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Tennessee Valley Authority's Campbell Creek Research Homes Project: FY 2013 Annual Performance Report October 1, 2012–September 30, 2013

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May 2014

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OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

TENNESSEE VALLEY AUTHORITY'S CAMPBELL CREEK RESEARCH HOMES PROJECT: FY 2013 ANNUAL PERFORMANCE REPORT OCTOBER 1, 2012–SEPTEMBER 30, 2013

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CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

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ACRONYMS

AHRI	Air-conditioning, Heating, and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CDD	cooling degree day
CFL	compact fluorescent light
COP	coefficient of performance
EER	energy efficiency ratio
EPRI	Electric Power Research Institute
ES	ENERGY STAR
FY	fiscal year
GFX	gravity-film heat exchanger
HDD	heating degree day
HPWH	heat pump water heater
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air conditioning
LCD	liquid crystal diode
LCUB	Lenoir City Utility Board
LED	light-emitting diode
NMBE	normalized mean bias error
NOAA	National Oceanic and Atmospheric Administration
OAT	outdoor air temperature
ORNL	Oak Ridge National Laboratory
PV	photovoltaic
RH	relative humidity
RMSE	root mean square error
SEER	seasonal energy efficiency ratio
SHR	sensible heat ratio
TVA	Tennessee Valley Authority
WH	water heater

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 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, of retrofitting of existing homes, and of high-performance new homes built from the ground up for energy efficiency.

This project was designed to compare three houses that represent 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 extensively monitor the structural components and the energy usage by component. In October 2013, the base case was also modified by replacing the builder-grade heating, ventilation, and air-conditioning (HVAC) system with a high-efficiency variable-speed unit.

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, used primarily 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 with a south-facing orientation; CC3 has a north-facing orientation and is located 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 more than 300 channels of continuous energy performance and thermal comfort data collection in the houses (100 for each house). The data will be used to evaluate the impact of energy-efficiency upgrades on the envelope, mechanical equipment, and demand-response options. Each retrofit will be evaluated incrementally, by both short-term measurements and calibrated building simulation model.

This report is intended to document the comprehensive testing, data analysis, research, and findings within the October 2012 through September 2013 (Fiscal Year [FY] 2013) timeframe at the Campbell Creek research houses. The following sections 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 is also provided. Finally, lessons learned and concluding remarks are highlighted.

2. REVIEW OF THE TECHNOLOGY PROGRESSION IN FY 2013

(Refer to Appendix A for past technology progression)

On October 2, 2012, a Carrier Greenspeed™ variable-speed air-source heat pump HVAC system (Figs. 1 and 2) was installed in CC1. This system consists of a 3 ton upstairs unit and a 2 ton downstairs unit. The units have a seasonal energy efficiency ratio (SEER) rating of 20.5 and a heating seasonal performance factor (HSPF) rating of 13.

Fig. 1. Carrier Greenspeed™ HVAC units.

Fig. 2. CC1 HPWH and Carrier air handler.

New GE heat pump water heaters (HPWHs) were installed in all three homes on March 5, 2013 (Fig. 2), as part of a load management study. These units had a modified design to allow the tanks to run at a higher temperature than standard units. At CC1 the standard electric water heater (WH) was replaced; at CC3 the solar water heater system was disabled and replaced, and the gravity-film heat exchanger was bypassed. At CC2 the existing GE HPWH (on standby) was replaced. The Sanden EcoCute CO_2 HPWH continued to operate at CC2 (through August) as part of an ongoing study by EPRI.

Sustainable Future removed the solar thermal hot water system from CC3 on April 6, 2013, including the panels from the roof (Fig. 3).

On April 9, 2013, a demand response relay was installed and successfully tested on the CC1 HVAC system. This was done to facilitate a demand-response study conducted by EPRI.

On May 8, 2013, a demand-response relay was installed and successfully tested on the CC2 HVAC system. This was done to facilitate a demand-response study conducted by EPRI.

On August 28, 2013, the GE HPWH was switched into service, and on August 29, 2013, the Sanden EcoCute CO_2 HPWH was removed from CC2.

Fig. 3. Sustainable Future removes solar thermal panels at CC3.

3. OVERALL PERFORMANCE OF HOUSES FROM OCTOBER 1, 2012, THROUGH SEPTEMBER 30, 2013

3.1 ANNUAL DASHBOARDS

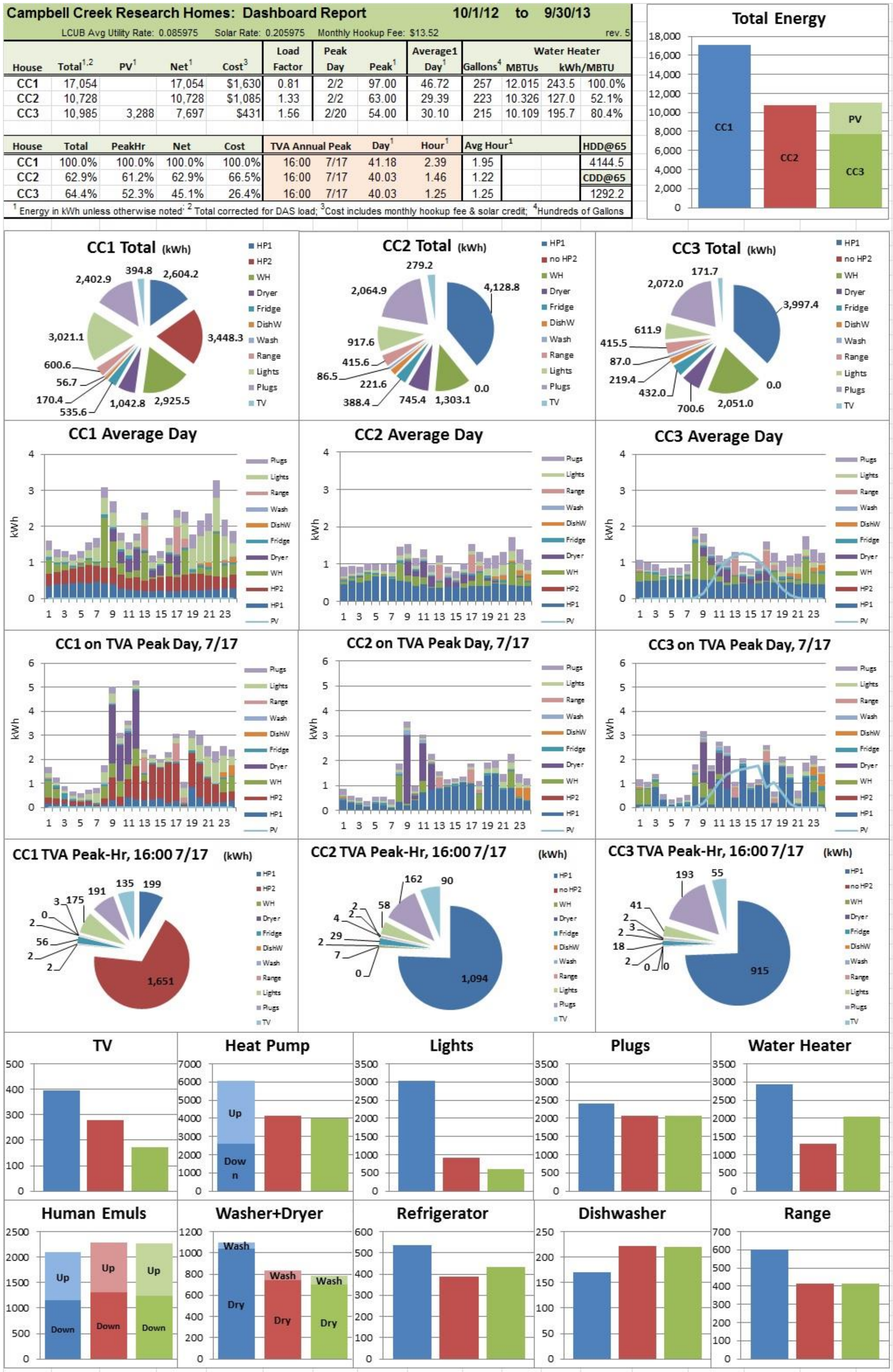
Figure 4 shows the energy dashboard for a full year of performance from October 1, 2012, through September 30, 2013. The annual energy consumption savings of CC2 and CC3 compared with CC1 are 37 and 36%, respectively. The net energy savings of CC3 compared with CC1, accounting for photovoltaic (PV) generation, is 55%. The load factors for the entire year are 0.23, 0.28, and 0.31 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 Utility 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, 24% of the total. The cooling load was 11%, and the water heating energy load was another 17% of the total. The annual plug loads (including TV) represent 16%, and the lights represent 18%. The dryer was 6% of the total builder house load. In the retrofit house, heating was the largest piece at 27%, followed by plug loads at 23%, cooling at 12%, water heating at 12%, lights at 9%, and dryer at 7%. In the high-performance house, heating and plug loads were the largest piece at 22% and 21%, respectively, followed by water heating at 19%, cooling at 14%, and the electric dryer at 7%.

The FY 2013 annual energy consumption for the heat pump, WH, 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. Over the entire one year period the heat pump in CC2 used 32% less energy and the heat pump in CC3 used 34% less than the one in CC1 (see Sect. 4.2 for a detailed analysis). The more efficient lighting in CC2 and CC3 saved 70 and 80% of the lighting energy, respectively, compared with the 100% incandescent lighting installed in CC1.

The ENERGY STAR (ES) refrigerators in CC2 and CC3 used 28 and 19% less energy, respectively, than the non-ES 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 31% energy savings compared with the single larger oven in CC1 under the same simulated cooking load in all three houses.

The ES dishwashers in CC2 and CC3 actually used ~30% more energy than the standard (non-ES) model in CC1. The ES model did save on hot water consumption: CC2 used 58 fewer gallons, and CC3 used 169 fewer gallons. Based on 157 Wh/gal, the measured electrical energy required to heat water with the standard electric WH in CC1, the ES dishwashers realized an annual hot water energy savings of only 9 and 18 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 346, 386, and 371 kWh, respectively, in CC1, CC2, and CC3. Thus even with hot water savings, the ES model used more energy annually than the non-ES dishwasher model in CC1.



Campbell Creek Research Homes: Dashboard Report 10/1/12 to 9/30/13

LCUB Avg Utility Rate: 0.085975 Solar Rate: 0.205975 Monthly Hookup Fee: $13.52 rev. 5

House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Load Factor	Peak Day	Peak[1]	Average1 Day[1]	Water Heater Gallons[4]	MBTUs	kWh/MBTU	
CC1	17,054		17,054	$1,630	0.81	2/2	97.00	46.72	257	12.015	243.5	100.0%
CC2	10,728		10,728	$1,085	1.33	2/2	63.00	29.39	223	10.326	127.0	52.1%
CC3	10,985	3,288	7,697	$431	1.56	2/20	54.00	30.10	215	10.109	195.7	80.4%

House	Total	PeakHr	Net	Cost	TVA Annual Peak		Day[1]	Hour[1]	Avg Hour[1]	HDD@65
CC1	100.0%	100.0%	100.0%	100.0%	16:00	7/17	41.18	2.39	1.95	4144.5
CC2	62.9%	61.2%	62.9%	66.5%	16:00	7/17	40.03	1.46	1.22	CDD@65
CC3	64.4%	52.3%	45.1%	26.4%	16:00	7/17	40.03	1.25	1.25	1292.2

[1] Energy in kWh unless otherwise noted; [2] Total corrected for DAS load; [3]Cost includes monthly hookup fee & solar credit; [4]Hundreds of Gallons

Fig. 4. FY 2013 dashboard for a full year from October 1, 2012, through September 30, 2013.

Table 1. FY 2013 annual kilowatt-hour usage by equipment for the three houses

Equipment/ appliances	House	Total kWh	% Savings
Heat pump	CC1	6,053	–
	CC2	4,129	32
	CC3	3,997	34
Water heater	CC1	2,926	–
	CC2	1,303	55
	CC3	2,051	30
Lights	CC1	3,021	–
	CC2	918	70
	CC3	612	80
Plug load	CC1	2,798	–
	CC2	2,344	16
	CC3	2,244	20
Refrigerator	CC1	536	–
	CC2	388	28
	CC3	432	19
Dishwasher	CC1	170	–
	CC2	222	–31
	CC3	219	-29
Range	CC1	601	–
	CC2	416	31
	CC3	416	31
Washer	CC1	57	–
	CC2	87	–53
	CC3	87	–53
Dryer	CC1	1,043	–
	CC2	745	29
	CC3	701	33

The ES 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 used by the CC1, CC2, and CC3 clothes washers was 4,672, 1,424, and 1,454 gal, respectively (note: all three machines were set to wash with hot and rinse with cold water). That is a savings of more than 3,200 gal of hot water per year for the ES models. The total kilowatt-hours required for washing clothes when energy to heat water is included are 790, 310, and 315 kWh, respectively—60% savings for the ES 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 45% for laundry in CC2 and CC3 compared with CC1.

The builder house is equipped with incandescent bulbs, the retrofit house with compact fluorescent light (CFL) bulbs, and the high-performance house with a combination of CFL and light-emitting diode lighting. The data show that lighting is a substantial part of the total load—the 3,000 kWh of annual energy used for lighting at CC1 was slightly more than the water heater and half that of the HVAC energy load. Lighting at CC1 was 18% of the total building load. The energy-efficient lighting packages show a 70% savings for CC2 and an 80% savings for CC3 compared with CC1. The plug loads are simulated in each home with a single TV and a pair of baseboard heaters. The plug load savings for CC2 and CC3 compared with CC1 can be accounted for by the fact that a portion of the simulated load in those homes is more energy-efficient plug-in lamps.

As noted in Sect. 2, substantial changes were made to water heating equipment during the year, so direct comparison of total annual WH energy for the houses is not useful. EPRI conducted an ongoing study of the Sanden EcoCute CO_2 HPWH. In March, three new GE HPWHs were installed as part of a load management study (refer to Sect. 4.4 for detailed analysis).

Figure 5 shows the monthly whole house energy data. The annual whole house energy savings for CC3 after accounting for onsite solar PV generation in comparison to CC1 is 55%. Section 3.4 provides further details on the solar generation.

The net system peak load for TVA during the study period occurred at 16:00 on July 17, 2013. With a daily peak of 28,726 MW, it was one of the all-time-high system peaks. An hourly energy breakdown for the three research homes for July 17 is shown on the dashboard in Fig. 4. Also shown in Fig. 4 are pie chart comparisons of the component loads during the peak hour (16:00) for that same day. The three charts in Fig. 6 compare the energy use for each house on the TVA peak day, July 17, with the actual peak day and with the daily average for each house. Note that appliances and WHs were being operated during seasonal off-peak hours on July 17 as part of the ongoing load management study.

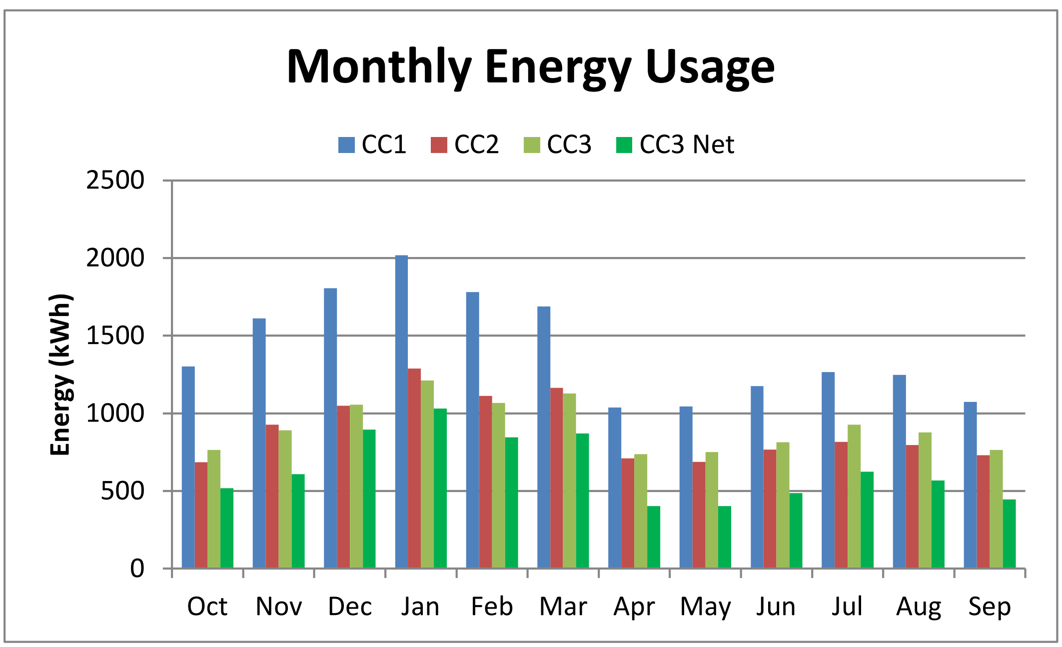
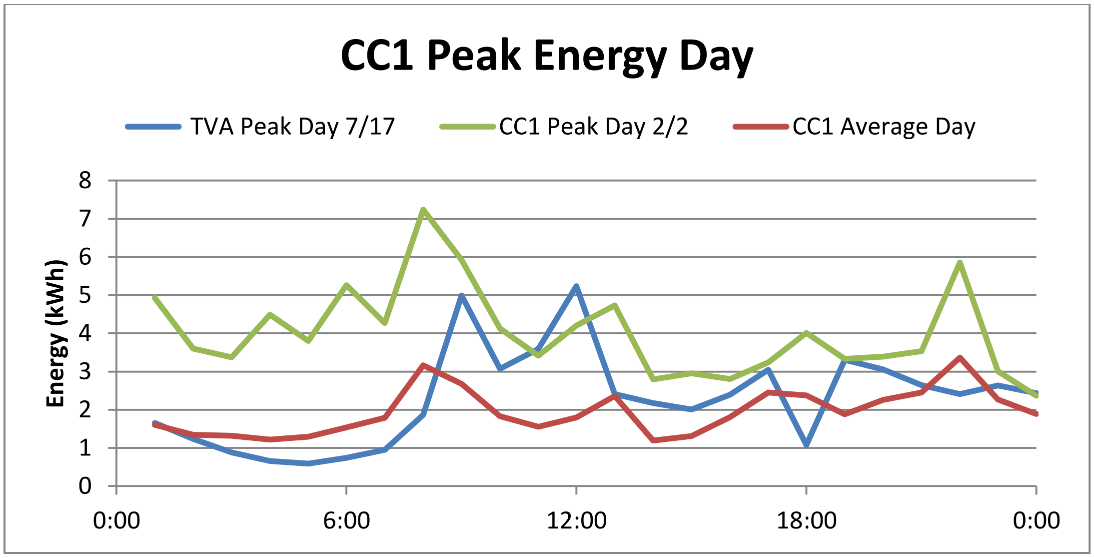
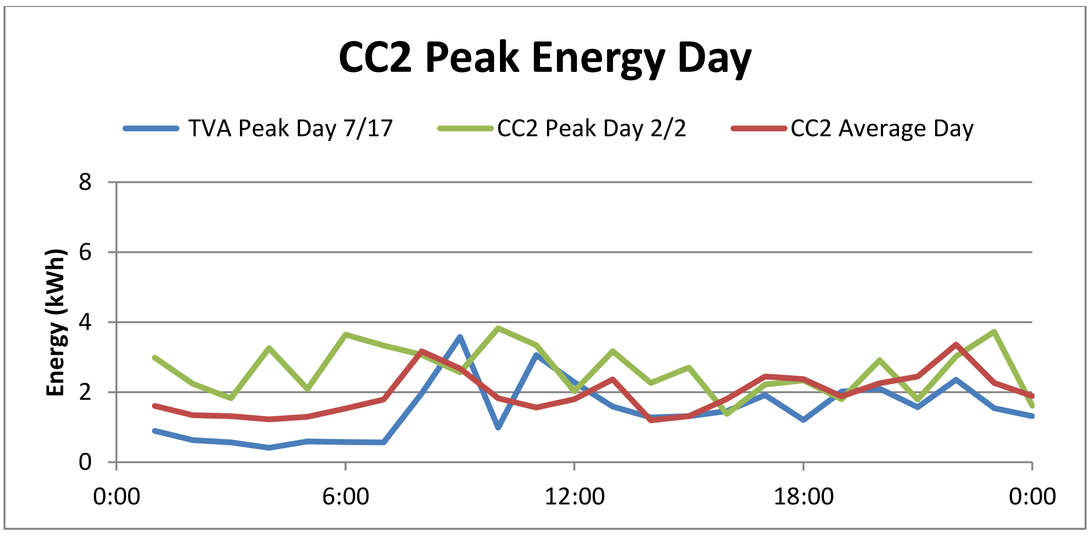


Fig. 5. Monthly energy totals from October 2012 through September 2013.





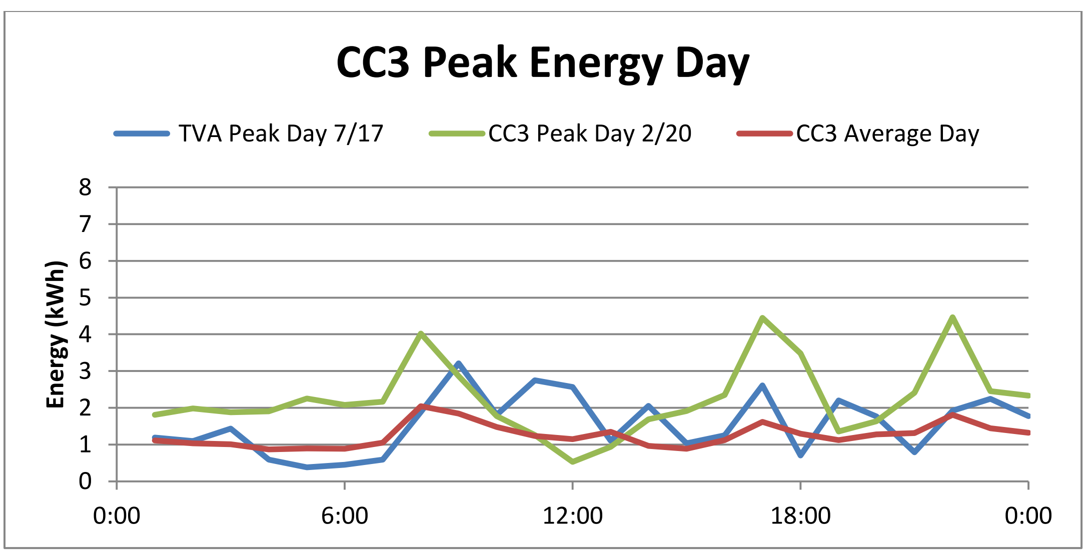


Fig. 6. Comparison of peak energy days with average days for each house.

3.2 WEATHER

Heating degree days (HDDs) and cooling degree days (CDDs) for FY 2013 were calculated using 60 min data from the weather station located at CC3 and a base of 65°F. They are compared in Table 2 with the 30-year normal data for the Knoxville area published by the National Oceanic and Atmospheric Administration (NOAA—comparative climatic data). Although the weather was cooler in October and November 2012, the 12 month period of this report was milder than the 30-year normal weather. The period overall had 12.5% more HDDs at 65°F and 10.1% less CDDs than has been normal over the past 30 years.

Table 2. HDDs at 65° and departure from normal

	FY 13 HDD[a] at 65°	Normal[b] HDD at 65°	Departure from normal	FY 13 CDD[a] at 65°	Normal[b] CDD at 65°	Departure from normal
Oct 12	310	210	100	38	28	10
Nov 12	620	470	150	2	3	–1
Dec 12	629	733	–104	4	0	4
Jan 13	745	841	–96	3	0	3
Feb 13	710	652	58	0	1	–1
Mar 13	675	467	208	6	5	1
Apr 13	275	227	48	62	27	35
May 13	123	65	58	137	110	27
Jun 13	6	3	3	267	282	–15
Jul 13	4	0	4	306	408	–102
Aug 13	3	0	3	296	381	–85
Sep 13	43	22	21	171	205	–34
Totals	4144	3685	459	1292	1450	–158

[a]HDD and CDD calculated from hourly data from Campbell Creek weather station using base 65° F.
[b]NOAA station 43, http://hurricane.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl

3.3 ENERGY COSTS

Monthly energy costs for each house are shown in Fig. 7. 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 3. The full-year energy cost for CC1 (builder house) was $1,630, compared with a net cost for CC3 (high-performance house) of $431, including the credit from the TVA solar buyback program, which is slightly more than $1 per day—a net cost savings of 74% compared with CC1. The annual energy cost for CC2 (retrofit house) was $1,189, a 33% whole-house energy cost savings compared with CC1.

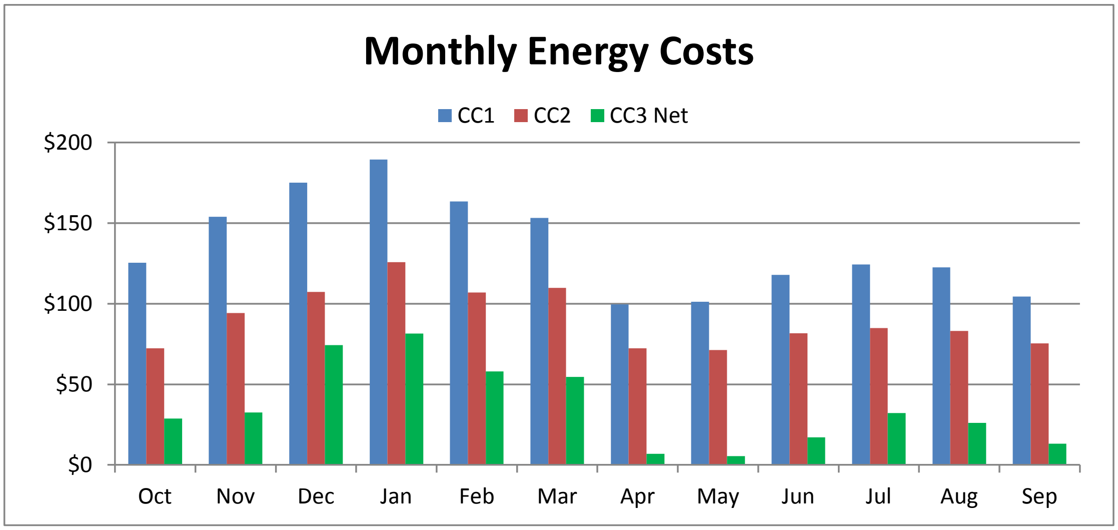


Fig. 7. Monthly energy costs (including generation partners solar credit).

Table 3. LCUB residential electrical rates ($/kWh)

	Utility rate	**Solar credit rate**	**Monthly hookup fee ($)**
Oct 2012	0.08597	0.20597	13.52
Nov 2012	0.08705	0.20705	13.52
Dec 2012	0.0895	0.2095	13.52
Jan 2013	0.08714	0.20714	13.52
Feb 2013	0.08412	0.20412	13.52
Mar 2013	0.0827	0.2027	13.52
Apr 2013	0.08286	0.20286	13.52
May 2013	0.08403	0.20403	13.52
Jun 2013	0.08873	0.20873	13.52
Jul 2013	0.08755	0.20755	13.52
Aug 2013	0.08736	0.20736	13.52
Sep 2013	0.08469	0.20469	13.52
Average	**0.085975**	**0.205975**	

3.4 SOLAR AND GENERATION PARTNER CREDIT

The 2.5 kW peak solar system on CC3 generated 3,288 kWh during FY 2013, an average of 9 kWh/day for the complete one year test period. Generation averaged 10.6 kWh per day for the six month period of April through September. The annual solar fraction for the house was 30%. Figure 8 shows the monthly generation from the PV system for the past four years, which averaged 274 kWh/month in FY 2013.

Figure 9 shows the monthly credit from solar energy production. The solar credits totaled $677, 61% of the $1,107 annual energy cost of CC3, which is a monthly average solar credit of $56.4 and a daily average of $1.85.

The total cost savings for CC3 compared with CC1 is $1,200 (Sect. 3.1). Savings from solar generation accounted for $677, or 56% of the $1,200. The balance of the savings, $523 (44%), is from energy efficiency improvements.

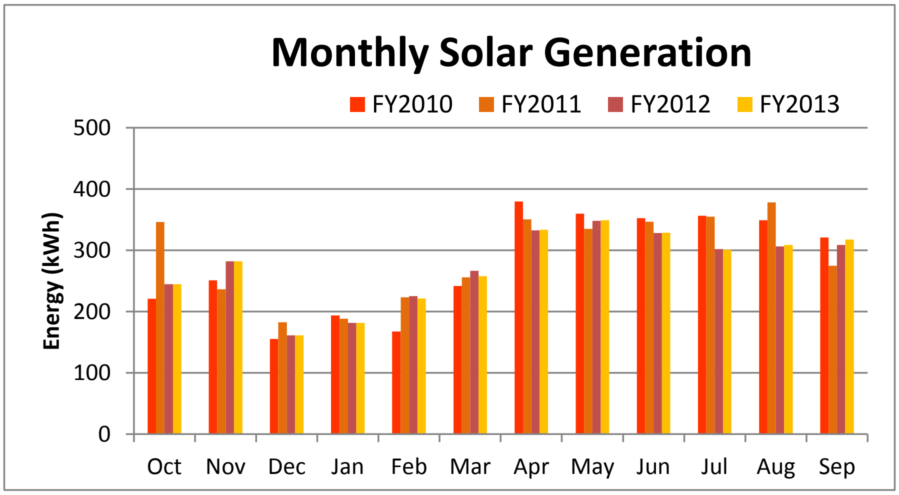


Fig. 8. Solar generation under TVA's generation partners program.

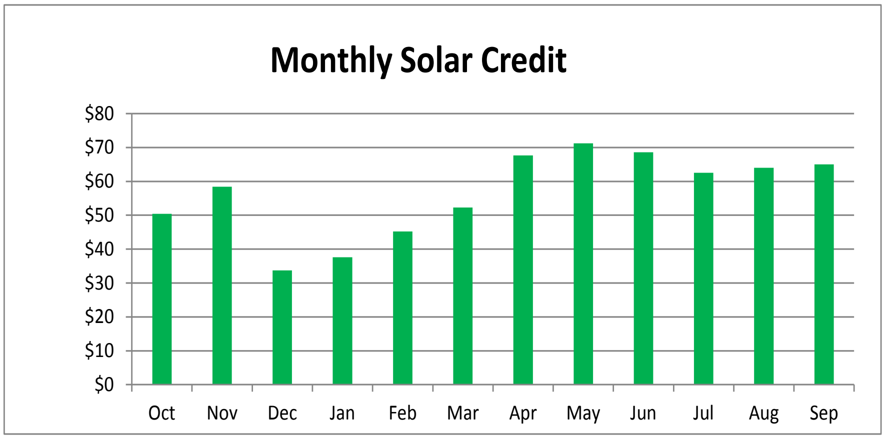


Fig. 9. Monthly generation partner credit for solar generation at CC3.

4. PERFORMANCE EVALUATION

4.1 HIGH HUMIDITY IN CC2

Higher humidity was observed in CC2, which has a sealed attic, than in CC1 and CC3, which have vented attics. After humidity was measured in four sealed and four vented attic homes, it was found that the attic and interiors were more humid in sealed-attic homes than in vented-attic homes.[1] This is because the sealed attic hinders a major drying pathway for the interior: up and out of the attic vents. Since any moisture moving from the interior to the attic is trapped, the attic moisture also rises. This lack of ventilation in the sealed attic combined with a lower sensible heat load of the home also results in shorter run times of the cooling system and thus less dehumidification of the home. The roof sheathing moisture content in CC2 has stayed below 20%, indicating a low potential for future material degradation. No mold or material damage was found during a visual inspection of the system. Also, the relative humidity at the roof sheathing has stayed within the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 160 design criteria except for a short time during the 2011/2012 winter. (This exception was the result of a combination of the sealed-attic design with minimal venting to the exterior and the unused attic ductwork, which usually provides a dehumidification pathway.)

It was also found that when the humidity was controlled using the HVAC system, 7% more energy was consumed. In the mixed-humid climate, this reduced the cost effectiveness of the sealed-attic design as a solution for bringing ducts into a semi-conditioned space. Therefore, other alternatives are being recommended, such as bringing ducts into the conditioned space in both new construction and retrofit work in a mixed-humid climate.

Initially it was thought that "solar-driven moisture" was at least one cause of the high attic and interior moisture levels. Solar-driven moisture has been suggested in the building community as an explanation for the migration of moisture through a shingle roof. It is believed to be caused by dew on top of roofs. The water finds its way between the shingles by capillary force and is driven through the underlying roof materials. This phenomenon has been observed in brick facade walls. To determine experimentally if the process was occurring in CC2, a vapor-impermeable membrane was installed under new shingles at CC2. The reroofing effort began on August 21, 2013, and continued until August 28, 2013 (Fig. 10).

To determine how the vapor barrier affected the moisture performance of the attic, the partial pressure of water vapor (absolute concentration of water vapor, measured under the roof deck) was plotted against temperature to see if the measured water vapor as a function of temperature decreased after the vapor barrier was installed. Figures 11 and 12 show the partial pressure of water vapor for September and October as a function of temperature for 2010 through 2013. The 2013 curves represent the period when the vapor barrier was present on the roof. Since solar insolation, and therefore temperature, is the main driver of the measured water vapor below the roof deck, comparing the same months provided similar solar loads on the roof and similar outdoor conditions. Notice that 2011 (green curve) is consistently the highest. This was the time when a ductless multi-split HVAC system was operating. It struggled to control humidity, in large part because the ducts in the attic were not being used and therefore did not provide dehumidification to the attic space (through duct leakage). The humid attic affected the interior space, making it more humid as well.

Fig. 10. Sample images of CC2 reroof.

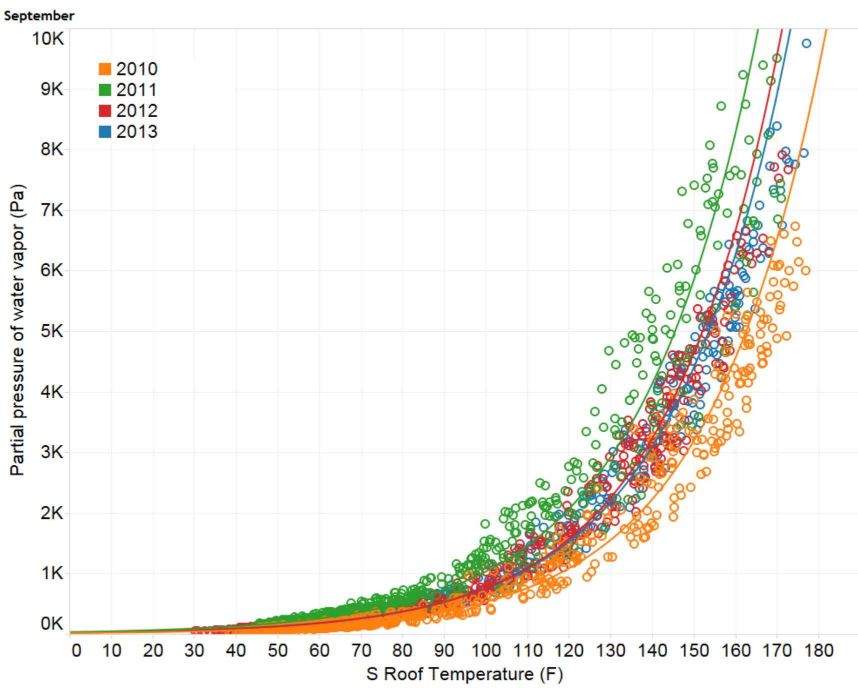


Fig. 11. September hourly measured water vapor concentration.

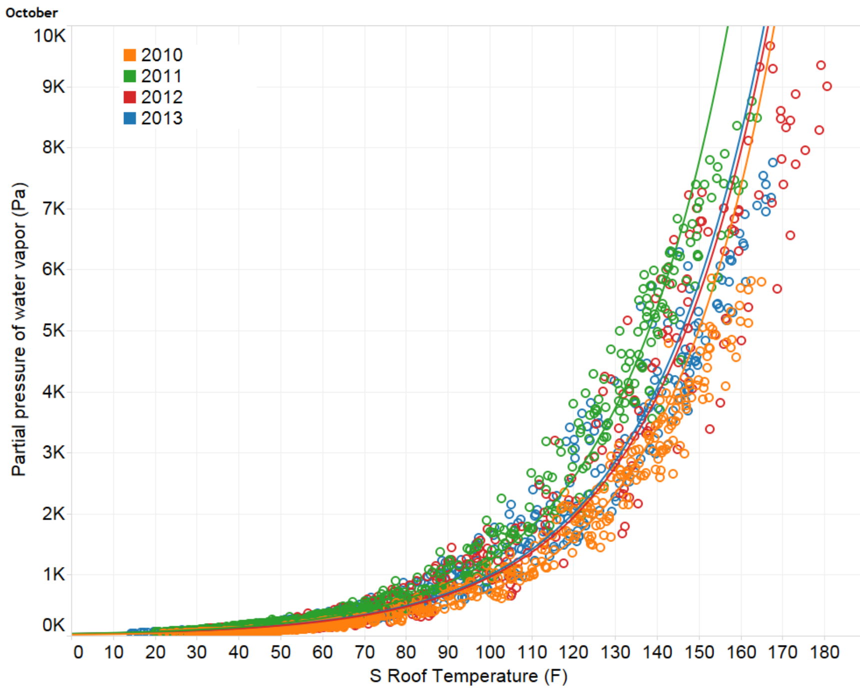


Fig. 12. October hourly measured water vapor concentration.

As can be seen in Figs. 11 and 12, the 2013 curves have not decreased compared with those for the other years. So the expected effect of the vapor barrier (i.e., reduction of vapor concentration) is not observed. The most likely reason is that solar-driven moisture is not occurring in this structure.

Solar-driven moisture has not been observed experimentally and is unlikely from a theoretical perspective. Mathematically, the lap dimensions of the shingles and the adhesive strip make it very unlikely that capillary forces are maintained to bring liquid water all the way through the lap. If this were to happen, and the air layer between the shingles and roof sheathing were constantly at saturation (100% relative humidity), the moisture content of the roof sheathing would have an insignificant increase in moisture. Therefore, solar-driven moisture is unlikely to be a significant contribution to increased moisture in CC2. Rather, according to ORNL research,[1] the high moisture in the sealed attic home can be attributed in part to the fact that sealed attics reduce sensible cooling loads in the home without impacting internal sources of moisture generation (e.g., cooking and showers). Therefore, the sensible heat ratio (SHR) in the home is decreased. If this SHR is much lower than the equipment SHR, then higher interior moisture levels in the sealed-attic home could result if no additional moisture mitigation measure is taken. Additionally, excess moisture that enters a vented attic can be removed via vents. However, this drying mechanism is hindered in the sealed attic because the soffit, gable, and ridge vents have been sealed with foam, thereby minimizing ventilation to the exterior. This effect also further decreases the home's SHR in the mixed-humid, climate-sealed attic home.

4.2 HVAC COMPARISON—BUILDER HOUSE CC1

Variable-capacity heat pumps are an emerging technology offering significant energy savings potential and improved efficiency. With conventional single-speed systems, it is important to appropriately size heat pumps for the cooling load, as over-sizing would result in cycling and not enough of the latent capacity required for humidity control. These appropriately sized systems for cooling are often under-sized for the heating load and require inefficient supplemental electric resistance heat to meet the heating demand. Variable-capacity heat pumps address these shortcomings by providing an opportunity to intentionally size systems for the dominant heating season load without the adverse effects of cycling or insufficient dehumidification in the cooling season. Such an intentionally sized system could result in significant energy savings in the heating season, as the need for inefficient supplemental electric resistance heat is drastically reduced. To this end, in FY 2013 the initial space-conditioning system in CC1 was replaced with a variable-capacity heat pump intentionally sized for the heating season load. The following discussion of results and analysis provides an opportunity to understand and evaluate the impact this would have on electric resistance heat use and dehumidification in homes in the TVA service area.

4.2.1 Equipment Description and Sizing

In CC1, there are two variable-speed, air-source heat pumps, one for each of the two zones, upstairs and downstairs. These heat pumps consist of an inverter-driven compressor outdoor unit coupled to a ducted air-handling unit. The upstairs air-handling unit sits in the attic and the downstairs unit in the garage. Each indoor unit uses a variable-speed blower with a brushless permanent magnet motor, as well as auxiliary electric resistance heat elements. Each unit can operate in two different modes: efficiency and comfort. In comfort mode, during cooling, the units run at lower indoor airflow rates, and the system adjusts this airflow in an attempt to maintain indoor humidity below the set point. In efficiency mode, the unit runs at higher airflow rates, and indoor humidity is not directly controlled.

As discussed, the space-conditioning systems were sized for the dominant heating season load. Shown in Table 4 are the rated capacities for the new-variable speed system, along with those for the original single-speed system for comparison. The rated capacity as a percentage of the Manual J[3] calculated load is also shown in Table 4 as a reference, along with system efficiencies for heating and cooling. The new downstairs unit is sized to approximately 120% of the design heating load and the upstairs unit to approximately 117% of the design heating load. In contrast, the original single-speed system was sized to 41% and 56% of the design heating load on level 1 and level 2, respectively.

Although the heating loads predicted from Manual J calculations suggest the equipment is “right-sized” for the heating season, a comparison of the maximum heating capacity and the average heating capacity delivered by the system during the FY 2013 heating season provides contrasting conclusions. As seen in Figs. 13 and 14, the maximum heating capacity is approximately 140% of the average measured capacity for level 1 and 340% for level 2 at the design temperature of 19°F (note Knoxville, Tennessee, commonly sees temperatures below the 19°F “design temperature”). The excessive mismatch between measured heating capacity and expected capacity from Manual J calculations for level 2 (which results in significant over-sizing) is largely because of the physical phenomenon that warm air rises and cold air falls. In this home, the heating capacity delivered by the level 1 system provides heat to both levels in the home.

Because cool air falls, the opposite effect can be seen in the cooling season. As shown in Figs. 15 and 16, at any given outdoor air temperature, the level 2 heat pump provides most of the cooling provided to CC1. At the design temperature of 97°F, the level 2 heat pump is only expected to be oversized by 30%, whereas the level 1 system will be oversized by 450%. Because both systems are oversized, we were able to “stress test” the ability of variable-capacity heat pumps to maintain interior comfort conditions (i.e., relative humidity and temperature) when the maximum capacity of the system exceeds the average required load.

Table 4. CC1 system sizing

		Level 1			Level 2		
		(kBtu/h)	(Percent of Manual J)	Efficiency	(kBtu/h)	(Percent of Manual J)	Efficiency
Original single-speed heat pump rated capacity	Cooling	18.0	167	13.0 SEER	28.0	140	13.0 SEER
	Low-temp heating	8.6	41	7.7 HSPF	14.0	56	7.7 HSPF
New variable-speed heat pump rated capacity	Cooling	24.2	224	19.1 SEER	33.4	167	19.2 SEER
	Low-temp heating	25.4	120	10.5 HSPF	29.2	117	10.5 HSPF

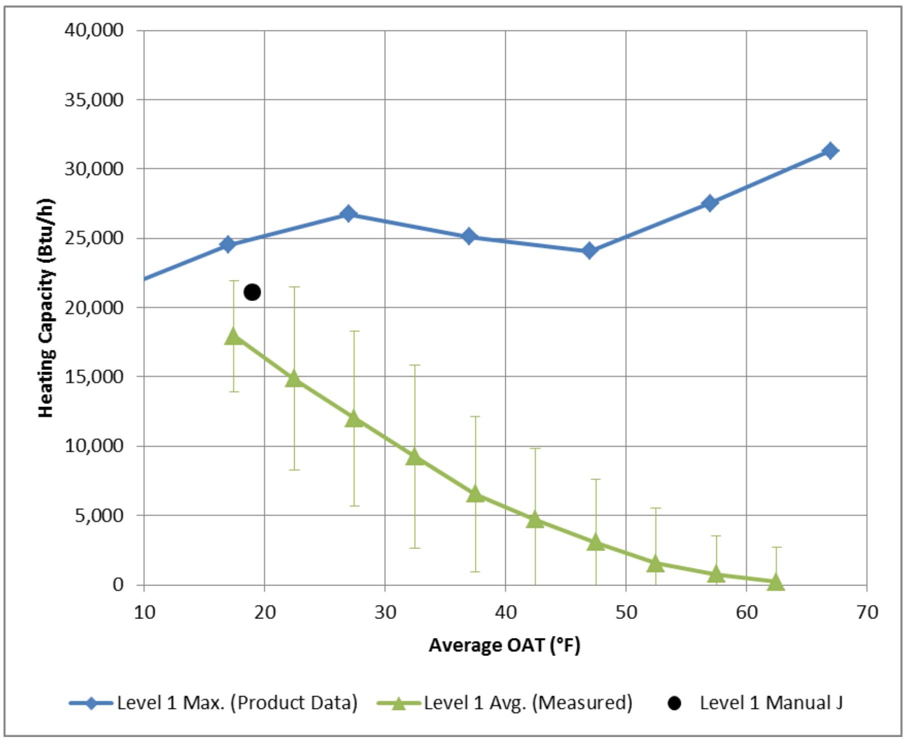


Fig. 13. CC1 level 1 maximum heating capacity, hourly delivered load, and Manual J design load.

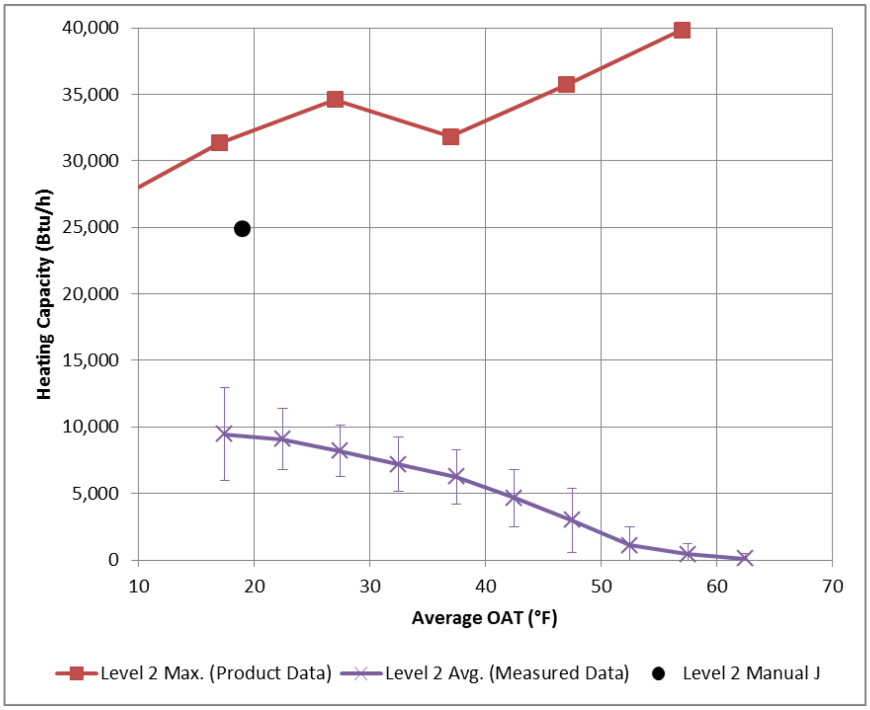


Fig. 14. CC1 level 2 maximum heating capacity, hourly delivered load, and Manual J design load.

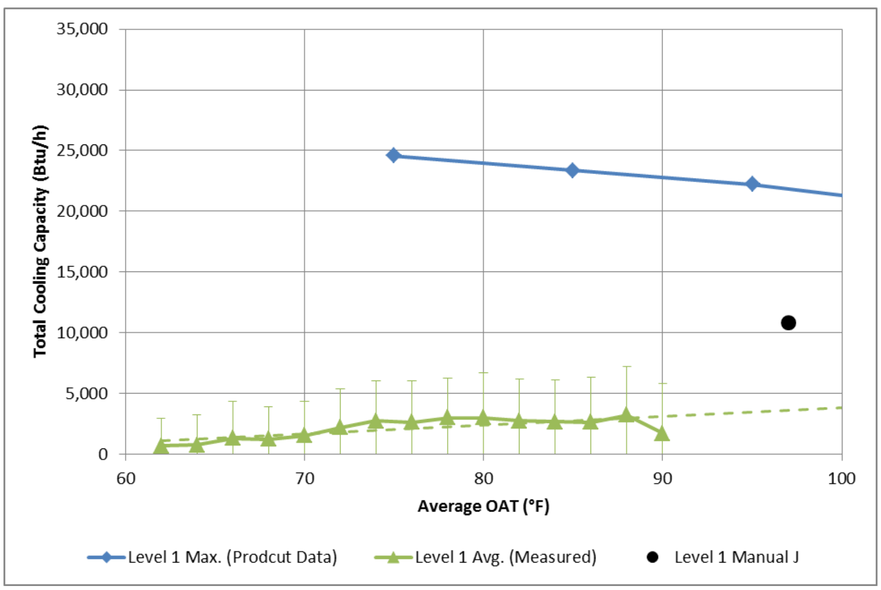


Fig. 15. CC1 level 1 maximum cooling capacity, hourly delivered load, and Manual J design load.

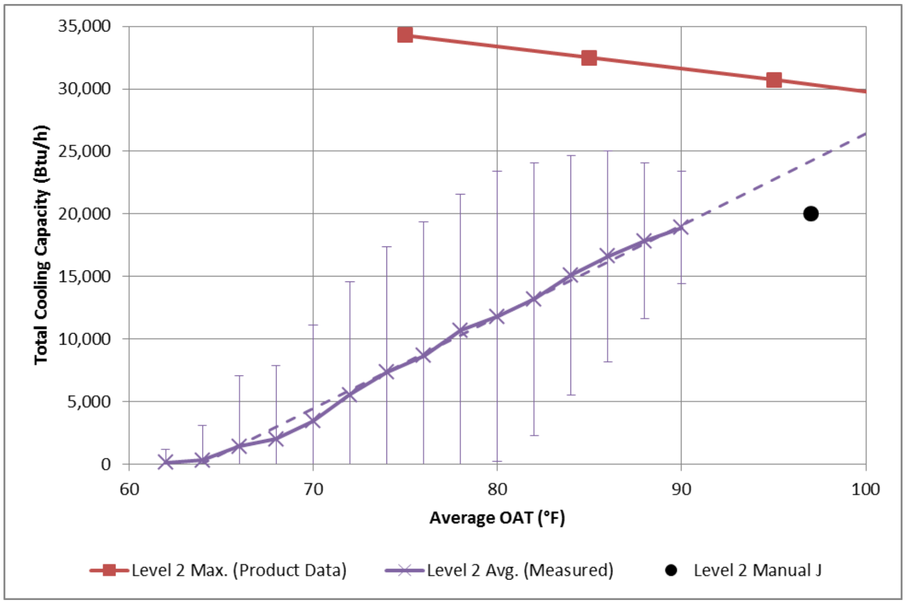


Fig. 16. CC1 level 2 maximum cooling capacity, hourly delivered load, and Manual J design load.

4.2.2 CC1 Energy Consumption

To allow direct comparison of the energy consumption of the systems, the data are normalized based on outdoor air temperature (OAT) to account for variations in the weather in different years. This is achieved by plotting the daily heat pump energy use against the average daily OAT and fitting separate polynomials to the heating and cooling data. The TMY3 average daily temperatures for Knoxville, Tennessee, are then used as inputs to the polynomials to generate heating, cooling, and annual energy uses.

Figure 17 shows annual heating and cooling energy use of the original single-stage heat pumps and the variable-capacity heat pumps in both the comfort and efficiency modes. The data included in this section span from December 2011 to September 2012 for the original single-stage heat pumps and from December 2012 to September 2013 for the variable-capacity heat pumps. The variable-capacity system offers a 25% reduction in heating season energy use when operating in comfort mode; the reduction is as much as 32% in efficiency mode. As with the heating season, the variable-capacity heat pumps show significant energy savings during the cooling season. The variable-capacity system offers a 41% reduction in energy use when operating in comfort mode and a 44% reduction in efficiency mode. On an annual basis, the variable-capacity system operated in comfort mode shows an annual savings of 2,989 kWh or 31% over the baseline system. When it is operated in efficiency mode, the energy savings increase to 3,489 kWh, or 37% over the baseline system.

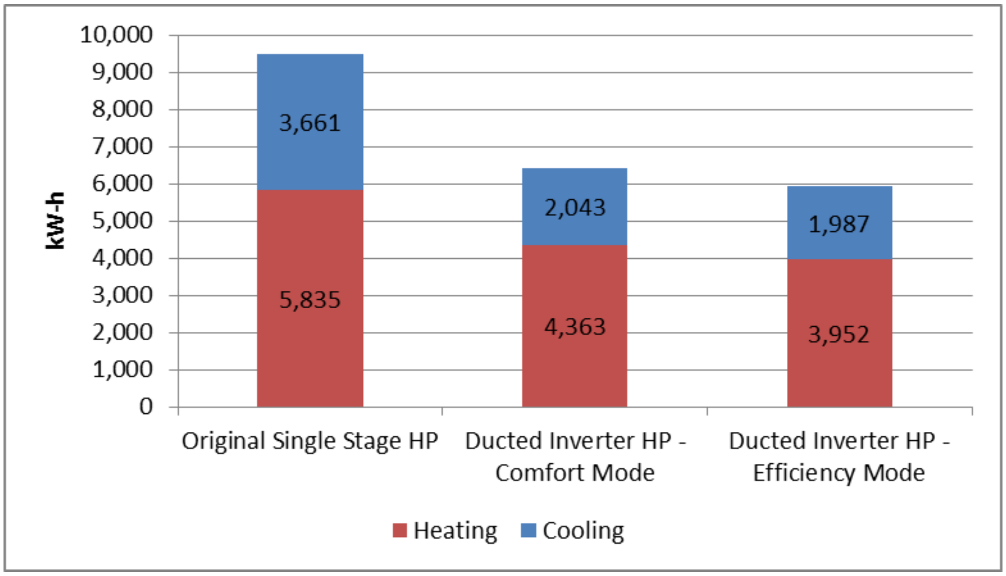


Fig. 17. CC1 TMY3 annual energy use for Knoxville, Tennessee.

Figure 18 shows the resistance heat use of both the original single-stage heat pumps and the variable-capacity heat pumps. For the variable-capacity system, Fig. 18 shows two curves: resistance heat use in defrost cycles is enabled for the first curve and disabled for the second. In the first case, resistance heat is used to prevent cold air from being blown into the house. There is only a slight difference in energy use moving from the first case to the second; this is because when resistance heat use is disabled during defrost cycles, cold air is blown into the house and the heat pump must compensate by providing additional heating to keep the house at the desired indoor temperature set point. When it was very cold outside, the drop in the indoor temperature during the defrost cycle was often enough to trigger supplemental resistance heat when the heat pump switched back to heating mode after the defrost cycle. This sometimes resulted in more resistance heat use than would have occurred if it had been enabled during the defrost cycle, as seen by the points with average daily temperatures below 35°F.

The variable-capacity system has a variable-speed compressor that can run at higher speeds when the OAT is lower and at lower speeds when the OAT is higher; this feature reduces the need for supplemental resistance heat. It achieves a 68% reduction in resistance heat use over the heating season (Fig. 18). The fact that these CC1 variable-capacity units are intentionally sized for the heating season, as discussed in the equipment sizing section of this report, also contributes to the reduction in resistance heat use.

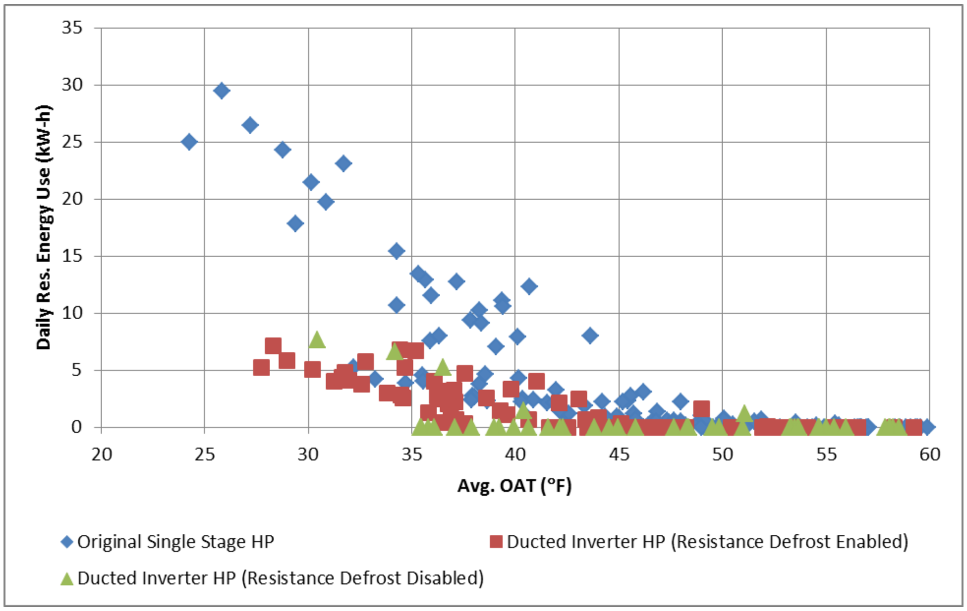


Fig. 18. CC1 resistance heat use.

4.2.3 Heating Season Efficiency

The average HSPF for each unit was calculated for the period of 12/8/2012 to 5/1/2013 (Table 5). The HSPF was normalized based on the OAT using the Air-conditioning, Heating, and Refrigeration Institute (AHRI) temperature bin weightings for the HSPF calculation. The efficiency of the level 2 unit was lower than expected. Once it was warm enough, the charge of the unit was checked and found to be about 15% low. However, the limited heating data available after the charge was added did not indicate a significant change in performance. In the winter of FY 2014, the user interface displayed OAT sensor faults. This required replacement of the unit's control board, and performance was improved after this change (also shown in Table 5). As expected, both systems operated more efficiently in efficiency mode than in comfort mode.

Table 5. CC1 heating efficiency

	Mode	Normalized average HSPF (Btu/Wh)
Level 1	Efficiency	10.1
	Comfort	10.0
Level 2	Efficiency	7.8/8.8[a]
	Comfort	6.8

[a]Data from Jan.–Mar. 2014 after control board replacement.

4.2.4 Cooling Season Performance

The cooling data included in this section span from May to September 2012 for the baseline system and from May to July 2013 for the variable-speed system. As with the heating season, these data have also been normalized by applying them to TMY3 data for Knoxville, Tennessee.

4.2.4.1 Comfort Assessment

In Figs. 19 and 20, the indoor humidity levels are plotted against the outdoor temperature for both the upstairs and downstairs systems operating in comfort and efficiency modes. During operation in comfort mode, no distinguishable difference in humidity levels can be seen compared with the baseline system. In the baseline case, the average daily indoor relative humidity (RH) levels are 46% and 44% for the downstairs and upstairs, respectively. Under the tested conditions, the average RH values change to 45% and 44%, respectively, in comfort mode operation and 50% and 49%, respectively, in efficiency mode. This leads to the conclusion that for the average home in mixed-humid climates, there is effectively no dehumidification penalty associated with sizing for the heating season load during comfort-mode operation. In efficiency-mode operation for the variable-speed HVAC system evaluated in this study, the increase in average daily RH is because of the reduced rate of latent heat removal, which results in additional energy savings. It is important to note that with both the baseline heat pumps and ducted inverter heat pumps, the indoor temperature set point remained at a constant 76°F.

In both modes of operation, the RH level was well below 60%, with an indoor temperature set point of 76°F to ensure adequate human comfort.

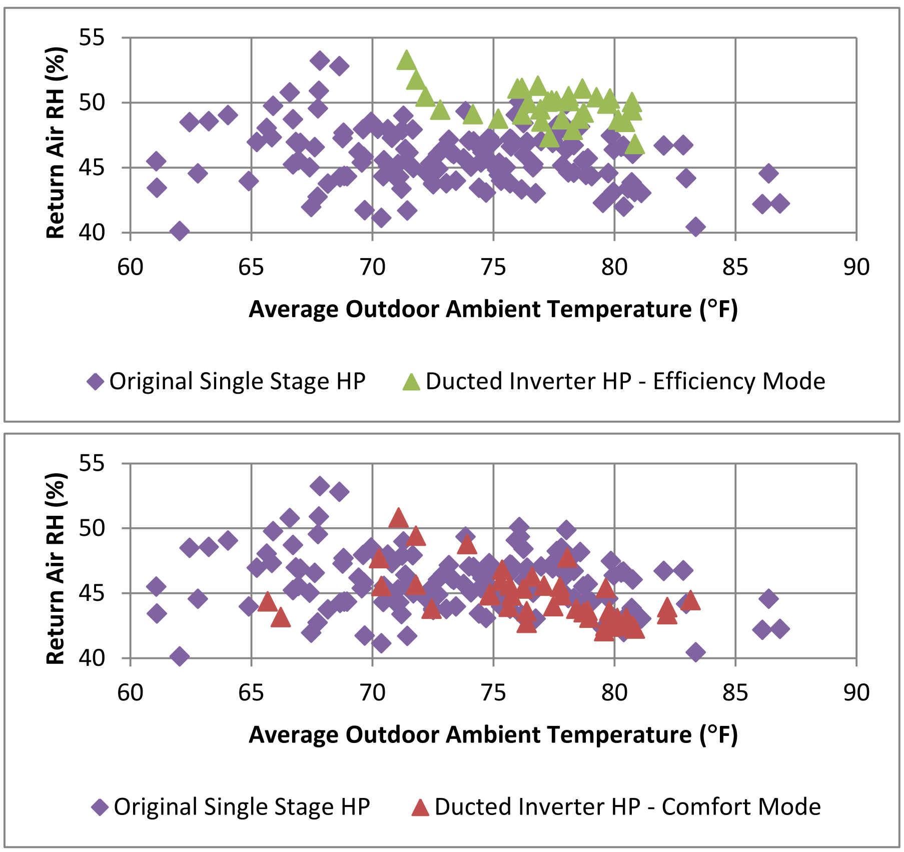
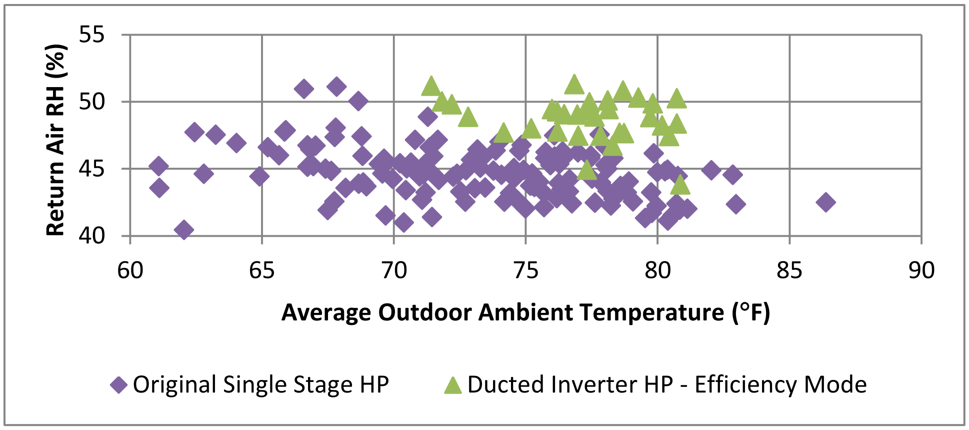


Fig. 19. CC1 level 1 indoor relative humidity comparison between comfort and efficiency modes.



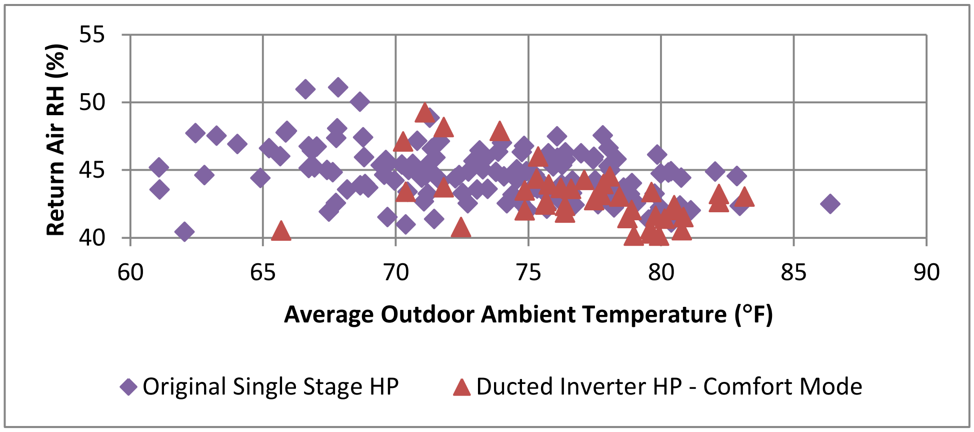


Fig. 20. CC1 level 2 indoor relative humidity comparison between comfort and efficiency modes.

4.2.4.2 Cooling Season Efficiency

The average cooling energy efficiency ratio (EER) was calculated from the measured data spanning from 5/1/2013 to 9/1/2013 (Table 6). As with the heating season data, the average EER for the cooling season was normalized based on the OAT using the AHRI temperature bin weightings for the SEER calculation. Both units showed very similar cooling performance although they were sized differently compared with the cooling load and therefore cycled at different intervals.

Table 6. CC1 cooling efficiency

	Mode	Normalized avg. EER (Btu/Wh)
Level 1	Efficiency	16.6
	Comfort	16.1
Level 2	Efficiency	17.6
	Comfort	16.8

4.3 HVAC COMPARISON—RETROFIT HOUSE CC2

An HVAC system similar to the system described in CC1 has been installed in CC2 since January 2012. The detailed performance characteristics of this system are detailed by Munk et al.[2] Therefore, only a summary of the projected annual energy consumption is presented subsequently.

The TMY3 normalized data for heating and cooling season energy use are combined for an annual energy use comparison in Fig. 21. The ducted inverter system operated in comfort mode would have an annual energy use of approximately 4,244 kWh; when it is operated in efficiency mode, the energy use would decrease to 3,967 kWh. This is an energy savings of 7% over comfort-mode operation. However, the difference between efficiency mode and comfort mode is primarily the result of heating season energy consumption. Because the system operates more efficiently in efficient mode than in comfort mode for both heating and cooling, the negligible difference in cooling energy is unexpected. This is discussed further in Sect. 5.2 of this report.

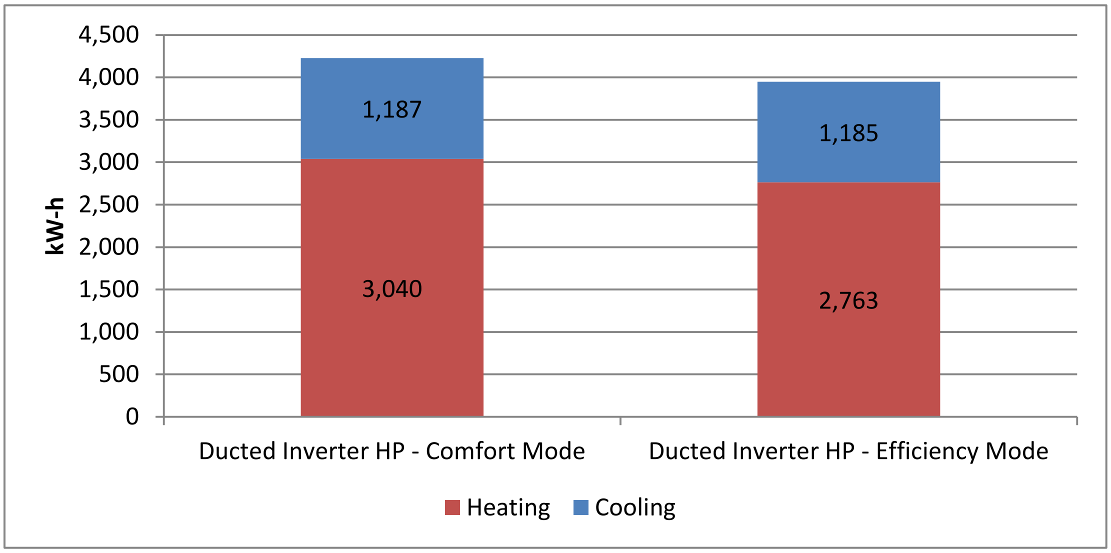


Fig. 21. CC2 TMY3 annual energy use for Knoxville, Tennessee.

4.4 WATER HEATER COMPARISON

The **US Department of Energy energy conservation standards for residential water heaters** require residential electric storage WHs with volumes larger than 55 gal to have an energy factor[1*] greater than 2.0 after April 2015. Although this standard will significantly increase the energy efficiency of WHs, large (>55 gal) electric resistance WHs will no longer be available. Since utilities use conventional large-volume electric storage WHs for thermal storage in demand-response programs, there is a concern that the amended standard will significantly limit demand-response capacity. To this end, ORNL partnered with TVA and GE to investigate the load management capability of HPWHs that meet or exceed the forthcoming WH standard.

Three HPWHs with the capability to receive demand-response signals were received from GE. To increase the thermal storage capacity, these HPWHs are capable of reaching a water temperature in the tank of up to 170°F. These systems were evaluated under the following performance criteria (compared with the baseline cases of a standard electric WH and/or the HPWH in standard electric hybrid mode):

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[*]http://www.energystar.gov/index.cfm?c=tax_credits.tx_definitions&dts=mcs

- Ability to meet all hot water demands
- Peak period energy use
- Overall efficiency

Because of existing WH research on the Sanden CO_2 HPWH in CC2, the new HPWHs with load management capability were installed only in CC1 and CC3 in FY 2013. This research activity is ongoing in FY 2014. FY 2013 research highlights and insight are discussed in the following.

4.4.1 Experimental Conditions

4.4.1.1 Hot Water Draw Profile

As described previously, CC1 represents standard construction practices and building technologies, while CC3 is representative of a high-performance home. Consistent with this approach, the appliances in CC1 are standard builder-grade appliances, whereas all-ES appliances are installed in CC3. As a result, the hourly and daily hot water draw patterns of the two homes differ, particularly on days when the ES clothes washer is operated. As shown in Table 7, during the 7 a.m. and 9 a.m. hours when the clothes washers are operated, the difference in hot water consumption between CC1 and CC3 is approximately 11 gal for each laundry cycle. The difference in hourly (and thereby daily) hot water consumption on laundry days facilitates the comparison of three distinct hot water draw profiles:

Table 7. Average hot water draws for CC1 and CC3

	Non-laundry days (gallons)		**Laundry days (gallons)**	
	(Sun, Mon, Fri, and Sat)		**(Tues, Wed, and Thurs)**	
	CC1	**CC3**	**CC1**	**CC3**
12 AM	0	0	0	0
1 AM	0	0	0	0
2 AM	0	0	0	0
3 AM	0	0	0	0
4 AM	0	0	0	0
5 AM	0	0	0	0
6 AM	0	0	0	0
7 AM	18.7	17.8	33.6	22.5
8 AM	4.7	4.6	4.7	4.6
9 AM	0.2	0.1	15.2	4.3
10 AM	0	0	0.1	0
11 AM	0	0	0	0
12 PM	4.7	4.6	4.7	4.6
1 PM	0	0	0	0
2 PM	0	0	0	0
3 PM	0	0	0	0
4 PM	0	0	0	0
5 PM	9.2	8.9	9.2	8.9
6 PM	0	0	0	0
7 PM	0	0	0	0
8 PM	0	0	0	0
9 PM	18.2	17.7	18.2	17.7
10 PM	1	0.7	3.6	2.7
11 PM	0.5	0.6	1.8	2.5
Average daily usage (4/5 - 9/30)	**57.2**	**55**	**91.1**	**67.8**

- Below-average hot water consumption (CC1 and CC3 non-laundry days)
- Average hot water consumption (CC3 laundry days)
- Above-average hot water consumption (CC1 laundry days)

4.4.1.2 HPWH tank temperature

A thermocouple was added near the location of the temperature sensor used by the HPWH internal algorithm for heat pump control operation (Fig. 22). As the temperature in the tank becomes stratified at different times during the day, the measured temperature is less representative of the average tank temperature and thereby the average thermal energy stored in the tank. However, the measured temperature can provide qualitative insight regarding the HPWH control and overall performance.

4.4.1.3 HPWH ambient temperature

The HPWHs are located in the conditioned space (i.e., pantry) in CC3 and in the garage in CC1. Because the HPWH uses heat from the ambient air to heat the water in the tank, the difference in temperature of the ambient air between CC1 and CC3 HPWHs will affect system performance. As shown in Fig. 23, the difference between the ambient temperatures in the two research houses ranged primarily from 5 to 10°F during the summer.

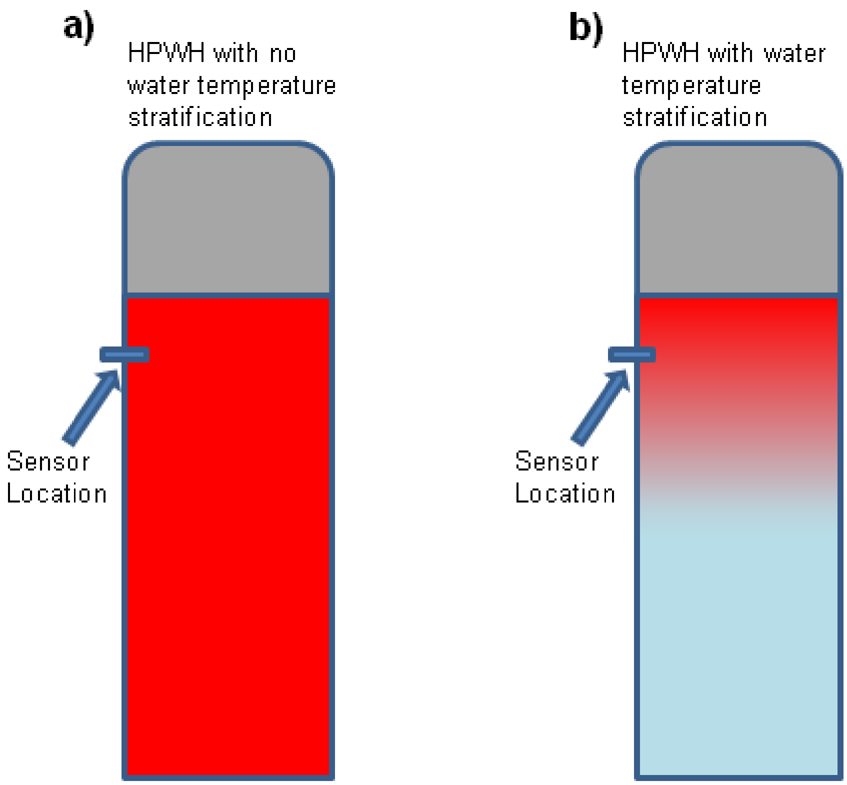

Fig. 22. Illustration showing the locations of the thermocouples used to measure tank temperature. (a) HPWH with a near-constant tank temperature. (b) Tank with stratified water temperature.

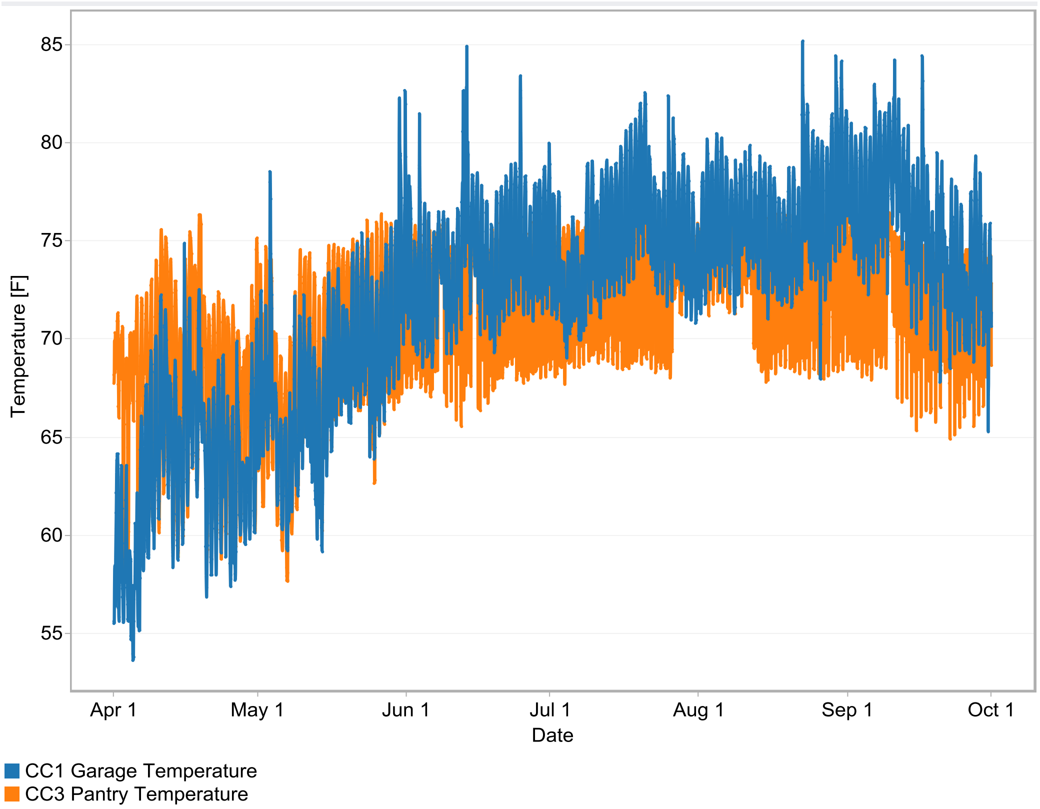

Fig. 23. CC1 garage and CC3 pantry temperatures.

During this study, four multiple load-managed temperature profiles were evaluated during the summer, and this report discusses two (schedule 3 and schedule 4). Schedules 1 and 2 are not discussed because they were used to investigate how the WH responded to changes in temperature set points and were not used to minimize peak energy consumption. For schedule 3, the tank was set to 170°F from 3 a.m. to 1 p.m. and then to 120°F throughout the peak power usage time until 9 p.m. During the nighttime hours, the tank was set to 140°F. For schedule 4, the tank temperature was raised to 170°F during the night and then reduced to 150°F at 6 a.m. During the peak hours, the set point was lowered to 120°F and then raised to 170°F after the peak.

As shown in Fig. 24, each temperature profile attempted to minimize the energy and power consumed during the TVA summer peak hours of 1 to 9 p.m. (shaded pink in the figures). For both schedules, the HPWH was set to use only the heat pump to meet water heating demand.

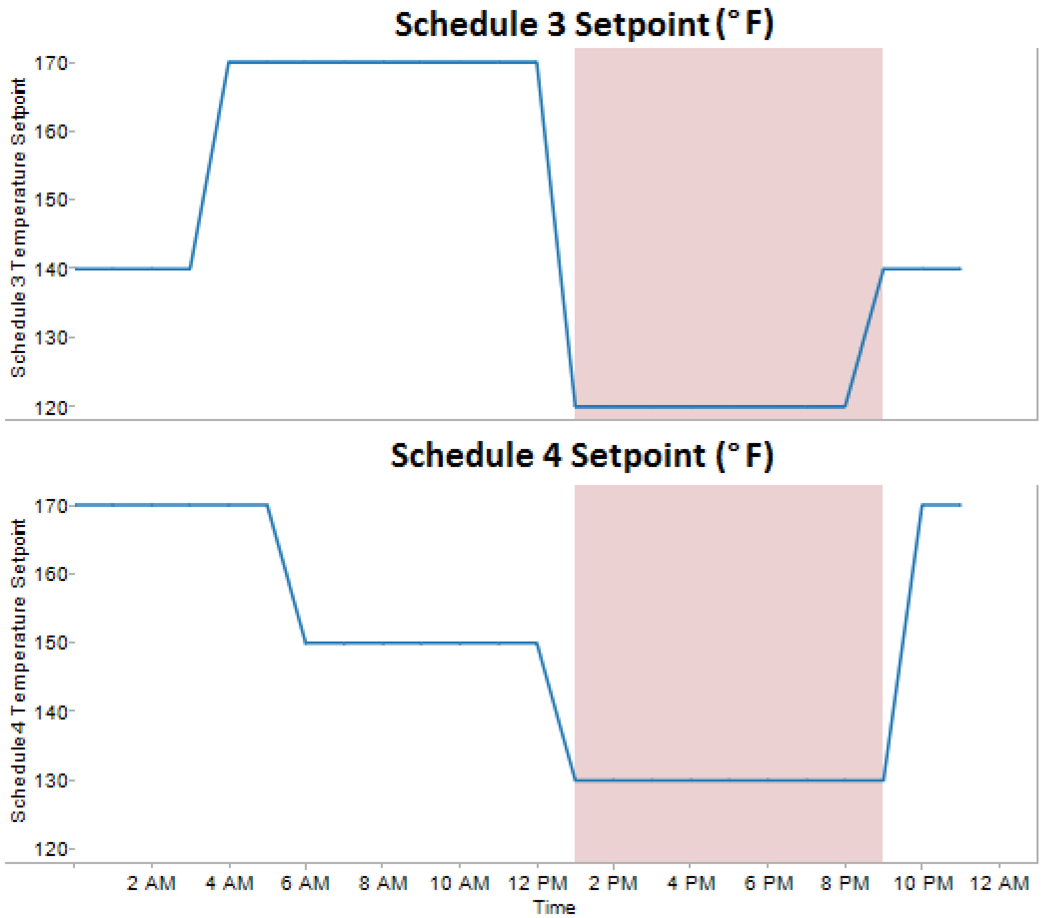

Fig. 24. Load-managed HPWH schedules 3 and 4. The blue lines are water heater set point temperatures.

4.4.2 Research Results

4.4.2.1 Baseline

As a baseline and for comparison, the power consumption during a typical laundry day and non-laundry day for the conventional storage WH installed in CC1 is shown in Figs. 25 and 26. During a water heating event, the storage WH used approximately 4,500 W, and it consumed 13.2 kWh and 8.5 kWh of average daily energy for laundry and non-laundry days, respectively. For both days, there was a water heating event during the summer peak hours.

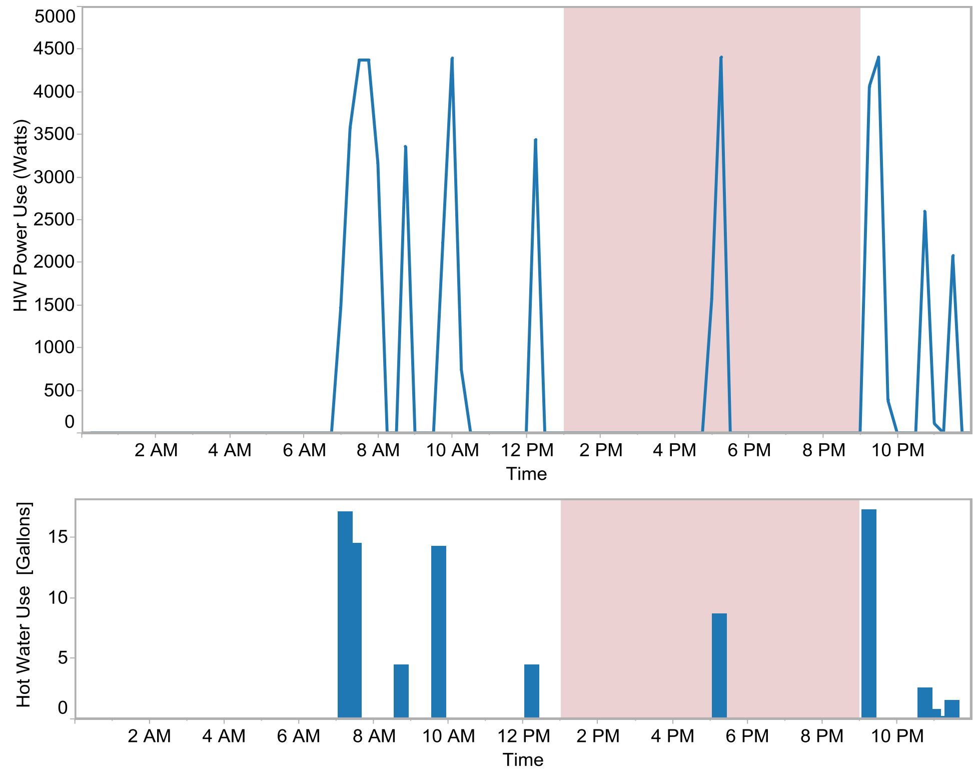

Fig. 25. Typical power and water consumption for the conventional storage water heater in CC1 (laundry day).

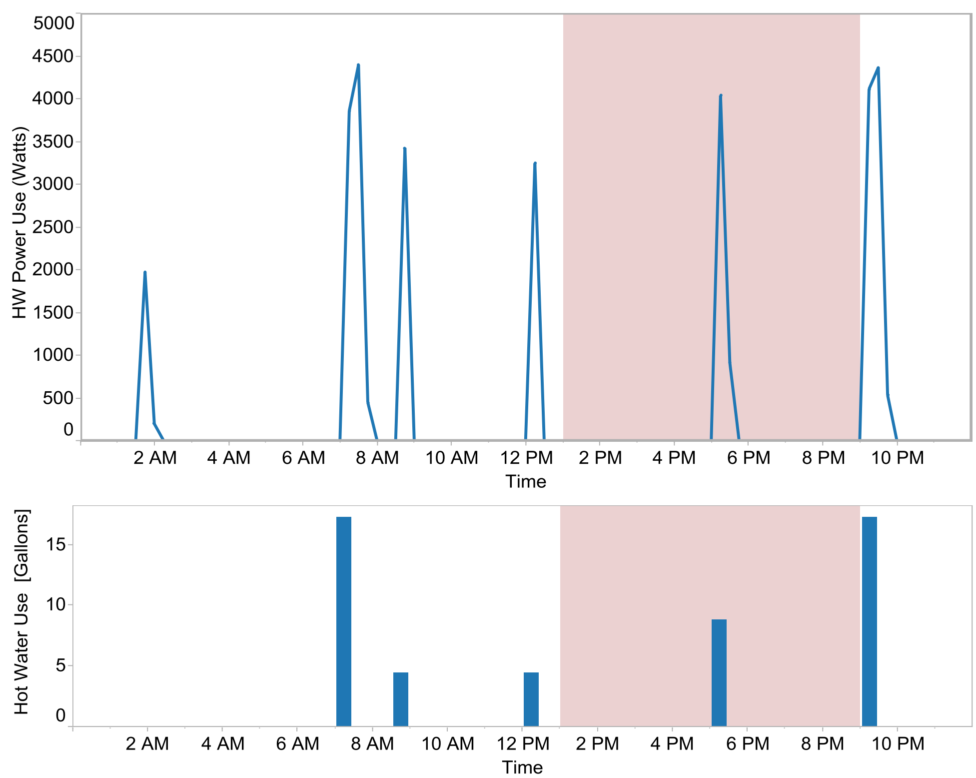

Fig. 26. Typical power and water consumption for the conventional storage water heater in CC1 (non-laundry day).

In contrast, the HPWH installed in CC1, with a factory default temperature setting of 120°F, consumed an average of approximately 440 W when resistance heat was not provided (i.e., heat pump only). On laundry days, as shown in Fig. 27, there was a water heating event requiring heat from the resistance element with an output of 4500 W, similar to the demand of the storage WH. However, even though resistance heat was used, the energy saved compared with the conventional storage WH was significant, with an average daily energy consumption for laundry days and non-laundry days of 6 kWh and 2.5 kWh, respectively.

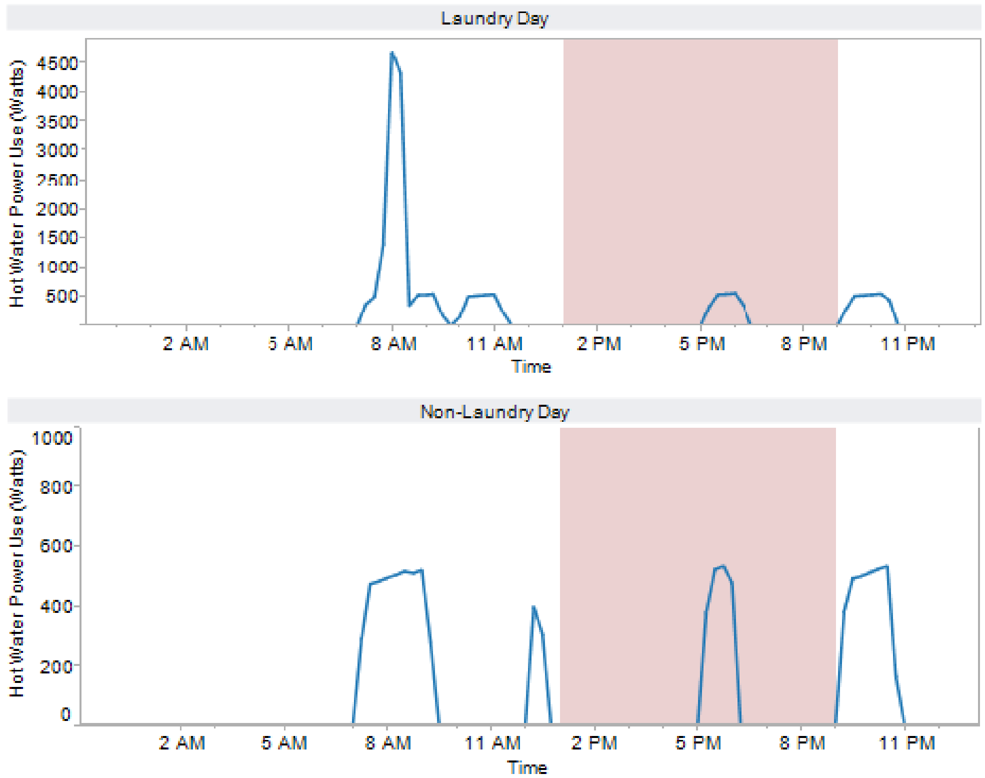

Fig. 27. Typical power for the CC1 HPWH power consumption in hybrid mode.

4.4.2.2 Load-Managed Water Heating Schedules

The power consumption profiles for schedules 3 and 4 for a typical non-laundry day are shown in Fig. 28. For schedules 3 and 4 on a non-laundry day, all of the hot water power consumption was successfully shifted from the summer peak period, but hot water demand was met. Although both schedules consumed more average daily energy than the baseline HPWH because of the energy required to achieve higher tank temperatures (Table 8), the energy savings compared with the standard electric storage WH are 58% and 61% for schedules 3 and 4, respectively.

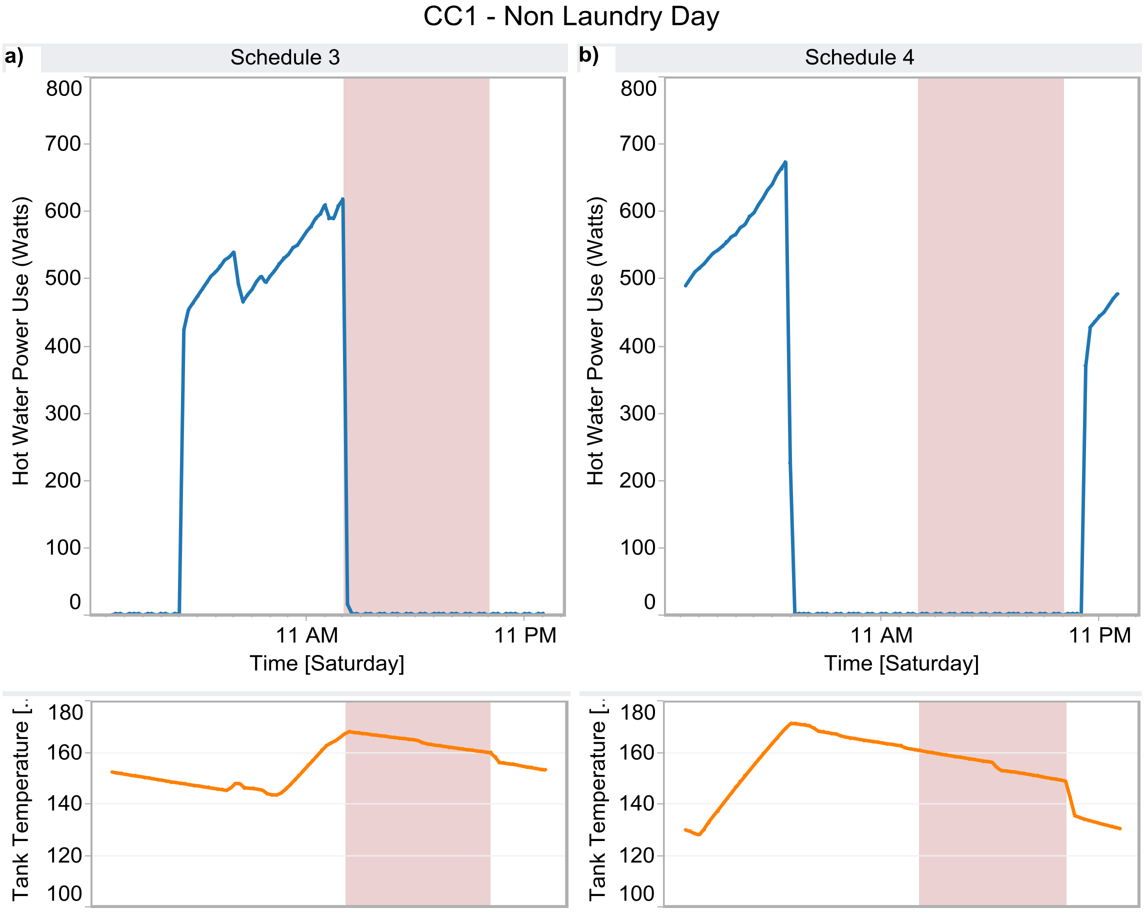

Fig. 28. Power consumption and tank temperature for CC1 on a typical non-laundry day: (a) Schedule 3, (b) Schedule 4.

Table 8. Average daily energy consumption of tested temperature profiles (during sample days)

CC1 average daily energy consumption (kWh)		
	Non-laundry day	**Laundry day**
Conventional storage water heater	8.5	13.2
Baseline HPWH	2.5	6.0
Schedule 3	3.6	4.8
Schedule 4	3.3	5.2

Also shown in Fig. 28 are the measured tank temperatures. The average daily measured temperature can be used to provide qualitative insight into the source of energy use variation between the different temperature schedules. The average daily tank temperature for the baseline HPWH is 120°F, in contrast to 155°F and 153°F for schedules 3 and 4, respectively. Since the heat pump provides all of the heat for the baseline HPWH and schedules 3 and 4 (Figs. 27 and 28), the higher average tank temperatures result in lower efficiencies for the heat pump. This contributes to the baseline HPWH average coefficient of performance (COP) of 2.8 and a lower COP of 2.0 for schedule 3. The lower efficiency for higher tank temperatures is also partly the result of greater thermal losses to the ambient environment.

The power consumption and tank temperatures for schedules 3 and 4 on a typical laundry day are shown in Fig. 29. Unlike on non-laundry days, water heating during the peak period was required to meet hot water demand for schedule 4 (similar to the baseline HPWH, Fig. 29). This is because there was not enough energy stored in the tank to meet the 9.2 gal of hot water demand at 5 p.m. without going below the 130°F temperature set point during this period. As shown in Fig. 29, the tank temperature (measured near the top of the tank) went as low as 117°F before the heat pump was able to provide sufficient heat to increase the temperature. On the other hand, no water heating was required during the peak period for schedule 3. This is because of the different timing of the temperature schedules and the stratified nature of the water temperatures in the tank (illustrated in Fig. 22). For schedule 3, the heat pump began delivering heat to the tank at 3:00 a.m. and continued until the peak period began at 1:00 p.m. By this time, sufficient heat had been delivered to the lower two-thirds of the tank to de-stratify the tank temperature so that the tank was full of hot water at the beginning of the peak period (illustrated by Fig. 22a). In contrast, schedule 4 had a full tank of hot water at a temperature of 170°F around 5 a.m. Although this is a greater amount of thermal energy than was achieved with schedule 3, most of the thermal energy was removed by the 50 gal of hot water draws between 5 a.m. and 12 p.m. Therefore, when the heat pump was activated at 12 p.m., a large portion of the tank contained 60°F water, but a smaller portion of the water near the top of the tank had a temperature near 150°F (illustrated by Fig. 22b). Because water heating stopped at 1 p.m. as a result of the temperature schedule, the tank remained stratified with only a small amount of hot water at the top of the tank, which was insufficient to meet the 5 p.m. hot water demand.

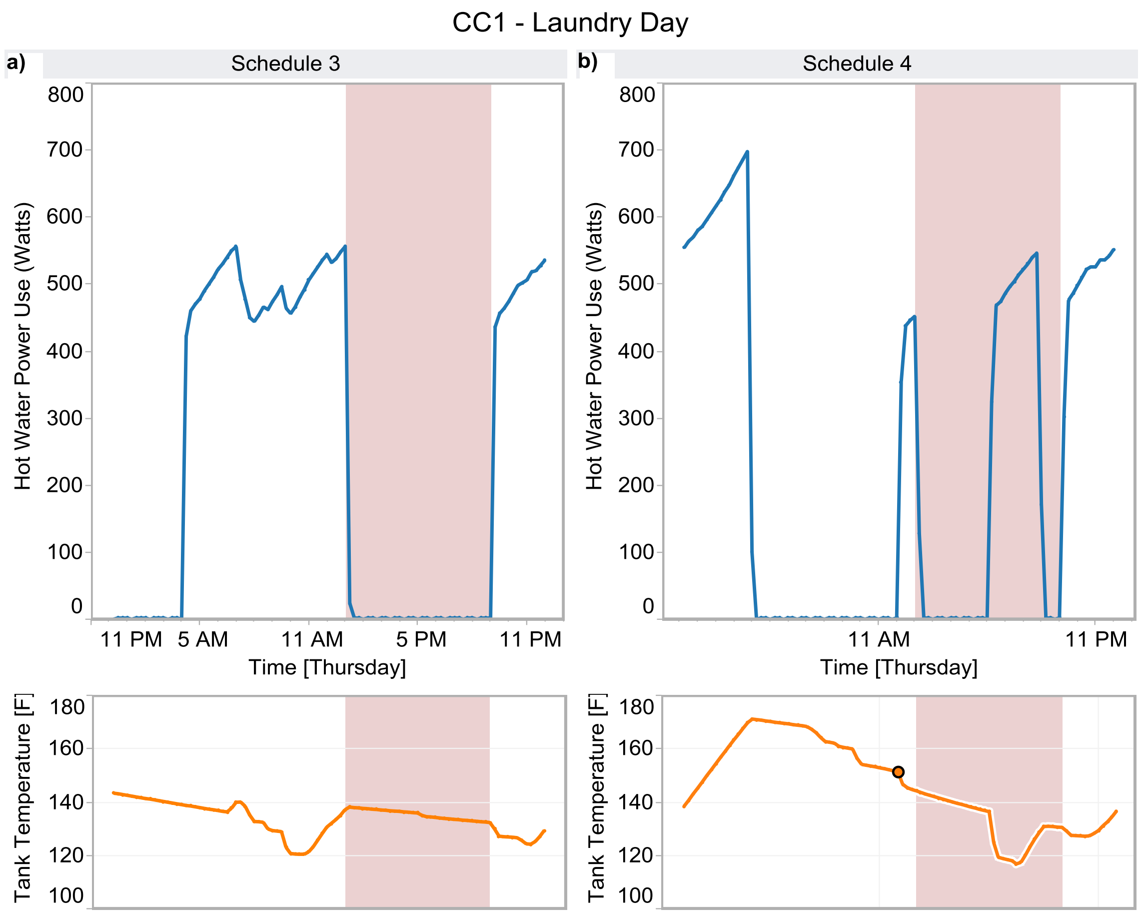

Fig. 29. Power consumption and tank temperature for CC1 on a typical laundry day: (a) schedule 3, (b) schedule 4.

On laundry days, unlike for non-laundry days, schedule 3 consumed less energy (approximately 8% less) than schedule 4, even though schedule 3 operated 45 minutes longer over the day than schedule 4. Because schedule 3 never achieved an average tank temperature as high as that of schedule 4, the heat delivered during schedule 3 had an average efficiency COP of approximately 2.4 compared with a COP of 2.2 during schedule 4.

As illustrated by the variation in energy performance and the ability to completely shift power as desired, there is no one-size-fits-all approach to load-managed heat pump scheduling. For an occupant profile with lower hot water consumption (non-laundry day), schedule 4 totally shifts the power consumption out of the peak summer period into the non-peak hours with lower energy use than schedule 3. Conversely, for an occupant profile with higher hot water consumption, schedule 4 not only has higher energy consumption than schedule 3 but also does not meet the primary requirement to shift the water heating load out of the summer peak period.

4.4.2.3 CC3 HPWH Energy Consumption

Detailed analysis was presented for CC1; however, because the operation and thereby the performance of the unit in CC3 was similar, only salient performance highlights are discussed in this section. In contrast to CC1, for CC2 and CC3, both schedule 3 and schedule 4 were able to successfully shift all water heating demand out of the peak summer period. Furthermore, since there was never sufficient water consumption to require the baseline HPWH (in hybrid mode) to use the resistance elements to provide water heating, the energy consumption for laundry and non-laundry days is similar in CC3, unlike in CC1. This shows it is easier to shift the peak load of the WH by using water-conserving appliances like the ES clothes washer in CC3. So energy efficiency aids demand response.

As shown previously in Table 7, the difference in hourly (and thereby daily) hot water consumption on laundry days facilitates an assessment of the impact of the load-managed temperature schedules on three distinct hot water draw profiles. As can be seen in Fig. 30, the HPWH efficiency achieved by the different schedules (from both CC1 and CC3) is highly dependent on the hot water draw pattern. To successfully meet load-shifting demands while achieving the highest energy efficiency, schedule 4 would be best for below-average and average occupant water consumption. Schedule 3 would be better for occupant profiles with higher water consumption.

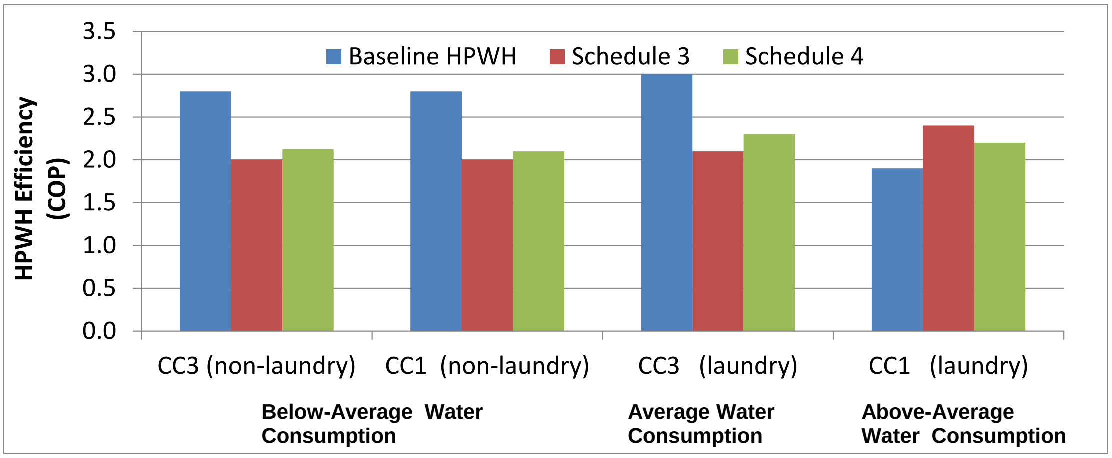

Fig. 30. HPWH efficiency for CC1 and CC3 load-managed temperature schedules.

5. KEY INSIGHTS GAINED

5.1 WHOLE-HOUSE ENERGY CONSUMPTION

In FY 2010, CC2 consumed approximately 3,735 kWh (38%) more energy than the 9,831 kWh used by CC3. The difference is primarily attributed to energy use for space conditioning, with CC3 and CC2 requiring 4,849 kWh and 7,901 kWh, respectively. Since the space-conditioning equipment in both homes was a 16 SEER, 9.5 HSPF heat pump, the difference in energy consumption is the result of the load required by the building envelope. CC3 has a tighter building envelope (2.5 ACH_{50} compared with 3.4 ACH_{50} for CC2), a greater wall R-value (R-22 versus R-13), and more energy-efficient windows (triple pane versus double pane). Therefore, the larger thermal load required by CC2 is expected.

In FY 2013, however, CC2 consumed only 132 kWh more than CC3. The thermal envelopes of both homes have remained consistent since construction; however, the building equipment has been replaced in both homes. CC3 has a heat pump with efficiency ratings of 18 SEER and 8.9 HSPF, whereas the heat pump in CC2 has efficiency ratings of 20.5 SEER and 13.0 HSPF. The greater rated efficiency and measured performance of the HVAC system in CC2 was largely able to compensate for its less efficient thermal envelope. It must be noted that demand-response schedules evaluated in CC2 during FY 2013 were not tested in CC3. However, the authors do not estimate that the demand-response schedules significantly contributed to the improved HVAC energy consumption of CC2 compared with CC3. CC2 also used 748 kWh less for water heating. Water heating in CC2 used a CO_2-based heat pump water heater for 11 months of the year while CC3 used solar water heating for approximately 6 months. Both homes were then converted to commercially available heat pump water heaters in late August.

5.2 HVAC

Warm air rises and cool air falls—this fact makes it challenging to appropriately size HVAC systems for a two-story home, particularly one in which the two levels are served by different HVAC systems. Most of the capacity required to keep the house at the indoor temperature set point is provided by the downstairs unit in the heating season and the upstairs unit in the cooling season, as seen in Figs 13–16. Since Manual J assumes that no heat transfer occurs between the first and second floors, the aforementioned phenomenon is not considered in cooling and heating load calculations. Therefore, the predicted cooling load indicates only a minor 125% cooling oversizing for the CC1 downstairs unit, whereas in reality the measured average capacity data indicate that it is 390% oversized (Fig. 15). Although it is expected that the average capacity would be lower than the design load conditions (i.e., 97°F), this difference is substantially larger than the expected deviation. Likewise, the upstairs unit's measured average capacity trend indicates that it is 165% oversized, which is essentially identical to the Manual J cooling load calculation. This indicates the real peak cooling load could be slightly higher because the upstairs unit provides some cooling to handle load from the downstairs.

In contrast, during the heating season, the downstairs unit delivers more heating than the upstairs unit despite the Manual J load calculations indicating the opposite. The maximum heating capacity of the level 1 unit is approximately 137% of the average measured capacity and for the level 2 unit is 332% of average measured capacity. The average load on the house at the design temperature of 19°F is 26,400 Btu/h compared with the Manual J design load, at the same OAT, of 54,600 Btu/h—more than double the average load on the house. Although the Manual J design loads indicate a significantly larger heating than cooling load, the measured data indicate that peak loads are essentially balanced between heating and cooling at roughly 26,000 Btu/h at the design OATs (note that Knoxville, Tennessee, commonly sees temperatures below the 19°F design temperature).

As seen in both heating and cooling modes, sizing based on modeled loads in two-story homes with two single zone systems is difficult. A single variable-capacity, zoned heat pump would allow the heating and cooling capacity to be directed where needed and allow heat loss/gain calculations for the entire home to ensure proper system sizing.

Figure 31 shows two sets of data. For the first set, resistance heat use in defrost cycles is enabled, and for the second set it is disabled. In the first case, resistance heat is used to prevent cold air from being blown into the house. When resistance heat use is disabled during defrost cycles, cold air is blown into the house, and the heat pump must compensate for this by providing additional heating to keep the house at the desired indoor temperature set point. When it was very cold outside, the drop in the indoor temperature during the defrost cycle was often enough to trigger supplemental resistance heat when the heat pump switched back to heating mode after the defrost cycle. This sometimes resulted in more resistance heat use than would have occurred if resistance heat had been enabled during the defrost cycle, as seen by the points with average daily temperatures below 35°F. The same phenomenon was also seen at CC1, as shown in Fig. 18.

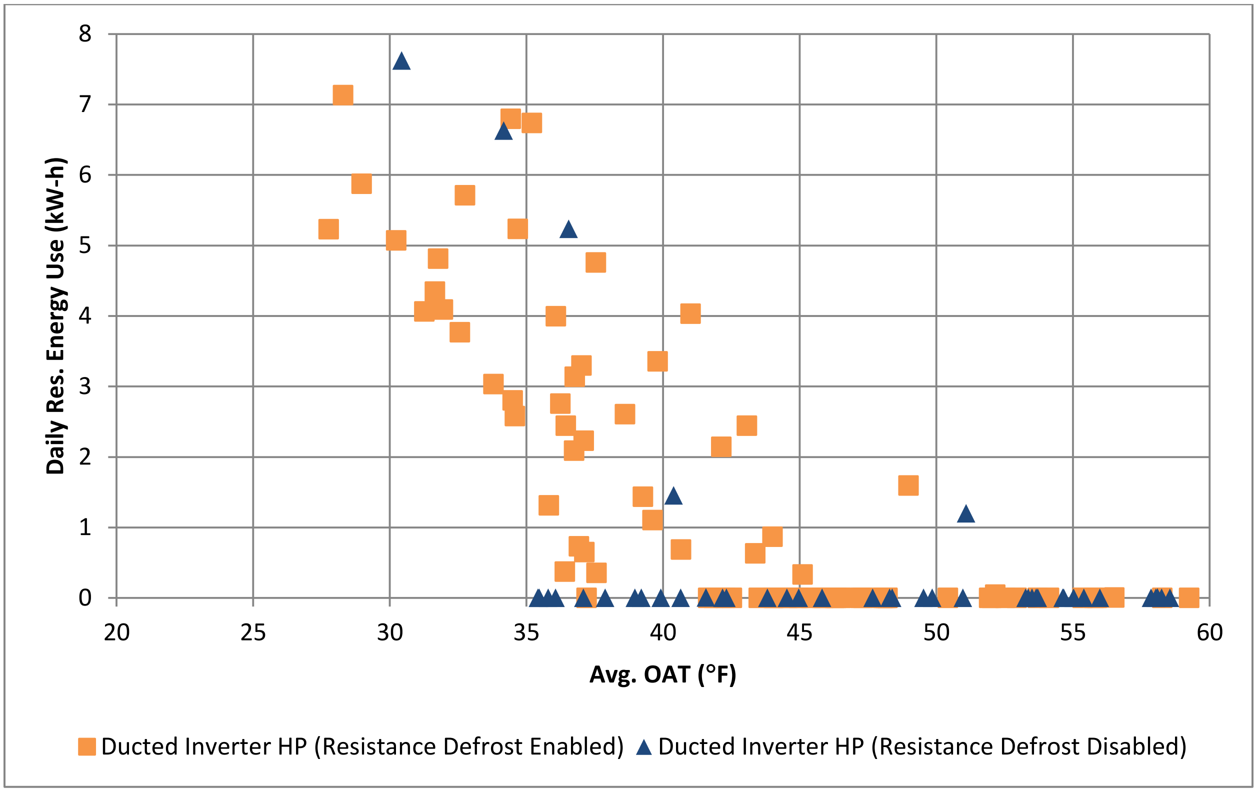

Fig. 31. Impact of disabling resistance heat during defrost cycles in CC2.

The efficiency analyses in CC1 and past year studies in CC2 indicate that the Carrier GreenSpeed™ units are 4% to 8% more efficient in efficiency mode than in comfort mode when cooling. However, the energy use comparisons between comfort and efficiency modes in the cooling season only show 3% savings for efficiency mode in CC1 and essentially no savings in CC2. This apparent discrepancy could be because of a combination of factors, including uncertainty in energy use predictions, measurement uncertainty, and slight variations in building load because of HVAC equipment operation (variations in duct leakage, useful fan work that eventually is converted to heat, etc.). Additional research would be required to fully ascertain the source(s) of this discrepancy.

5.3 BUILDER HOUSE (CC1) BASELINE

To use the CC1 house (builder house before the HVAC system replacement) as a base case when required, a detailed calibrated simulation model of the CC1 house was developed. Figure 32 shows the comparison of daily energy consumption predicted by the calibrated model and the measured energy consumption profile of the base case house for 2011. As is evident from the figure, the calibrated simulation results match fairly well with the measured data, even at the daily energy consumption level, with an annual energy use difference of 0.4% (i.e., measured use of 21,890 kWh vs. simulated use of 21,800 kWh). The monthly normalized mean bias error (NMBE) and coefficient of variation root mean square error (CV[RMSE]) were 0.4% and 3.6%, respectively. The daily NMBE and CV(RMSE) were 0.4% and 11.8%, respectively. This is well within the acceptance range provided by ASHRAE Guideline 14-2012. Besides the whole-house energy consumption, the component-level simulated and measured data were compared, and the results matched very well (Table 9). This calibrated model can be used confidently to predict the energy performance of CC1 (builder house) in the future.

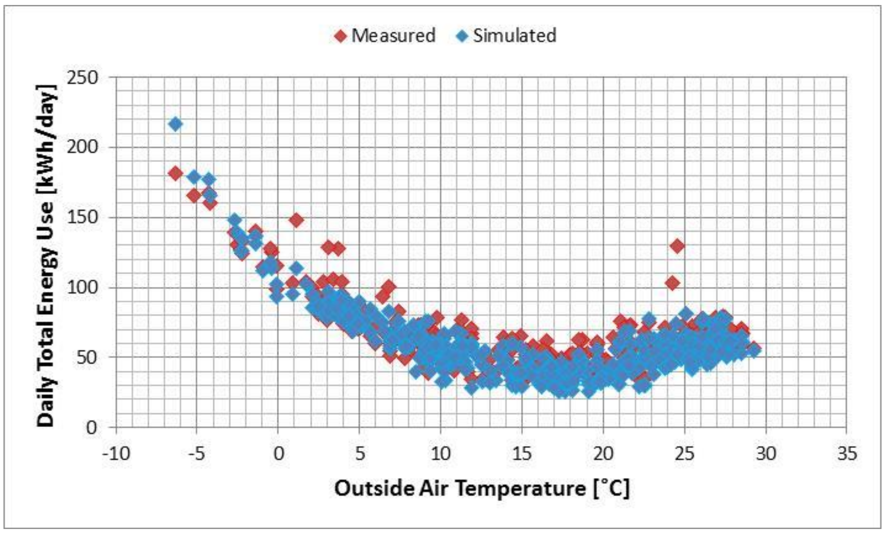

Fig. 32. Comparison of simulated and measured daily energy consumption.

Table 9. End use measured and simulated energy consumption (2011 calendar year)

End use	Measured (kWh)	Simulated (kWh)	% Diff
H/C+Fan	**9,420**	**9,246**	**1.85%**
Heating/Cooling	8,027	7,967	0.75%
Fan	1,393	1,279	8.17%
DHW	**3,945**	**4,032**	**-2.21%**
Lighting + App	**8,525**	**8,524**	**0.00%**
Lighting	2,682	2,682	0.00%
Appliances	5,843	5,843	0.00%
Total Energy	**21,889**	**21,802**	**0.40%**

6. CONCLUSIONS

CC1 consumed 17,054 kWh of total energy during FY 2013; CC2 used approximately 37% less, and CC3 approximately 36% less. However, since PV panels supplied 3,288 kWh of the total load, CC3 required 55% less energy from the grid for FY 2013. In addition to the valuable insights provided by the reduction in energy consumption afforded by the various combinations of energy conservation measures in the three homes, other key points of interest and lessons gleaned from the past year are described subsequently.

The heating and cooling season performance of the variable-capacity heat pumps in CC1 and CC2 indicates that these systems perform significantly better than the prior single-speed heat pumps, offering an energy savings potential of up to 37%. The efficiency analyses in CC1 and past year studies in CC2 indicate that the Carrier GreenSpeed™ units are 4% to 8% more efficient in efficiency mode than in comfort mode when cooling and up to 13% more efficient in heating. However, the energy use comparisons between comfort and efficiency modes in the cooling season show only 3% savings for efficiency mode in CC1 and essentially no savings in CC2. This apparent discrepancy could be because of a combination of factors, including uncertainty in energy use predictions, measurement uncertainty, and slight variations in building load because of HVAC equipment operation (variations in duct leakage, useful fan work that eventually is converted to heat, etc.).

The comfort assessment indicates that variable-capacity heat pumps allow for intentional oversizing relative to the cooling load with no associated penalty in latent heat removal during operation in comfort mode. This intentional oversizing can reduce or eliminate the need for supplemental electric resistance heat in the heating season and reduces peak hourly power draw, which is of particular interest to utilities. Because of imbalances in the heating and cooling loads and the limited capacity range of single speed ducted, split-system heat pumps, it is difficult in most climates to size a heat pump appropriately for both heating and cooling. This is particularly true in two-story homes with separate space conditioning systems for each level, as seen in this study. The sizing issue is aggravated by the difficulty of modeling heat transfer between upstairs and downstairs zones (see Sect. 5 for additional information). Given adequately sized ductwork, a single unit variable-capacity, zoned system might be preferable to traditional upstairs/downstairs single-speed units in two-story homes. Variable-capacity heat pumps are able to mitigate this problem by allowing the unit to run at reduced capacity for longer periods of time, reducing cycling losses that exist with single-speed heat pumps. To increase comfort, oversized variable-speed heat pumps should be run in a mode that allows for enhanced dehumidification while cooling.

The retrofit home (CC2) with the sealed attic was evaluated to better understand the moisture performance of sealed attics, which have become a growing retrofit and new-construction trend in the Southeast. As has been the case in other homes with sealed attics, we observed that the attics and interiors of sealed-attic homes were more humid than the attics and interiors observed in vented-attic homes. This is because of the lack of ventilation in the sealed attic combined with a lower sensible heat load, which results in shorter run times of the cooling system and thus less dehumidification. This can cause elevated interior moisture compared with a vented-attic home. Initial study shows that the energy required to make the home comfortable again could decrease the sealed attic savings by 70%. Other methods are currently being investigated to determine a less energy-intensive way to dehumidify the sealed attic home. The researchers also determined that solar-driven moisture does not seem to be a significant source of moisture in the home. This research is also ongoing.

Despite the elevated attic and interior moisture in the sealed-attic home, no mold or material degradation has been found. The roof sheathing moisture content has stayed below 20%, indicating low potential for material degradation. Also, the RH at the roof sheathing has stayed within the ASHRAE 160 design criteria except for a short time during the 2011/2012 winter. This was because of a combination of the sealed-attic design (minimal venting to the outside) and the fact that the ductwork, which usually provides a dehumidification pathway, was not operated in the attic.

Two different heat pump water heater tank schedules were discussed in this report to assess the ability to eliminate water heater peak period energy use by pre-heating water in the tank to increase the stored thermal energy. One schedule had lower total energy consumption with no peak hour energy use for the low-energy consumption profile, while the other temperature strategy was more appropriate for the medium- and high-water consumption profiles in this study. This observation illustrates the importance of designing a temperature set point schedule to match the home's hot water consumption pattern. An optimal temperature set point strategy would require the ability to predict the home's daily energy consumption profile and respond appropriately.

7. REFERENCES

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APPENDIX A: PAST TECHNOLOGY PROGRESSION

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

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.

The dryer at CC1 was changed by GE on December 2009 to one of the same models 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 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).

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 temperature delivery 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. 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 2012 and was salvaged by TVA.

On November 19, 2010, a Daikin ducted inverter HVAC system was installed at CC3 to replace the baseline two-stage zoned system. 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 in. plasma TV was added that had an average daily energy consumption of 1.04 kWh (with 8.5 h/day of on time). At CC2, a 55 in. liquid crystal diode (LCD) TV was installed that had an average daily energy consumption of 0.77 kWh. At CC3, a 55 in. LED/LCD TV was added with an average daily kWh consumption of 0.46 kWh.

A Mitsubishi Lossnay energy recovery ventilator 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 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 US Department of Energy Building America benchmark.

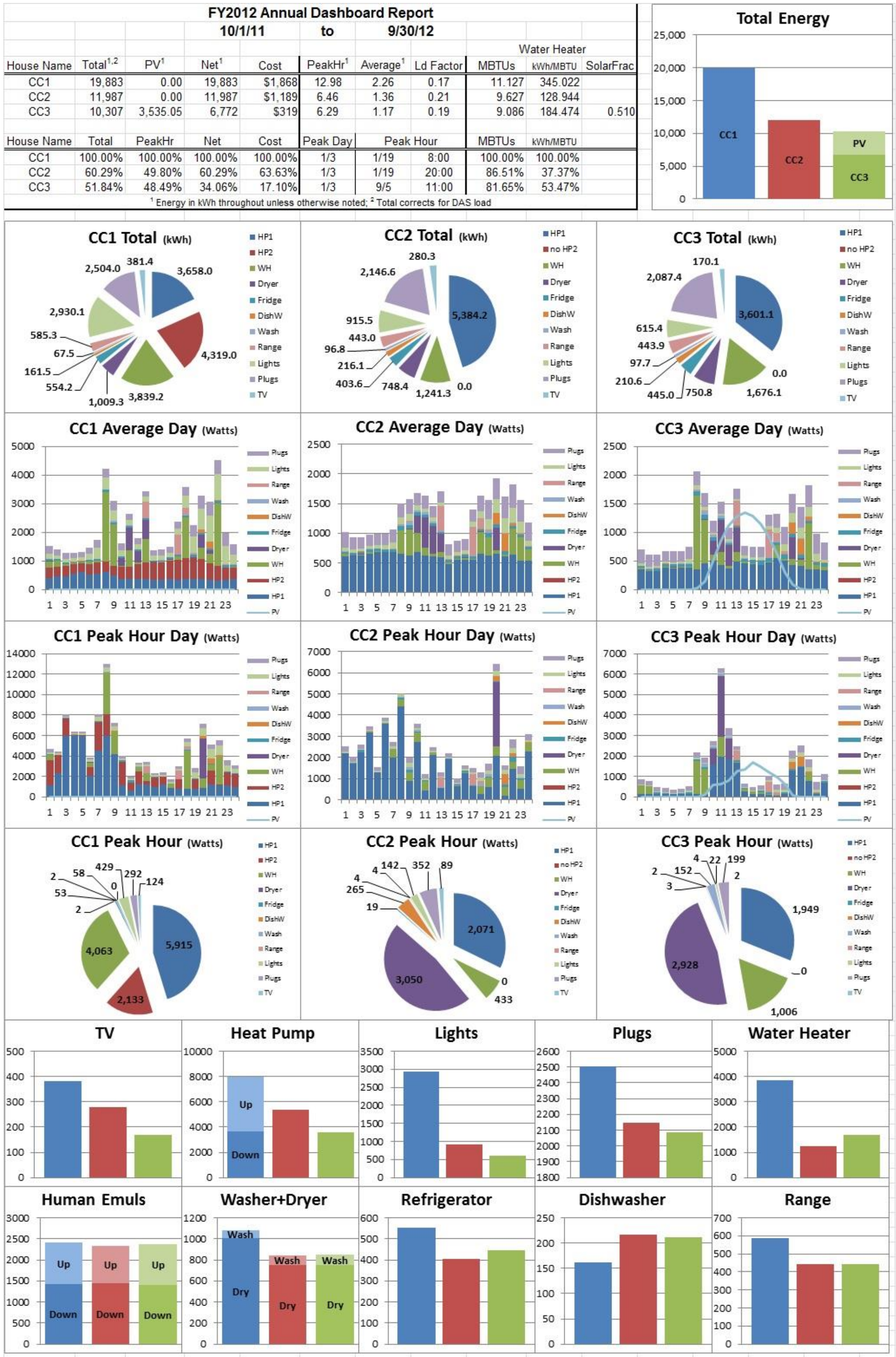
A heat recovery system was installed at CC3 in May 2011 to allow evaluation of a system designed to capture waste heat from the shower, clothes washer, and dryer, and to use this waste heat to offset some of the hot water energy needs of the house. The system included a gravity-film heat exchanger (GFX) 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 six week test period concluded, the equipment remained in place; however, use of the dryer heat exchanger and the recirculating pump 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.

APPENDIX B: PAST ANNUAL DASHBOARDS



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	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. B-1. FY 2012 annual dashboard.

FY2011 Annual Dashboard Report										
			10/1/10		to	9/30/11				
								Water Heater		
House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	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

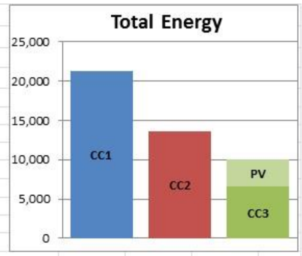


Fig. B-2. FY 2011 annual dashboard.

B.1 FY 2013 MONTHLY DASHBOARDS

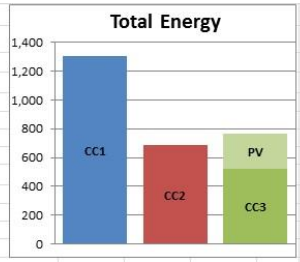
Dashboard Report

10/1/12 to 10/31/12

House	Total[1,2]	PV[1]	Net[1]	Cost	Daily Average[1]	Load Factor	Peak Day	Water Heater Gallons	MBTUs	kWh/MBTU	SolarFrac
CC1	1,302	0.00	1,302	$125.48	1.75	0.29	10/30	2148	0.905	349.636	
CC2	684	0.00	684	$72.32	0.92	0.13	10/30	1815	0.759	113.714	
CC3	764	244.86	519	$28.75	1.03	0.22	10/30	1670	0.729	235.163	0.378

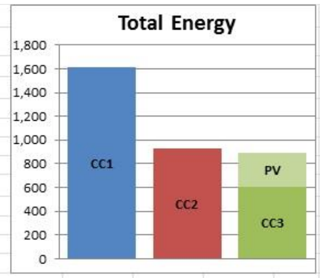
House	Total	PeakHr	Net	Cost	Peak Hour	Peak[1]	MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	10/9 10:00	6.14	100.00%	100.00%	HDD@65 310.2
CC2	52.52%	111.62%	52.52%	57.64%	10/8 11:00	6.85	83.82%	32.52%	CDD@65
CC3	58.65%	74.96%	39.85%	22.91%	10/29 19:00	4.60	80.50%	67.26%	37.8

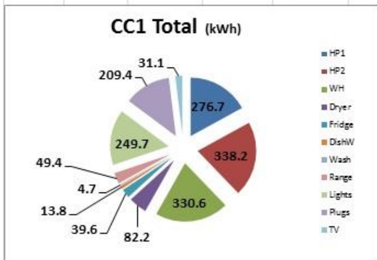
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load

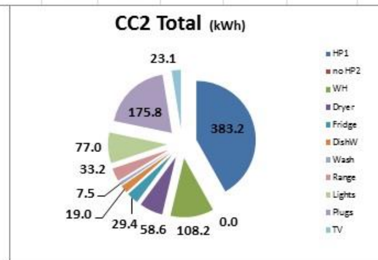


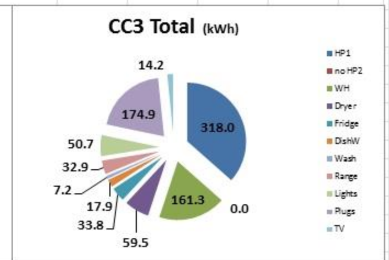
Dashboard Report											
			11/1/12		to		11/30/12				
					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	SolarFrac
CC1	1,612	0.00	1,612	$153.88	2.24	0.32	11/29	2024	0.953	347.050	
CC2	927	0.00	927	$94.24	1.29	0.33	11/29	1798	0.786	137.593	
CC3	890	281.97	608	$32.60	1.24	0.29	11/7	1665	0.799	201.836	0.417
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	11/25	8:00	6.95		100.00%	100.00%	620.6
CC2	57.51%	56.12%	57.51%	61.24%	11/24	22:00	3.90		82.52%	39.65%	CDD@65
CC3	55.19%	61.85%	37.70%	21.18%	11/14	22:00	4.30		83.88%	58.16%	2.2

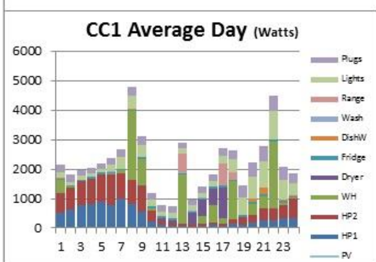
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load

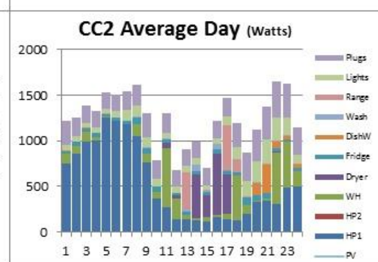


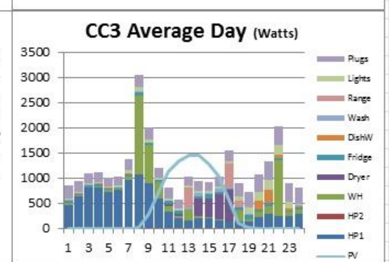


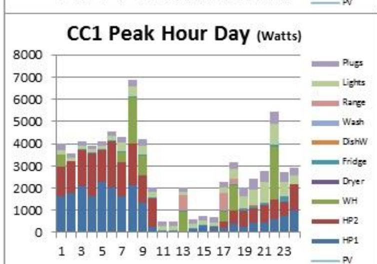


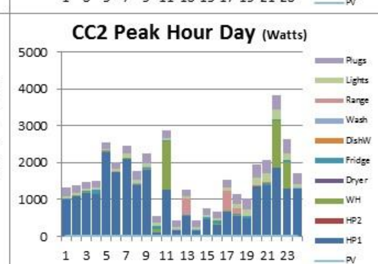


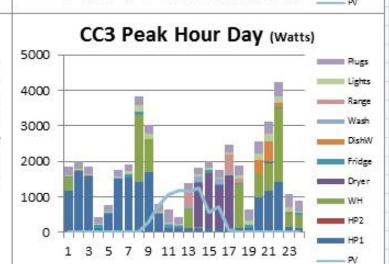


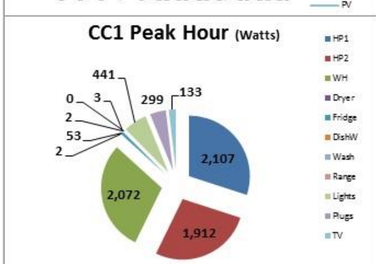


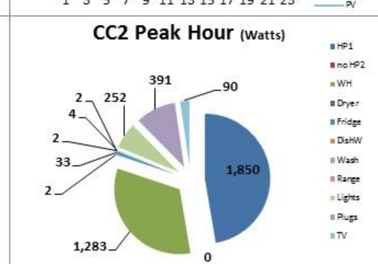


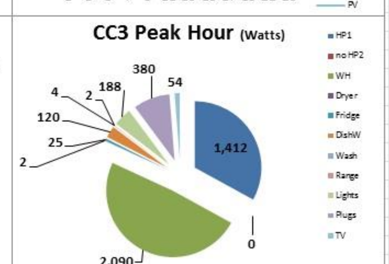


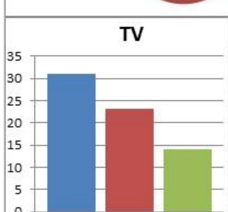


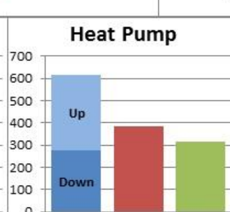


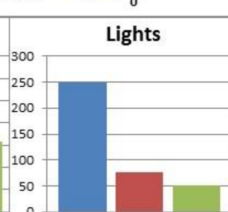


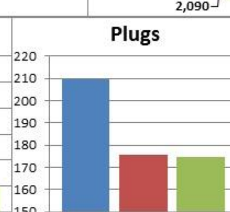


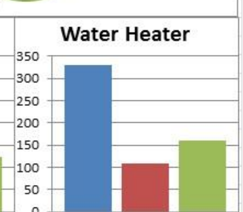


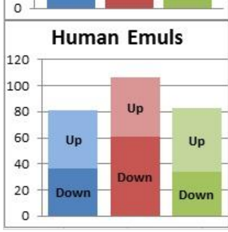


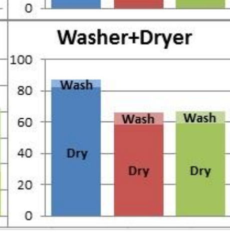


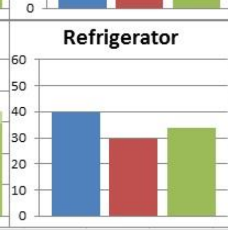


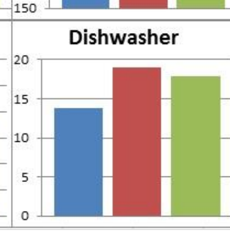


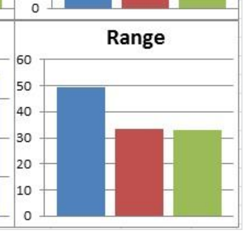








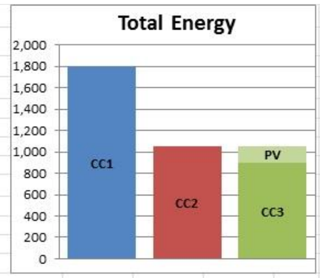


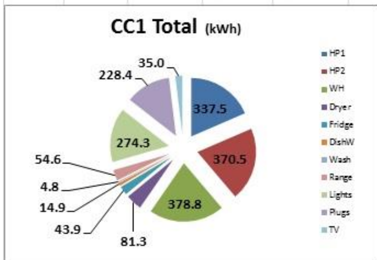


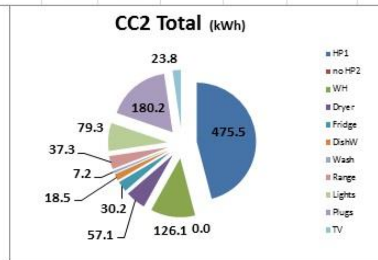
Dashboard Report											
			12/1/12		to	12/31/12					
					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	SolarFrac
CC1	1,805	0.00	1,805	$175.09	2.43	0.29	12/27	2174	1.089	347.751	
CC2	1,048	0.00	1,048	$107.34	1.41	0.37	12/31	1864	0.917	137.523	
CC3	1,055	161.08	894	$74.22	1.42	0.33	12/27	1754	0.867	279.617	0.155

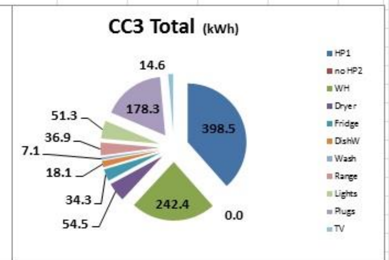
House	Total	PeakHr	Net	Cost	Peak Hour	Peak[1]	MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	12/3 8:00	8.46	100.00%	100.00%	629.4
CC2	58.06%	45.02%	58.06%	61.30%	12/26 23:00	3.81	84.18%	39.55%	CDD@65
CC3	58.46%	51.24%	49.53%	42.39%	12/26 17:00	4.34	79.60%	80.41%	3.9

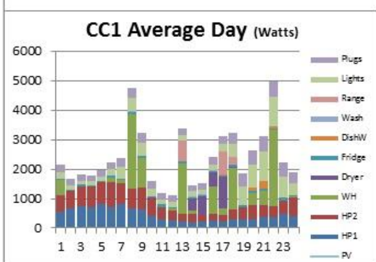
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load

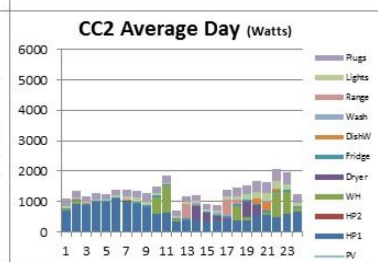


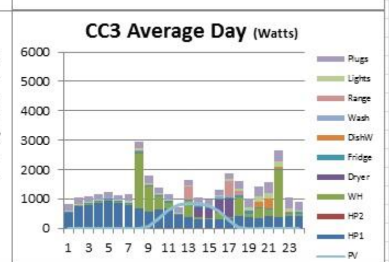


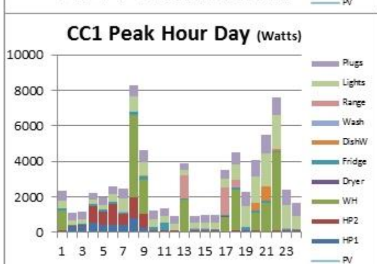


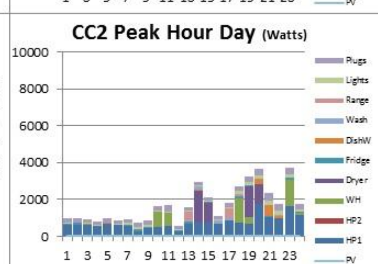


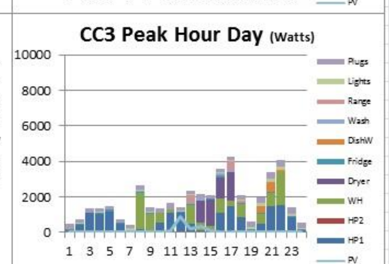


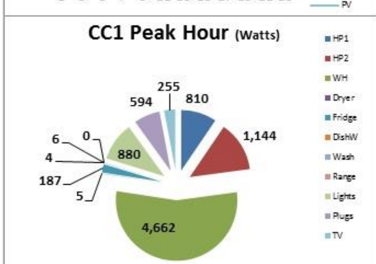


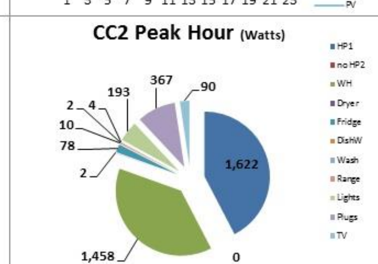


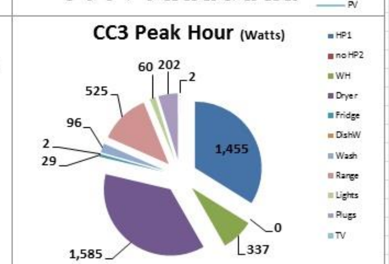


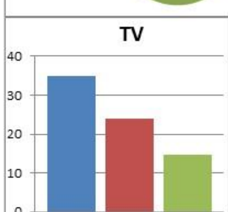


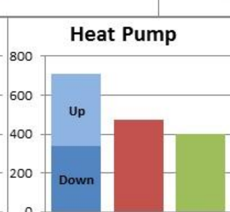


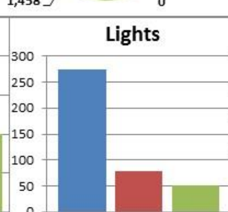


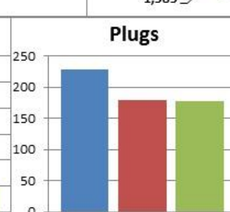


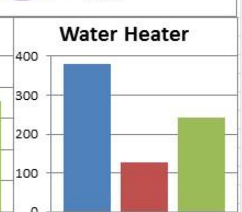


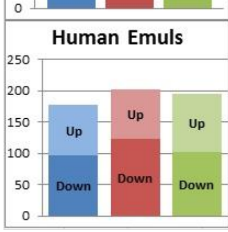


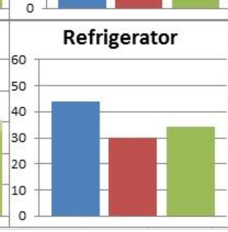


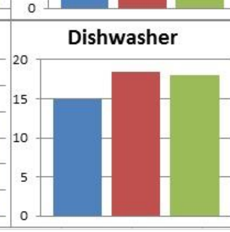


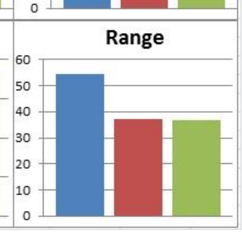






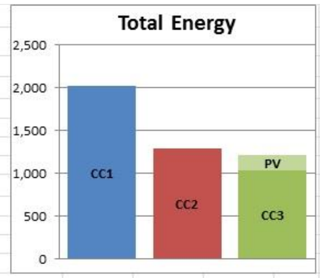


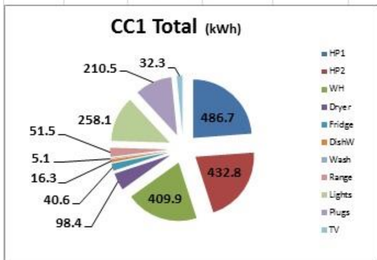


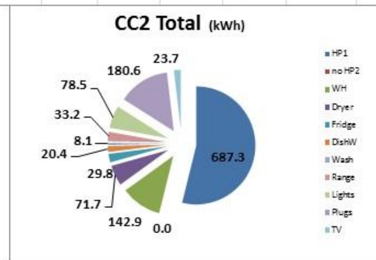


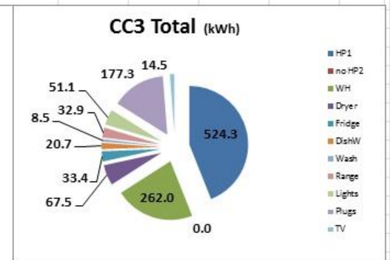
Campbell Creek Research Homes: Dashboard Report					1/1/13	to	1/31/13				
	LCUB Utility Rate: 0.08714		Solar Rate: 0.20714		Monthly Hookup Fee: $13.52						rev. 3
					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	SolarFrac
CC1	2,019		2,019	$189.46	2.71	0.35	1/22	2164	1.187	345.477	
CC2	1,289		1,289	$125.84	1.73	0.39	1/22	1943	1.037	137.803	
CC3	1,213	181.61	1,031	$81.52	1.63	0.34	1/25	1829	0.977	268.083	0.149
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	1/18	8:00	7.82		100.00%	100.00%	745.1
CC2	63.83%	56.54%	63.83%	66.42%	1/5	6:00	4.42		87.40%	39.89%	CDD@65
CC3	60.06%	61.75%	51.07%	43.03%	1/31	20:00	4.83		82.38%	77.60%	2.7

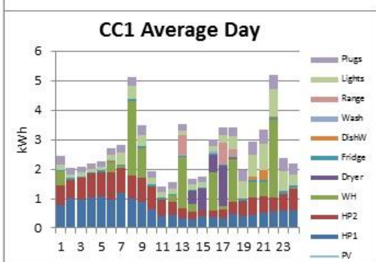
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.

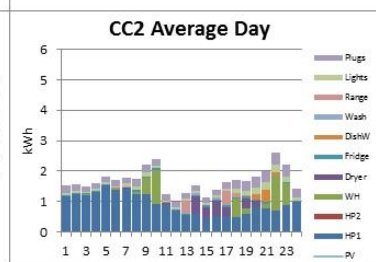


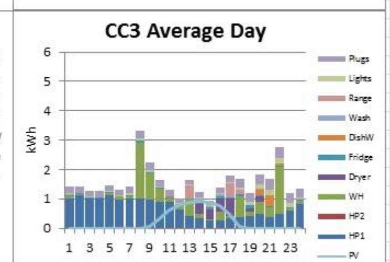


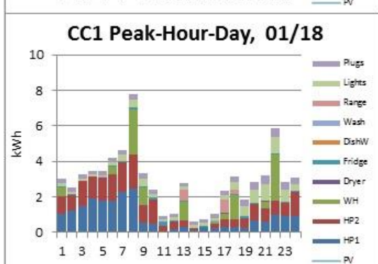


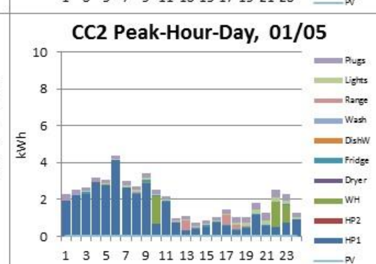


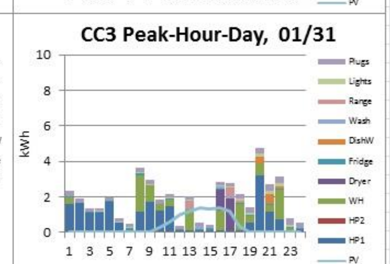


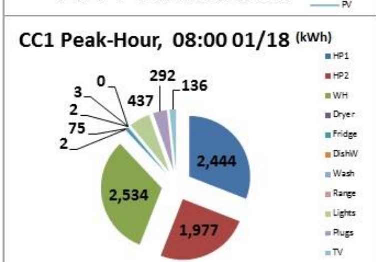


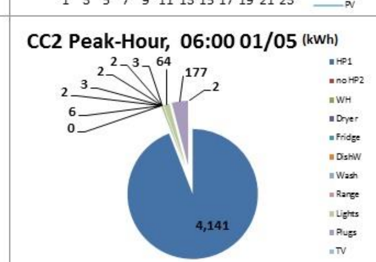


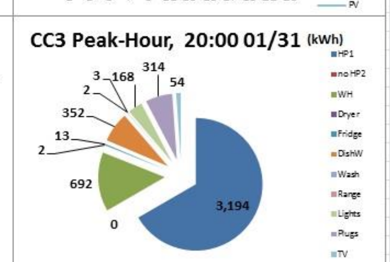


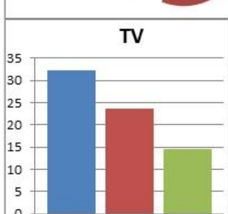


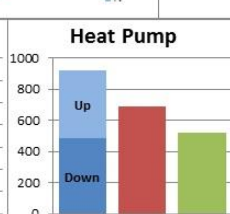


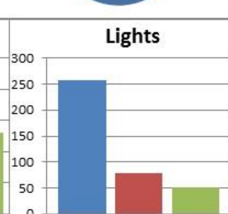


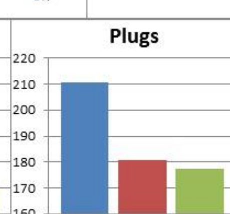


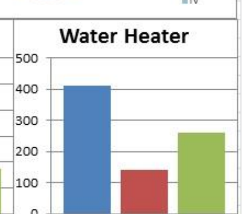


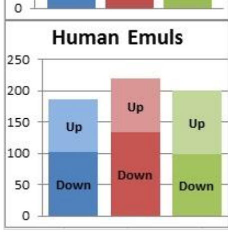


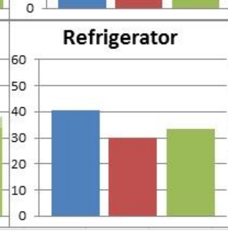


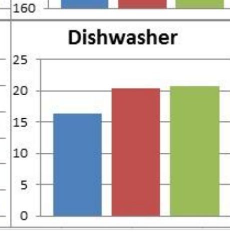


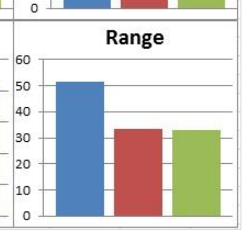








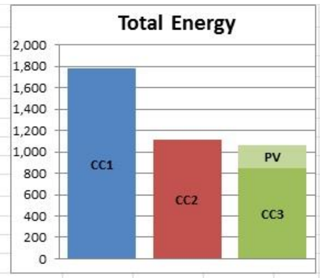


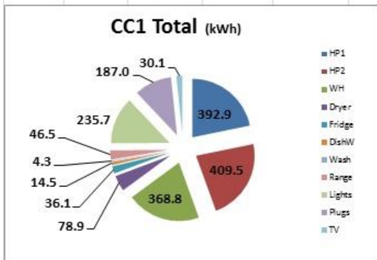


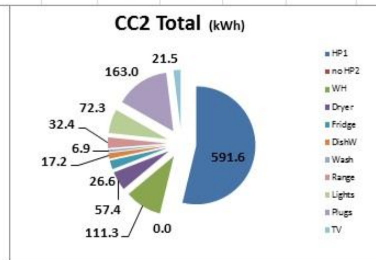
Campbell Creek Research Homes: Dashboard Report							2/1/13	to	2/28/13	
	LCUB Utility Rate: 0.08412		Solar Rate: 0.20412		Monthly Hookup Fee: $13.52					rev. 1
					Daily	Load	Peak	Water Heater		
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	SolarFrac
CC1	1,782		1,782	$163.42	2.65	0.36	2/2	1896	1.066	345.838	
CC2	1,111		1,111	$106.98	1.65	0.37	2/2	1742	0.934	119.142	
CC3	1,066	221.61	845	$57.88	1.59	0.26	2/20	1630	0.889	246.648	0.204

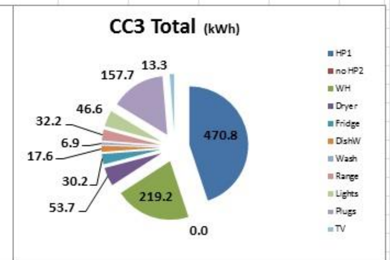
House	Total	PeakHr	Net	Cost	Peak Hour	Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	2/17 8:00	7.35		100.00%	100.00%	683.1
CC2	62.38%	60.22%	62.38%	65.46%	2/4 10:00	4.42		87.60%	34.45%	CDD@65
CC3	59.84%	84.02%	47.40%	35.42%	2/16 22:00	6.17		83.35%	71.32%	0.0

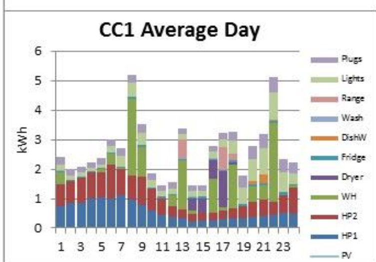
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.

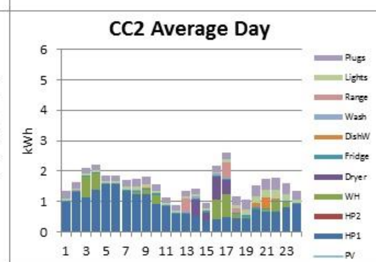


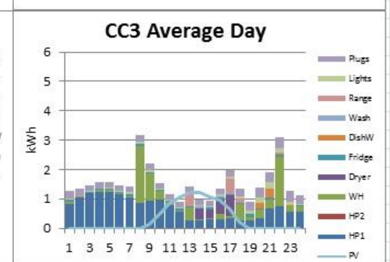


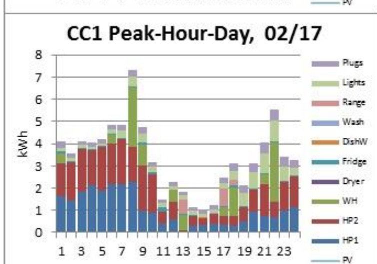


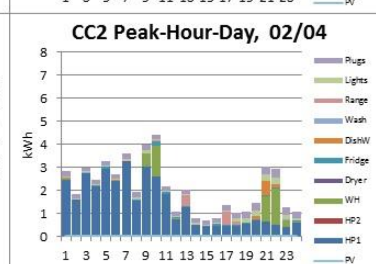


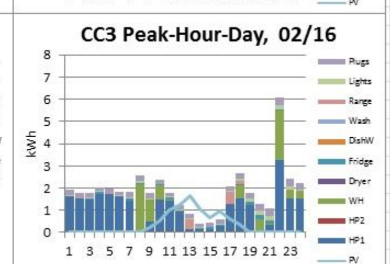


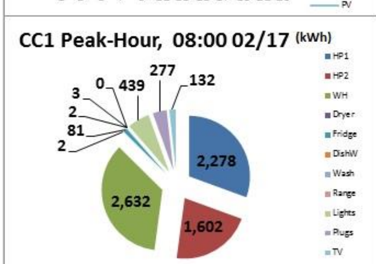


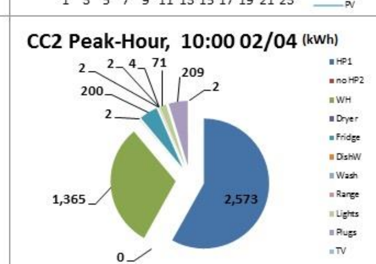


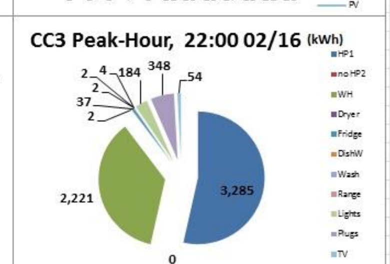


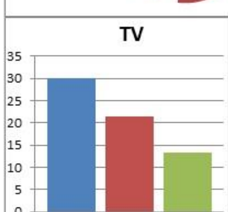


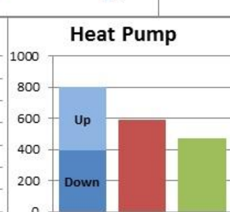


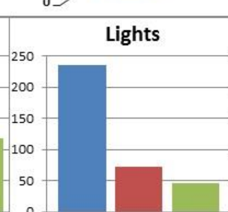


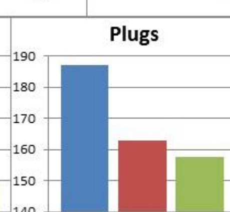


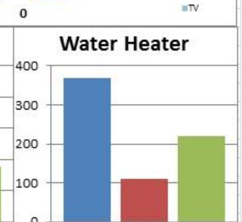


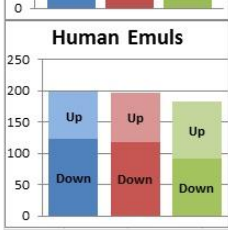


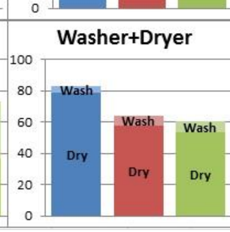


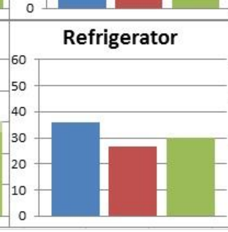


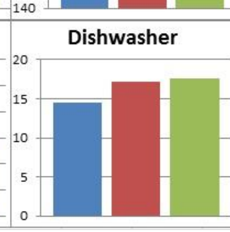


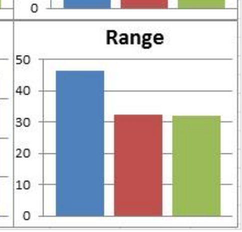










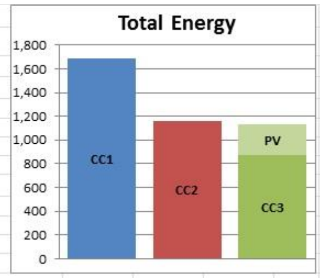


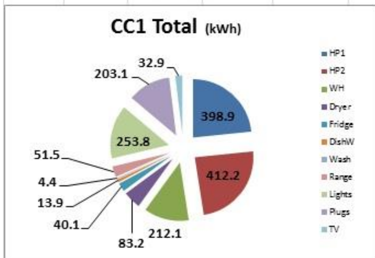
Campbell Creek Research Homes: Dashboard Report 3/1/13 to 3/31/13

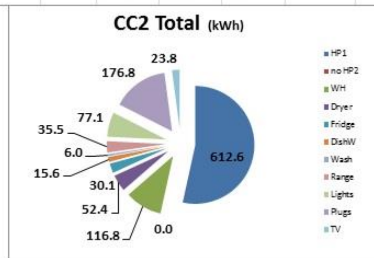
LCUB Utility Rate: 0.0827 Solar Rate: 0.2027 Monthly Hookup Fee: $13.52 rev. 5

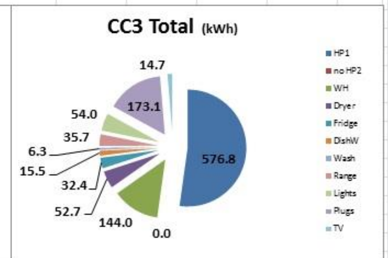
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Daily Average[1]	Load Factor	Peak Day	Water Heater Gallons	Water Heater MBTUs	Water Heater kWh/MBTU	
CC1	1,689		1,689	$153.20	2.27	0.28	3/6	2203	1.150	184.438	
CC2	1,164		1,164	$109.78	1.56	0.31	3/6	1999	1.042	112.008	
CC3	1,129	258.08	871	$54.59	1.52	0.24	3/7	1940	1.031	139.717	
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	3/4	8:00	8.04		100.00%	100.00%	687.5
CC2	68.93%	61.79%	68.93%	71.66%	3/6	16:00	4.97		90.64%	60.73%	CDD@65
CC3	66.83%	77.52%	51.55%	35.63%	3/29	3:00	6.23		89.65%	75.75%	6.2

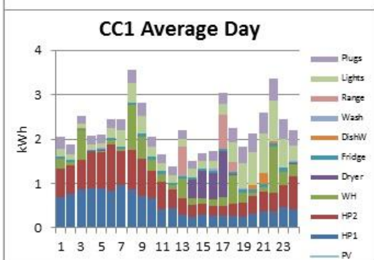
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.

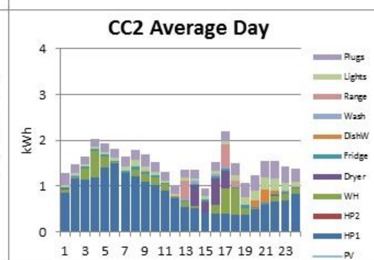


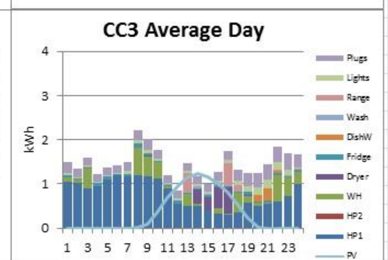


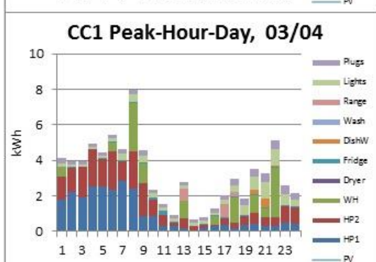


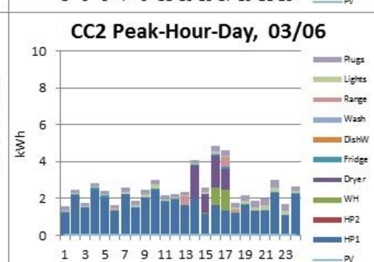


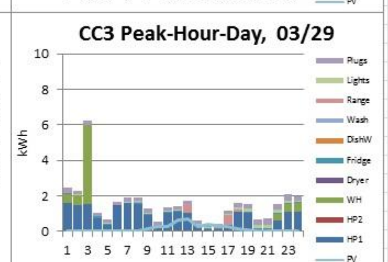


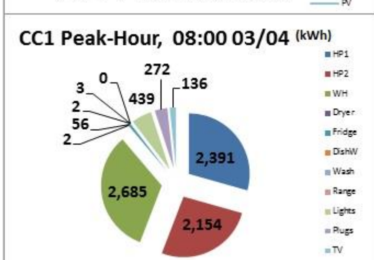


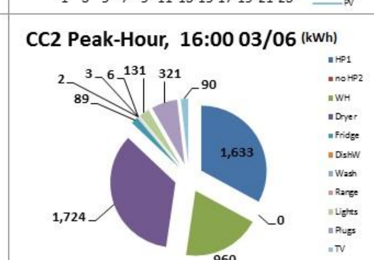


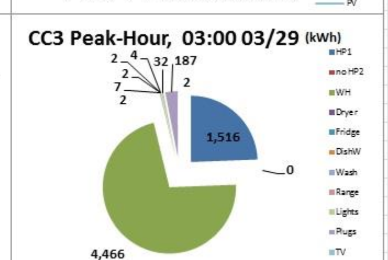


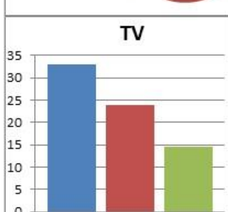


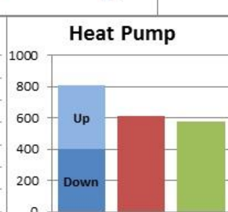


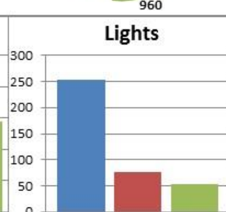


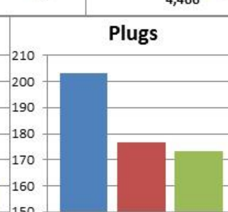


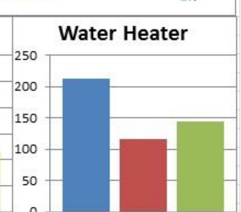


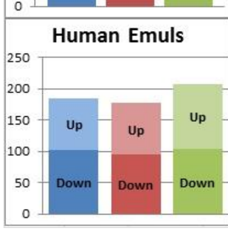


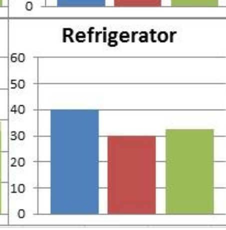


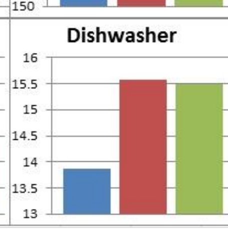


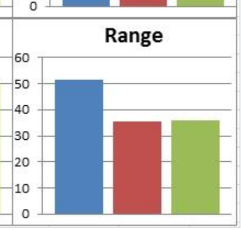










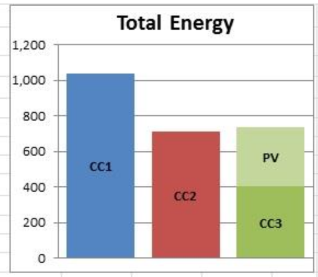


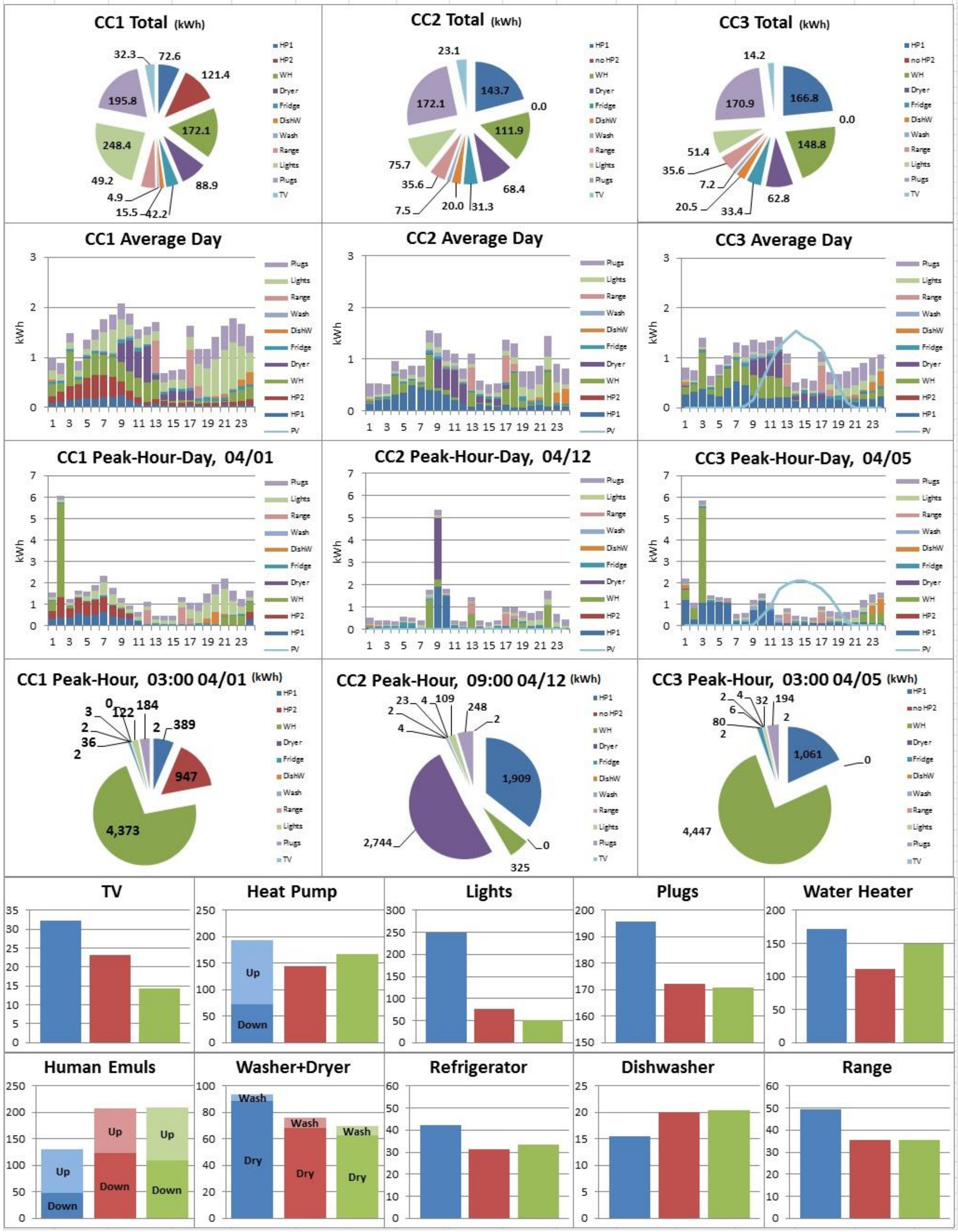
Campbell Creek Research Homes: Dashboard Report **4/1/13 to 4/30/13**

LCUB Utility Rate: 0.08286 | Solar Rate: 0.20286 | Monthly Hookup Fee: $13.52 | rev. 2

					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	
CC1	1,038		1,038	$99.53	1.44	0.24	4/4	2254	1.122	153.467	
CC2	709		709	$72.27	0.98	0.18	4/4	1910	0.959	116.678	
CC3	736	333.35	403	$6.95	1.02	0.18	4/4	1898	0.950	156.661	
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	4/1	3:00	5.98		100.00%	100.00%	286.4
CC2	68.28%	89.67%	68.28%	72.61%	4/12	9:00	5.36		85.54%	76.03%	CDD@65
CC3	70.91%	97.66%	38.81%	6.99%	4/5	3:00	5.84		84.69%	102.08%	57.9

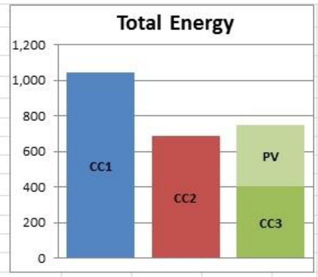
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.

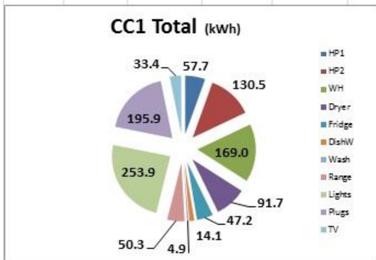


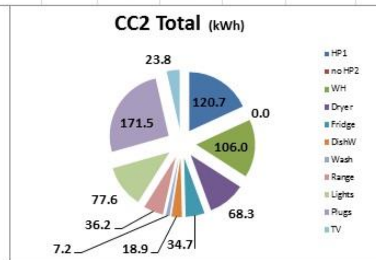


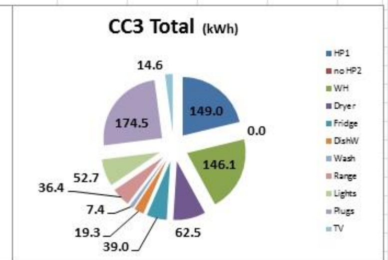
Campbell Creek Research Homes: Dashboard Report					5/1/13	to	5/31/13				
	LCUB Utility Rate:	0.08403	Solar Rate:	0.20403	Monthly Hookup Fee:	$13.52					rev. 4
					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	
CC1	1,044		1,044	$101.25	1.40	0.22	5/30	2256	1.063	158.996	
CC2	686		686	$71.16	0.92	0.26	5/28	1872	0.877	120.857	
CC3	751	349.06	402	$5.42	1.01	0.25	5/1	1900	0.893	163.611	
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	5/30	12:00	6.30		100.00%	100.00%	125.3
CC2	65.72%	57.06%	65.72%	70.29%	5/28	10:00	3.59		82.53%	76.01%	CDD@65
CC3	71.95%	63.13%	38.52%	5.35%	5/28	10:00	3.97		84.00%	102.90%	131.6

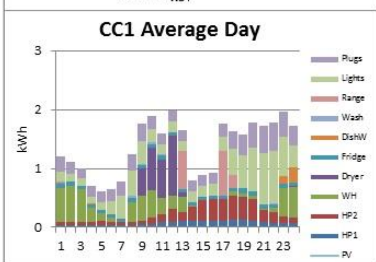
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.

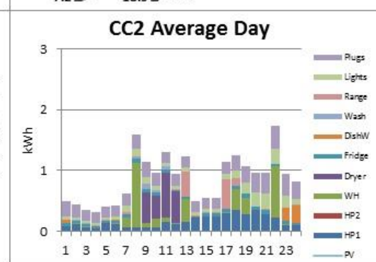


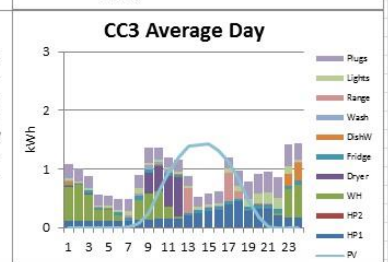


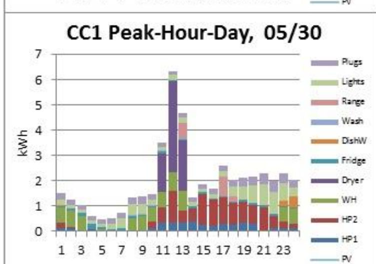


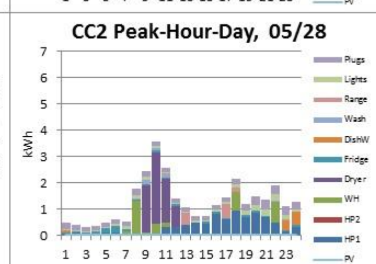


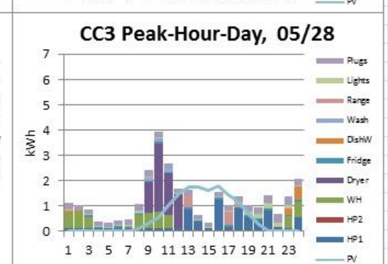


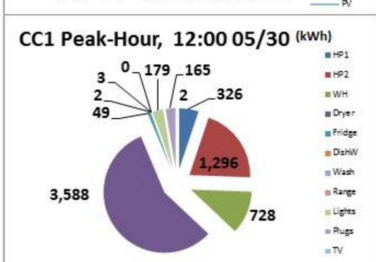


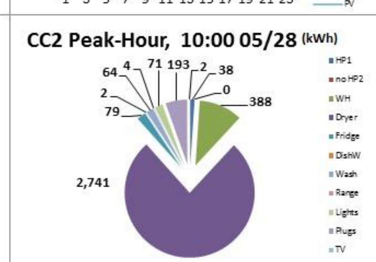


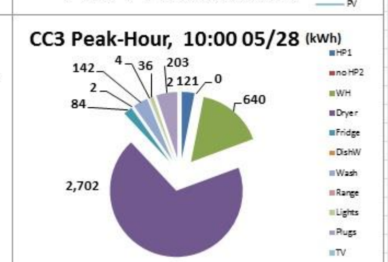


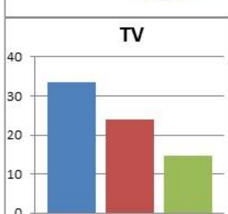


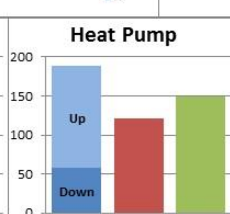


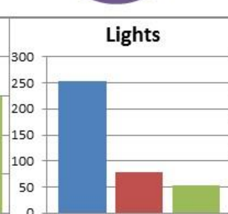


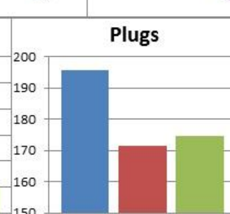


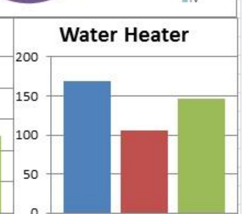


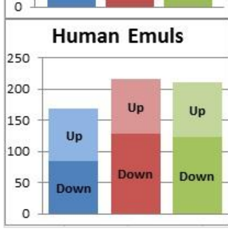


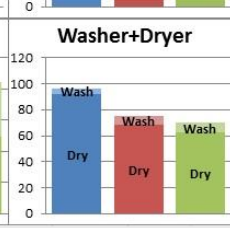


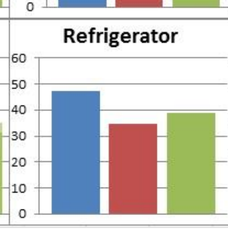


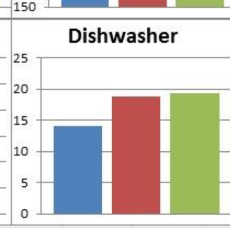


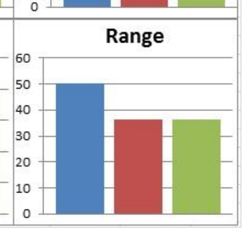






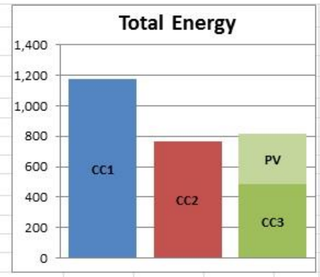






Campbell Creek Research Homes: Dashboard Report					6/1/13	to	6/30/13				
	LCUB Utility Rate: 0.08873		Solar Rate: 0.20873		Monthly Hookup Fee: $13.52						rev. 1
					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	
CC1	1,175		1,175	$117.78	1.63	0.28	6/12	2138	0.912	158.227	
CC2	767		767	$81.58	1.07	0.34	6/12	1833	0.786	112.533	
CC3	814	328.72	485	$17.07	1.13	0.31	6/12	1801	0.769	159.605	
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	6/5	10:00	5.77		100.00%	100.00%	6.4
CC2	65.29%	53.84%	65.29%	69.26%	6/25	9:00	3.11		86.20%	71.12%	CDD@65
CC3	69.26%	63.49%	41.30%	14.50%	6/8	18:00	3.67		84.35%	100.87%	270.5

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.

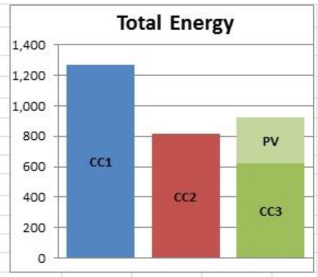


Campbell Creek Research Homes: Dashboard Report 7/1/13 to 7/31/13

LCUB Utility Rate: 0.08755 Solar Rate: 0.20755 Monthly Hookup Fee: $13.52 rev. 2

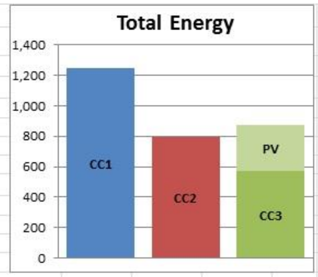
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Daily Average[1]	Load Factor	Peak Day	Water Heater Gallons	MBTUs	kWh/MBTU	
CC1	1,266		1,266	$124.36	1.70	0.31	7/17	2183	0.897	168.602	
CC2	815		815	$84.87	1.10	0.29	7/17	1923	0.776	112.399	
CC3	926	301.14	625	$32.12	1.24	0.30	7/17	1866	0.774	171.963	
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	7/23	9:00	5.53		100.00%	100.00%	3.9
CC2	64.42%	68.80%	64.42%	68.25%	7/2	9:00	3.81		86.55%	66.66%	CDD@65
CC3	73.17%	74.76%	49.38%	25.83%	7/2	9:00	4.14		86.36%	101.99%	301.9

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.



Campbell Creek Research Homes: Dashboard Report					8/1/13	to	8/31/13				
	LCUB Utility Rate: 0.08736		Solar Rate: 0.20736		Monthly Hookup Fee: $13.52					rev. 2	
					Daily	Load	Peak	Water Heater			
House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Average[1]	Factor	Day	Gallons	MBTUs	kWh/MBTU	
CC1	1,248		1,248	$122.55	1.68	0.31	8/6	2104	0.857	179.467	
CC2	796		796	$83.06	1.07	0.25	8/6	1855	0.739	122.639	
CC3	877	308.73	568	$26.06	1.18	0.32	8/13	1785	0.739	176.369	
House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]		MBTUs	kWh/MBTU	HDD@65
CC1	100.00%	100.00%	100.00%	100.00%	8/6	10:00	5.48		100.00%	100.00%	3.4
CC2	63.77%	77.38%	63.77%	67.78%	8/20	9:00	4.24		86.23%	68.34%	CDD@65
CC3	70.24%	68.16%	45.50%	21.27%	8/8	12:00	3.73		86.19%	98.27%	296.3

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3]Cost includes monthly hookup fee and solar credit.



Campbell Creek Research Homes: Dashboard Report 9/1/13 to 9/30/13

LCUB Utility Rate: 0.08469 Solar Rate: 0.2047 Monthly Hookup Fee: $13.52 rev. 5

House	Total[1,2]	PV[1]	Net[1]	Cost[3]	Load Factor	Peak Day	Peak[1]	Average Day[1]	Water Heater Gallons	Water Heater MBTUs		
CC1	1,073		1,073	$104.39	0.27	9/11	50.44	35.76	2109	0.815	145.3	100.0%
CC2	731		731	$75.43	0.20	9/3	34.36	24.35	1737	0.713	178.6	123.0%
CC3	764	318	446	$13.13	0.26	9/3	33.68	25.47	1798	0.693	139.1	95.7%

House	Total	PeakHr	Net	Cost	Peak Hour		Peak[1]	Avg Hour[1]	HDD@65
CC1	100.0%	100.0%	100.0%	100.0%	9:00	9/11	5.47	1.49	43.2
CC2	68.1%	91.7%	68.1%	72.3%	9:00	9/3	5.02	1.01	CDD@65
CC3	71.2%	71.6%	41.6%	12.6%	9:00	9/3	3.92	1.03	181.1

[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load; [3] Cost includes monthly hookup fee and solar credit.