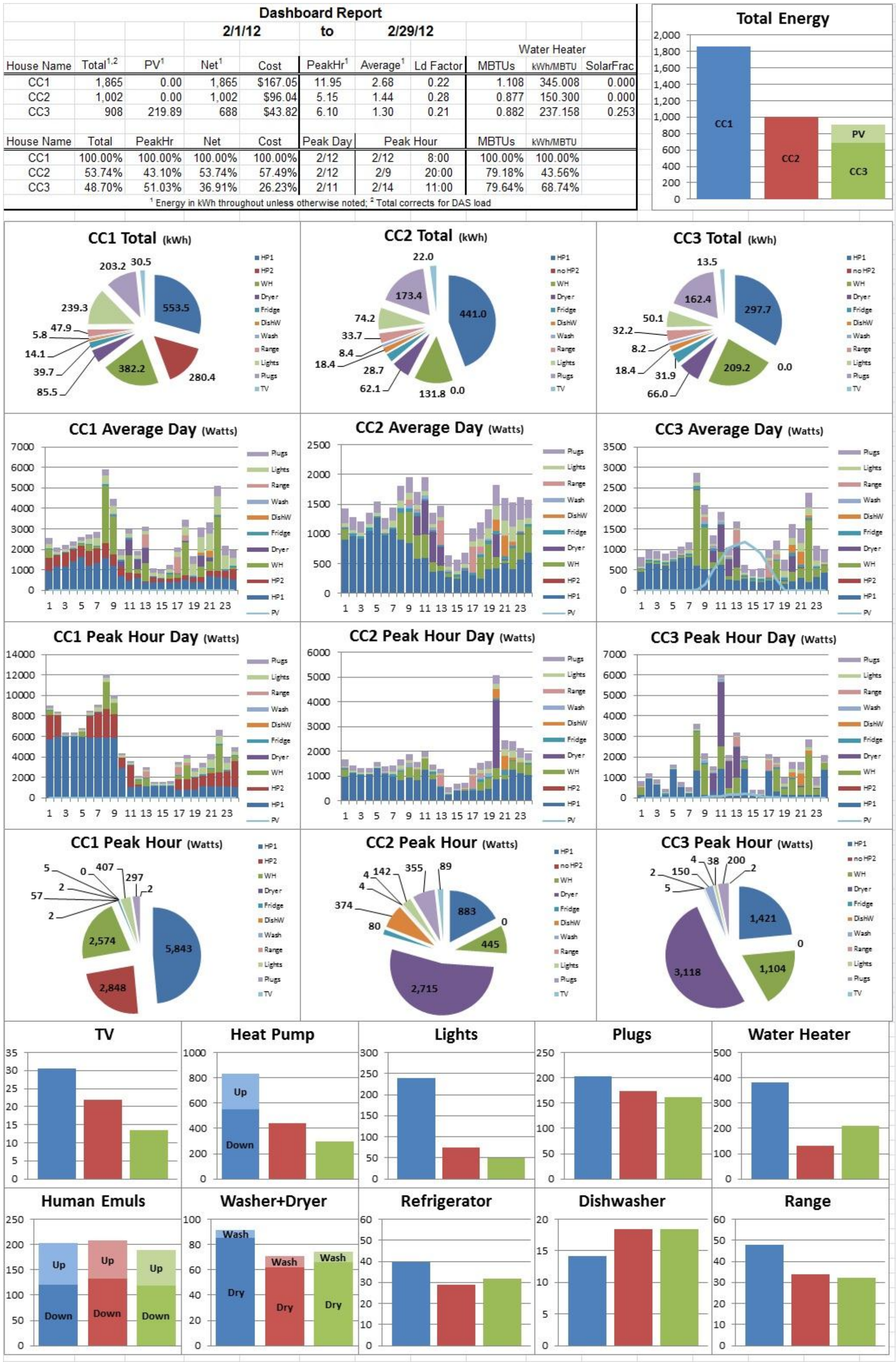
1/1/12 to 1/31/12

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	2,303	0.00	2,303	$209.26	12.98	3.10	0.24	1.141	346.005	0.000
CC2	1,514	0.00	1,514	$142.25	6.46	2.04	0.31	0.974	132.615	0.000
CC3	1,090	190.56	900	$67.14	5.41	1.47	0.27	0.963	257.130	0.187

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	1/3	1/19	8:00	100.00%	100.00%
CC2	65.76%	49.80%	65.76%	67.98%	1/3	1/19	20:00	85.37%	38.33%
CC3	47.34%	41.72%	39.07%	32.08%	1/3	1/12	20:00	84.44%	74.31%

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

Fig. A.32. January 2012 dashboard.



Dashboard Report

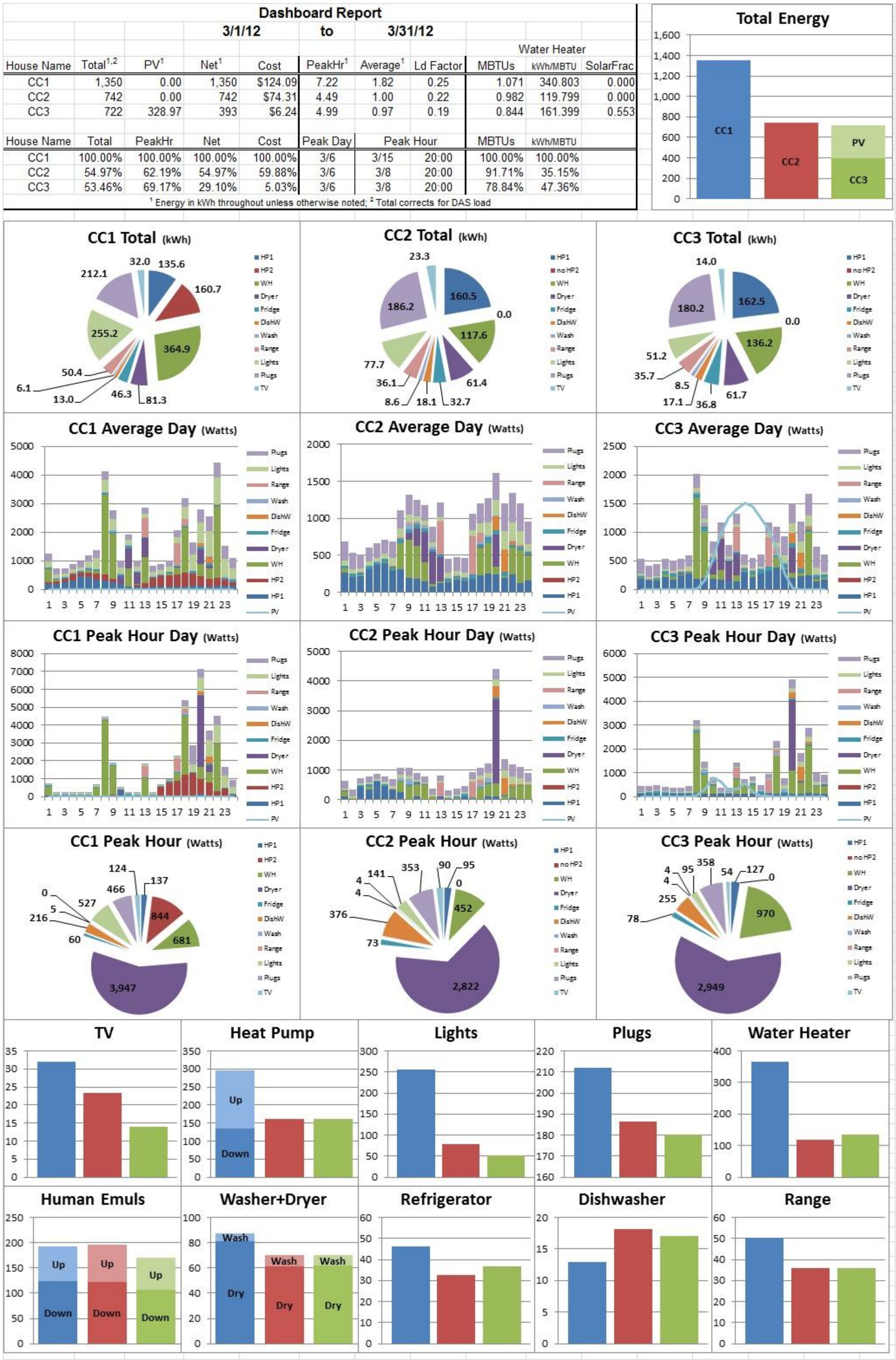
2/1/12 to 2/29/12

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,865	0.00	1,865	$167.05	11.95	2.68	0.22	1.108	345.008	0.000
CC2	1,002	0.00	1,002	$96.04	5.15	1.44	0.28	0.877	150.300	0.000
CC3	908	219.89	688	$43.82	6.10	1.30	0.21	0.882	237.158	0.253

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	2/12	2/12	8:00	100.00%	100.00%
CC2	53.74%	43.10%	53.74%	57.49%	2/12	2/9	20:00	79.18%	43.56%
CC3	48.70%	51.03%	36.91%	26.23%	2/11	2/14	11:00	79.64%	68.74%

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

Fig. A.33. February dashboard.



Dashboard Report

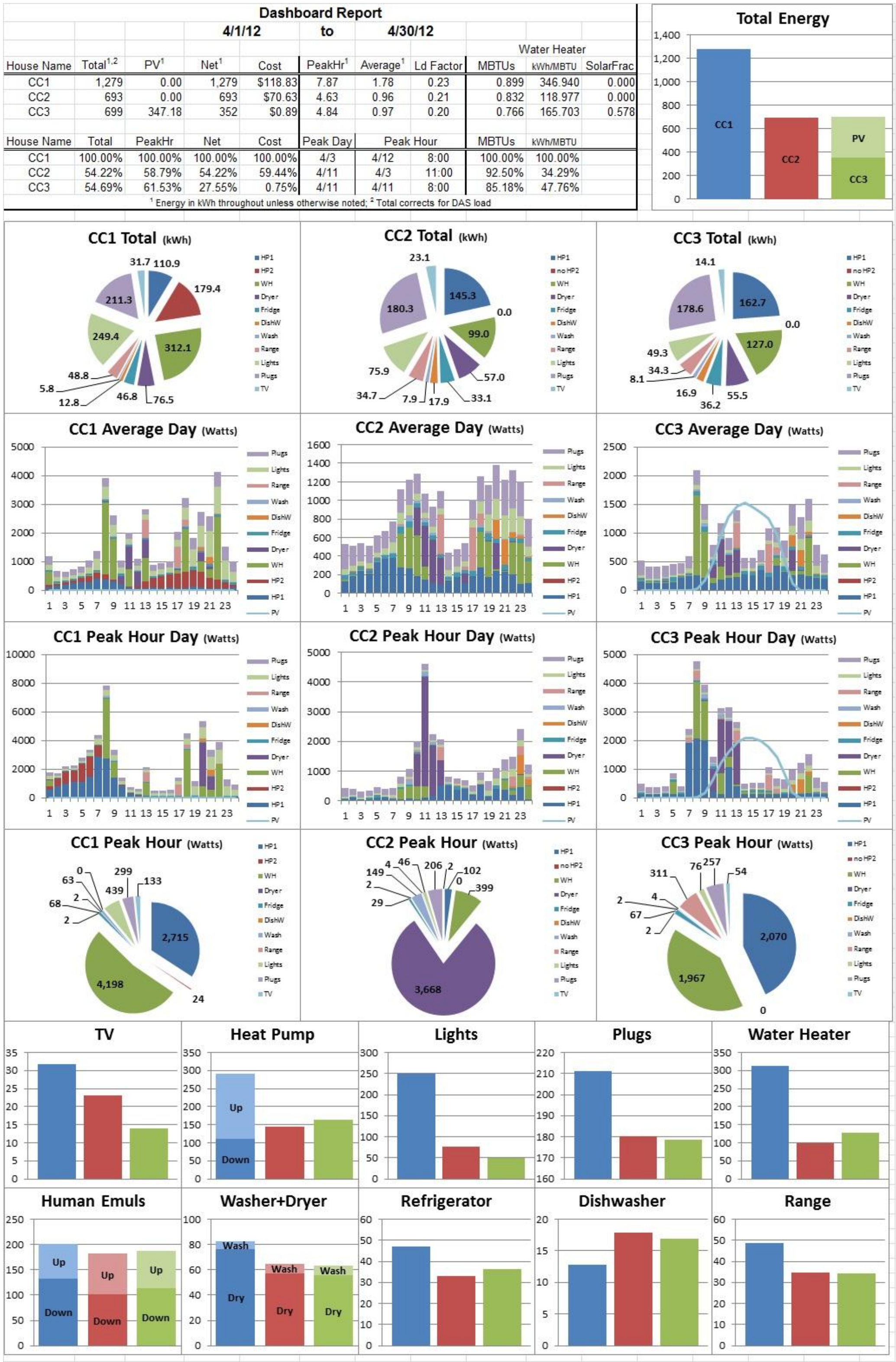
3/1/12 to 3/31/12

								Water Heater		
House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,350	0.00	1,350	$124.09	7.22	1.82	0.25	1.071	340.803	0.000
CC2	742	0.00	742	$74.31	4.49	1.00	0.22	0.982	119.799	0.000
CC3	722	328.97	393	$6.24	4.99	0.97	0.19	0.844	161.399	0.553

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	3/6	3/15	20:00	100.00%	100.00%
CC2	54.97%	62.19%	54.97%	59.88%	3/6	3/8	20:00	91.71%	35.15%
CC3	53.46%	69.17%	29.10%	5.03%	3/6	3/8	20:00	78.84%	47.36%

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

Fig. A.34. March dashboard.



Dashboard Report

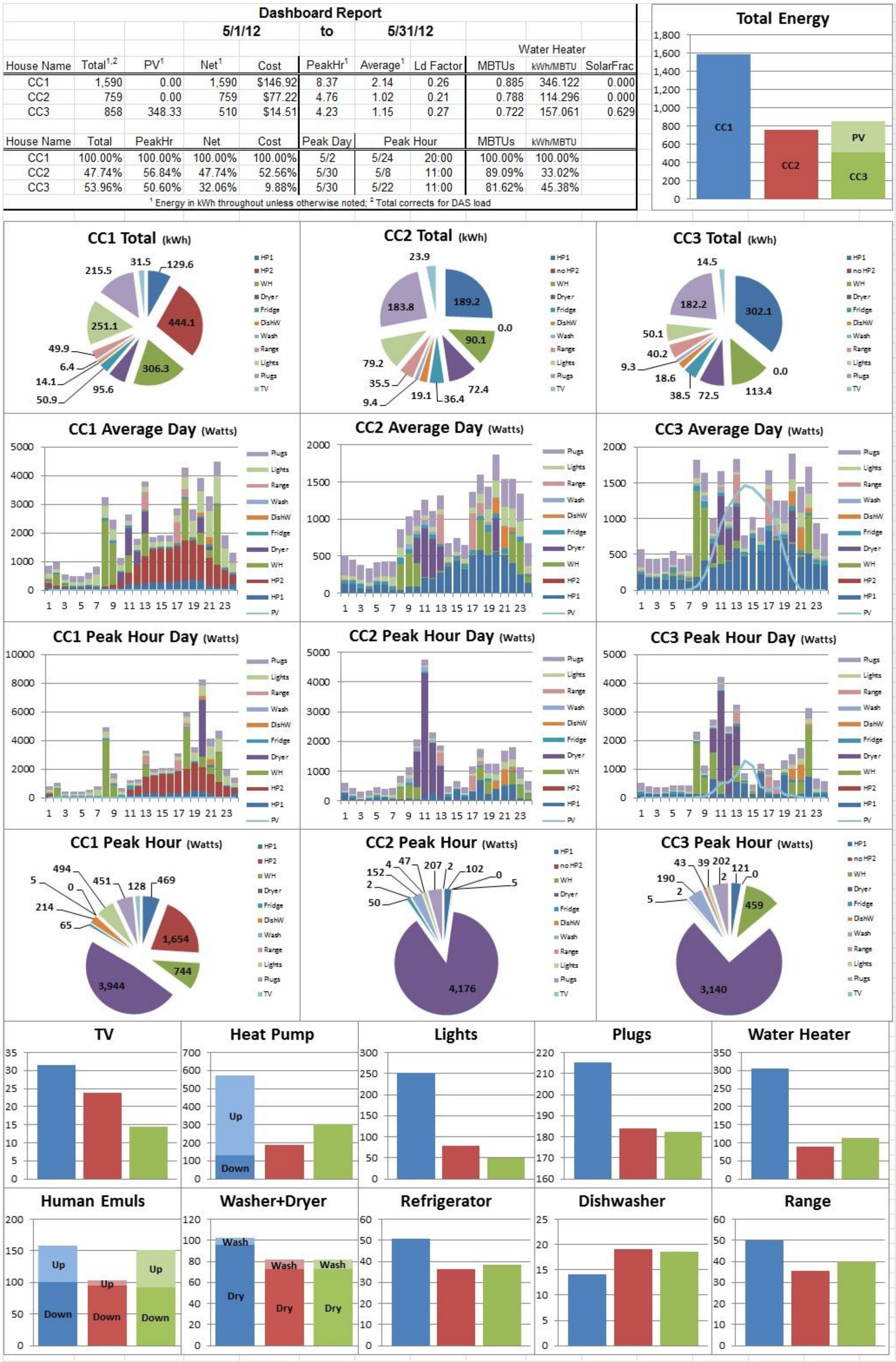
4/1/12 to 4/30/12

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,279	0.00	1,279	$118.83	7.87	1.78	0.23	0.899	346.940	0.000
CC2	693	0.00	693	$70.63	4.63	0.96	0.21	0.832	118.977	0.000
CC3	699	347.18	352	$0.89	4.84	0.97	0.20	0.766	165.703	0.578

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	4/3	4/12	8:00	100.00%	100.00%
CC2	54.22%	58.79%	54.22%	59.44%	4/11	4/3	11:00	92.50%	34.29%
CC3	54.69%	61.53%	27.55%	0.75%	4/11	4/11	8:00	85.18%	47.76%

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

Fig. A.35. April 2012 dashboard.



Dashboard Report

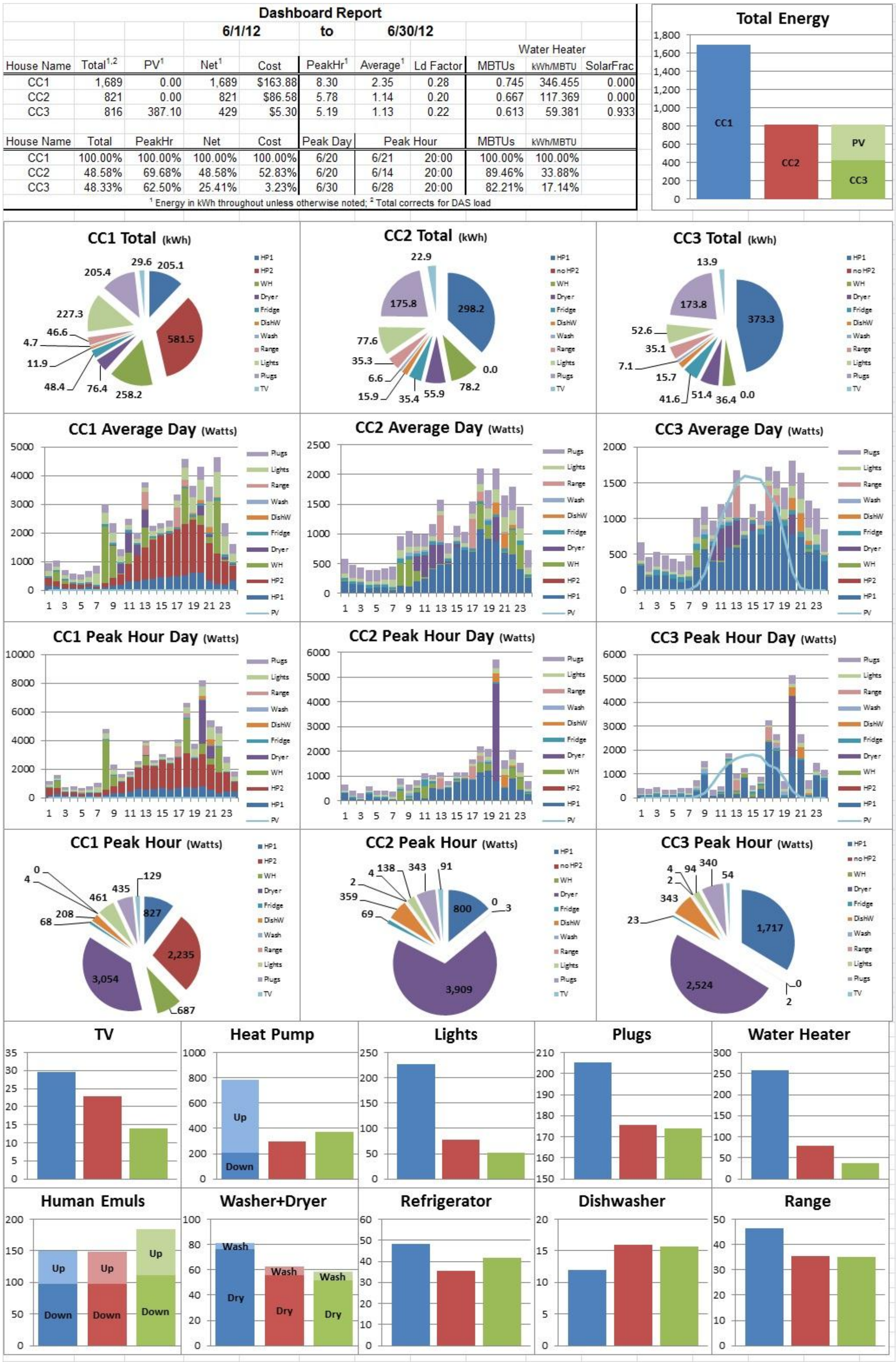
5/1/12 to 5/31/12

								Water Heater		
House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,590	0.00	1,590	$146.92	8.37	2.14	0.26	0.885	346.122	0.000
CC2	759	0.00	759	$77.22	4.76	1.02	0.21	0.788	114.296	0.000
CC3	858	348.33	510	$14.51	4.23	1.15	0.27	0.722	157.061	0.629

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	5/2	5/24	20:00	100.00%	100.00%
CC2	47.74%	56.84%	47.74%	52.56%	5/30	5/8	11:00	89.09%	33.02%
CC3	53.96%	50.60%	32.06%	9.88%	5/30	5/22	11:00	81.62%	45.38%

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

Fig. A.36. May 2012 dashboard.



Dashboard Report

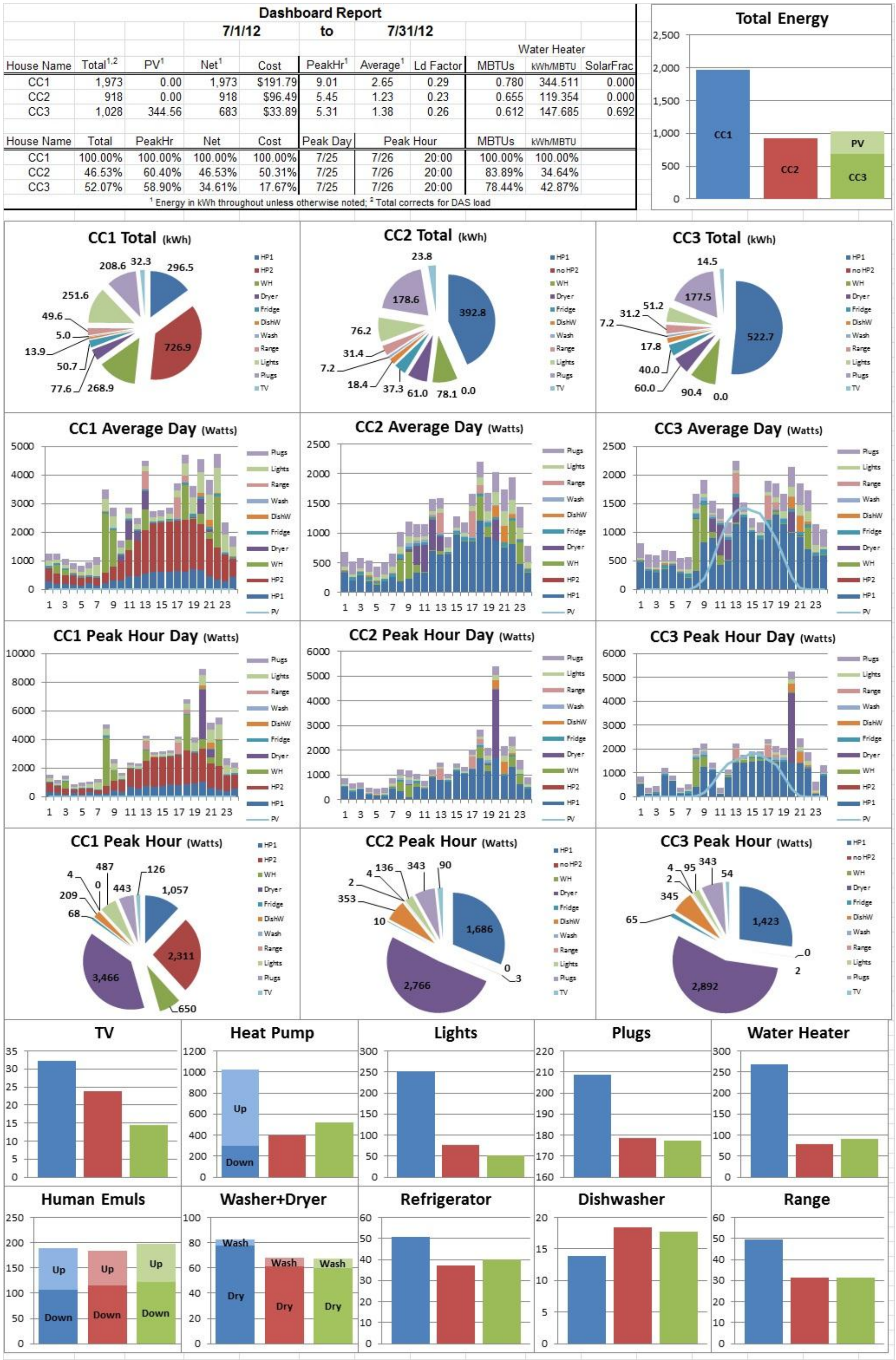
6/1/12 to 6/30/12

House Name	Total^{1,2}	PV^{1}	Net^{1}	Cost	PeakHr^{1}	Average^{1}	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,689	0.00	1,689	$163.88	8.30	2.35	0.28	0.745	346.455	0.000
CC2	821	0.00	821	$86.58	5.78	1.14	0.20	0.667	117.369	0.000
CC3	816	387.10	429	$5.30	5.19	1.13	0.22	0.613	59.381	0.933

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	6/20	6/21	20:00	100.00%	100.00%
CC2	48.58%	69.68%	48.58%	52.83%	6/20	6/14	20:00	89.46%	33.88%
CC3	48.33%	62.50%	25.41%	3.23%	6/30	6/28	20:00	82.21%	17.14%

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

Fig. A.37. June 2012 dashboard.



Dashboard Report

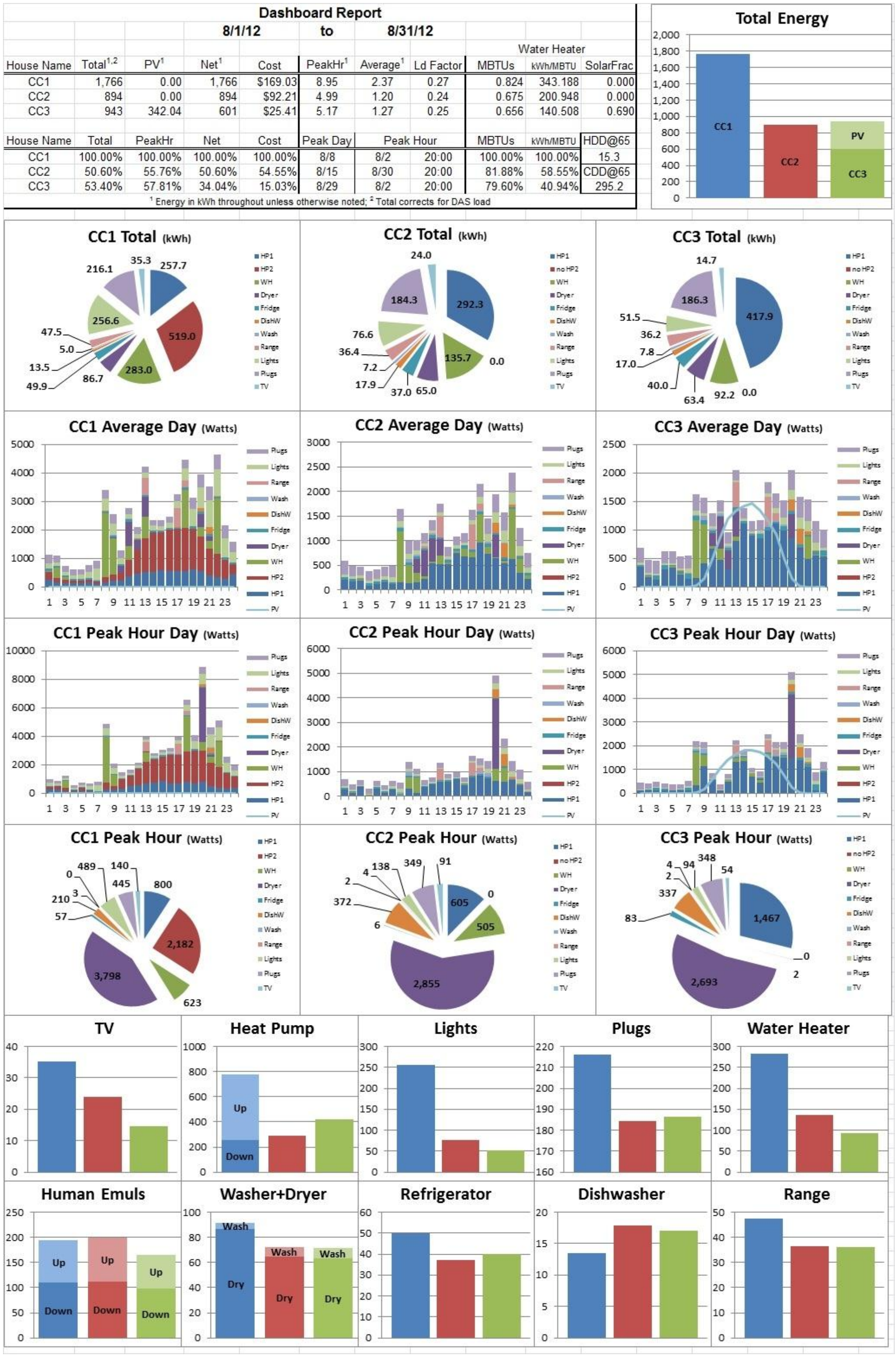
7/1/12 to 7/31/12

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,973	0.00	1,973	$191.79	9.01	2.65	0.29	0.780	344.511	0.000
CC2	918	0.00	918	$96.49	5.45	1.23	0.23	0.655	119.354	0.000
CC3	1,028	344.56	683	$33.89	5.31	1.38	0.26	0.612	147.685	0.692

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	7/25	7/26	20:00	100.00%	100.00%
CC2	46.53%	60.40%	46.53%	50.31%	7/25	7/26	20:00	83.89%	34.64%
CC3	52.07%	58.90%	34.61%	17.67%	7/25	7/26	20:00	78.44%	42.87%

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

Fig. A.38. July 2012 dashboard.



Dashboard Report

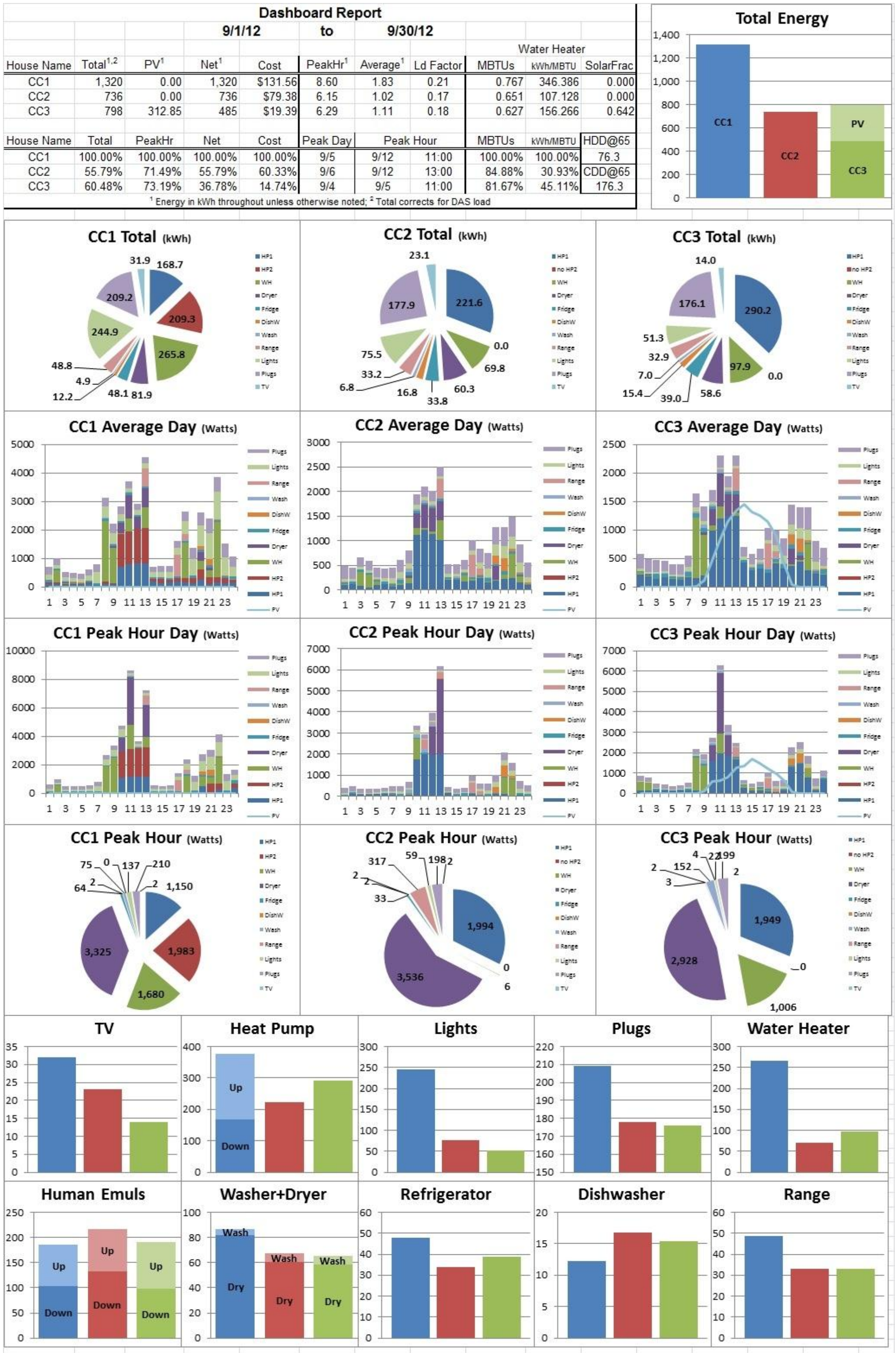
8/1/12 to 8/31/12

House Name	Total^{1,2}	PV^{1}	Net^{1}	Cost	PeakHr^{1}	Average^{1}	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,766	0.00	1,766	$169.03	8.95	2.37	0.27	0.824	343.188	0.000
CC2	894	0.00	894	$92.21	4.99	1.20	0.24	0.675	200.948	0.000
CC3	943	342.04	601	$25.41	5.17	1.27	0.25	0.656	140.508	0.690

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	8/8	8/2	20:00	100.00%	100.00%	HDD@65 15.3
CC2	50.60%	55.76%	50.60%	54.55%	8/15	8/30	20:00	81.88%	58.55%	CDD@65 295.2
CC3	53.40%	57.81%	34.04%	15.03%	8/29	8/2	20:00	79.60%	40.94%	

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

Fig. A.39. August 2012 dashboard.



Dashboard Report

9/1/12 to 9/30/12

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,320	0.00	1,320	$131.56	8.60	1.83	0.21	0.767	346.386	0.000
CC2	736	0.00	736	$79.38	6.15	1.02	0.17	0.651	107.128	0.000
CC3	798	312.85	485	$19.39	6.29	1.11	0.18	0.627	156.266	0.642

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	9/5	9/12	11:00	100.00%	100.00%	HDD@65 76.3
CC2	55.79%	71.49%	55.79%	60.33%	9/6	9/12	13:00	84.88%	30.93%	CDD@65
CC3	60.48%	73.19%	36.78%	14.74%	9/4	9/5	11:00	81.67%	45.11%	176.3

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

Fig. A.40. September 2012 dashboard.

FACT SHEET

Campbell Creek Research Houses: A Transformational Impact

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Background

As a unique testing facility designed in collaboration between TVA, ORNL, and EPRI, TVA built three experimental homes at Campbell Creek to evaluate the relative impact of efficient technologies and construction techniques on residential energy use. The project compares the energy performance of three research houses: the Builder House, acting as a benchmark and representing typical new home construction practices (IECC 2006), the Retrofit House, which is the Builder House with a major whole house energy efficiency retrofit package, and the High Performance House, being constructed as the most efficient home the market could tolerate. The three homes have almost identical floor plans, and were designed to determine the energy savings of whole house retrofits and high performance housing over an IECC 2006 home. The homes were completed in early 2009.

In order to have a valid and accurate comparison, these unoccupied homes require occupancy simulation. Using home automation equipment the lighting, clothes washer and dryer, refrigerator/freezer doors, hot water usage, dishwasher and oven operation were controlled as average real occupants would. The homes are maintained at the same temperature set points for heating and cooling. Hundreds of sensors to monitor energy use of all subsystems as well as temperature and humidity were placed inside the homes.

Project Findings

HVAC and water heating are the largest energy uses in the home and are therefore the easiest to target for energy savings. HVAC energy savings could be obtained by both reducing the load of the building envelope, and by increasing the mechanical system efficiency. The largest energy savings found in the Retrofit House was obtained by moving the ducts inside the conditioned space (by converting the attic to a conditioned mechanical room with spray foam) and simultaneously tightening the envelope, reducing the capacity of the HVAC and increasing the efficiency of the unit.

Water heating efficiencies can be improved by using solar or HPWH technology. Solar is slightly more efficient as tested, but HPWHs are much less costly and have less installation issues.

Changing from incandescent lighting to fluorescent lighting represents a significant energy reduction and is something that the average homeowner can easily do.

Manufacturers and Suppliers

The following partners have contributed to the Campbell Creek Research project: Associated Equipment Company, Daikin, Dow Chemicals, Big Frog Mountain, BioBased Insulation, Carrier, Fantech, General Electric, Johns Manville, Louisiana Pacific, Mitsubishi, Sanden, Serious Materials, and Sustainable Future.

Energy Savings Features

Builder House

- Meets 2006 IECC

Retrofit House (energy savings of 37%)

- 3 ton heat pump, up to 20 SEER and 13 HSPF (Installed in Jan 2012)
- Attic cathederalized sealed with spray foam and spray fiberglass and sealed
- Heat pump water heater
- Compact fluorescent lighting
- Ducts completely inside the conditioned space

High Performance House (energy savings of 67%)

- Advanced air-tight construction. The walls are 2 inches thicker than the builder and retrofit houses with twice the R value
- SEER 18, HSPF 8.89, inverter driven, ducted HP, 24 kBtu/hr rated cooling capacity, 27 kBtu/hr rated high heating capacity (Installed in Nov 2010)
- Ducts and indoor coil inside the conditioned space
- Photovoltaic array on the roof with 2.5 kW capacity
- Solar thermal water heating system
- Fluorescent/LED lighting
- Triple pane windows

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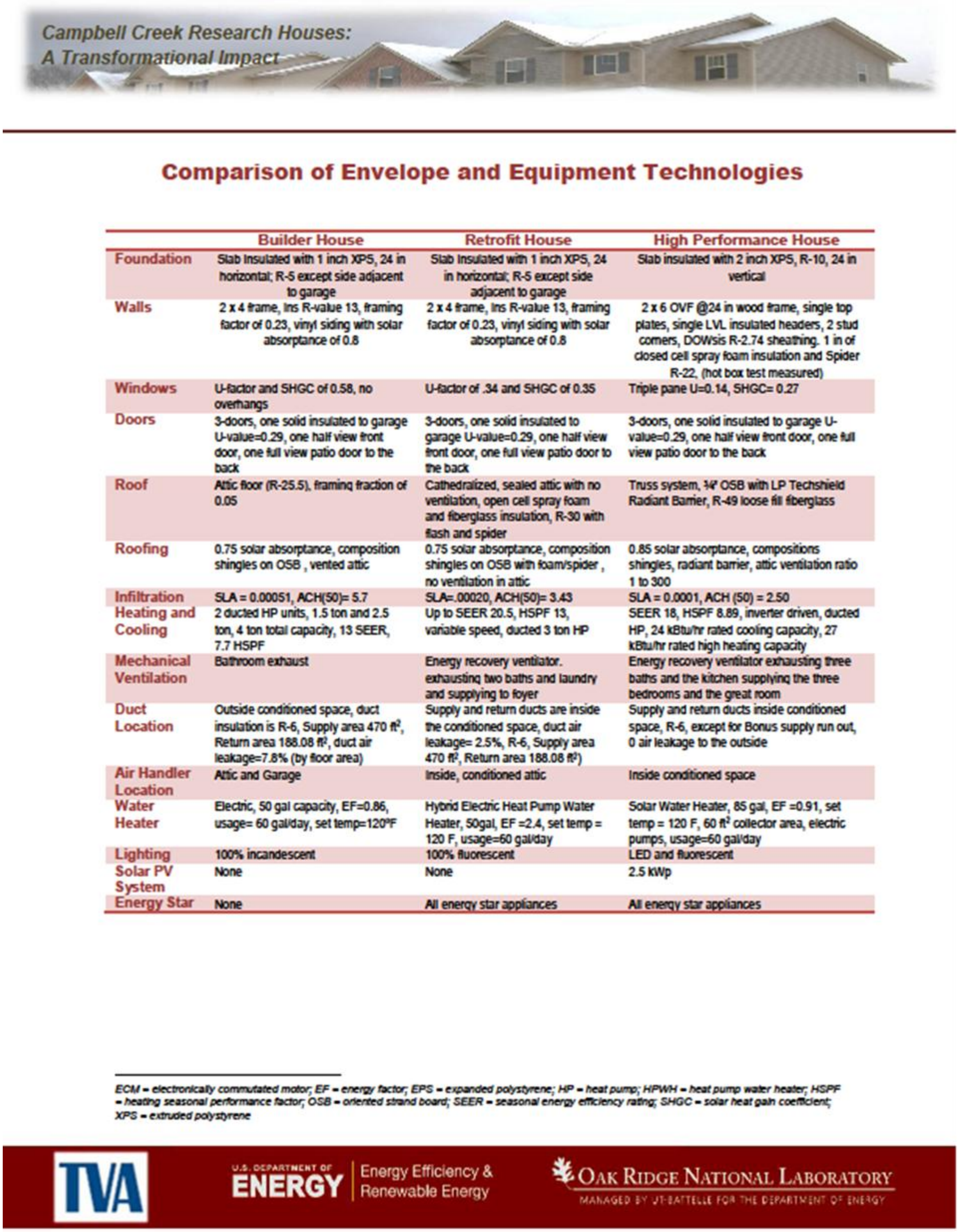

Campbell Creek Research Houses:
A Transformational Impact

Comparison of Envelope and Equipment Technologies

	Builder House	Retrofit House	High Performance House
Foundation	Slab Insulated with 1 inch XPS, 24 in horizontal; R-5 except side adjacent to garage	Slab Insulated with 1 inch XPS, 24 in horizontal; R-5 except side adjacent to garage	Slab insulated with 2 inch XPS, R-10, 24 in vertical
Walls	2 x 4 frame, Ins R-value 13, framing factor of 0.23, vinyl siding with solar absorptance of 0.8	2 x 4 frame, Ins R-value 13, framing factor of 0.23, vinyl siding with solar absorptance of 0.8	2 x 6 OVF @24 in wood frame, single top plates, single LVL insulated headers, 2 stud corners, DOWsis R-2.74 sheathing. 1 in of closed cell spray foam insulation and Spider R-22, (hot box test measured)
Windows	U-factor and SHGC of 0.58, no overhangs	U-factor of .34 and SHGC of 0.35	Triple pane U=0.14, SHGC= 0.27
Doors	3-doors, one solid insulated to garage U-value=0.29, one half view front door, one full view patio door to the back	3-doors, one solid insulated to garage U-value=0.29, one half view front door, one full view patio door to the back	3-doors, one solid insulated to garage U-value=0.29, one half view front door, one full view patio door to the back
Roof	Attic floor (R-25.5), framing fraction of 0.05	Cathedralized, sealed attic with no ventilation, open cell spray foam and fiberglass insulation, R-30 with flash and spider	Truss system, ¼" OSB with LP Techshield Radiant Barrier, R-49 loose fill fiberglass
Roofing	0.75 solar absorptance, composition shingles on OSB , vented attic	0.75 solar absorptance, composition shingles on OSB with foam/spider , no ventilation in attic	0.85 solar absorptance, compositions shingles, radiant barrier, attic ventilation ratio 1 to 300
Infiltration	SLA = 0.00051, ACH(50)= 5.7	SLA=.00020, ACH(50)= 3.43	SLA = 0.0001, ACH (50) = 2.50
Heating and Cooling	2 ducted HP units, 1.5 ton and 2.5 ton, 4 ton total capacity, 13 SEER, 7.7 HSPF	Up to SEER 20.5, HSPF 13, variable speed, ducted 3 ton HP	SEER 18, HSPF 8.89, inverter driven, ducted HP, 24 kBtu/hr rated cooling capacity, 27 kBtu/hr rated high heating capacity
Mechanical Ventilation	Bathroom exhaust	Energy recovery ventilator. exhausting two baths and laundry and supplying to foyer	Energy recovery ventilator exhausting three baths and the kitchen supplying the three bedrooms and the great room
Duct Location	Outside conditioned space, duct insulation is R-6, Supply area 470 ft², Return area 188.08 ft², duct air leakage=7.8% (by floor area)	Supply and return ducts are inside the conditioned space, duct air leakage= 2.5%, R-6, Supply area 470 ft², Return area 188.08 ft²)	Supply and return ducts inside conditioned space, R-6, except for Bonus supply run out, 0 air leakage to the outside
Air Handler Location	Attic and Garage	Inside, conditioned attic	Inside conditioned space
Water Heater	Electric, 50 gal capacity, EF=0.86, usage= 60 gal/day, set temp=120°F	Hybrid Electric Heat Pump Water Heater, 50gal, EF =2.4, set temp = 120 F, usage=60 gal/day	Solar Water Heater, 85 gal, EF =0.91, set temp = 120 F, 60 ft² collector area, electric pumps, usage=60 gal/day
Lighting	100% incandescent	100% fluorescent	LED and fluorescent
Solar PV System	None	None	2.5 kWp
Energy Star	None	All energy star appliances	All energy star appliances

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ECM – electronically commutated motor; EF – energy factor; EPS – expanded polystyrene; HP – heat pump; HPWH – heat pump water heater; HSPF – heating seasonal performance factor; OSB – oriented strand board; SEER – seasonal energy efficiency rating; SHGC – solar heat gain coefficient; XPS – extruded polystyrene

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