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Tennessee Valley Authority's Campbell Creek Energy Efficient Homes Project: 2010 First Year Performance Report July 1, 2009–August 31, 2010

November 2010

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Energy and Transportation Science Division

TENNESSEE VALLEY AUTHORITY'S CAMPBELL CREEK ENERGY EFFICIENT HOMES PROJECT: 2010 FIRST YEAR PERFORMANCE REPORT JULY 1, 2009–AUGUST 31, 2010

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ACRONYMS

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

EXECUTIVE SUMMARY

The Campbell Creek research project supports the retrofit residential housing goals of the Tennessee Valley Authority (TVA) and the U.S. Department of Energy. Data from the first year of the project, which was initiated by TVA in March 2008, were collected from three houses of similar size, design, and solar and wind exposure, all with simulated occupancy and all located in the Campbell Creek community of Farragut in west Knox County, Tennessee. All of the houses have simulated occupancy—automated mechanisms replicate the occupancy of a family of three, including regularly opening and closing the refrigerator, using the oven, running the clothes dryer, or taking a shower. The three study houses can be characterized as follows.

- The "Builder House" (baseline house, or CC1), representative of a standard, IECC 2006 code-certified, all-electric house built by the builder to sell around 2005–2008.
- The "retrofit house" (or CC2), which included modifications that could be made to existing houses to improve energy efficiency. The data collected from CC2 will be used to evaluate the impact of energy-efficient upgrades to the envelope, mechanical equipment, or demand-response options. Each retrofit will be evaluated incrementally by both short-term measurements and using a calibrated computer model.
- The third house (or CC3) was designed as a transformation of the CC1 (builder house) with the most advanced energy-efficiency features, including solar electricity and hot water, that market conditions are likely to permit within the 2012–2015 period.

This report covers data collected from CC1, CC2, and CC3 during the performance period from July 1, 2009, to August 31, 2010. TVA will use these data to determine the benefits of retrofit packages and high performance new home packages. The data will also help builders and homeowners make smart decisions about products and technologies when retrofitting existing houses and building new high performance houses.

The annual peak loads of conventional all-electric homes with heat pumps occur on very cold winter mornings. The average 1 h peak demand for the CC1 was 14 kW. . As demonstrated by CC2, cost effective 30%–40% whole house energy savings retrofits can cut this peak demand by a third. Well designed, built-new, all-electric homes in the valley can cut this peak in half as shown by CC3. The annual load factor for all three test houses is 0.165. This means that the return on the electric power infrastructure investment for all three homes could be the same. (Annual load factor is defined as the average hourly electric demand for the whole house divided by the peak hourly demand across the entire year.)

In the future customers that will be first to "deep" retrofit or build high performance new homes will also likely have plug-in hybrid electric vehicles (PHEVs). During the 1 year study period, it was shown that at least one PHEV available in 2009 doing a 32-mile round trip commute, 5 days a week, can deliver load factors greater than typical all-electric homes in the TVA region during both peak winter and peak summer months.

As the residential market moves toward much more energy-efficient houses, all-electric homes will gain market share in the TVA region. This market transformation will also result in the electric dryer becoming a much more important contributor toward peak monthly load demand. This study has shown that as houses become more efficient, the dryer tends to dominate the peak load profile not only in the cooling months but also the winter. Heat pump dryers appear to be an attractive technology for TVA to encourage; TVA can use time-of-day pricing to encourage off-peak usage of those appliances. Several heat pump dryers are available internationally; this report recommends one be installed in CC2 or CC3 for the next test period.

Energy costs for CC3, the most energy efficient of the three houses, totaled less than $450 for the entire year, which was a year of temperature extremes for the region. This averages out to about $37 per month for a three-bedroom, two-and-a-half-bath house.

CC2, the retrofit house, demonstrated that good insulation, efficient appliances, and air ducts routed through conditioned space produce very good results for a moderate investment. The incremental costs of the advanced house features making up the retrofit upgrade added about $10,000.

A typical all-electric 2400 ft^2 home built in the 2000–2010 time frame (like CC1) in the TVA service territory, with an average energy usage pattern, has daily energy costs of around $5. Installing a well-integrated energy package in new Tennessee homes can reduce that cost to less than $1/day. The $30,000 incremental cost of the energy package could be financed in a 30-year mortgage (at 5.23%), which would have neutral cash flow (i.e., break even) for the homeowner after TVA, federal, and state incentives are factored in.

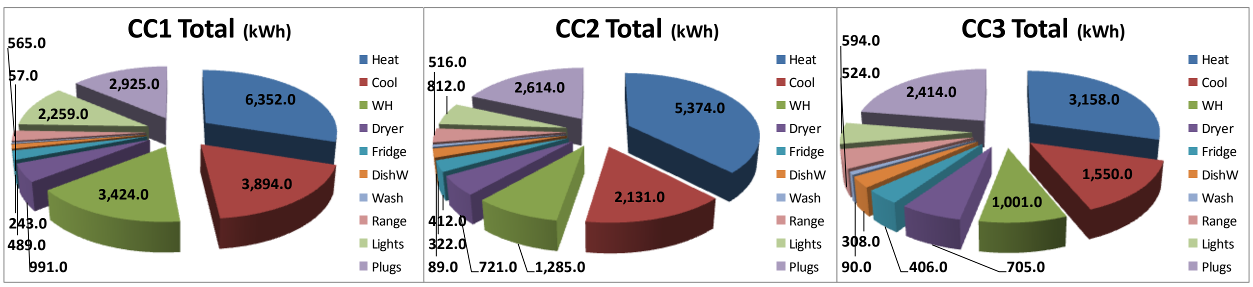


Figure ES.1. CC1, CC2, and CC3 annual energy breakdown, August 2009–July 2010.

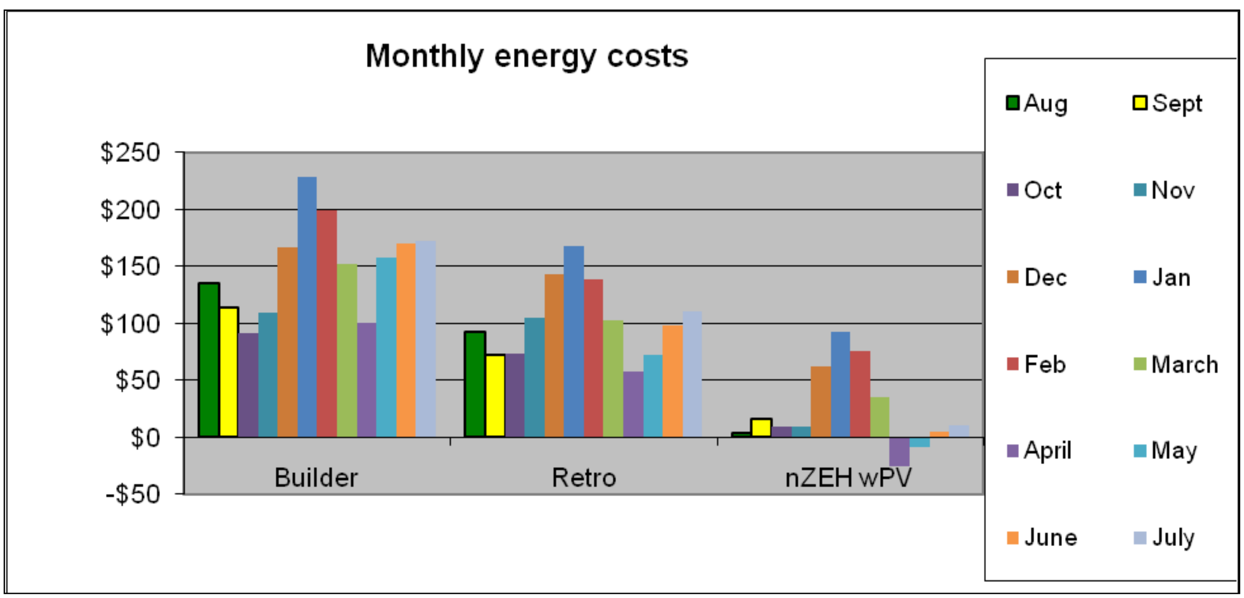


Figure ES.2. Monthly energy cost for each house, August 2009–July 2010 (including Generation Partners credit); nZEH = CC3.

Working with General Electric and statistics showing the average number of clothes washings per week to be 7 loads for our simulated occupancy of three, we determined a hot water savings of 13.4 gal/day in CC2 and CC3 with an Energy Star–rated clothes washer compared to the conventional washer in CC1.

The number of people using hot water for clothes washing today is somewhere between 20% and 50%. Because detergents designed for cold water washing are readily available, plumbing only cold water to the clothes washing machine could result in additional energy savings.

Before determining paybacks of advanced water heating systems, an important variable is calculating hot water usage, which on a national average for an occupancy of three can vary from 66 to 54 gal of hot water per day, depending on clothes washing technology and homeowner operating practices.

The incremental cost of low-emissivity (low-E), gas-filled windows was only $0.85 higher per square foot of window area than "builder installed" regular two pane windows in 2008.

When a thermostat is replaced, the entire heat pump system should be recommissioned to make sure the sequence of operation is optimized for the particular installation. For example, when does the unit go into high-speed indoor fan mode or high-capacity compressor mode or resistance heating? What levels of fresh air are provided at the different modes of operation? Homeowners need information about real energy savings available from proper heat pump thermostat operation in wintertime, setback at night and during hours of no occupancy, and setup during the summer for their specific installations. General rules of thumb are insufficient. This information could be made available by some simple homeowner set of diagnostics that could be run on the thermostat. Real-time heating, ventilation, and air conditioning energy consumption available at the thermostat for both homeowner feedback and equipment adaptive learning would lead to substantial retrofit energy savings.

By far the largest retrofit energy savings found in houses with ducts outside the conditioned envelope are obtained by moving the ducts inside the conditioned space and simultaneously tightening the envelope. Converting the attic to a conditioned mechanical room with spray foam costs around $5–6K. For homeowners in Tennessee's mixed humid climate, finding the optimum installed cost of sufficient foam to avoid moisture problems and the remaining needed R-value of lower cost fiberglass or cellulose is needed.

The solar photovoltaic (PV) system in CC3 was problem free after 2 years of operation. Oak Ridge National Laboratory and TVA have been testing these TVA generation-partner compliant systems since 2002, and all properly installed and commissioned systems were problem free as well.

The solar drain back water heater equipment on CC3 was problem free after the first year of operation. With durability issues still an occasional concern, it was determined to continue testing this equipment for at least another test period.

This report describes a 75% energy savings compared to the Building America (BA) Benchmark. Compared to the benchmark house with a Home Energy Rating System (HERS) score of 136, CC3 has a HERS rating of 34. Without the PV system, CC3 maintains a 65% energy savings over the benchmark. The solar electric fraction for this house was measured at 30%. The cost to build CC3, including all market-valued donations and labor, is $353,570, or $141/ft^2, including the installed cost of the 2.5 kWp solar PV system and solar water heater.

One of the uses of this report is to aid builders and homeowners in making the "right" decisions in building a high performance house. The detailed drawings, specifications, and lessons learned from the construction process are presented, as well as the results of the analysis of the 121 sensors monitoring the performance of CC3. This information is specifically helpful for those considering 2 × 6 optimum-value framing, solar water heating, and solar PV systems. The 90 sensors in CC2 have also provided useful information for those designing deep energy-efficiency retrofits for their homes.

The precommercial heat pump water heater in CC2 was taken out of service and replaced on March 22, 2010, with a commercial unit with a more efficient compressor; this resulted in higher field performance coefficient of performance (COP) than the precommercial prototype we had been testing at about 2.2 compared to about 2.4.

In January 2010, CC1's two heat pumps made up the largest fraction of energy usage, 66% of the total, or 1998 kWh. The resistance backup heaters accounted for 43% of the space heating energy or 862 kWh; the resistance heaters accounted for 28% of the whole house energy demand. In February, the two heat pumps used a total of 1608 kWh; the resistance backup heaters, 438 kWh or 27%; and the resistance heaters, 16% of the whole house energy demand.

In CC2 in January 2010, the single-heat-pump two-zoned system accounted for the largest fraction of energy used, 65% of the total, or 1486 kWh; the resistance backup heaters required 41%, or 615 kWh, of the space heating energy; and the resistance heaters required 27% of the whole house energy demand in January 2010. In February, the single heat pump required 1216 kWh; the resistance backup heaters required 394 kWh or 32% of the space heating energy; and the resistance heaters required 21% of the whole house energy demand. It was discovered after the first year of operation that the 3-ton Amana heat pump that was specified to be a two-speed capacity compressor system was only a single speed. The indoor fan, which had an electronically commutated motor, always delivered the same cubic feet per minute of indoor air even when one of the zones was not calling for conditioning. This error resulted in a larger indoor fan power consumption in CC2 than necessary, which would have been avoided if the two speed compressor machine had been installed as specified.

In January 2010, CC3's 2-ton heat pump used the largest fraction of energy, 88%, or 1089 kWh. The resistance backup heaters required 455 kWh, or 42%, of the space heating energy. In February, the single heat pump accounted for a total of 809 kWh. The resistance backup heaters required 234 kWh or 29% of the space heating energy. These resistance heat fractions were larger than they would have been if the 2-ton heat pump compressor had been allowed to go into the high-capacity mode. A thermostat change-out to provide remote control prevented the unit from optimum performance for most of the 2009–2010 winter.

An analysis of the CC3 heat pump demand finds that the heating balance point is 54°F. In general, the house needs no heating until the outdoor temperature is 17°F below the thermostat setting of 71°F. The balance point found for CC2 was 61°F.

CC1's heating season months from October through April cost $713, compared to CC3's net cost of $219 (an energy cost savings of 69%). The costs are based on the Lenoir City Utility Board's actual monthly residential rates.

For CC3, the AC solar generation from the 2.5 kW_p solar system generated 9 kWh/day for the test period. The energy cost savings from the builder to CC3 is $844 due to energy efficiency and $666 from the solar credits.

TVA hit an all-time daily-energy-generation record on January 8, 2009: 701,387 MWh. The average daily use per hour for the day was 29,224 MWh. On January 8, CC1 used 152 kWh; CC2, 113 kWh; and CC3, 76 kWh. The peak hour for CC1 and CC2 was 7:00 to 8:00 AM. The peak on January 8 for CC1 was 11 kWh; CC2, 8.64 kWh; and CC3, 7.42 kWh.

CC2 and CC3 will continue to have different retrofits until 2012 to get ever closer to maximum affordable energy efficiency in the TVA mixed humid climate.

In Tennessee, a homeowner can install a cost-effective retrofit package for a typical new home like CC1 (3 bedroom, 2.5 bath, 2400 ft^2) that has a predicted 42% energy savings and achieves neutral cash flow based on electricity rates of $0.093/kWh, a 10-year mortgage at 6% interest, and available 2010 federal, state, and utility incentives.

Based on measured data from almost 100 sensors and a computer simulation of the CC2 with typical occupancy patterns and energy services for three occupants, energy for this all-electric house is predicted to cost only $3.76/day. By contrast, CC1 would require $6.46/day. Based on a full year of measured data with the houses operated under simulated occupancy, CC2 used an average of 39.5 kWh/day. The $10,000 incremental cost of the retrofit package described in this report, assuming that windows, heat pump, water heater, and major appliances must be replaced and this replacement cost is not considered in the cash flow analysis, has a positive cash flow to the homeowner. With the base house being an average new home built in 2008 and local electricity rates more than $0.02/kWh lower than the national average, the 42% whole house savings should be exceeded in most other homes originally built before 1990 with a more positive cash flow.

This report describes a cost-effective retrofit package for a typical new home that has a predicted 42% energy savings and achieves neutral cash flow based on electricity rates of $0.093/kWh, a 10-year mortgage at 6% interest, and available federal, Tennessee state, and utility incentives in 2010. This three-bedroom two-and-a-half-bath, 2400-ft^2 house has a HERS rating of 68 after retrofit and 101 before retrofit.

1. PROJECT OVERVIEW

1.1 BACKGROUND

This research project was initiated by TVA in March 2008 and encompasses three houses that are of similar size, design and located within the same community—Campbell Creek, Farragut TN—with simulated occupancy. Situated in a valley in west Knox County, these Houses are a typical example of the developments in the TVA service territory. The design is a prime example of a marketable house in the area based on the sales of other homes of similar size and design. The southern orientation of the house is ideal for providing natural day lighting and minimizing harsh direct sunlight in the east and west, where canopies are not as effective as on southern exposures. This report covers the performance period from July 1, 2009, to August 31, 2010. It is the intent of TVA that this "Valley Data" will inform electric utilities future residential retrofit incentive program.

The first house is the "builder house" (baseline house), which is a standard all-electric house as would be built in 2005–2008 as a "builder spec." This house is identified by "CC1" in this document.

The second house is the "retrofit house," which used modifications that could be made to existing houses to improve the performance. The data collected from CC2 will be used to evaluate the impact of energy efficient upgrades to the envelope, mechanical equipment, or demand response options. Each retrofit will be evaluated incrementally by both short term measurements and computer modeling using a calibrated model. This house will be designated by "CC2."

The third house was designed to take the "builder house" and transform it to maximum energy efficiency as market conditions are likely to permit within the 2012–2015 time period. This house is referred to throughout this report as "CC3."

The energy data collected will be used to determine the benefits of retrofit packages and high performance new home packages. There are over 300 channels of continuous energy performance and thermal comfort data collection in the houses. (100 for each house)

This Research Supports TVA and DOE's Retrofit Residential Housing Goals

DOE Building Technologies Program strategic goal is to create technologies and design approaches that lead to maximum affordable energy efficient homes by 2020. These future houses are expected to have efficiency gains of 60%–70% with the balance supplied by renewable technologies. This research project supports the national goals of energy efficiency retrofits on existing homes. The 2010 DOE retrofit goals are to find retrofit packages that attain 30% whole house energy savings as documented by pre and post HERS evaluations or equivalent.

HERS Index

HERS Index is a rating system based on the International Energy Conservation Code (IECC) for houses. This is similar to a fuel mileage rating for a car.

A HERS rating of 100 is close to a new home meeting the 2006 International Energy Conservation Code. A HERS Index of 0 is a house that produces as much energy as it uses annually. Each of these houses has a HERS rating as outlined below. Part of the evaluation includes a blower door test—rated in air-changes-per hour (ACH) at 50 Pascal differential pressures. HERS ratings for the three houses are CC1, 101; CC2, 68; and CC3, 34.

1.2 ENVELOPE AND TECHNOLOGY SUMMARY

1.2.1 CC1 ("builder house"; same as third-party-certified model house built and audited in 2008 in the subdivision)

- This house has the "all-electric" upgrade. This entails heat pump servicing the main level instead of gas furnace and air-conditioner
- Two SEER 13 single speed heat pumps with a total capacity of 4.0 tons (upstairs capacity = 2.5 tons, downstairs capacity = 1.5 tons)
- Slab construction—with 1 in. × 24 in. perimeter XPS horizontal insulation except for along the garage wall
- Blower Door 5.7 ACH at 50 Pascal
- HERS index equals 101

1.2.2 CC2 ("retrofit house")

Envelope

- Slab construction—with 1 in. × 24 in. perimeter XPS horizontal insulation except for along the garage wall
- High performance windows U-value of 0.34 and SHGF of 0.33
- Sealed and insulated Attic with spray foam and sprayed fiberglass (attic space within the insulation and air barrier layer)
- Backing and sealing the insulated knee walls in the bonus room
- Blower Door 3.4 ACH at 50 Pascal
- HERS index equals 68

HVAC

- One 3 ton SEER 16 heat pump with two speed high-efficiency (ECM) indoor fan motor, single capacity compressor and 2 zone dampers one responding to the thermostat on the first floor the other for the second floor.
- Automated whole house mechanical balanced ventilation with synchronized bath exhaust to meet ASHRAE 62.2 standards.
- Ducts 100% inside the conditioned space.

Electrical

- Energy efficient lights, 100% fluorescent
- Energy Star appliances

Plumbing

- 50 gal heat pump water heater including a heat trap

1.2.3 CC3

Envelope

- 2 X 6 advanced framing air tight construction using flash (foam) and Spider sprayed (fiberglass with adhesive) and structural insulating sheathing with taped seams. This wall is 2 in. thicker than those in CC1 and CC2 with twice the R value!

- High performance triple pane windows U-value of 0.15 and SHGF of 0.26,
- Slab perimeter vertical insulated with 2 in. XPS foam, R-10
- R-50 spray fiberglass ceiling insulation (conventional vented attic) and radiant barrier on underside of roof deck.
- Blower Door 2.4 ACH at 50 Pascal
- HERS index equals 34.

HVAC

- Single HVAC system (2 ton) SEER 16 heat pump with ECM fan motor and two speed compressor. System has zone dampers serving both floors.
- Ducts and indoor coil inside the conditioned space
- Jump ducts installed from each bedroom to central hall where the central upstairs return register is located.
- Mechanical ventilation with an Energy Recovery Ventilator exhausting three baths, laundry and kitchen, and supplying the three bedrooms and great room upstairs and the living room and dining room downstairs.

Electrical and Appliances

- Electric circuit kill switches are located at room exits, servicing power to the entertainment system in the great room and home office in the bonus room
- Energy Star, energy efficient lighting fixtures with 100% fluorescent.
- Energy Star GE appliances
- Solar Photovoltaic—2.5 kW_{peak} installed on south facing roof. The system is grid connected through TVA's Green Power Switch Generation Partners program.

Plumbing

- Drain back solar domestic water heating system with 85 gal storage tank
- PEX (cross-linked polyethylene) homerun plumbing
- Grey water (waste water from non-plumbing systems like washing machines, showers, and baths) plumbing separate from black water (water contaminated with toilet waste) coming from the second floor[*]
- Waste heat recovery piping run from the refrigerator, dishwasher and dryer duct[*]

1.3 OCCUPANCY SIMULATION OVERVIEW

Two computer systems work together at the Campbell Creek research houses to simulate occupancy. All three houses have the same capabilities and the goal is to have the simulations run simultaneously in all three houses. A LabVIEW® controlled occupancy simulation system opens and closes the refrigerator and freezer doors, starts clothes washer cycle, mists clothes in dryer and starts dryer cycle, turns on and off the shower, dishwasher, and range. A custom Simple Control (http://www.simplecontrol.com/) system turns on and off lights, plug loads (miscellaneous sensible loads in the house that are not otherwise simulated), and the sensible heat from occupants.

An ftp server run from CC1 serves both the LabVIEW® and Simple Control system with schedules every night. This feature makes it very simple to populate both systems in all three houses with a new schedule.

[*]Not installed in first year of evaluation.

An alarm system was set up in March 2010; this system sends emails to ORNL researchers if values from the data are out of expected defined ranges. This has reduced the amount of lost data enormously. Most of the faults are a result of lights not turning on or off as programmed. Compared to occupant differences in real houses these faults are trivial in the big picture of comparing three houses to each other and having to account for occupant variations.

1.4 DASHBOARDS

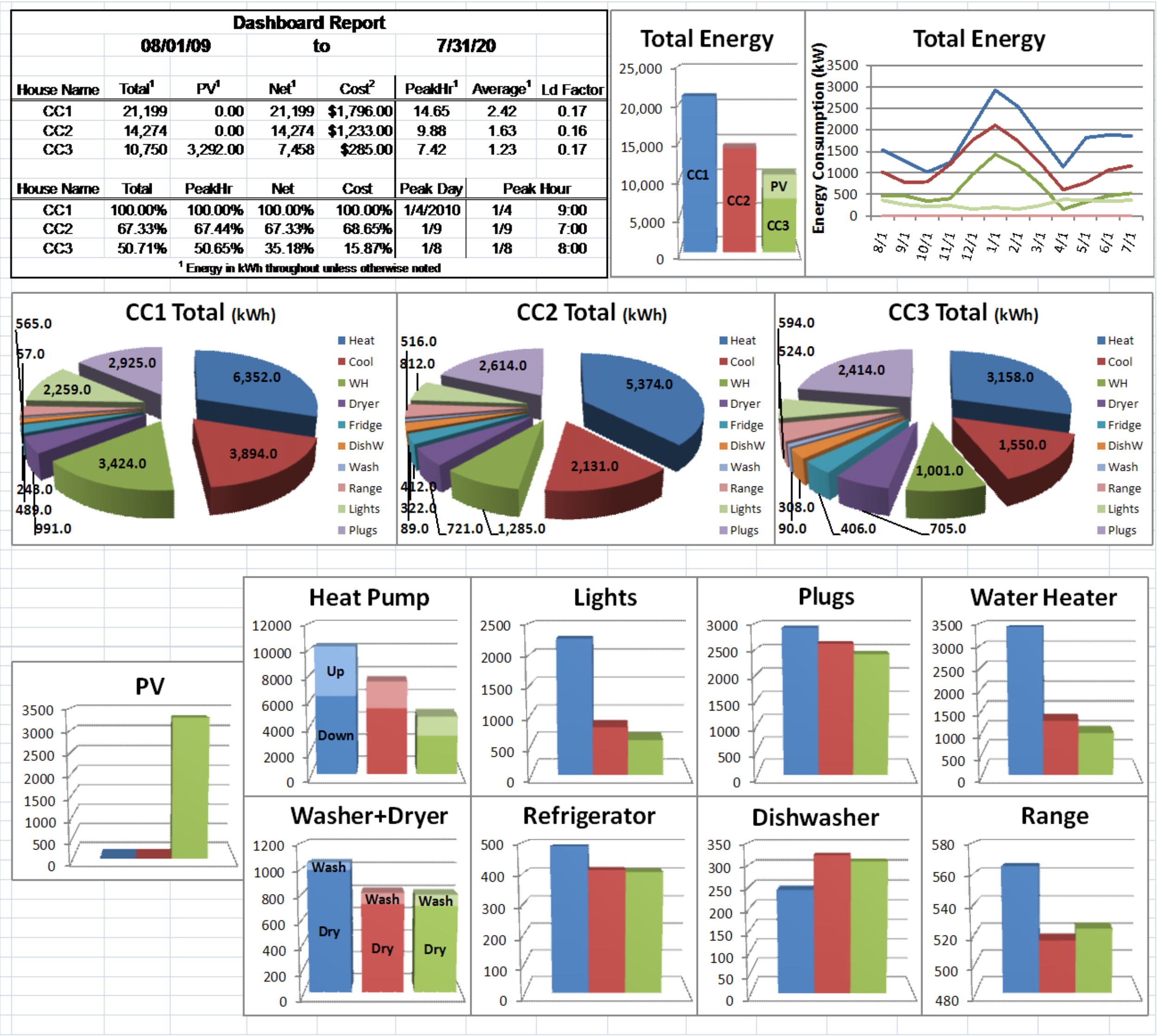
1.4.1 Full Year with Cleaned Up Raw Data

Figure 1 shows the dashboard for a full year of performance from August 1, 2009, until July 31, 2010. The annual energy savings of CC2 compared to the Builder is 33%. The CC3 net energy savings compared to Builder using the actual consumption is 65%. The peak hourly demand occurred during a cold snap in January 2010. CC2 had a 33% lower absolute peak and CC3 had a 49% lower peak. The load factors for the entire year are about the same 0.17. The pie charts in Figure 1 show the full year energy demands for all the loads in each of the houses. Bar charts are provided to quickly compare energy uses in all three houses of the heat pumps, lights, plug loads, water heating, washer/dryer combo, refrigerator, dishwasher and the range. In the bar chart labeled Heat Pump, “up” is referring to upstairs unit in the attic and “down” is the unit servicing the main level with the indoor coil located in the garage.

Table 1 shows the actual monthly residential rates at the time these measurements were made and used to generate the costs shown in Figure 1 and the monthly dashboards presented in this report. The monthly cost also take into account a hook up fee of $7.25 per month.

This data comes from correcting the raw monthly data bases to reflect identified simulated occupancy control and measurement problems identified throughout the testing period. There were considerably less problems later in the year, once an alarm system was set up to quickly identify data interruptions caused by events such as power outages and delayed controller restarts. The monthly heat pump, PV, water heater, lights, and plug loads for all three houses are shown in Table 2. Values shown in red are monthly kilowatt-hours adjusted due to various identified issues described in Sect. 3, Energy Use Breakdowns, for each month.

The last row in Table 2 shows the annual percentage energy savings with reference to CC1 of each major energy user. The heat pump in CC2 used 27% less energy than CC1 over the entire one year period. The CC3 heat pump used 54% less than CC1. The energy savings for water heating reflect not only the more efficient heat pump water heater in CC2 and the solar water heater in CC3, they also reflect the measured reduction of 14 gal less of hot water needed to wash clothes and dishes with the Energy Star appliances in CC2 and CC3 that are not in CC1. The more efficient lighting in CC2 and CC3 saved 64% and 74% respectively compared to the 100% incandescent lighting installed by the builder in CC1. The plug load differences reflect the energy needed to run the CC1 master bath exhaust fan 24/7 for ventilation compared to the master bath fan in CC2, which runs a bit less often compared to no fan energy in the plug load for CC3. The ERV fans, that take care of ventilation air in CC3 is included in the HP column.



Dashboard Report							
	08/01/09		to		7/31/20		
House Name	Total[1]	PV[1]	Net[1]	Cost[2]	PeakHr[1]	Average[1]	Ld Factor
CC1	21,199	0.00	21,199	$1,796.00	14.65	2.42	0.17
CC2	14,274	0.00	14,274	$1,233.00	9.88	1.63	0.16
CC3	10,750	3,292.00	7,458	$285.00	7.42	1.23	0.17
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour	
CC1	100.00%	100.00%	100.00%	100.00%	1/4/2010	1/4	9:00
CC2	67.33%	67.44%	67.33%	68.65%	1/9	1/9	7:00
CC3	50.71%	50.65%	35.18%	15.87%	1/8	1/8	8:00

[1] Energy in kWh throughout unless otherwise noted

Figure 1. Dashboard for a full year from August 1, 2009, until July 31, 2010; blue bar = CC1, red = CC2, and green = CC3, units are kWh unless noted otherwise.

Table 1. Actual monthly residential rates

Month	Rate ($/kWh)
January 09	0.0921
February	0.0921
March	0.0921
April	0.08665
May	0.08665
June	0.08665
July	0.08366
August	0.08366
September	0.08366
October	0.08187
November	0.08083
December	0.07713
January 10	0.07569
February 10	0.07504
March 10	0.07828
April 10	0.08205
May 10	0.08270
June 10	0.08616
July 10	0.08831

Table 2. Monthly kWh for the heat pumps, PV in CC3, water heating, lights, and plug loads

	Heat pump			PV	Water heater			Lights			Plugs		
	CC1	CC2	CC3	CC3	CC1	CC2	CC3	CC1	CC2	CC3	CC1	CC2	CC3
9-Aug	669	479	354	360	207	57	24	202	69	48	261	251	252
9-Sep	437	241	216	253	200	58	105	202	69	48	257	249	262
9-Oct	152	206	46	221	238	129	85	202	69	48	252	241	235
9-Nov	404	616	150	251	252	129	73	163	66	49	243	211	209
9-Dec	1182	1136	644	156	286	161	117	160	74	53	240	215	117
10-Jan	1999	1486	1099	194	333	170	157	162	67	59	236	215	128
10-Feb	1608	1216	809	167	331	120	136	171	59	46	259	190	187
10-Mar	812	630	358	242	391	129	178	202	66	51	243	211	209
10-Apr	196	84	53	380	324	94	57	193	64	46	232	208	215
10-May	864	233	197	360	307	85	52	207	70	49	236	213	208
10-Jun	982	533	357	353	281	77	39	191	69	48	230	203	194
10-Jul	942	645	425	356	273	77	31	205	69	48	237	206	200
Sum	10245	7505	4708	3292	3424	1285	1054	2259	812	594	2925	2614	2414
%savings		26.8%	54.0%			62.5%	69.2%		64.1%	73.7%		10.6%	17.5%

The last row in Table 3 shows the annual percentage energy savings resulting from refrigerator, dishwasher range, clothes washer and dryer in CC2 and CC3 compared to the builder spec models in CC1. The refrigerator in CC2 and CC3 use about 16% less energy than the refrigerator in CC1 over the one year period. The Energy Star dishwasher in CC2 and CC3 saves most of its energy by using less hot water, which is not reflected in the fact that those units with the same washing load consume about 30%

Table 3. Monthly kilowatt-hour loads for the refrigerator, dishwasher, range, and clothes washer and dryer in all three houses

	Refrigerator			Dishwasher			Range			Washer			Dryer		
	CC1	CC2	CC3	CC1	CC2	CC3	CC1	CC2	CC3	CC1	CC2	CC3	CC1	CC2	CC3
9-Aug	51	42	40	19	26	23	48	45	45	5	8	8	66	40	40
9-Sep	47	38	34	19	26	20	48	42	45	5	8	7	60	40	40
9-Oct	42	33	35	19	27	27	48	45	45	5	8	8	69	43	43
9-Nov	39	30	32	20	28	27	44	42	41	4	7	7	87	72	65
9-Dec	38	31	32	22	29	29	48	45	45	4	6	6	87	72	66
10-Jan	36	30	32	23	28	29	49	45	45	4	8	9	87	72	66
10-Feb	33	29	29	22	24	27	43	41	41	5	7	7	83	65	61
10-Mar	33	31	31	24	29	27	49	47	44	5	8	7	91	67	68
10-Apr	35	33	33	19	27	25	47	40	40	5	7	7	85	62	58
10-May	43	37	35	19	26	26	48	45	45	5	8	8	97	62	70
10-Jun	45	39	36	19	26	25	46	45	45	5	7	8	85	62	62
10-Jul	46	39	37	19	26	25	47	36	41	5	8	8	94	65	65
Sum	489	412	406	243	322	308	565	516	524	57	89	90	991	721	705
%savings		15.8	17.1		-32.5	-26.6		8.6	7.2		-56.1	-58.0		27.2	28.8

more kWh operating energy than the builder spec model in CC1. The electric ranges in CC2 and CC3 use the smaller of the two ovens available in the installed models, which lead to about an 8% electric energy savings compared to the single larger oven in CC1 under the same simulated cooking load in all three houses. The Energy Star washer with a much higher revolutions per minute in the dry cycle uses a bit more energy than the conventional clothes washer. The big savings is in the amount of hot water savings needed and the fact that the higher spin rate forces more of the water out of the washed clothes, which results in dryer energy savings. The Energy Star washer and dryer combination in CC2 and CC3 saves 24% electric energy compared to the builder spec models in CC1. The actual hot water savings show up in the water heating columns in Table 2. Hot water is used to wash all the clothes in these houses. The base hot water demand scheduled in CC1 is 66 gal/day. The measured hot water savings from the Energy Star dishwasher and clothes washer and dryer lead to a demand of 54 gal/day.

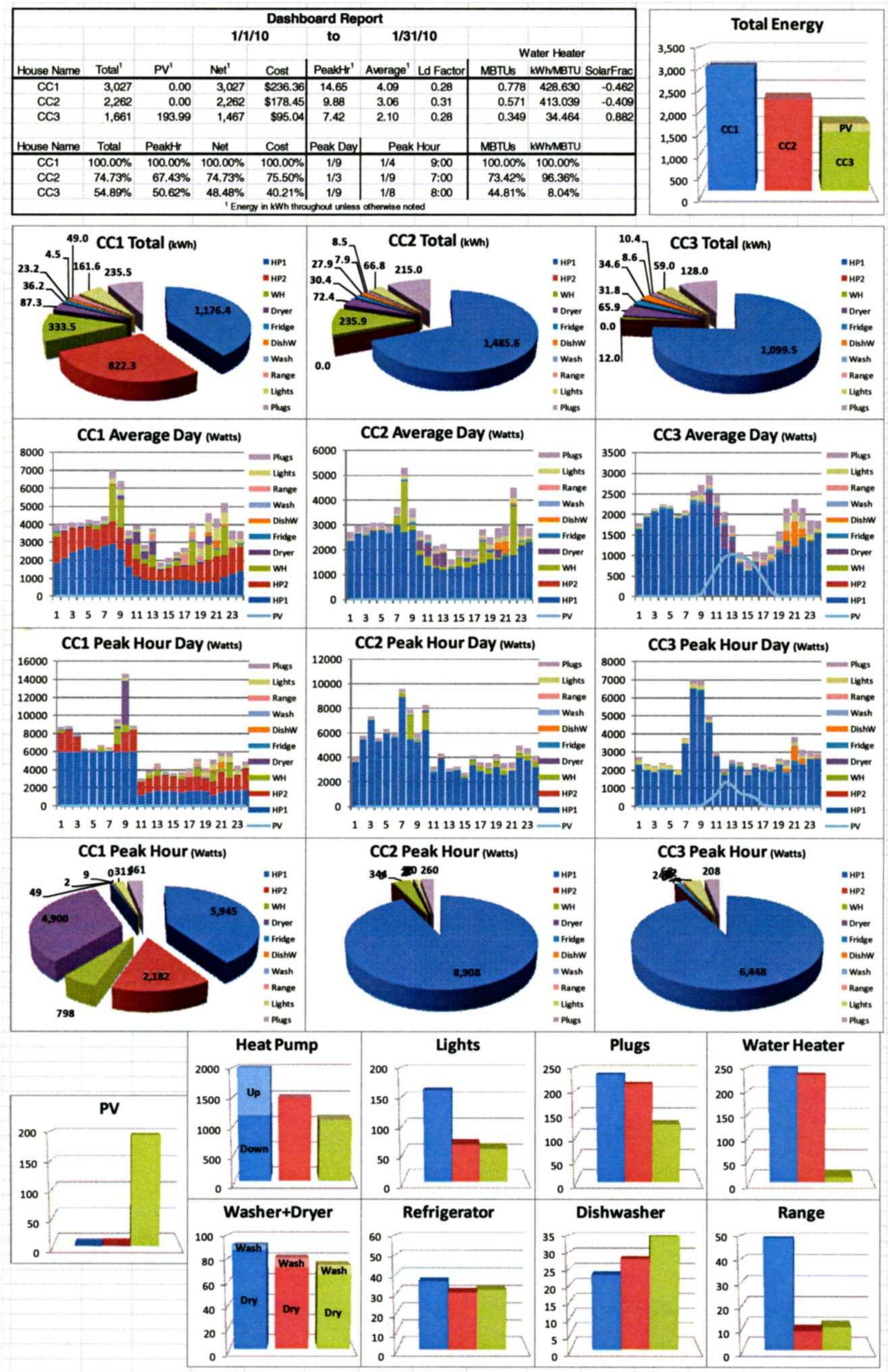
Table 4 is the sum of the sub metered data shown in Tables 2 and 3. With all the known raw data cleansing the annual whole house energy savings of CC2 compared to CC1 is 33%. The energy savings after accounting for the onsite solar PV generation results in an annual whole house savings of 65%. The 2.5 kW_{peak} solar PV fraction is about 31% of the total kWh usage of CC3.

Table 4. Monthly kilowatt-hour totals from August 2009 until July 2010

	Total		
	CC1	**CC2**	**CC3**
9-Aug	1528	1016	474
9-Sep	1275	770	526
9-Oct	1027	802	351
9-Nov	1256	1201	402
9-Dec	2065	1768	952
10-Jan	2929	2121	1430
10-Feb	2554	1749	1175
10-Mar	1850	1219	731
10-Apr	1137	620	156
10-May	1826	779	331
10-Jun	1884	1059	461
10-Jul	1866	1170	522
Sum	21197	14274	7511
%savings		32.7	64.6

1.4.2 Monthly Dashboards

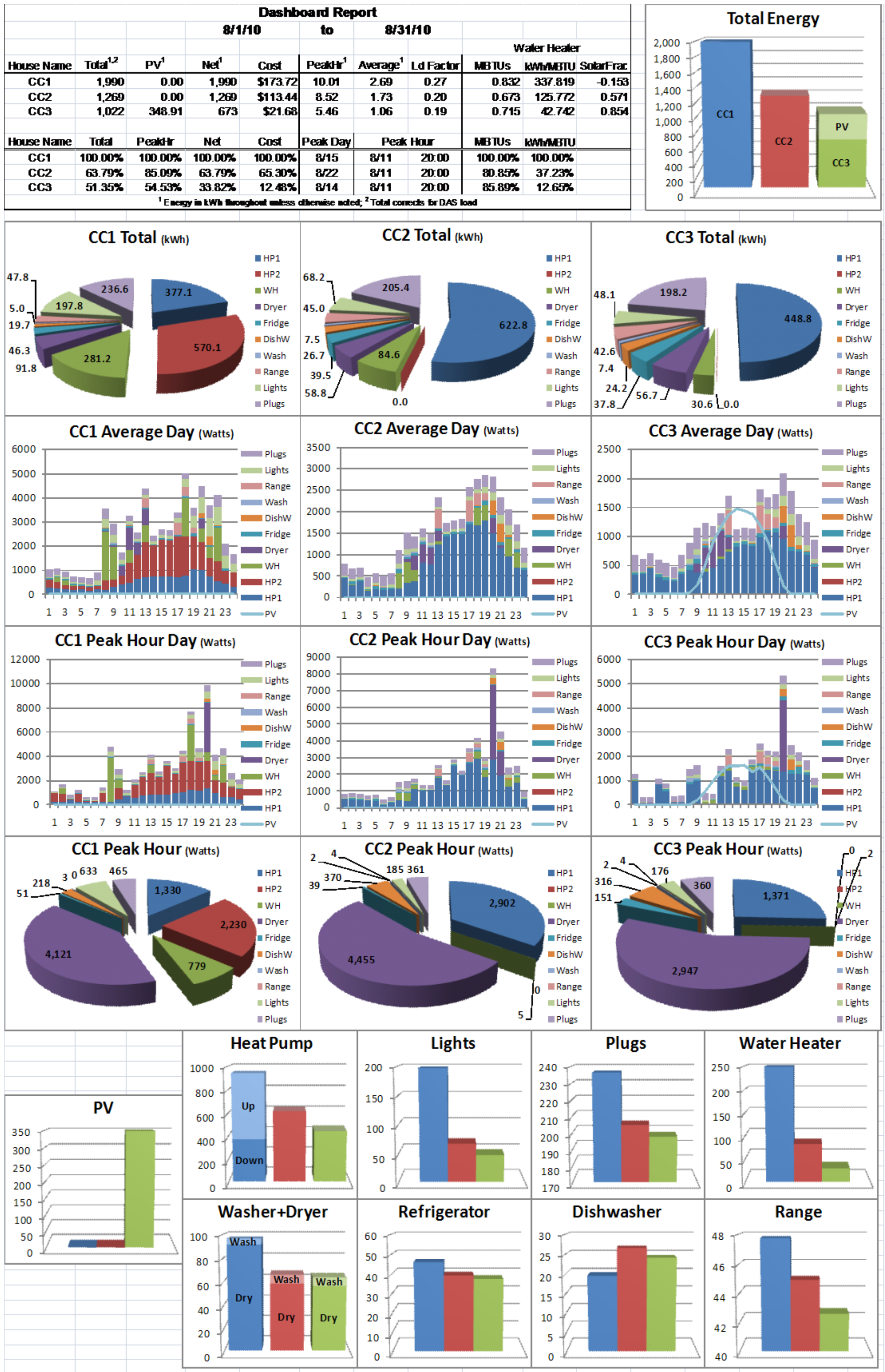
Figure 2 shows the monthly Dashboard for January 2010, the coldest Month of the test period. This display is used to help maintain a high quality data collection system in all three test houses. The most important information from the three house comparison can be ascertained in a quick scan of this one page concentration of performance data. Figure 3 shows the dashboard for August 2010 the hottest month of the data collection period. The full set of Dashboards from July 2009—August 2010 are displayed in Appendix A.



Dashboard Report										
			1/1/10		to	1/31/10				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	3,027	0.00	3,027	$236.36	14.65	4.09	0.28	0.778	428.630	-0.462
CC2	2,262	0.00	2,262	$178.45	9.88	3.06	0.31	0.571	413.039	-0.409
CC3	1,661	193.99	1,467	$95.04	7.42	2.10	0.28	0.349	34.464	0.882
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	1/9	1/4	9:00	100.00%	100.00%	
CC2	74.73%	67.43%	74.73%	75.50%	1/3	1/9	7:00	73.42%	96.36%	
CC3	54.89%	50.62%	48.48%	40.21%	1/9	1/8	8:00	44.81%	8.04%	

[1] Energy in kWh throughout unless otherwise noted

Figure 2. January 2010 dashboard; blue bar = CC1, red = CC2, and green = CC3; units are kWh .



Dashboard Report

8/1/10 to 8/31/10

House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	1,990	0.00	1,990	$173.72	10.01	2.69	0.27	0.832	337.819	-0.153
CC2	1,269	0.00	1,269	$113.44	8.52	1.73	0.20	0.673	125.772	0.571
CC3	1,022	348.91	673	$21.68	5.46	1.06	0.19	0.715	42.742	0.854

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	8/15	8/11	20:00	100.00%	100.00%
CC2	63.79%	85.09%	63.79%	65.30%	8/22	8/11	20:00	80.85%	37.23%
CC3	51.35%	54.53%	33.82%	12.48%	8/14	8/11	20:00	85.89%	12.65%

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

Figure 3. August 2010 Dashboard; blue bar = CC1, red = CC2, and green = CC3; units are kWh .

2. OVERALL PERFORMANCE OF HOUSES FROM OCTOBER 1, 2009, TO APRIL 30, 2010

2.1 ENERGY USE FROM CLEANED UP RAW DATA SETS

The weather for July 2009 through July 2010 was normal for the total heating season but considerably warmer than normal for the cooling season, by Table 5. The test period had 36% more cooling degree days (CDDs) at 65°F than long term normal. July and August 2010 had 45% more CDDs than July and August 2009.

Table 5. Heating degree days (HDDs) at 65°F and departure from normal

	HDDs at 65°F	Normal HDDs at 65°F	Departure from Normal	Cooling degree days (CDDs) at 65°F	Normal CDDs at 65°F	Departure from normal
July 2009	0	0	0	318	380	-62
August 2009	0	0	0	361	347	+14
September 2009	14	30	-16	223	180	+43
October 2009	261	230	+31	8	23	-15
November 2009	475	518	-43	0	1	-1
December 2009	767	787	-20	0	0	
January 2010	948	882	+66	0	0	
February 2010	839	696	+143	0	0	
March 2010	520	510	+10	0	2	-2
April 2010	128	254	-126	43	19	+24
May 2010	25	80	-55	195	95	+100
June 2010	0	6	-6	435	254	+181
July 2010	0	0	0	501	380	+121
August 2010		0		481	347	
Sum Sept 09–August 10	3977	3993	+16	1929	1301	+465

The whole house energy usage for each house is shown in Figure 4. CC3 is shown without and with the solar PV system. The pre-commercial HPWH in CC2 was taken out of service and replaced on March 22, 2010, with a commercial unit, which has a more efficient compressor and has resulted in higher field performance COP than the pre-commercial prototype, which had been installed in CC2, 2.4 compared to 2.2. This chart uses the values shown in Tables 2–4 above.

Figure 5 shows a pie chart of the pieces that make up the total annual kWh used in CC1, CC2, and CC3. In CC1, the space heating load makes up the largest fraction of energy usage, 30% of the total. The cooling load 18% and water heating energy required 16% of the total. The annual plug loads represent 14% followed closely by the lights representing 11%. In CC2, heating is the largest piece at 38%, followed by plug loads, 18%, then cooling, 15%, water heating 9%, lights, 6% and the dryer, 5%. In CC3, heating also is the largest piece at 29%, plug loads 22%; cooling 14%, water heating 9%, and the electric dryer 7%.

2.2 ENERGY COSTS

The monthly energy costs for each house are shown in Figure 6. All three houses have simulated occupancy energy demands embedded in the costs as well as exterior lighting. The energy to run the

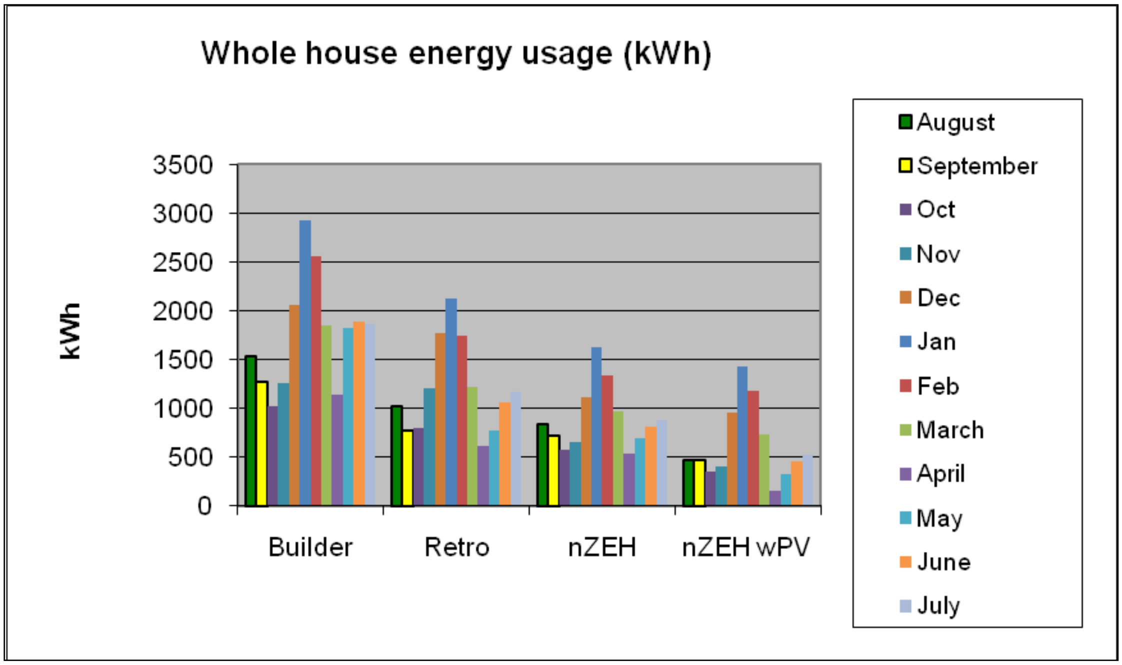


Figure 4. **Whole house monthly kilowatt-hour comparisons from August 2009 through July 2010 (*nZEH = CC3).***

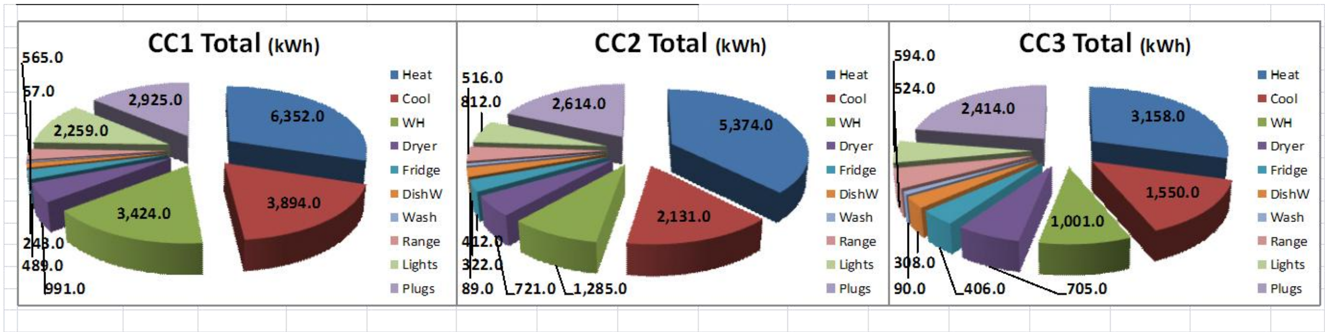


Figure 5. CC1, CC2, and CC3 annual energy breakdown from August 2009 to July 2010.

compressors located in each garage to power the pneumatic refrigerator and freezer door openers are not included in the energy costs. The costs shown are based on the LCUB actual monthly residential rates shown in Table 1. The full year energy cost for CC1 was $1800 compared to the net cost for CC3 of $300. The annual energy cost for CC2 was $1200, which is a 33% whole house energy cost savings compared to the builder.

2.3 SOLAR AND GENERATION PARTNER CREDIT

The AC Solar generation from the 2.5 kW_{peak} solar system on CC3 generated 9 kWh/day average for this one complete year test period. The total annual energy cost savings from the builder to the CC3 is $1510; $844 (or 56%) of the savings are due to energy efficiency and $666 (or 44%) from the solar credits. Figure 7 shows that an average 274 kWh/month was generated from the PV system. Figure 8 show that this solar energy production yields an average $55 monthly solar credit. This is an average daily solar credit of $1.82.

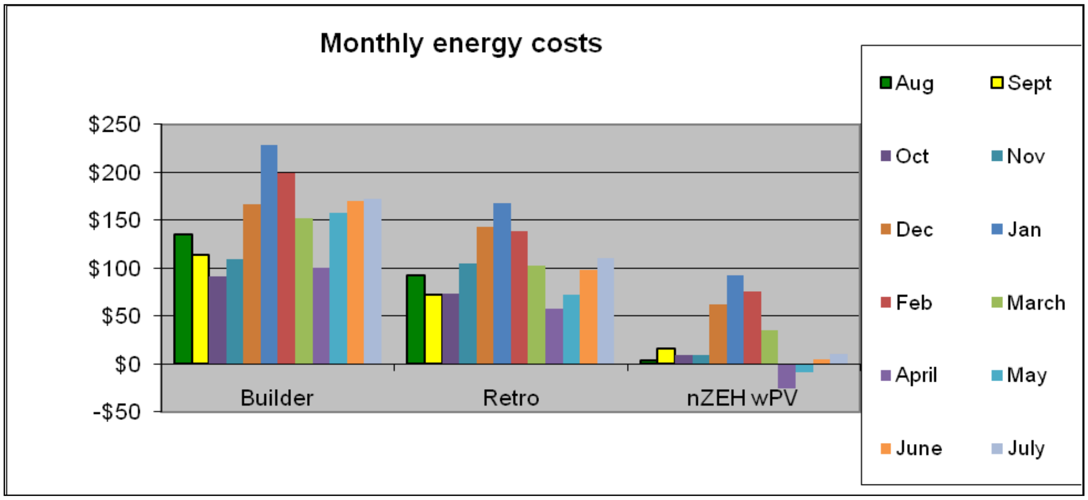


Figure 6. Monthly energy cost for each house, August 2009–July 2010 (including Generation Partners credit); *nZEH = CC3*.

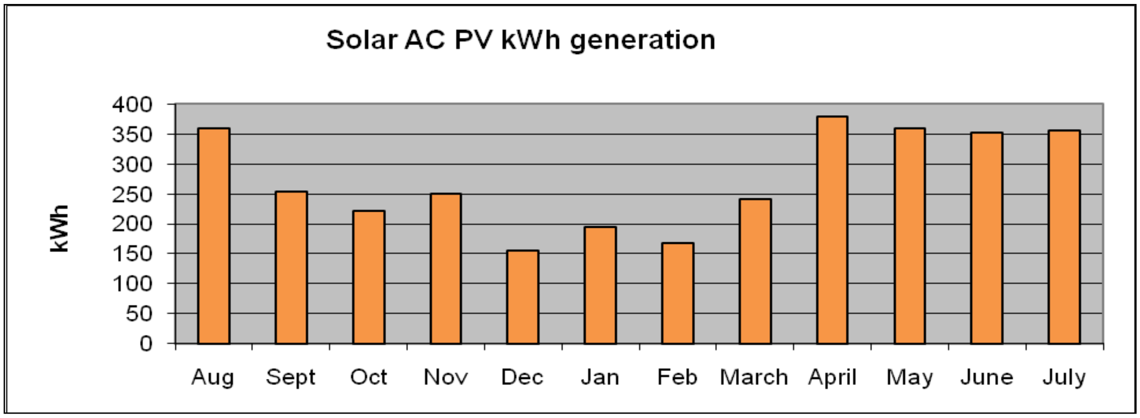


Figure 7. Solar generation under TVA's Generation Partners, from August 2009 until July 2010.

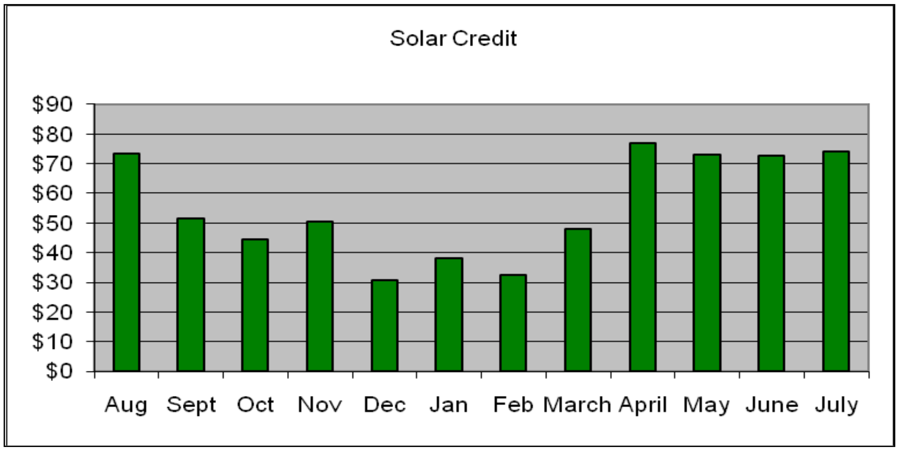


Figure 8. Monthly generation partner credit for AC solar generation in CC3, from August 2009 until July 2010.

2.4 PEAK DEMAND PROFILES

Monitoring data is scanned continuously and integrated into 15 minute intervals. The energy sub metering is collecting watt-hours. By summing the four 15 minute intervals the average wattage for that hour is what is used to identify the peak wattage each month. The 24- hourly demand for the day in which this peak hour occurs during January, February, March and July 2010 are shown in Figures 9 and 12. The houses may peak at different times. These peak demand profiles show the sum of the 15 minute intervals and represent the average wattage for each hour. The 15 minute data is also available for additional analysis.

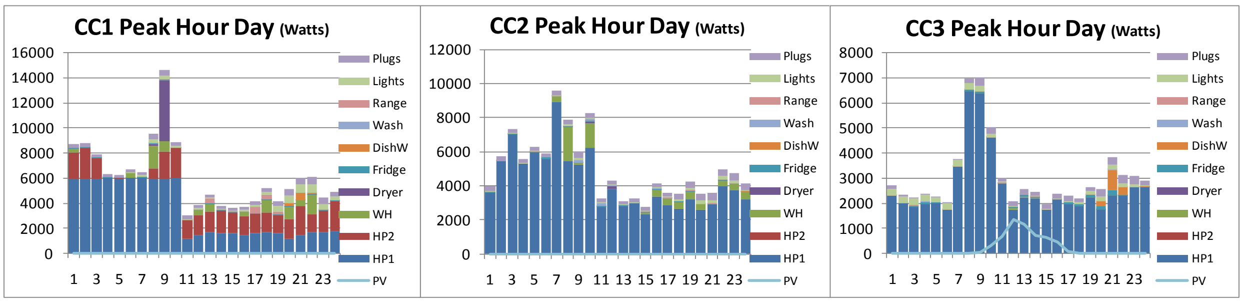


Figure 9. 24 h kW profile on the day that contains the peak hour in January 2010

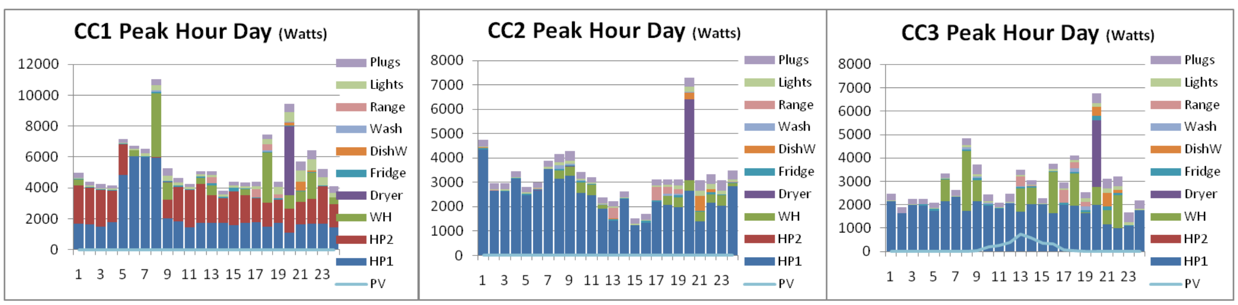


Figure 10. 24 h kW profile on the day that contains the peak hour in February 2010

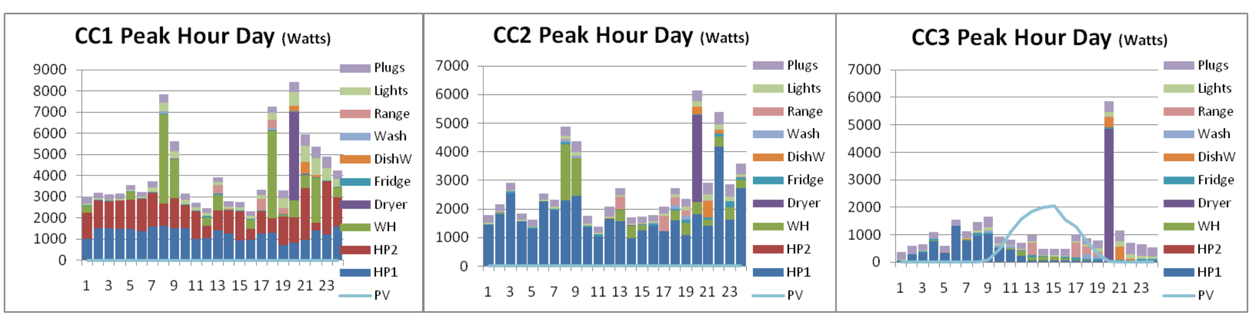


Figure 11. 24 h kW profile on the day that contains the peak hour in March 2010

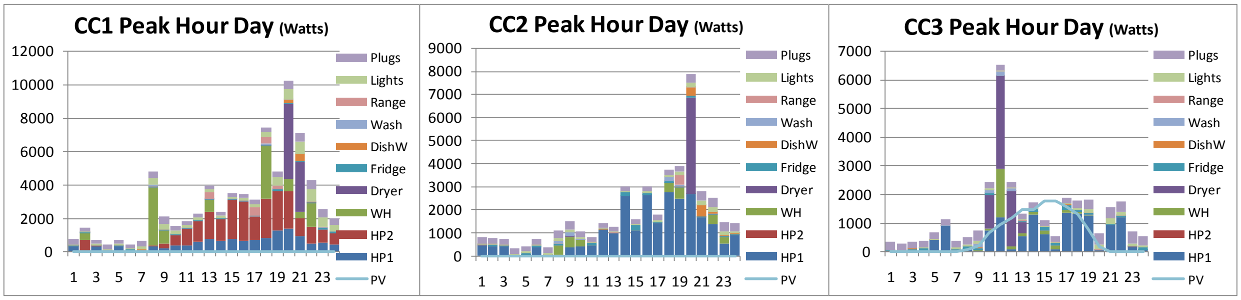


Figure 12. 24 h kW profile on the day that contains the peak hour in July 2010

2.4.1 January 2010

TVA hit an all-time daily energy generation record on January 8, 2009, of 701,387 megawatt-hours. The average daily use per hour for the day was 29,224 megawatt-hours. On January 8, CC1 used 152 kWh, CC2 113 kWh, and CC3 76 kWh. The peak hour for CC1 and CC2 was 7:00 to 8:00 AM. The peak on January 8 for CC1 was 11 kWh, 8.64 for CC2 and 7.42 for CC3.

2.4.2 February 2010

The peak kW in CC1 for the entire month of February was 11.12, for CC2 7.51 and for CC3 7.05. The peak occurs in the evening at the same time the electric dryer is running in CC2 and CC3. Figure 10 shows that the peak in CC1 occurs in the morning when the first floor heat pump is running hard and the electric water heat is recharging at the same time right after the morning showers between 7:00 and 8:00 AM.

2.4.3 March 2010

Figure 11 shows that the peak for March in all 3 houses occurs between 7:00 and 8:00 PM. In all three houses the dominate load is the electric dryer. The more efficient the house the more dominate the dryer becomes to creating the monthly hourly peak. The peak load reduction benefits of having the heat pump water heater in CC2 and the solar water heater in CC3 are very apparent in the data displayed in Figure 11.

2.4.4 July 2010

Figure 12 shows the day in which the peak hour occurs during the summer season. In all three houses it is all about when the dryer is run. The peak in CC1 and CC2 occur in the late afternoon, generally coinciding with the TVA system peak in the summer. In CC3 the peak occurs in late morning in July 2010. The peak is around 10 kW in CC1, 8 kW in CC2 and 6.5 kW in CC3. Note that at this time the solar PV system was generating about 1kW so this peak as seen by the grid was really only 5.5 kW, almost half that of CC1. The profiles for each month are shown in the monthly dashboards displayed in the Appendix.

2.5 AVERAGE DAILY PROFILES

Figures 13–15 show average daily usage profiles for all three houses for January, February, and March 2010, three winter months. On the average February and March day CC3 average day hourly peak is less than 50% of CC1. CC2 on the average February and March day has an hourly peak between 34%–50% less than CC1.

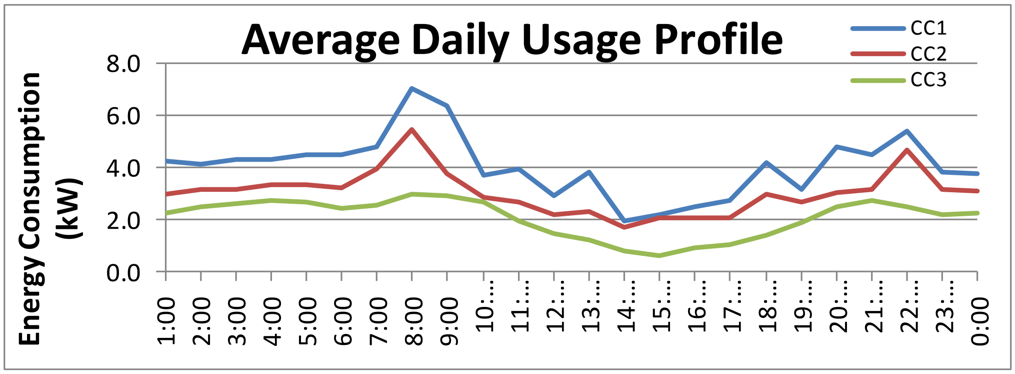


Figure 13. Average daily usage profiles for January 2010.

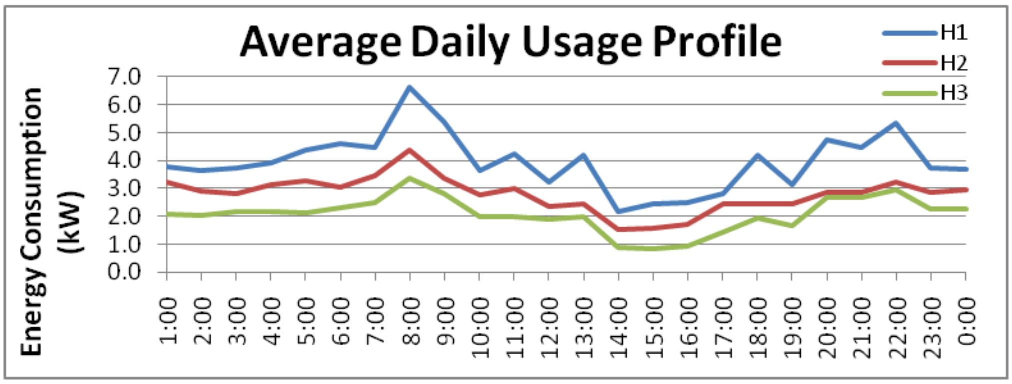


Figure 14. Average daily usage profiles for February 2010.

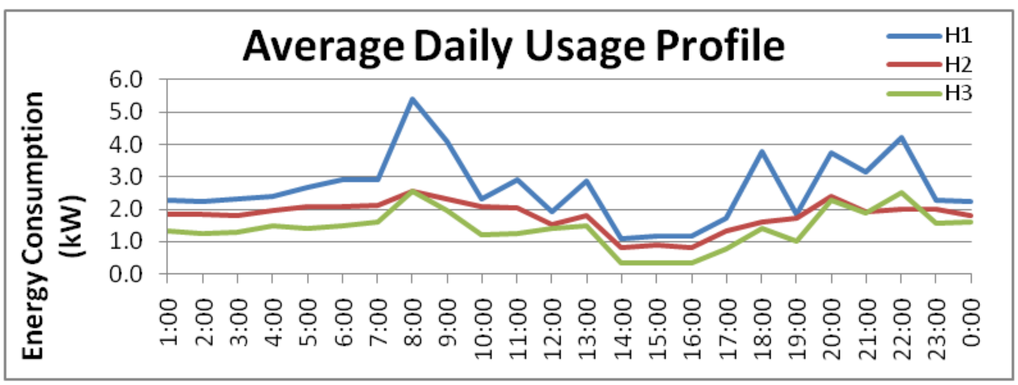


Figure 15. Average daily usage profiles for March 2010.

Figure16 shows the average daily usage profiles for all three houses for July 2010, which is generally the month in which TVA hits all time summer system peak capacity. On the average July day CC3 average day hourly peak is around 2 kW, about 60% less than average peak found in CC1. CC2 on the average July day has an hourly peak between 6:00 to 8:00 PM of around 3 kW 40% less than CC1.

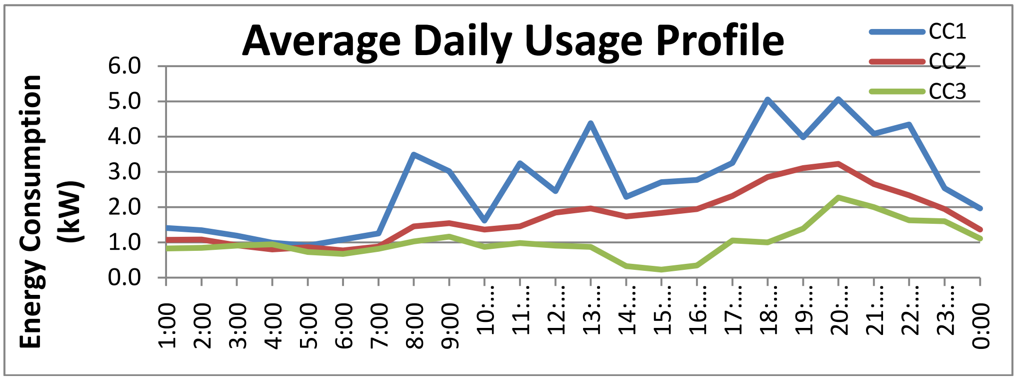


Figure 16. Average daily usage profiles for July 2010.

2.6 LOAD FACTORS

The load factors are calculated monthly for each house and displayed at the top of the dashboards. The load factor is the ratio of average hourly kilowatts over peak hourly kilowatts. Figure 17 shows the running monthly load factors for each house from September 2009 until August 2010. The most interesting months (January and August) have the extreme weather. The CC1 has the highest load factor in August and the lowest in January. Load factors improve for CC3 if one assumes that the same family that buys a high performance house also will commute to work 5 days a week, about 16 miles one way, in a plug-in hybrid electric vehicle (PHEV) and recharge at night (always off peak). After commuting in a 2008 PRIUS with an after-market Hymotion 123—5 kWh battery for 2 months, the average recharge consumed 6.2 kWh. Adding that amount to the monthly total electric demand and then calculating the load factor for CC3 is shown on the graph as the "CC3-PV+PHEV." This shows a higher load factor for CC3 than CC1 in both the peak cooling and heating months of the year. This is perceived by electric utilities as a very good finding because it saves peak capacity but does not erode utility revenue, permitting the utility providers to continue offering low cost energy services to the residential market.

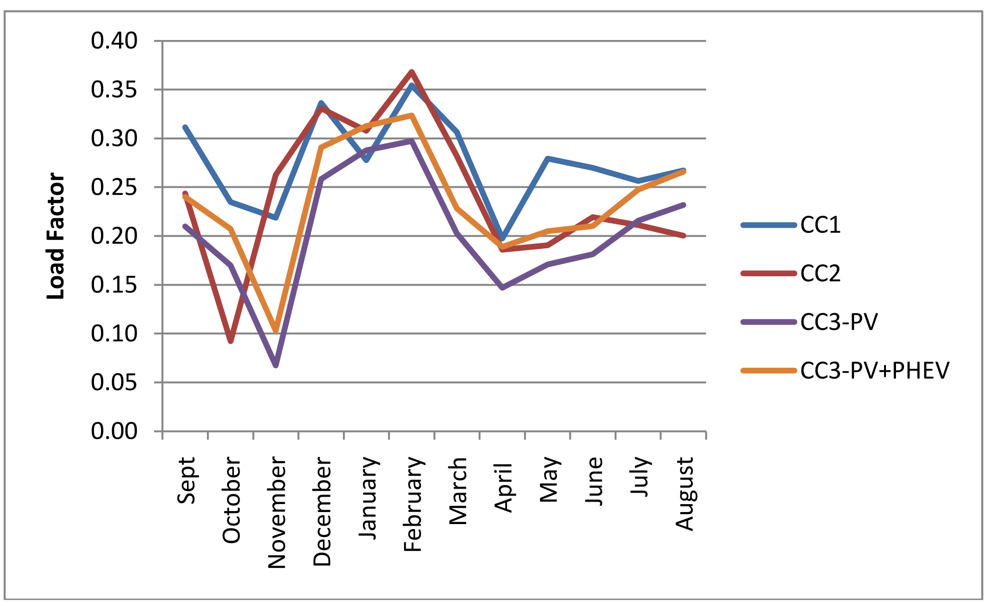


Figure 17. Load factors.

3. ENERGY USE BREAKDOWNS

This section provides the comparative energy performance of each of the major systems in all three houses for each month from July 2009 until August 2010. The systems covered are heat pump, lights, plug loads, water heater, washer and dryer, refrigerator, dishwasher, and range. The discussion below addresses how the raw data were cleaned up for the 12-month totals shown in Figure 1 of this report.

3.1 JULY 2009

Figure 18 shows a series of bar charts that compare the major energy systems total usage for all three houses in July. The heat pump in CC2 is about a third less than CC1 and CC3 uses about half the energy of CC1. Most of the cooling energy in CC1 is used by the upstairs heat pump, which is located in the hot attic. All zones of these houses are kept at 76°F.

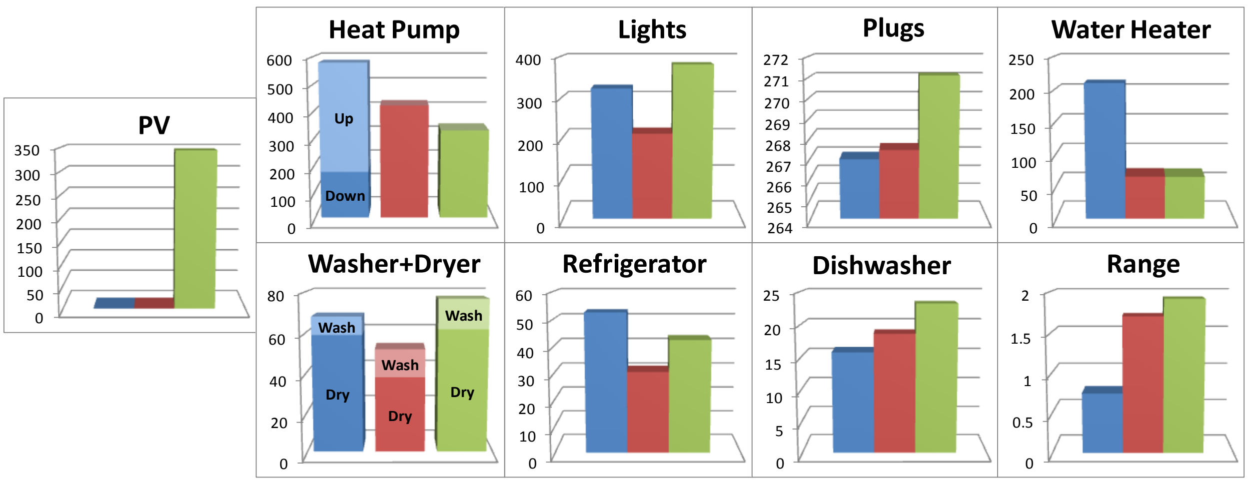


Figure 18. Systems comparisons for July 2009; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

The lights in CC2 save about a third. Since this house has 100% CFL and the builder has 0% CFL a 75% savings was expected. CC3 lights are higher than CC1. This illustrates a lighting simulation control problem. This month was not used in the annual analysis because of this type of startup problem.

The plug loads as expected are all the same. The CC3 values are a bit higher since the strip heater simulating plug loads had stuck on from July 10 through the 13th.

The water heating savings are very large thanks to the hybrid water heater in CC2 and the solar water heater in CC3. The water heating load is the same in the retrofit and CC3. With July high solar isolation, one expects the solar water heater to perform better than the hybrid water heater. A closer look at the data and the log book shows that on July 8, 2009, repairs to the solar water heater instrumentation caused excessive recorded energy consumption.

The washer and dryer in CC2 have a 24% savings to the laundry equipment in CC1. This savings does not reflect hot water energy savings that is picked up in the water heater comparison. The CC3 laundry equipment bar reflects the excessive dryer energy problem caused by the occupant simulation controls.

The Energy Star refrigerator in CC2 shows a savings of 42% compared to the standard builder unit in CC1. All of the refrigerators have the same food loading and have the same schedule of simulated door openings. The two identical refrigerators in the retrofit and CC3 eventually do prove to have similar energy usage.

The dishwasher in CC1 used 16 kWh, retro 19 kWh, and CC3 23 kWh. The two units in the retro and CC3 are the same model and loaded with the same set of dishes and scheduled the same. All these simulated occupancy start up problems were eventually cleaned up.

3.2 AUGUST 2009

Figure 19 shows a series of bar charts that compare the major energy systems August kWh consumption for all three houses. The heat pump consumption in CC2 is 29% less than that of CC1, and CC3 uses 47% less energy than CC1. The upstairs heat pump uses 69% of the cooling energy in CC1.

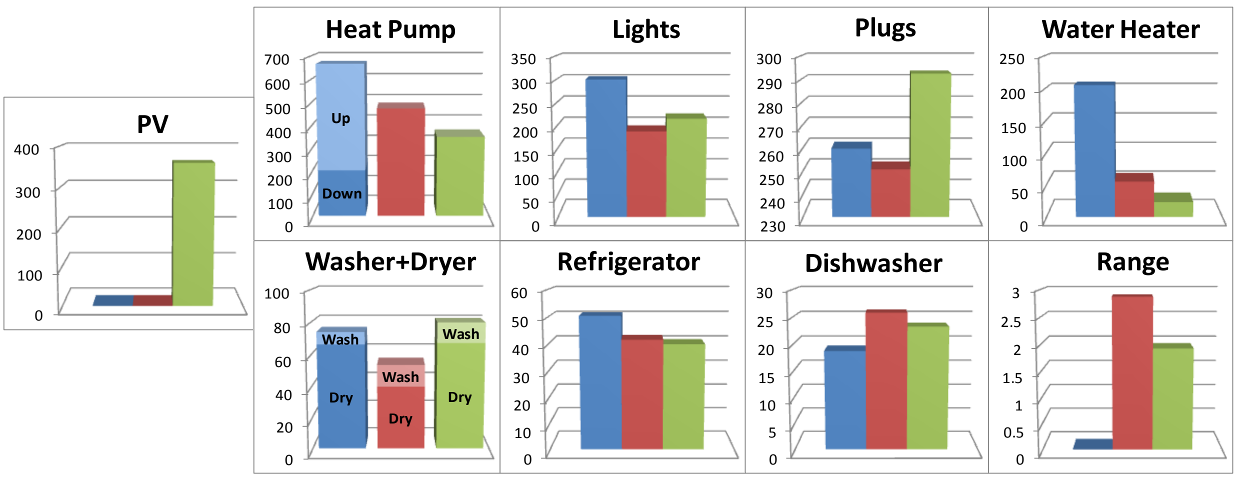


Figure 19. Systems comparisons for August 2009; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

The lights in CC2 show 37% less than CC1. The CC3 lights show 28% less than CC1. Based on observations in following months the lighting kWh values have been corrected as follows. CC1 lighting load was reduced by 99 kWh to 202, CC2 lighting was reduced 121 kWh to 69 and CC3 reduced 169 kWh to 48 kWh. These are values consistent with the measurements made during the summer months of 2010.

The plug loads for CC3 was 14% higher than the other two houses. For 30 hours starting on August 8th the strip heater in CC3 was stuck in the on position and for this same time period the down stairs strip heater was stuck in the off position in CC2. The only correction made to the plug load data was that the CC3 plugs were reduced 14% to be no higher than that measured in CC2. The change was from 293 kWh to 252 kWh.

The water heating savings are very large thanks to the hybrid water heater in CC2 and the solar water heater in CC3. The water heating energy savings for August in the retrofit is 72% and in CC3 88% over CC1. In August the solar water heater used only 24 kWh compared the hybrid water heater, which used 57 kWh, a 58% savings.

The washer and dryer in CC2 have a 23% savings to the laundry equipment in CC1, same as measured in July. The CC3 dryer was still using excessive energy in August, due to over wetting the load prior to each dry cycle. The monthly total kWh for the CC3 dryer was adjusted down from 67 kWh to 40 kWh consistent with the more accurate measurement of the dryer energy demand in CC2.

The Energy Star refrigerator in both the retro and CC3 saved 20% compared to the standard builder unit in CC1. The problem discovered in July data had been resolved. These measurements are in line with expectations.

The dishwasher in CC1 used 19 kWh, retro 26 kWh, and CC3 23 kWh. The two units in the retro and CC3 are the same Energy Star model and loaded with the same set of dishes and scheduled the same. Discussions with GE confirmed that the Energy Star appliance does use more internal energy but saves in hot water energy compared to the builder spec model in CC1. This water savings for these houses results in 0.6gal/day.

The range controls had not been operational in August 2009 so the monthly data was changed to be consistent with the measurements made in the summer of 2010. CC1 was increased from 0 to 48 kWh, CC2 from 3 to 45 kWh and CC3 from 2 to 45 kWh.

3.3 SEPTEMBER 2009

Figure 20 shows a series of bar charts that compare the major energy systems September kWh usage for all three houses. The heat pump in CC2 uses 45% (compared to 29% in August) less than CC1 and CC3 uses 51% (compared to 47% savings in August) less energy than CC1. In CC1, 72% (consistent with the 69% found in August) of the cooling energy in CC1 is used by the upstairs heat pump.

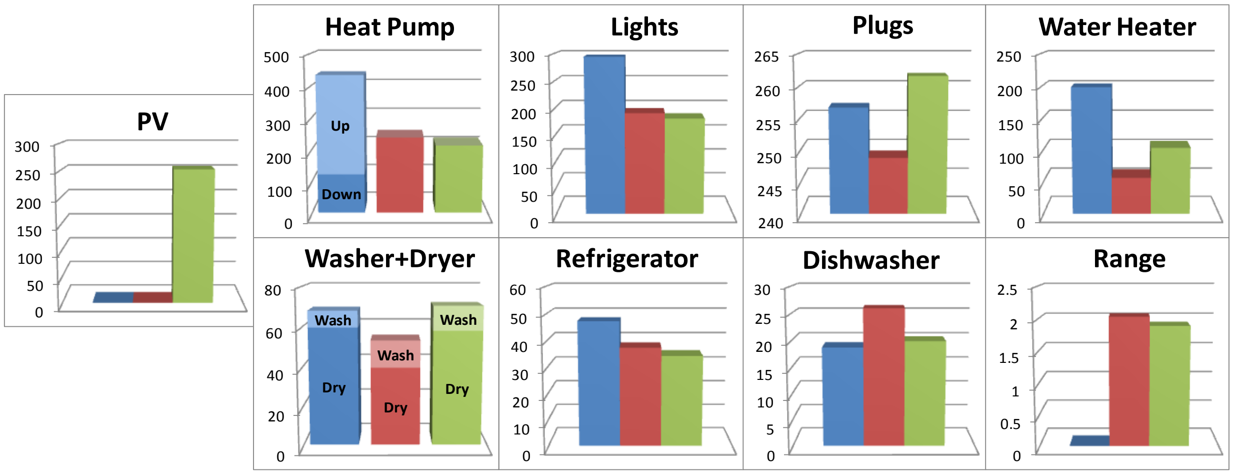


Figure 20. Systems comparisons for September 2009; blue bar = CC1, red = CC2, and green = CC3, units are kWh.

The lights in CC2 showed 35% less than CC1. CC3 lights used 39% less than CC1. Expectations are that the lighting savings in the retro and CC3 should be similar. However a savings due to CFL compared to incandescence is typically reported to be a 75% savings. CC1 lighting load was reduced by 93 kWh to 202, CC2 lighting was reduced 123 kWh to 69 and CC3 reduced 133 kWh to 48 kWh. These are values consistent with the measurements made during the summer months of 2010.

The plug loads for all three houses, as expected, are all about the same. This is consistent with what was measured in July 2009. In August the CC3 was 14% higher than the other two houses. A closer look at the hourly data shows that on three days it appears as if the lights were stuck in the “on” position for a couple of hours when the other houses were only using about 25% of the lighting energy. This did not have a significant impact on monthly total lighting load in CC3 so no corrections to the light load data was made to any of the houses.

The water heating savings are very large thanks to the hybrid water heater in CC2 and the solar water heater in CC3. The water heating load savings for August in the retrofit is 71% (dead on compared to August findings of 72%) and in CC3 48% compared to 88% in August and 66% in July. In September the solar water heater used only 105 kWh compared to the hybrid water heater, which used 58 kWh. As expected with less solar isolation in September the performance of the solar water heater will fall off compared to the other water heaters in this study. September almost set a record for rainfall. A very rainy cloudy period from 16th to the 22nd resulted in some significant call for back up resistance heat. It rained every day an average of 0.4 in.

The washer and dryer in CC2 have a 21%, consistent with the 23% savings in July and August, to the laundry equipment in CC1. The CC3 dryer was still using excessive energy in September due to the load being overly wet prior to each dry cycle. This led to a data base reduction in the monthly kilowatt-hour dryer load of 18 kWh to 40 kWh.

The Energy Star refrigerator in the retro saved 19%, consistent with the August measurements and CC3 saved 34% compared to the standard builder unit in CC1. These measurements are in line with expectations.

The dishwasher in CC1 used 19 kWh same as in August, retro 26 kWh same as in August, and CC3 20 compared to 23 kWh in August. The two units in the retro and CC3 are the same Energy Star model and loaded with the same set of dishes and scheduled the same. This month the lower CC3 dishwasher energy usage is surprising since this was 6 kWh lower than CC2s dishwasher.

The range controls had not been operational in September 2009 so the monthly data was changed to be consistent with the measurements made in the summer of 2010. CC1 was increased from 0 to 48 kWh, CC2 from 2 to 45 kWh and CC3 from 2 to 45 kWh.

3.4 OCTOBER 2009

Figure 21 shows a series of bar charts that compare the major energy systems October kWh usage for all three houses. The heat pump in CC2 was not being controlled properly by a miswired thermostat so the energy consumption is not representative of the attainable performance. Despite this problem the measured numbers were used in the final analysis. The CC3 heat pump only used 45 kWh compared to CC1 of 152 kWh, a 70% savings.

The lights in CC2 and CC3 save about 60% compared to CC1. Since CC2 and CC3 have 100% CFL and the builder has 0% CFL this is close to the 75% savings expected. Yet the lighting load in all three houses was later found to be too high so adjustments were made as follows; CC1 lighting load was reduced by 137 kWh to 202, CC2 lighting was reduced 85 kWh to 69 and CC3 reduced 91 kWh to 48 kWh. These are values consistent with the measurements made during the summer months of 2010.

The plug loads are all very similar as expected, using between 234 and 250 kWh.

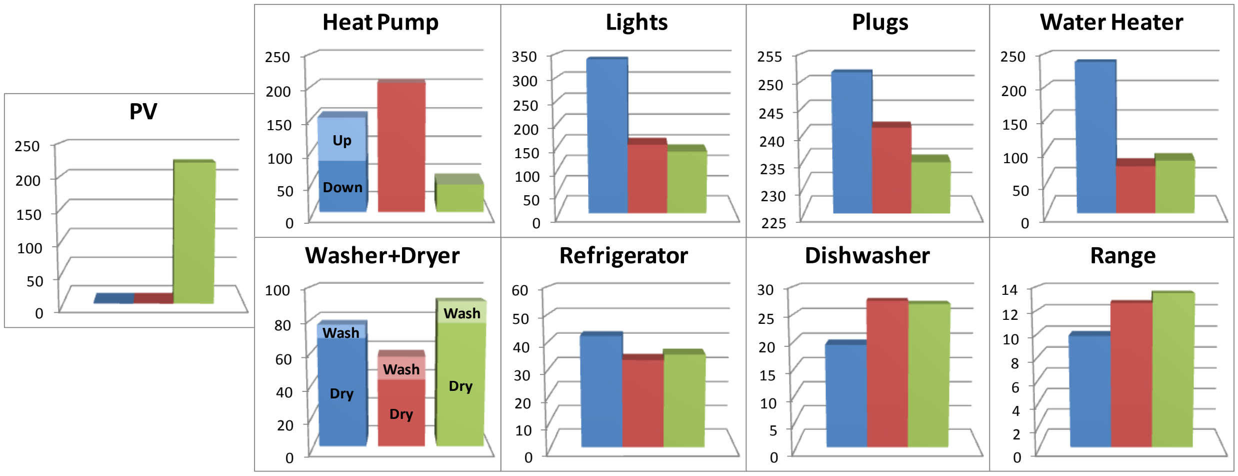


Figure 21. Systems comparisons October 2009; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

The water heating energy consumption for CC1 and CC3 are accurate. The solar water heater compared to the conventional electric water heater in the garage of CC1 results in a savings of 74%. The solar fraction for the month of October was 0.41. At least some solar water heater back up electric was needed 2 out of every 3 days in October. The simulated occupancy controls were not operating correctly in CC2 and as a result an average of only 20 gal per day of hot water was being called for compared to 52 in CC1 and CC3. The monthly kWh for CC2 water heating was increased 53 kWh to total 129 kWh for the final analysis.

The washer and dryer in CC2 have a 26% savings to the laundry equipment in CC1. This is consistent to that reported in previous months. However the dryer in CC3 used 81% more energy than the same dryer doing the same service as that in CC2. On October 20 Tony Gehl discovered the dryer exhaust duct had disconnected itself in the laundry room from the vent pipe through the wall. He reattached it and on October 28 discovered that the dryer exhaust flow sensor had caused the dryer duct to plug with lint. A major finding is that if you do not keep your dryer exhaust duct clean it has been measured over a month period to almost double the amount of dryer energy. This also can result in a fire hazard. This issue resulted in decreasing the dryer energy in CC3 35 kWh to a total of 43 kWh for the month, the same as measured in CC2.

The Energy Star refrigerator in CC2 saves 21% compared to the standard builder unit in CC1. The refrigerator in CC3 saved 16% compared to the builder unit. These savings are consistent with those reported in previous months.

The dishwasher in CC1 used 19 kWh, retro 27 kWh, and CC3 27 kWh. The two units in the retro and CC3 are the same model and loaded with the same set of dishes and scheduled the same. The absolute numbers are a bit higher than those reported in September.

The range controls had still not been operational in October 2009 so the monthly data was changed to be consistent with the measurements made in the summer of 2010. CC1 was increased from 9 to 48 kWh, CC2 from 12 to 45 kWh and CC3 from 13 to 45 kWh.

3.5 NOVEMBER 2009

Figure 24 shows a series of bar charts that compare the November major energy systems usage for all three houses. The single 2 ton heat pump in CC3 conditioning 2512 ft^2 used 63% less kWh than the two heat pumps with a total of 4.0 tons in CC1. CC2 is showing excessive energy consumption because of a faulty thermostat installation by Simple Controls. To make the monthly data adjustment all the winter months HP totals were plotted against heating degree days (HDDs) at 65°F as shown in Figure 22. The HDD at 65°F for November 2009 was 475, when plugged into the linear curve fit with an R^2 of 0.99 the monthly total is 616 kWh. So that value replaced the 825 kWh recorded for November 2009 for the final analysis. The curve fit equation in Figure 22 can be used to estimate the heating balance point temperature in CC2, which comes out to 61°F.

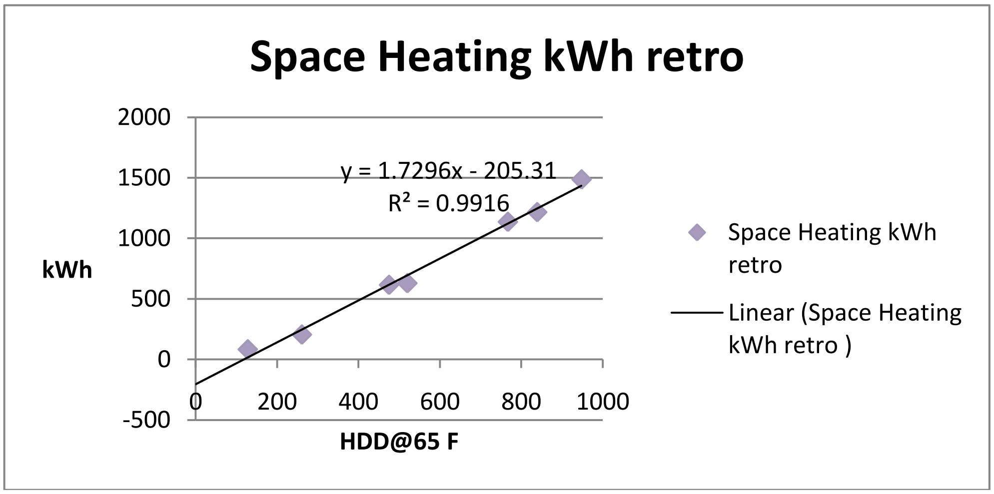


Figure 22. Monthly total HDDs at 65°F vs kilowatt-hours for CC2.

The lights in CC2 summed to a total kWh 59% less than CC1. CC3 lights used 70% less than CC1. This represents a savings of 3.5 kWh/day as a result of switching from 100% incandescent to 100% CFL. Improvements to the lighting controls have kept the same on lighting times, in all three houses. These comparisons are in line with the expectations of a house full of incandescent lights compared to CFLs.

The plug loads for all three houses are expected to be about the same. Figure 23 shows the November plug loads did not synchronize until November 22. Looking at the plug loads from later months with consistent behavior results in data corrections for the monthly plug loads for CC1 of 243 up 135 kWh from that recorded, CC2 211 up 59 kWh from that recorded and CC3 209 up 126 kWh from that recorded.

The solar water heating savings in November is 71% compared to the conventional electric unit in the garage of CC1. That is an average savings of 6 kWh/day. The hybrid water heater began malfunctioning in November. This was the second pre-commercial unit to fail in CC2. GE shipped two commercial units to the site on February 11, 2010. The unit was replaced on Feb. 12, 2010. This lead to a water heating increase of 36 kWh to 129 kWh, which is the same as that found in March 2010 a month with similar cold water delivery temperatures as those found in November.

The washer and dryer simulation was off for some of the days this month so no credible data collected. Being consistent with the monthly dryer totals from other months, CC1 was increased 34 kWh to 87, CC2 44 kWh to 72 kWh and CC3 11 kWh to 65 kWh.

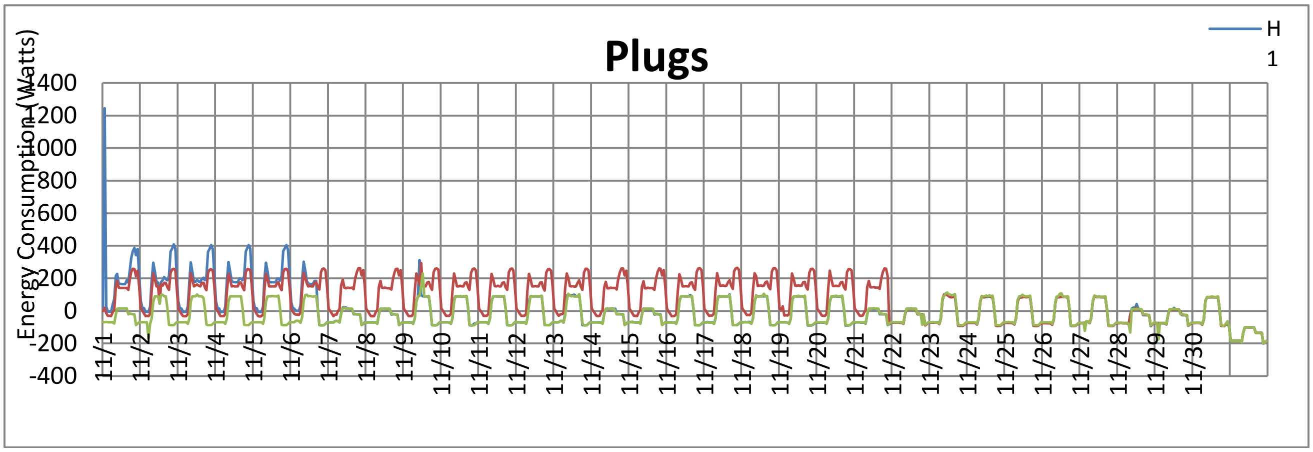


Figure 23. Shows that the plugs are the same in all three houses starting on November 22, 2009.

The Energy Star refrigerator in the retro saved 22%, consistent with the October measurements and the refrigerator in CC3 saved 18% compared to the standard builder unit in CC1. These measurements are in line with expectations.

The dishwasher in CC1 used 20 kWh same as in November, retro 28 kWh same as in August, and CC3 27, very similar pattern as October.

The ranges in all three houses are using about the same amount of energy. The single large oven is running in CC1 and the smaller muffin oven is turned on in CC2 and CC3.

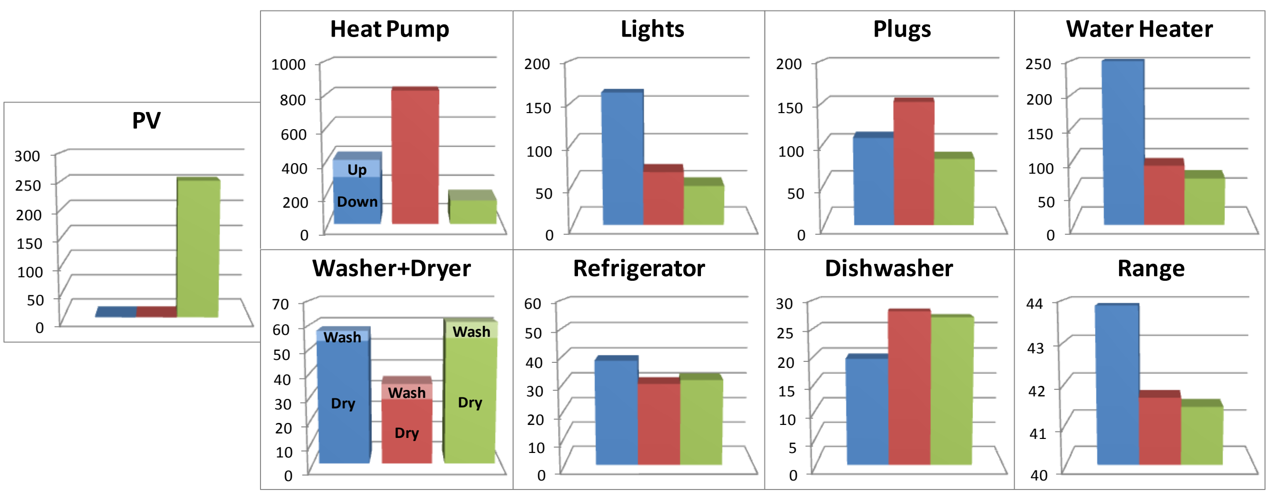


Figure 24. Systems comparisons for November 2009; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.6 DECEMBER 2009

Figure 26 shows a series of bar charts that compare the December major energy systems usage for all three houses. The single 2 ton heat pump in CC3 conditioning 2512 ft^2 used 46% less kWh than the two heat pumps with a total of 4 tons in CC1. CC2 is showing excessive energy consumption because of a faulty thermostat installation by Simple Controls. Carroll Heat and Air were called to the site twice in

December and concluded the unit was operating correctly on December 17, 2009. The total HP kWh is felt to be too high but was not changed for the final analysis.

The lights in CC2 used 54% less energy than CC1 very similar to the savings found in November of 59%. CC3 lights used 67% less energy than CC1, which was very consistent with the 70% found in November.

The plug loads for all three houses as expected are all about the same. The plugs for CC2 totaled 210 kWh. The CC1 plug loads were 277 kWh, caused by 2 days that had electric heaters stuck in the on position as shown in Figure 25. The plug loads were adjusted to 217 kWh (down 60 kWh). The plug loads for CC3 measured up to only 117 kWh, so this was increased to the same average daily plug load of 6.7 kWh, which brought the total up 91 kWh to 208 kWh.

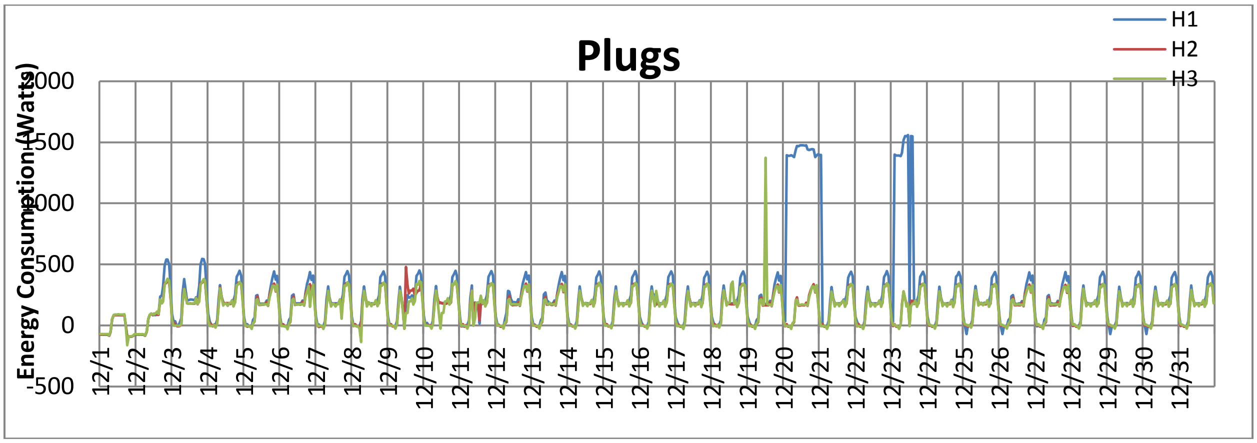


Figure 25. Hourly plug loads for all three houses for December 2009.

The solar water heater back up electric circuit was accidently cut off on December 1 and therefore the "occupants" had been provided cold showers much of the month. The solar system was operating properly but with no back up electric so the same hot showers being delivered in CC1 were not happening in CC3. The electric backup for the solar water heater was adjusted for the final analysis by adding 107 kWh to bring the summation for the month to 117 kWh. This value was derived by using the same ratios found in the PV generation on CC3 from month to month. The hybrid water heater saved 44% compared to the standard water heater in CC1. GE shipped two commercial units to the site on February 11, 2010. The unit was replaced on Feb. 12, 2010.

The washer and dryer were not providing the same simulated service in all three houses this month. The data was adjusted to reflect values measured during months in which the simulated occupancy loads were accurate. CC1 was increased by 61 to 87 kWh, CC2 increased 29 to 72 kWh and CC3 increased 31 to 66 kWh.

The Energy Star refrigerator in the retro and CC3 saved about 16%, consistent with the October and November. The Energy Star refrigerators use 1 kWh/day.

The dishwasher in CC1 used 22 kWh similar to November, retro 28 kWh same as in November and August, and CC3 35 kWh a bit higher than found in November so this value was reduced 6 kWh bring its total to 29 kWh.

The range in CC2 and CC3 were clearly not doing as much cooking so for the final analysis the range kWh was increased 32 kWh to 45 making it the same as measured in CC1.

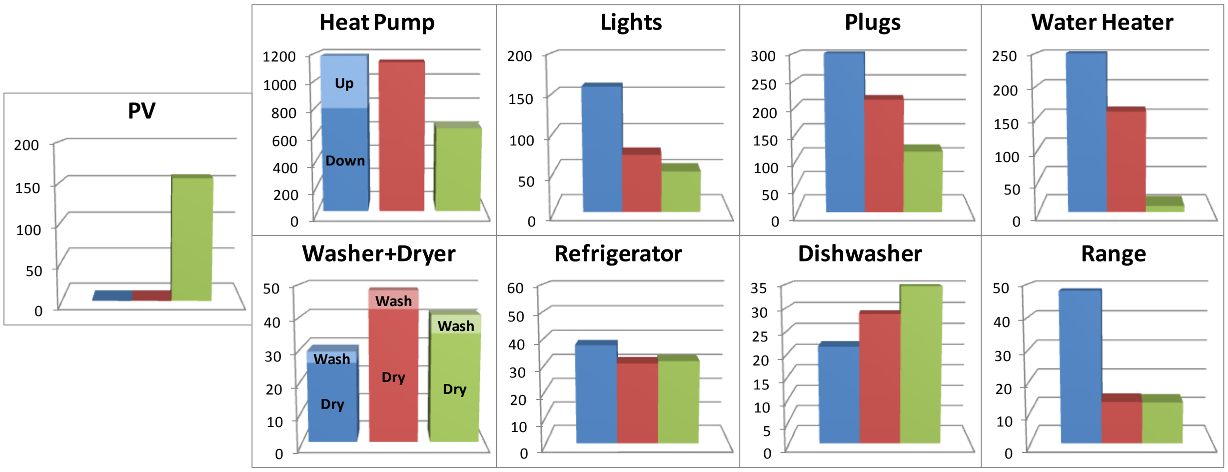


Figure 26. Systems comparisons for December 2009; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.7 JANUARY 2010

Figure 27 shows a series of bar charts that compare the January 2010 major energy systems usage for all three houses. The single 2 ton heat pump in CC3 conditioning 2512 ft^2 used 46% less kWh than the two heat pumps with a total of 4.0 tons and HSPF of 7.6 in CC1. This is the exact same percentage savings as found in December 2009. CC2 single 9.5 HSPF heat pump saved 26% compared to CC1. The average temperature in all three houses and on both floors was 71°F $\pm$1°F.

The lights in CC2 use 59% less than the lights in CC1, very similar to the savings found in November 54% and December of 59%. The CC3 lights used 64% less than CC1, which was very consistent with the 67% found in December and 70% found in November.

The plug loads for all three houses as expected are all about the same, with CC1 using 236 kWh and CC2 215 kWh. CC3 was lower than expected so it was adjusted in a similar manner as for December. The plug loads for CC3 measured up to only 128 kWh so this was increased to the same average daily plug load of 6.7 kWh, which brought the total up 80 kWh to 208 kWh.

The solar water heating back up electric circuit was still cut off for the entire month of January and the hybrid water heater problems worsened. The Hybrid water heater unit was replaced on February 12, 2010, in CC2. The unit may have used more resistance back up heat than if it was 100% healthy but it was no fault of our simulated control, nor data acquisition system that caused the poor performance so the measured kWh in CC2 is unaltered for the final analysis. However since the backup solar water heating resistance coil was accidentally cut off it was reasonable to estimate the increased water heating energy for the solar water heater system in CC3, which was increased 145 kWh to 157 kWh. The resistance energy used in CC1 was used to help estimate this correction to the database.

The washer and dryer comparisons were considered good in January. Working with GE a door latch switch that needed to be shorted to insure continuous simulated control was identified as the problem and was worked around in late December. The measured data stands unaltered.

In January the Energy Star refrigerator in the retro and CC3 saved 16% and 12% respectively, consistent with the October, November, and December performance measurements.

The dishwasher in CC1 used 23 kWh similar to November and December, retro 28 kWh same as in November, December and August, and CC3 35 the exact same as found in December so this value was reduced 6 kWh bring its total to 29 kWh as done for the December dishwasher total kWh.

The small oven in CC2 and CC3 for December and for January was found to use between 9-13 kWh/month compared to the regular large oven in CC1 of 48 kWh. The oven in CC2 and CC3 were clearly not doing as much cooking so for the final analysis the range kWh was increased 32 kWh to 45 for CC2 and for CC3 increased 35 kWh for a revised kitchen range total of 45 kWh. These are monthly values consistent with measurements made in the summer of 2010.

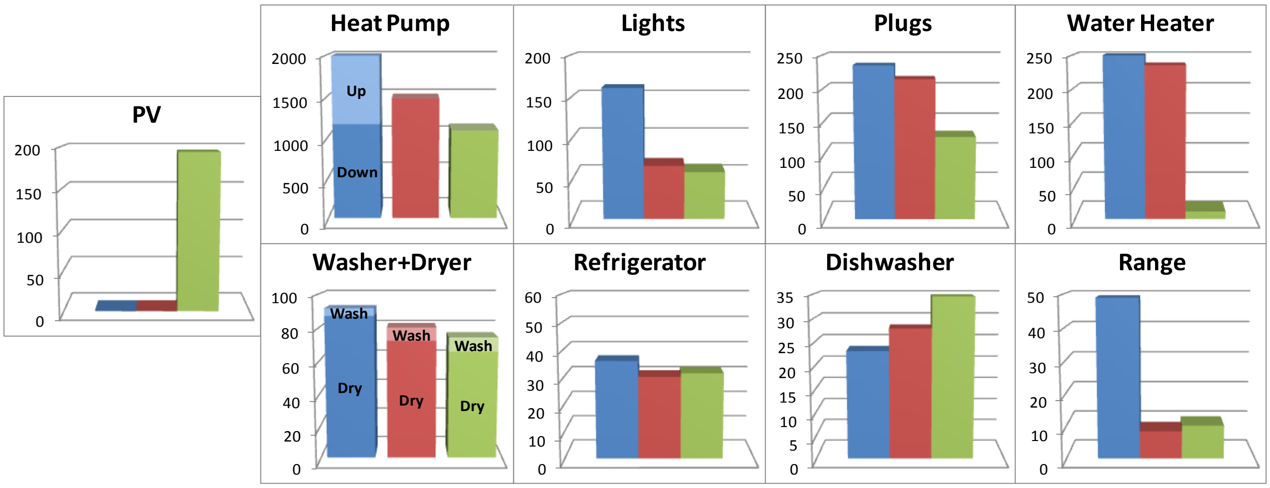


Figure 27. Systems comparisons for January 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.8 FEBRUARY 2010

Figure 28 shows series of bar charts that compare the major energy systems February total kWh usage for all three houses. The heat pump in CC2 used 1217 kWh compared to the builder of 1609 kWh, a savings of 24%. CC3 heat pump only used 810 kWh a 50% savings. It is believed that if the CC3 heat pump was allowed to operate at high speed that this energy savings during these heating months would be even higher.

The lights in CC2 and CC3 save about 70% compared to CC1. Since CC2 and CC3 have 100% CFL and the builder has 0% CFL this is close to the 75% savings expected.

The plug loads in CC1 are 259 kWh, which includes the 24/7 operation of the master bathroom fan that exhausts 30 CFM. The ventilation power was about 189 kWh in both the Retrofit and the CC3 houses—as expected, very similar to each other. The plug loads in CC3 and CC2 are also a bit smaller than CC1 because the plug-in lighting included in this load is CFLs in CC2 and CC3 compared to incandescent in CC1.

The water heating use in CC2 was 120 kWh compared to the resistance water heater consumption of 332 kWh, in CC1. That represents a 74% savings. The water heating energy in CC3 compared to CC1 results in a savings of 59%. The solar fraction for the month of February was 0.25. At least some solar water heater back up electric was needed on 68% of the days in February.

The Energy Star refrigerator in the retro and CC3 houses saved 12% compared to the standard builder unit in CC1.

The dishwasher in CC1 used 22 kWh, retro 24 kWh, and CC3 27 kWh. The two units in the retro and CC3 are the same model and loaded with the same set of dishes and scheduled the same. The dishwashers in CC2 and CC3 have from the beginning of these tests consumed 2–5 kWh/month more than the dishwasher in CC1.

The kitchen range kWh totals for February looked pretty good except for the oven in CC2, which had stuck in the on position for a few days resulting in the need to reduce this measured value 10 kWh resulting in a new total of 41 the same as measured in CC3.

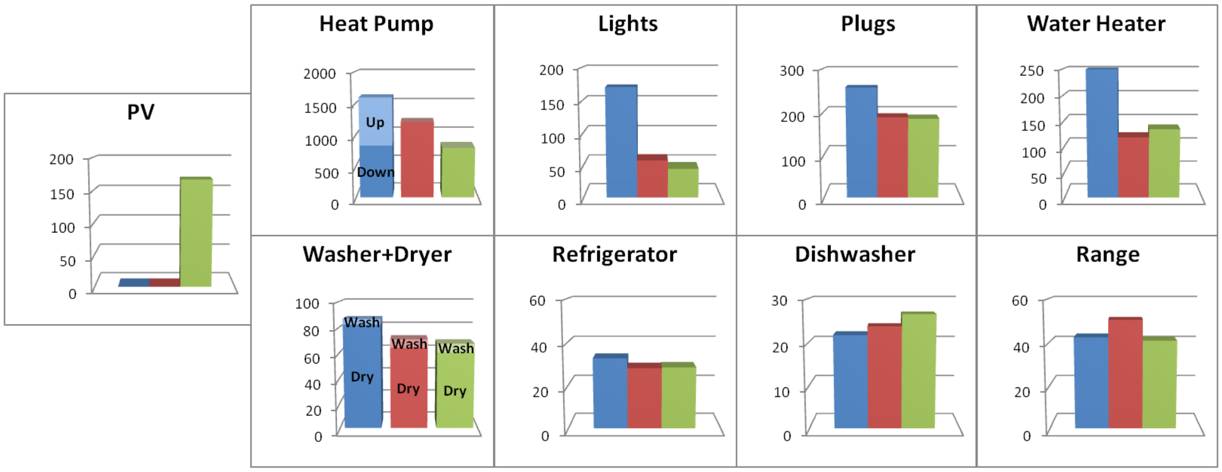


Figure 28. Systems comparisons February 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.9 MARCH 2010

Figure 29 shows a series of bar charts that compare the March major energy systems kWh usage for all three houses. The single 2 ton heat pump in CC3 conditioning 2512 ft^2 used 56% less kWh than the two heat pumps with a total of 4.0 tons in CC1. CC2 used 22% less kWh to heat than CC1.

The lights in CC2 used 67% less than CC1. CC3 lights used 75% less than CC1.

CC3 water heating savings in March is 54% compared to CC1. The new commercial hybrid water heater was installed on February 12, 2010. The March water heating savings in CC2 is 67% compared to CC1. The Energy Star clothes washers are all programmed to use hot water. The horizontal axis units in the retro and CC3 and the more efficient dishwashers in these houses result in 14 gal less per day of hot water. So, the water heater savings in part is due to the lower hot water demand, 52 gal/day compared to 66 in CC1.

The washer and dryer in the retro and CC3 continue to save about 22% of the kWh required in CC1. Because the horizontal axis units in the retro and CC3 pre-dry the wet clothes, the drier needs less energy to dry the clothes.

The Energy Star refrigerator in the retro and CC3 saved 6%, which is about half the savings observed in previous months. It appears as if the refrigerator in CC1 used about 2 kWh less this month, which is in the noise.

The dishwasher in CC1 used 24 kWh in March, retro 29 kWh, and CC3 27, very similar pattern as seen in previous months. The Energy Star units save hot water but use more energy themselves cleaning the dishes.

The ranges in all three houses are using about the same amount of energy. The single large oven is running in CC1 and the smaller muffin oven is turned on in CC2 and CC3.

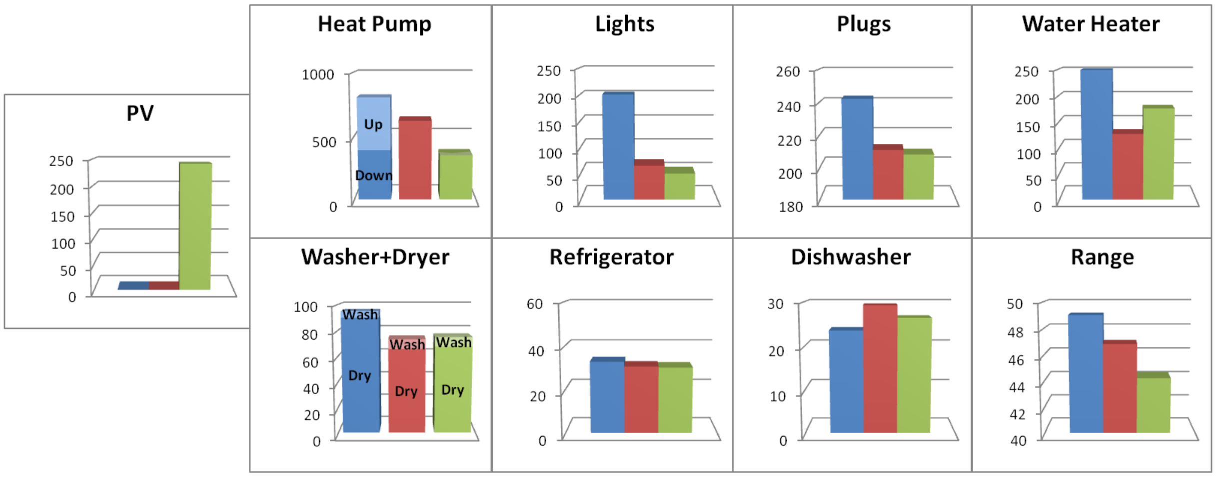


Figure 29. Systems comparisons for March 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.10 APRIL 2010

Figure 30 shows a series of bar charts that compare the April 2010 major energy systems kWh usage for all three houses. The single 2 ton heat pump in CC3 conditioning 2512 ft^2 used 73% less kWh than the two heat pumps with a total of 4 tons and HSPF of 7.6 in CC1. CC2 single 9.5 HSPF heat pump saved 57% compared to CC1. The month of April required several manual thermostat changes from heating to cooling and back to heating. So the energy savings this month are from a mixture of heating and cooling periods within the month.

The lights in CC2 use 67% less energy than the lights in CC1, the same percentage savings as found in March. CC3 lights used 76% less energy than CC1, which was very consistent with the 75% found in March.

The water heating in CC3 saved 82% compared to the builder. The water heating in CC2 saved 71% compared to CC1.

The washer and dryers in the retro and CC3 this month saved 28% compared to these appliances in CC1.

The Energy Star refrigerator in the retro and CC3 saved 6%, consistent with March 2010 performance measurements.

The dishwasher in CC1 used 19 kWh, retro 27 kWh, and CC3 25kWh. These are consistent with much of the trend observed for both summer and winter months.

The small ovens in CC2 and CC3 for April are found to use 40 kWh/month compared to the regular large oven in CC1 of 47 kWh. This is a 15% cooking energy savings.

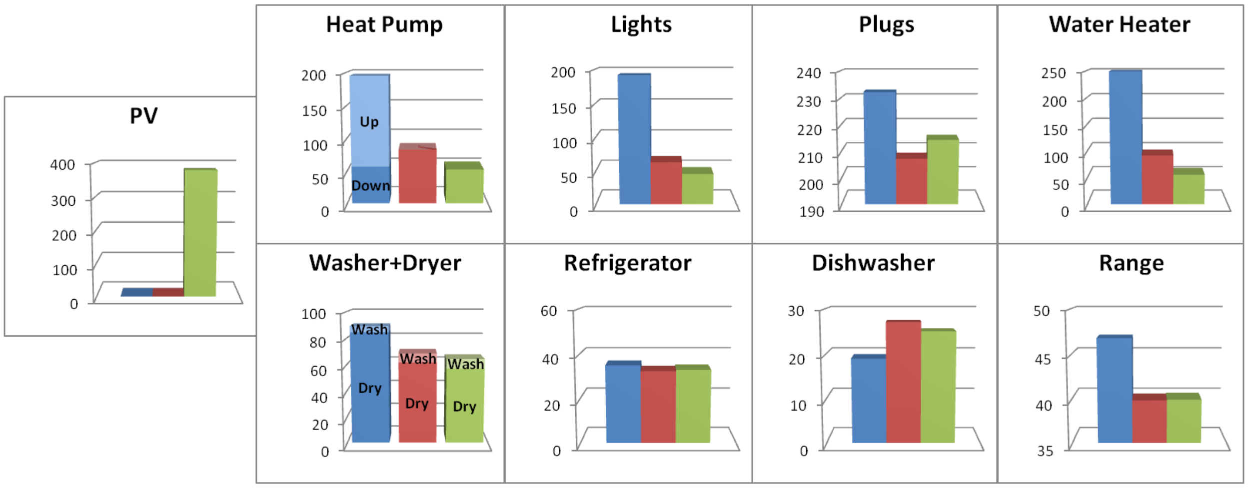


Figure 30. Systems comparisons for April 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.11 MAY 2010

Figure 31 shows a series of bar charts that compare the May 2010 major energy systems kWh usage for all three houses. The single 2 ton SEER 13 two speed compressor heat pump in CC3 used 77% less kWh than the two heat pumps with a total of 4 tons and SEER 13 in CC1. CC2 3-ton, single speed compressor with SEER 16 saved 73% compared to CC1. The month of May had the heat pumps in cooling mode.

The lights in CC2 use 64% less than the lights in CC1, this percentage savings is similar to what was found in April and March. CC3 lights used 76% less than CC1, which was very consistent with the savings measured in March and April.

The water heating in CC3 saved 83% compared to the Builder. The water heating in CC2 saved 72% compared to CC1. These are the same level of savings reported in April.

The washer and dryers in the retro saved 32% and CC3 this month saved 25% compared to these appliances in CC1. A few dryer runs were missed in CC2 this month but data was not adjusted since this was only about 8 kWh.

The Energy Star refrigerator in CC2 and CC3 saved 14% and 19% respectively.

The dishwasher in CC1 used 19 kWh, retro 26 kWh, and CC3 26kWh. These are consistent with the trend observed for both summer and winter months.

The small ovens in CC2 and CC3 for May used 45 kWh compared to the regular large oven in CC1 of 48 kWh. This is a 6% cooking energy savings.

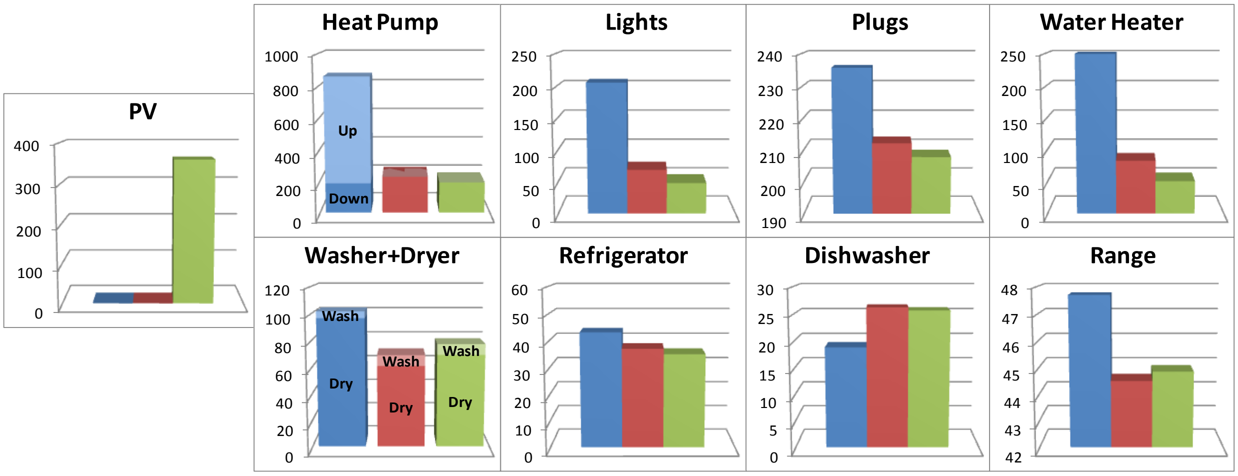


Figure 31. Systems comparisons for May 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.12 JUNE 2010

Figure 32 shows a series of bar charts that compare the June 2010 major energy systems kWh usage. The heat pump in CC3 used 64% less kWh than the two heat pumps in CC1. CC2 heat pump saved 46% compared to CC1.

The lights in CC2 use 64% less than the lights in CC1. CC3 lights used 75% less than CC1, which was very consistent with the savings measured in March, April, and May.

The water heating in CC3 saved 86% compared to the Builder. The water heating in CC2 saved 73% compared to CC1. These are the same level of savings reported in April and May.

The dryer in CC2 missed a few drying cycles so the monthly total was increased 14 kWh totaling 70 kWh for the final analysis to be consistent with what the same dryer in CC3 was using. The dryer in CC1 used 90 kWh.

The Energy Star refrigerator in the retro and CC3 saved 14% and 20% respectively, a similar pattern as measured in May.

The dishwasher in CC1 used 19 kWh, retro 26 kWh, and CC3 25kWh. These are consistent with the trend observed for both summer and winter months.

The small ovens in CC2 and CC3 for June used 45 kWh compared to the regular large oven in CC1 of 48 kWh. This is a 6% cooking energy savings. Same as measured in May.

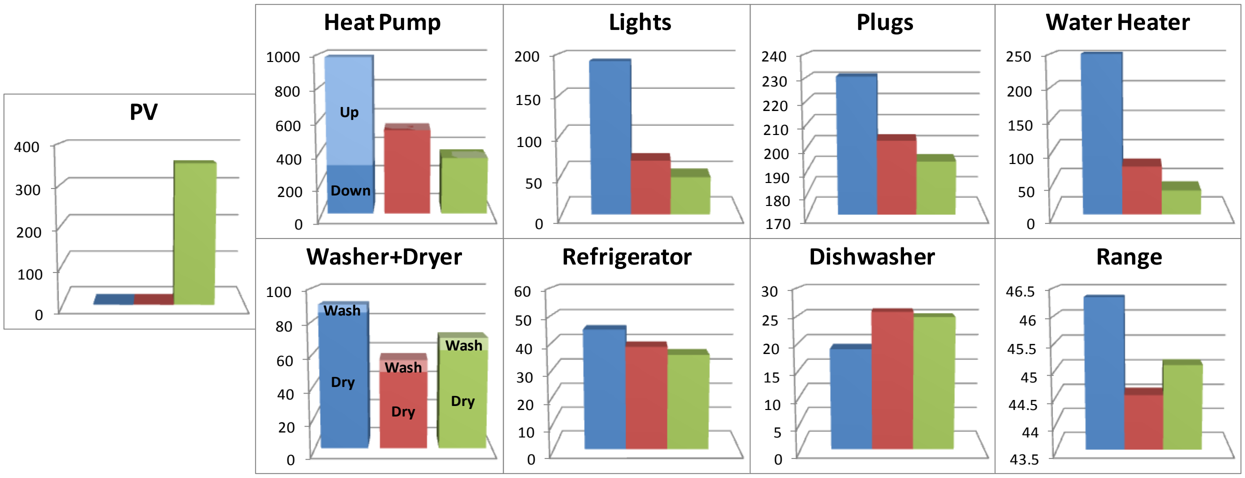


Figure 32. Systems comparisons for June 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.13 JULY 2010

Figure 33 shows a series of bar charts that compare the July 2010 major energy systems kWh usage. The heat pump in CC3 used 55% less kWh than the two heat pumps in CC1. CC2 heat pump saved 32% compared to CC1.

The lights in CC2 use 64% less than the lights in CC1, very similar percentage savings as found in March, April, May, and June. CC3 lights used 77% less than CC1, which was very consistent with the savings measured in March, April, May, and June.

The water heating in CC3 saved 89% compared to the Builder. The water heating in CC2 saved 72% compared to CC1. These are similar levels of savings reported in April, May, and June.

The dryer in CC2 missed a few drying cycles so the monthly total was increased 13 kWh totaling 70 kWh for the final analysis to be consistent with what the same dryer in CC3 was using. The dryer in CC1 used 90 kWh.

The Energy Star refrigerator in CC2 and CC3 saved 15% and 20% respectively.

The dishwasher in CC1 used 19 kWh, retro 26 kWh, and CC3 25kWh. These are consistent with the trend observed for both summer and winter months.

The small ovens in CC2 and CC3 for July used 36 and 41 kWh respectively compared to the regular large oven in CC1 of 47 kWh. The summation of the CC2 and CC3is a bit lower than it has been but the data was not altered.

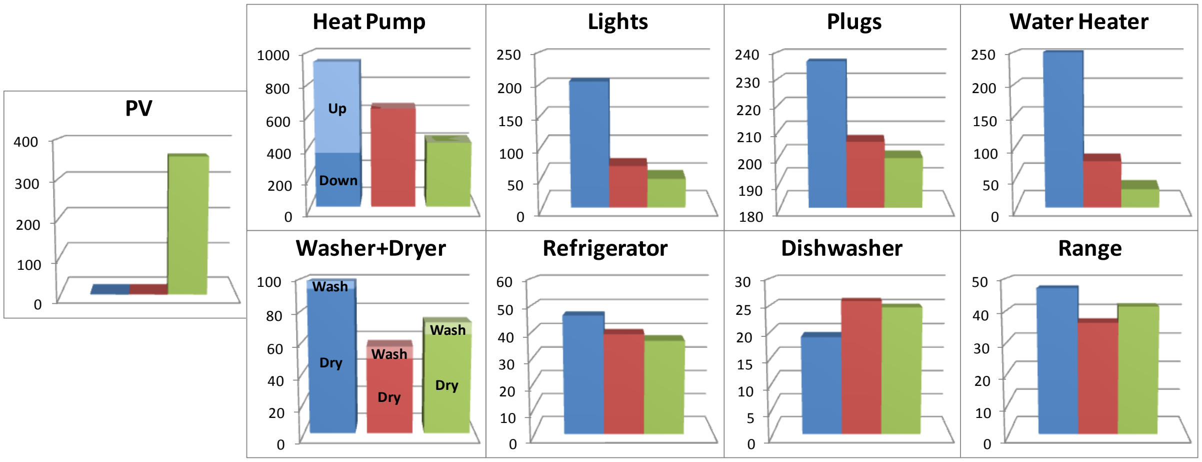


Figure 33. Systems comparisons for July 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh.

3.14 AUGUST 2010

Figure 34 shows a series of bar charts that compare the August 2010 major energy systems kWh usage. The heat pump in CC3 used 53% less kWh than the two heat pumps in CC1. CC2 heat pump saved 34% compared to CC1.

The lights in CC2 used 66% less energy than the lights in CC1, similar to the percentages for March, April, May, June, and July. CC3 lights used 76% less than CC1, very consistent with the savings measured in March, April, May, June, and July.

The water heating in CC3 saved 89% compared to the Builder. The water heating in CC2 saved 70% compared to CC1. These are similar levels of savings reported in April, May, June, and July.

The washer and dryer in CC2 and CC3 saved about 33% compared to the washer and dryer in CC1.

The Energy Star refrigerator in CC2 and CC3 saved 13% and 17% respectively.

The dishwasher in CC1 used 20 kWh, retro 27 kWh, and CC3 24kWh. These are consistent with the trend observed for both summer and winter months.

The small ovens in CC2 and CC3 for July used 45 and 43 kWh respectively compared to the regular large oven in CC1 of 48 kWh.

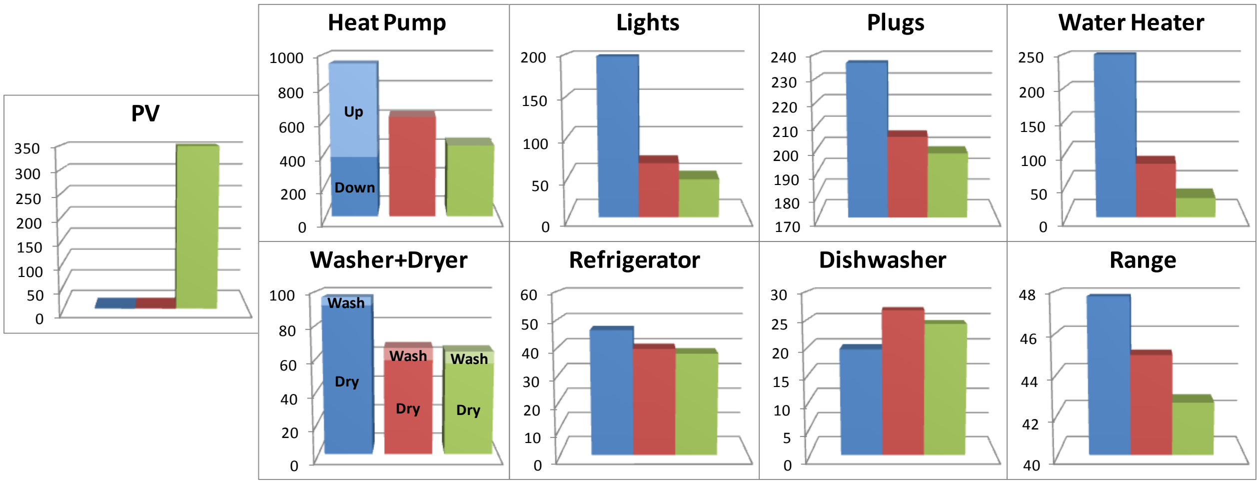


Figure 34. Systems comparisons for August 2010; blue bar = CC1, red = CC2, and green = CC3; units are kWh .

4. ENERGY USAGE MEASUREMENTS COMPARED TO ENGINEERING MODEL PREDICTIONS USING TMY3 WEATHER

4.1 RETROFIT HOUSE

The monthly energy consumption values in Table 6 show three comparisons of measurements compared to predictions. The first is a comparison of the space heating energy modeled compared to the adjusted measurements. The TMY3* weather tape used to generate this estimate has very similar HDDs as experienced during the measurement period from September 1, 2009, until August 2010. The total heating season loads are very close. The model predictions use the Building America (BA) Benchmark modeling procedure (Hendron 2010), which is the same source document used to simulate occupancy in the Campbell Creek research houses. The second comparison is for the space cooling model predictions compared to the adjusted measurements. The summation of cooling energy measurements is 22% greater than the model prediction. Table 5 shows that the CCD at 65°F during the measurement period was 48% greater than normal. The third model vs measurement comparison is the total house. The prediction is less than 3% greater than the measured data. CC2 was modeled with the Energy Gauge software (FSEC 2009) using TMY3 for Knoxville, Tennessee. April comparisons are showing relatively large measured vs modeled differences mostly because this is a swing month between heating and cooling. Without using the same weather data large differences are expected from year to year. Because the values are much lower compared to the dominant heating and cooling months, the April discrepancy amounts to a small impact on annual totals.

Table 6. Retrofit model predicted energy use compared to measurements

Month	Space heat modeled	Space heat measured	space cool modeled	Space cool measured	Hot Water modeled	Other modeled	Total modeled	Total measured
	(kWh)	(kWh)	(kWh)	(kWh)	kWh	(kWh)	(kWh)	(kWh)
Jan	1405	1486			201	508	2118	2121
Feb	1131	1216			178	450	1763	1749
Mar	604	630			162	508	1269	1219
April	358	84	36		136	492	1022	620
May			206	233	118	508	828	779
June			384	533	92	492	978	1059
July			504	645	82	508	1097	1170
August			478	623	84	508	1065	1158
Sept	0		234	241	93	492	839	770
Oct	287	206	25		122	508	925	802
Nov	530	616			140	492	1172	1201
Dec	1062	1136			179	508	1753	1768
Total	5377	5374	1867	2275	1587	5974	14828	14417

4.2 CC3

The monthly energy consumption predictions compared to monthly measurements of CC3 are shown in Table 7. The measurements of the heating load are 7% above the total annual predictions. The annual total cooling energy measurements are 34% above the model predictions; however, the CDD at 65°F for the measurement period is 48% above normal. The solar water heater electric load for the pumps and the backup electric resistance heater measurements for the full year is less than 5% below the model prediction. The last two columns in Table 7show that the total whole house electric load measured is only

*TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period (from the National Renewable Energy Laboratory National Solar Radiation Database).

4% below the model prediction. The model used to conduct the simulations is Energy Gauge, using TMY3 for Knoxville. In general there is reasonable agreement in the major sub-metered data and the model predictions for CC3.

Table 7. Predictions vs measurements of CC3 energy use with typical BA occupancy (Sept-09–Aug-10)

Month	Space heat modeled (kWh)	Space heat measured (kWh)	Space cool modeled (kWh)	Space cool measured (kWh)	Solar water heating modeled (kWh)	Solar water heating measured (kWh)	Total electric modeled (kWh)	Total electric measured (kWh)
Jan-10	823	1099	0		169	157	1521	1704
Feb-10	659	809	0		138	136	1274	1342
Mar-10	329	358	0		109	178	967	973
April-10	176	53	23		69	57	780	536
May-10	0		98	197	73	52	700	691
June-10	0		247	357	51	39	810	813
July-10	0		345	425	51	31	925	878
Aug-10	0		333	449	48	31	910	894
Sept-09	0		159	216	57	105	728	779
Oct-09	112	46	20		75	85	736	572
Nov-09	253	150	0		112	73	877	653
Dec-09	605	644	0		157	117	1291	1199
Total	2958	3159	1225	1644	1111	1061	11519	11034

4.3 CC1

The monthly energy consumption predictions compared to monthly measurements from CC1 are shown in Table 8. The model of the heating loads 56% more than the measurements of the heating load in CC1. After checking and rechecking the model inputs nothing closed this gap. The annual total cooling energy predictions from the model measurements are 20% above the measurements however, with the CDD at 65°F for the measurement period 48% above normal this indicates the model is over predicting the actual cooling energy load as well. The good news is that the water heating electric load model is within 2.5% of the measurements. What this means is that if the computer program developed for analysis of these houses is used to make energy savings predictions, those savings are going to be higher when the base case is a model of CC1. This program has been used to compare with 5 Habitat for Humanity houses and for the most part was able to be calibrated quite well with the measurements.

Table 8. Predictions vs measurements of CC1 energy use with typical BA occupancy (Sept-09–Aug-10)

Month	Space heat modeled (kWh)	Space heat measured (kWh)	Space cool modeled (kWh)	Space cool measured (kWh)	Water heating modeled (kWh)	Water heating measured (kWh)	Total modeled (kWh)	Total measured (kWh)
Jan-10	2863	1994			369	333	3871	2929
Feb-10	2323	1608			335	331	3247	2554
Mar-10	977	812			354	391	1989	1850
April-10	499	196			316	324	1451	1137
May-10	0		247	233	294	307	1193	1826
June-10	0		567	533	255	281	1462	1884
July-10	0		803	645	243	273	1710	1866
Aug-10	0		739	623	239	281	1634	1873
Sept-09	0		381	241	244	207	1269	1275
Oct-09	354	152			280	200	1301	1027
Nov-09	818	404			302	238	1763	1256
Dec-09	2077	1182			345	252	3054	2065
Total	9910	6353	2737	2275	3576	3498	23944	21543

5. COST EFFECTIVENESS OF THE ENERGY SAVING FEATURES INSTALLED IN THE RETROFIT AND CC3 HOUSES

5.1 RETROFIT HOUSE

5.1.1 Construction Cost

Table 9 provides the actual costs to construct CC2. Market valued donations are noted as well within the table. The estimated total construction cost for CC2 is $106/ft^2. This includes 15% builder profit and overhead. The same detailed costs are available on CC1 and are used to generate the incremental costs in the next section for each of the energy efficient technologies above and beyond those found in CC1.

Table 9. Detailed construction costs (estimates) for CC2

Phase code	Phase description	Retrofit- 2 Story
1005	Land	53,528.00
1010	Site Management	1,552.93
1015	Site Labor	7,101.98
1020	Carpenter / punch out	0.00
1022	Loan costs	218.73
1025	Loan interest	9,208.83
1030	Building permits	411.88
1033	Address Stone	80.10
1035	Water meter	1,710.93
1040	House plans	57.01
1045	Temporary electric	393.77
1050	Temporary water	187.98
1055	Temporary Gas	36.14
1060	Dumpster	911.91
1065	Temporary toilet	0.00
1070	Insurance – WC	206.00
1075	Decorator	400.00
1085	Survey fees	488.33
1090	Grading	3,872.50
1095	Bobcat	137.69
1105	Hauling fees	174.38
1110	Erosion control	0.00
1115	Temporary drive rock	0.00
1120	Footing – concrete	1,929.35
1125	Footing – Labor	825.00
1130	Reinforcing – Mat	287.02
1140	Block/mortar – Mat	428.76
1145	Block – Labor	921.00
1150	Block sand	0.00
1195	Termite treatment	200.00
1200	Concrete slab – Mat	2,405.69
1205	Concrete slab – Labor	840.00

Table 9. (continued)

Phase code	Phase description	Retrofit- 2 Story
1210	Slab – rock	3,404.67
1215	Slab prep	0.00
1220	Slab fill – Labor	0.00
1230	Framing – Mat	14,003.06
1235	Framing – Labor	10,065.00
1240	Siding – Mat	9,685.00
1250	Ext windows / doors	3,952.07
1265	Roofing – Mat	1,847.82
1270	Roofing – Labor	990.00
1275	Brick veneer – Mat	2,180.03
1280	Brick veneer – Labor	1,677.00
1285	Brick sand – Mat	0.00
1290	Brick cleaning – Labor	250.00
1305	Plumbing – Mat	3,292.50
1310	Plumbing – Labor	4,765.00
1315	HVAC	7,143.75
1320	Electrical	7,873.50
1325	Security	200.00
1330	Telephone	125.00
1335	Cable wiring	0.00
1345	Fireplace	1,540.00
1360	Water line	235.00
1365	Sewer line	235.00
1370	Gas line	44.50
1375	Electric line	850.00
1380	Phone line	0.00
1385	Cable Line	0.00
1390	Service line ditch	240.00
1395	Insulation	1,910.00
1400	Sheetrock – Mat	8,912.64
1410	Cabinets/vanities	4,110.95
1415	Kitchen countertops	369.27
1420	Vanity tops	670.50
1425	Interior trim – Mat	3,052.56
1430	Interior trim – Labor	2,451.00
1435	Garage door	1,270.00
1440	Lighting	2,131.09
1442	Outdoor Lighting	143.26
1445	Painting – Mat	5,589.00
1465	Tile flooring – Mat	2,376.56
1470	Tile flooring – Labor	1,515.98
1480	Underlayment - Labor	0.00
1495	Hardwood floor	460.19
1500	Carpet	3,406.97
1510	Appliances	0.00

Table 9. (continued)

Phase code	Phase description	Retrofit- 2 Story
1515	Towel bars	216.31
1530	Mirrors	362.45
1535	Shower doors	365.93
1540	Closet shelving	523.52
1545	Final grading	0.00
1575	Ext handrail/column- Mat	61.23
1580	Ext handrail/column- Lab	0.00
1595	Driveway concrete	561.99
1600	Driveway concrete - Lab	641.67
1605	Driveway forming - Mat	238.10
1610	Driveway forming - Labor	0.00
1615	Driveway prep. - Mat	0.00
1617	Driveway rock	0.00
1620	Brick steps – Labor	0.00
1625	Mailbox – Mat	205.00
1630	Landscape – Labor	1,500.00
1631	Landscape - Materials	0.00
1635	Sod	2,240.00
1640	Lawn maintenance - Labor	0.00
1645	Irrigation system - Lab	2,500.00
1660	Interior clean-up	830.20
1665	Exterior clean-up	160.00
1670	Miscellaneous – Mat	3,249.92
1675	Miscellaneous - Labor	0.00
1680	Clean driveway	0.00
1700	Truck expenses	200.00
1900	Overhead allocation	0.00
2000	Completion bonuses	1,383.60
3000	Taxes	29.36
4000	Change Orders	0.00
	Total construction expenditures	**216,695.34**
	Private-sector donations	
	BioBased® SPF insulation and installation, 1345 ft^2	2,690.00
	Spider insulation and installation (attic)- Johns Manville	1,310.00
	Total private-sector donations	**4000.00**
	Total costs, construction and donations	**($220,695.34)**
	Total with 15% builder profit and overhead markup (2400 sq ft)	**$253,799.64 ($106/ft^2)**

5.1.2 Incremental Retrofit Cost Compared to CC1

Table 10 shows the incremental cost of the energy efficiency features installed in CC2 over the cost of the builder features installed in CC1. The incremental costs were derived as if the retrofits were done on CC1 using the invoice differences between the features on CC1 compared to the costs on CC2. The incremental costs are obtained with the assumption for example that the house needs new windows, water heater, and a replacement heat pump. Overall the entire retrofit incremental cost package is $9,132. After available federal, TVA and State of TN incentives the cost to the homeowner drops to $6882.

The retrofit package amortized cost is evaluated assuming the homeowner borrowed money from the TVA in-home evaluation program (LCUB (Lenoir City Utility Board) one of the TVA distributors), which in April 2010 was offering a 10 year term loan at 6% interest for heat pumps. This is an option available and the monthly loan payment is included in the electric bill. The annual monthly payments would be $76.22. If this investment monthly cost is at least equaled by the resulting energy savings, the homeowner would reach a positive cash flow. This is thought of as acceptable to most homeowners since this would mean no additional cash is necessary to make this affordable.

Table 10. Detailed incremental costs for the energy efficiency features installed in CC2

Increment	Incremental Cost ($)	Amortized Cost ($/year)
CFL	$883	$118
Energy Star Refrigerator	$132	$18
Energy Star Washer& Dryer	$700	$93
Water heater trap	$30	$4
Hybrid water heater	$1,221	$163
Windows double pane low-E, gas-filled	$250	$33
SEER 16 heat pump, ECM fan motor	$0	$0
Ducts inside conditioned space	$0	$0
Improved ACH from 5.7 to 3.43 at 50 Pa	$5,916	$788
Mechanical ventilation	$0	$0
Total energy efficient investment	$9,132.00	$1,217
REBATES / INCENTIVES		
TVA in-home evaluation	$500	$67
Energy retrofit federal tax incentive	$1,500	$200
TN State heat pump incentive	$250	$33
incentive total	$2,250	$300
Total Incremental Cost Including Incentives	$6,882	**$917**

5.1.3 Neutral Cash Flow Analysis

The monthly energy bills using actual residential rates paid at the site of the Campbell Creek Research houses is shown in Table 11. The annual cost savings is $584. This does not reach the neutral cash flow for the first year after the retrofit but it is simple pay back of about 12 years. Another way of looking at the $6,882 energy efficiency retrofit investment is that has an 8.5% return. In September 2010 most Bank CDs were paying less than 1%.

Table 11. Monthly energy costs using the adjusted measured data on CC1 and CC2

	CC1 measured	CC2 measured
9-Sep	$135	$92
9-Oct	$114	$72
9-Nov	$91	$73
9-Dec	$109	$104
10-Jan	$167	$144
10-Feb	$229	$168
10-Mar	$199	$139
10-Apr	$152	$103
10-May	$101	$58
10-Jun	$158	$72
10-Jul	$170	$99
1-Aug	$172	$111
9-Sep	$173	$110
	$1,834	$1,250

Many of the houses in the TVA service territory that are candidates for deep energy efficient retrofits will not have quite as low energy cost as CC1. Table 12 shows a neutral cash flow analysis that is based on a starting total annual electric consumption of 25,359 kWh higher than the measured CC1 from September 2009 until August 2010 of 21,543. Using the EnergyGauge model of a house very similar to CC1, the energy savings of each of the retrofits is determined from the easiest to the most difficult to determine the cost effectiveness of each component incrementally as well as cumulatively until CC2 is reached. The overall result is that the package of retrofit technologies is cost effective with an annual positive cash flow to the homeowner of $69.

To pass the neutral cash flow analysis the summation of the retrofit energy savings must equal or exceed the added amortized cost for the retrofit loan. The first retrofit shown in the top row of Table 12 is conversion of all the lights from 100% incandescent to 100% CFL. The added cost of converting all of the lights in the house to CFL is the actual lighting cost differential from the Builder to CC2. There were a few fixtures that were changed to accommodate the CFLs in an aesthetically acceptable manner. This CFL conversion cost was $883. The amortized cost is $118 and the energy savings $125/year so the neutral cash flow to the homeowner is a savings of $7/year. Of course this does not account for the longer life of the CFL than the incandescent bulbs. Another way of looking at the cost effectiveness is that the CFL conversion will have a 7 ½ year simple payback. This will be shorter simple payback after accounting for expected longer service life of the CFL.

Table 12 lists a series of individual retrofits in the order from what would be considered the easiest to the most difficult to perform. In reality the goal of getting the HVAC equipment into the conditioned space is enabled by more than one of the listed individual measures. Exactly how you allocate energy savings benefits to individual increments is somewhat a matter of opinion.

Table 12. Detailed construction costs (estimates) for CC2

Increment	Site energy (kWh)	Builder (local costs) ($/year)	Measure value ($/year)	Package savings ($/year)	Energy savings technology kWh	Incremental cost ($)	Amortized cost ($/year)	Annual cost ($/year)
Builder House model (BH)	25359	$2,358						
BH + CFL	24016	$2,233	$125	$125	1343	$883	$118	$7
BH + Energy Star Fridge	23946	$2,227	$7	$131	70	$132	$18	-$11
BH ++ Energy Star Washer & Dryer	23129	$2,151	$76	$207	817	$700	$93	-$17
BH ++ water heater trap	23090	$2,147	$4	$211	39	$30	$4	$0
BSP +Hybrid water heater	21787	$2,026	$121	$332	1303	$1,221	$163	-$41
BSP ++ Windows double pane low-E, gas-filled	21105	$1,963	$63	$396	682	$250	$33	$30
BSP ++ SEER 16 heat pump	19060	$1,773	$190	$586	2045	$0	$0	$190
BSP ++ Ducts inside conditioned space	15139	$1,408	$365	$950	3921	$0	$0	$365
BSP ++ Improved ACH from 5.8 to 3.43 at 50 Pa	14292	$1,329	$79	$1,029	847	$5,916	$788	-$709
BSP ++ mechanical ventilation	14762	$1,373	-$44	$986	-470	$0	$0	-$44
total energy efficient investment	14762	$1,373	$986	$986	10597	$9,132.00	$1,217	-$231
REBATES / INCENTIVES								
TVA in-home evaluation						$500	$67	
Energy retrofit federal tax incentive						$1,500	$200	
TN State heat pump incentive						$250		
incentive total						$2,250	$300	
Total Incremental Cost Including Incentives						$6,882	**$917**	$69

Refrigerator. The Energy Star refrigerator investment should have a positive annual cash flow but the builder grade refrigerator is a very good one since the measured daily energy demand was 1.15 kWh/day compared to the builder refrigerator usage of 1.37 kWh/day with identical food loading weight and volume and automated daily door openings.

Thermal trap. The next row in Table 12 shows the energy savings resulting from installing a thermal trap above the water heater. Energy Gauge predicts this savings would be $30/year in energy cost and it is estimated that the added cost for a plumber to add when installing a new water heater is $30. A couple of 90 deg elbows and a couple of feet of water pipe is all the material needed to plumb a thermal trap on the hot water supply line coming out of the water heater.

HPWH. The GE hybrid water heater is now available at Lowes, Home Depot, and Sears with the lowest listing at $1498 on March 31, 2010. The cost of the electric water heater in CC1 was $277.50. The incremental cost used in the neutral cash flow analysis is $1220.50.

Windows. In the development selected to build the three research houses, which include the Builder and Retrofit Houses the base model uses regular double pane windows. The cost of the 294.5 ft^2 of the regular double pane windows on CC1 was $3702.99 the upgraded double pane low-emissivity (low-E), gas filled used in CC2 was $3952.07. The incremental cost used for these windows is $250 or $0.85/$ft^2$. The window retrofit has a positive cash flow of $30 without incentives.

HVAC. The same contractor and the same Amana heat pump brand were used in both the Builder and Retrofit Houses. CC1 was equipped with a 2.5-ton SEER-13, 7.7-HSPF unit with 4.75 kW of resistance backup in the attic serving the upper level and a 1.5-ton, SEER-13, 7.7-HSPF unit with 4.75 kW of resistance backup in the unconditioned garage serving the main level. The attic unit uses 70% of the cooling energy in CC1 for three of the hottest months of the year, July–September 2009. From May to September 2010 the attic HP consumed 67% of the cooling energy and was servicing 59% of the total house floor area. The unit that is in the worst environment, a hot attic, is called upon to provide most of the cooling. The HVAC contractor, who was asked to keep very good cost records for these installations, charged $7143.75 for both the Builder and Retrofit Houses.

For CC2 the Manual J calculation found that the right size for the single heat pump to be located in the insulated and sealed attic was 2 or 2.5 tons. The HVAC contractor felt that 3 tons was appropriate based on his experience. The design called for a two-zone system with the single 2 speed compressor unit located in the attic. The layout for the supply and return duct system was very similar for both houses except for the addition of a return trunk run through the back bedroom closet on the upper level to the ceiling of the hallway on the first floor, and a supply trunk to connect the unit in the attic to the supply duct system located between the two levels through 16 in. trusses in the floor. This second large trunk also consumed a corner of the same bedroom closet. Motorized dampers, zone-control board, and a 6 in. ventilated air duct connected to the return plenum of the unit were also added in CC2. The HVAC contractor found that his expenses were about the same for these two systems. The invoiced cost for CC2 HVAC is exactly the same as CC1, $7143.75. The incremental cost used in Table 12 is zero.

Placing the ducts inside the conditioned space has the largest return on investment, followed by the change from two heat pumps totaling 4.0 tons of capacity located outside the conditioned space in CC1 to a single 3-ton, zone-controlled unit positioned inside the conditioned space in CC2. The incremental cost of placing the ducts inside the conditioned space is assumed to be zero. The cost of foaming the attic was all levied to the “airtightness” improvement on the next line. The simulation results from EnergyGauge are used to predict that getting the HVAC system from almost completely outside the conditioned space to 100% inside saves 3921 kWh, or 37% of the total energy savings of this retrofit package.

Insulating and sealing the attic has the largest first cost. The foam insulation and installation was donated by BioBased Insulation®. The 2 in. of JM Spider™ used to cover the foam was donated by Johns Manville. The total estimated value of the material and installation was $4000. The result was that R-30 was installed under the roof sheathing and on the gable walls, compared to R-30 of blown in loose-fill Fiberglass in the conventional vented attic in CC1. The original design was to use enough foam to control moisture and air-seal the attic and to then cover the 1 to 3 in. of foam with the lower-cost Spider™. The fiberglass after repeated attempts would not build up to R-30, so the actual installation is 6 in. of mostly low-density foam and 2 in. of Spider. The foam needed to have an ignition barrier covering. In this case, the JM Spider™ provides the necessary ignition barrier and adds R-8 to the assembly. The incremental cost used of $5,916 is attained by soliciting several foam quotes for R-30 alone on an attic sheathing and gable area similar to CC2 of 1972 ft^2 at a cost of \$3/ft^2. This includes the cost of sealing the soffit, gable, and ridge vents and working in more confined space such as in a real retrofit application. In CC2 the foam and Spider™ were installed in the attic without the top floor drywall in place. However, the HVAC unit had been installed prior to insulation, which added labor cost to work around it. In a real retrofit, the project could be staged to install the insulation prior to setting the replacement HVAC unit and ducts in the attic. The incremental cost of sealing and insulating the attic in this study represents 65% of the total. The elimination of all envelope leaks in the top floor ceiling and enabling placement of the ducts and indoor heat pump unit inside the conditioned envelope result in a reduction of the whole-house ACH at 50 Pa from 5.7, as measured in CC1 and the development's "Model House," to 3.43 in CC2. This leads to 45% of the whole-house savings from the retrofit package.

In a true retrofit the cost of removing the insulation in the attic floor is recommended by the spray foam insulators. This is because of the uncertainty of the amount of conditioned air leakage, which may occur in the summer time to avoid moisture problems in the attic. Table 13 provides a reasonable cost range in 2010 for this retrofit.

Table 13. Cost range for true retrofit of low density to R-30 SPF installed in an attic; assuming 1354 ft^2 attic floor area, 10/12 roof pitch, 1763 ft^2*

	Price range			Average price	Low end	High end
	Low	High	Average			
Remove existing insulation on attic floor	$0.40	$0.75	$0.58	$779	$542	$1,016
Insulate the roof deck with 6–8 in. of 0.5 lb foam	$1.50	$1.75	$1.63	$ 2,865	$2,644	$ 3,085.
Install intumescent paint ignition barrier	$0.75	$1.10	$0.93	$1,631	$ 1,322	$1,939
				$ 5,274	$ 4,508	$6,040

CC1 depends on the bathroom exhaust fans for ventilation. Typically occupants do not run the bath exhaust fans except during showering and other bathroom usage. However, the plan was that in all three research houses the mechanical ventilation would be controlled at an average of 30 CFM. It turns out that there was variation in the average ventilation rates. Less than 30 CFM was measured in CC2 on average closer to 20 CFM. The decision to shoot for the same CFM is based on the need to assume similar indoor air quality in all three houses with simulated occupancy. Energy usage is simulated; indoor air pollutants are not. The energy penalty for running the bath exhaust fan 24/7 and pulling a measured 30 CFM from the house was 569 Wh/year.

5.2 CC3

5.2.1 Construction Cost

A detailed breakdown of the cost to construct CC3 in 2008 is shown in Table 14. The actual costs were broken down using invoices and spreadsheets made available by John Kerr, the builder. The table also shows the market value of all donations. The estimated cost to construct CC3 was $307,452, including 15% overhead and profit, the overall cost is $353,570, or $141/ft^2.

Table 14. Detailed construction costs (estimates) for CC3

Phase code	Phase description	Cost ($)
1005	Land	53,435.00
1010	Site management	1,381.65
1015	Site labor	12,155.40
1020	Carpenter / punch out	0.00
1022	Loan costs	1,017.79
1025	Loan interest	8,133.32
1030	Building permits	411.88
1033	Address stone	80.10
1035	Water meter	1,710.93
1040	House plans	126.79
1045	Temporary electric	386.51
1050	Temporary water	274.32
1055	Temporary gas	0.18
1060	Dumpster	290.00
1065	Temporary toilet	76.47
1070	Insurance – WC	0.00
1075	Decorator	400.00
1085	Survey fees	494.25
1090	Grading	2,358.13
1095	Bobcat	197.69
1105	Hauling fees	28.24
1110	Erosion control	0.00
1115	Temporary drive rock	0.00
1120	Footing - concrete	1,709.76
1125	Footing - labor	847.00
1130	Reinforcing - Mat	470.65
1140	Block/mortar - Mat	1,436.25
1145	Block - labor	1,206.00
1150	Block sand	0.00
1195	Termite treatment	200.00
1200	Concrete slab - Mat	2,626.37
1205	Concrete slab - labor	910.00
1210	Slab - rock	3,496.19
1215	Slab prep	148.95
1220	Slab fill - labor	0.00

Table 14. (continued)

Phase code	Phase description	Cost ($)
1230	Framing - Mat	14,502.85
1235	Framing - labor	10,642.00
1240	Siding - Mat	9,435.00
1250	Ext windows / doors	855.98
1265	Roofing - Mat	2,259.74
1270	Roofing - labor	990.00
1275	Brick veneer - Mat	2,058.62
1280	Brick veneer - labor	1,872.00
1285	Brick sand - Mat	1,013.11
1290	Brick cleaning - labor	0.00
1305	Plumbing - Mat	4,715.22
1310	Plumbing - labor	5,297.58
1315	HVAC	7,578.75
1320	Electrical	8,026.25
1325	Security	200.00
1330	Telephone	125.00
1335	Cable wiring	385.00
1345	Fireplace	1,540.00
1360	Water line	235.00
1365	Sewer line	235.00
1370	Gas line	44.50
1375	Electric line	850.00
1380	Phone line	0.00
1385	Cable Line	0.00
1390	Service line ditch	240.00
1395	Insulation	0.00
1400	Sheetrock - Mat	8,912.64
1410	Cabinets/vanities	4,562.28
1415	Kitchen countertops	398.76
1420	Vanity tops	676.00
1425	Interior trim - Mat	3,219.39
1430	Interior trim - Labor	2,450.00
1435	Garage door	1,270.00
1440	Lighting	3,754.28
1442	Outdoor lighting	143.26
1445	Painting - Mat	7,076.00
1465	Tile flooring - Mat	2,576.16
1470	Tile flooring - labor	2,079.50
1480	Underlayment - labor	0.00
1495	Hardwood floor	460.19
1500	Carpet	3,406.97
1510	Appliances	0.00
1515	Towel bars	215.82
1530	Mirrors	354.20
1535	Shower doors	365.10
1540	Closet shelving	475.50
1545	Final grading	0.00
1575	Ext handrail/column- Mat	506.32

Table 14. (continued)

Phase code	Phase description	Cost ($)
1580	Ext handrail/column- labor	0.00
1595	Driveway concrete	2,525.10
1600	Driveway concrete - labor	595.00
1605	Driveway forming - Mat	0.00
1610	Driveway forming - labor	0.00
1615	Driveway prep. - Mat	0.00
1617	Driveway rock	0.00
1620	Brick steps - labor	0.00
1625	Mailbox - Mat	0.00
1630	Landscape - labor	1,500.00
1631	Landscape - materials	0.00
1635	Sod	2,240.00
1640	Lawn maintenance - labor	0.00
1645	Irrigation system - labor	2,410.00
1660	Interior clean-up	785.20
1665	Exterior clean-up	0.00
1670	Miscellaneous - Mat	3,695.80
1675	Miscellaneous - labor	0.00
1680	Clean driveway	0.00
1700	Truck expenses	0.00
1900	Overhead allocation	0.00
2000	Completion bonuses	1,361.40
3000	Taxes	0.00
4000	Change orders	0.00
6510	Shared management	13,884.69
7110	Interest - lots held	778.12
	Total construction expenditures	**241,789.10**
	Donations	
1265	Techshield roof sheathing	1,000.00
1230	DOW SIS wall sheathing	3,600.00
1510	GE Energy Star appliances	9,418.00
1670	Solar water system	10,333.39
1395	Foam insulation	4,000.00
1395	Fiberglass Spider and batt insulation	2,500.00
1250	Triple-pane windows	10,000.00
1315	Energy recovery ventilator	1500.00
1315	2-ton heat pump	4,000.00
1320	Solar PV system	13,401.24
1320	Installation of PV system - Big Frog Mountain	4,407.41
1040	Drawings	1,503.00
	Total donations	65,663.04
	Total costs, construction and donations	307,452.14
	Total with 15% builder profit and overhead	353,569.96
	$\$/ft^2$	140.75

5.2.2 Incremental Construction Cost Compared to CC1

The incremental cost for each of the technologies contributing to the high energy performance in CC3 is shown in Table 15. The list is prioritized from the most cost effective to the least. The method used to derive these incremental costs is explained in the next section; Neutral Cash Flow Analysis.

Table 15. Prioritized list of energy efficiency and site generation technologies by annualized cost[a]

Technology	First cost ($)	Annual cost ($)
Ducts inside conditioned space	2,000	184
SEER-16 heat pump	750	148
Compact fluorescent lighting	883	60
R-49 attic insulation	300	32
Energy Star washer and dryer	700	31
Slab edge insulation of R-10	400	3
Move west and east windows to south	2	2
Energy Star refrigerator	132	-4
U-0.2 doors	253	-6
Radiant Barrier under roof sheathing	207	-12
Double-pane windows to triple, low-e, gas-filled	1,900	-17
Improve ACH from 5.8 to 2.4 at 50 Pa	800	-35
Improve floors over garage	500	-39
ERV	3,000	-219
Improve walls from R-13 to R-22	4,508	-277
Solar PV	17,809	-296 [a]
Solar water heater	9,733	-385 [a]

[a]after rebates

5.2.3 Neutral Cash Flow

Table 16 shows the neutral-cash-flow analysis for CC3 using the BA Benchmark Definition (Hendron 2009). The analysis was conducted using a house similar to CC1 at Campbell Creek and comparing it to CC3. Using the actual local electrical rate in 2008, the total annual energy cost for CC1 with 2512 ft^2 was $2,385. The actual measured energy cost for CC1 was less however, as of January 1, all three houses including CC1 are ventilated at an average rate of 30 CFM, which is the value used in the model to simulate these houses. CC1 has slab edge insulation, which is not included in the model because the builder did not install any in the other three dozen houses in the development. The in situ measured attic R-value in CC1 was closer to R-40 rather than the specified R-30. Another difference is that CC1 is only 2400 ft^2 and not 2512 ft^2 as modeled. The larger size of CC3 resulted from exercising the builder option of adding a pantry, which can be used to house the mechanical equipment completely inside the conditioned space.

Without the solar PV, but including the solar water heater, neutral cash flow using a 30 year mortgage at 7% interest is not achieved. The house operation with all the added energy efficiency features and with no available incentives would cost $787 per year more than the annualized mortgage and energy cost of CC1. Subtracting available federal, state of Tennessee and utility incentives reduces this cost to $200; adding the solar PV site generation and the available tax and utility incentives for PV increases it to $417/year. This cash flow analysis assumes a loan of 30 year term at 7% interest. If the interest was

5.23%, which is available in September 2010 to some new home buyers. Neutral Cash Flow would be met in CC3.

To bring this house to a neutral cost sticking with the 7% would require another up front incentive package for energy efficiency of $5220. This is within the levels of the energy efficiency incentives proposed in the federal Home Star Jobs US Congressional legislation bill for “Gold Star” performance. In 2010 the House of Representatives passed this legislation, but the Senate held up their vote in August 2010.

The lighting load, plug load, and dryer load assumed for CC3 total 4504 kWh. With aggressive energy management and mindful-energy usage behavior it is possible to reduce this load by 30%, saving $125 per year. If a national, state or utility incentive of $292/year was available for houses that have a third-party-certified HERS lower than 50 without the PV the DOE BA neutral-cost criteria could be met. A scenario resulting in an increase in the residential electric rate from $0.93/kWh to $0.158 would be another way of generating an additional $292/year savings resulting in CC3 meeting the neutral-cash-flow criteria.

Table 16 shows a list of the energy efficiency and site generation technologies in CC3 prioritized from the best annualized cost to the worst. Incentives for specific technologies, but not those based on whole-house performance, are included in the calculation of technology specific cash flow. Placing the ducts inside the conditioned space has the largest return on investment, followed by the change from two heat pumps totaling 4.0 tons of capacity located outside the conditioned space in CC1 to a single, 2-ton, 2 capacity compressor, ECM indoor fan motor and zone-controlled unit positioned inside the conditioned space in CC3.

The Energy Star refrigerator should have a positive annual savings, but the builder-grade refrigerator was a good refrigerator, since the measured daily energy demand was 1.37 kWh/day, compared to the Energy Star refrigerator in CC3 (controlled for identical automated door openings) that used 1.15 kWh/day . The BA Benchmark refrigerator uses 1.83 kWh/day.

The radiant barrier located on the underside of the roof sheathing only cost an additional $207 for this house, but the EnergyGauge model predicts an annual energy savings of $4.84 over the BA Benchmark house. This converts to a simple payback of 43 years. This ventilated attic has R-49 insulation over the ceiling joists and has no HVAC equipment.

The R-6 windows in CC3 came very close to a positive cash flow. The triple-pane windows’ incremental cost over the two-pane, “no low-E, no-gas” windows was $8.30/ft^2. This was based on an invoice for the same type of triple-pane windows purchased for an ORNL office (Building 3147) in September 2009.

The cost and energy savings resulting from the air tightness improvement in CC3 are difficult to break out from the other individual technologies used in this building. The cost is based mostly on the lead carpenter’s report that he spent an additional 40 hours providing backing and extra sealing in the walls and ceilings of CC3. Obviously many other features contribute to the air tightness, such as getting the ducts inside the conditioned space, better windows, and foam flashing and taped DOW structural insulated sheathing (SIS) board in the walls. Most of the added cost in the floors above the garage and the cantilevered floor above the porch improved air tightness in several ways, but only the energy savings from the modest increase in R-value was used in the model to allocate the energy savings for these improvements.

Table 16. Neutral-cash-flow analysis for CC3 using the Building America (BA) criteria

Increment	Site Energy (kWh)	Builder Standard Local Costs ($/yr)	Measure Value ($/yr)	Package Savings ($/yr)	Energy savings savings from technology kWh	Incremental cost $	Amortized cost $	annual cost	meet netrual $
BA Benchmark	33070	$3,076							
Builder Standard (BSP)	25647	$2,385			7423				
BSP + CFL	24242	$2,255	$131	$131	1405	$883	$71	-$60	yes
BSP ++ Energy Star Fridge	24171	$2,248	$7	$137	71	$132	$11	$4	no
BSP ++ Energy Star Washer & Dryer	23232	$2,161	$87	$225	939	$700	$56	-$31	yes
BSP ++ R-49 attic insulation	22635	$2,105	$56	$280	597	$300	$24	-$32	yes
BSP ++ U=0.2 doors	22487	$2,091	$14	$294	148	$253	$20	$6	no
BSP ++ SEER 16 heat pump	20257	$1,884	$207	$501	2230	$1,000	$80	-$128	yes
BSP ++ move 2 windows from W&E to south	20230	$1,881	$3	$504	27	$2	$0	-$2	yes
BSP ++ Windows double pane to triple	18778	$1,746	$135	$639	1452	$1,900	$152	$17	no
BSP ++ Ducts inside conditioned space	15080	$1,402	$344	$983	3698	$2,000	$160	-$184	yes
BSP ++ Improved ACH from 5.8 to 2.4@50	14769	$1,374	$29	$1,012	311	$800	$64	$35	no
BSP ++ ERV	14552	$1,353	$20	$1,032	217	$3,000	$240	$219	no
BSP ++ Solar Water Heater	12847	$1,195	$159	$1,190	1705	$9,733	$777	$618	no
BSP ++ improved walls from 13 to 22	11959	$1,112	$83	$1,273	888	$4,508	$360	$277	no
BSP ++ Slab edge insulation of R-10	11584	$1,077	$35	$1,308	375	$400	$32	-$3	yes
BSP ++ improved floors over garage	11570	$1,076	$1	$1,309	14	$500	$40	$39	no
BSP ++ Radient Barrier under roof sheathing	11518	$1,071	$5	$1,314	52	$207	$17	$12	no
total energy efficient investment	11518	$1,071	$1,314	$1,314	14129	$26,318	$2,101	$787	no
Total energy efficient investment with incentiv	11518	$1,071	$1,314	$1,314	14129	$18,969	$1,514	$200	no
Site Generation (solar PV)	3281	$699	$699			$17,809	$1,422	$296	
Total with Site Generation	8237	$372		$2,013	17,410	$44,127	$3,523	$1,510	
REBATES / INCENTIVES									
Energy efficient builder house ($2000)						$2,000	$160		
Solar water heater tax incentive (30%)						$3,100	$247		
PV solar tax incentive (30%)						$5,343	$427		
TVA generation partner ($1000)						$1,000	$80		
Tennessee State Heat Pump incentive						$250	$20		
TVA in-home evaluation						$500	$40		
Energy retrofit federal tax incentive						$1,500	$120		
incentive total						$13,692	$1,093		
Total Incremental Cost to Buyer Including Incentives						$30,435	$2,430	$417	
extra incentive						5220	$417		

The energy-recovery ventilator is another technology that is tough to isolate. You have to ventilate, and the power load of the fans works against the energy savings. The cost to install these units with completely separate ducts sucking from the wet rooms and blowing to the dry comes with a significant added first cost. At the same time, indoor-air-quality benefits, which are not accounted for in the neutral-cash-flow analysis, do obviously represent added value.

The annual cost of the solar PV system, accounting for the federal tax incentive of 30%, the TVA generation partner incentive of $1000, and TVA's current buyback rate, is $296. An incentive to reduce carbon equivalent to an increased buyback rate for the solar kWh from $0.12 to $0.21/kWh above the residential rate would make the 2.5-kWp PV system cost-neutral for CC3.

The relatively poor neutral-cost performance of the walls is because these houses are research houses. They are rented for research purposes from 2009 through 2012. Every year in the fall the technology packages will be retrofitted and the houses will be monitored for another year. The experimental plan called for extremely tight walls in CC3 because of the difficulty of retrofitting air tightness after initial construction. These walls have redundant air retarders, taped DOW SIS, and 1 in. of closed-cell, flashed foam sprayed against the inside of the DOW SIS. This effort contributes to the high annualized cost for the ASTM-hot-box-measured, R-22 walls in CC3, as compared to the cost of the nominal "R-13" walls (actually closer to whole-wall R-11) in CC1.

The solar water heater had the worst payoff of all the technologies selected for this house, with an annual net cost of $385/year after the 30% federal tax incentive.

Table 17 summarizes the neutral-cash-flow analysis conducted for CC3. Keep in mind that if the 30-year mortgage rate was 5.23% instead of the 7% assumed by the BA Benchmark Protocol neutral cash flow analysis would be met with the complete package of upgrades installed in CC3.

Table 17. Summary of BA neutral-cash-flow analysis for CC3 using a 30-year mortgage at 7% interest

	Initial value	**Annual amortized cost[a]**
Added Annual Mortgage Cost w/o Site Gen., w/o incentives		($2,101)
Net Cash Flow to Consumer w/o Site Gen., w/o incentives		($787)
Added Annual Mortgage Cost w/o Site Gen., with incentives		($1,514)
Net Cash Flow to Consumer w/o Site Gen. with incentives		($200)
Mortgage Cost with Site Gen. w/o incentives		($3,523)
Net Cash Flow to Consumer with Site Gen., w/o incentives		($1,483)
REBATES / INCENTIVES		
State of Tennessee Heat Pump rebate	-250	$20
TVA Generation Partner	-1000	$80
TVA Energy Right	-500	$40
IRS 50% saver	-2000	$160
Federal Solar PV	-5,343	$427
Federal Solar water heater	-3100	$247
Federal energy retrofit 30% tax incentive	-1500	$120
Total incentives	-13,263	$1173
Incremental mortgage cost w PV with incentives	30,435	($2,430)
Net cash flow to consumer with site gen. with incentives		($417)

[a]Annual amortized cost assumes a 30-year mortgage at 7% interest.

6. CONSTRUCTION

6.1 RETROFIT HOUSE

6.1.1 Major Features

CC2 is a 2400-ft^2, two-story dwelling (Figure 35). The front of the house faces the south. The floor plan shown below has three bedrooms, bonus room, living-dining room, kitchen, laundry room, two-and-a-half bathrooms, and an attached garage. The walls and roof are made of typical 2 × 4 frame construction. The walls are rated R-13 with the attic ceiling at R-30. The slab is insulated along the perimeter with 1 in. thick × 24-in. horizontal R-5 extruded polystyrene on all sides except that adjacent to the garage (Figure 36).

Figure 35. Picture of south elevation of CC2 from the street in July 2009.

Figure 36. Extruded polystyrene placed along exterior foundation/slab.

A blower-door test of CC2 measured 3.43 ACH at 50 Pa on June 9, 2009. The HVAC unit is a 3-ton, SEER-16, single speed compressor unit in the sealed, conditioned attic (see Figure 37) with a dual-zone control system and mechanical ventilation with run time set to deliver an average of 30 CFM.

Figure 37. The three-ton HVAC unit in the conditioned, sealed attic space.

The water heater for the Retrofit located in the unconditioned garage is GE’s new Hybrid Electric Water Heater, commercially available from Lowes, Sears, and Home Depot (Figure 38). This Energy Star, 50 gal water heater has a COP of 2.35. More than 50% more efficient than standard electric water heaters, the device uses a vapor compression cycle to pull heat from the surrounding air to heat water in the tank.

6.1.2 Floor Plans, Cross Sections, and Elevations

6.1.2.1 Floor plan

Figures 39 and 40 show the floor plans for CC1 and CC2. The first level has an open floor plan with most of the structural walls along the perimeter. Note that the structural walls are indicated with a grey tone. The two-car garage is attached and unconditioned with a conditioned space above. The walls adjacent to the garage, the exterior walls of the garage, and the floor of the bonus room above the garage are insulated. However, the insulation between the garage and the bonus room is done poorly, with no blocking of likely uncontrolled air flow anywhere and a 12 in. air gap left between the floor of the bonus room and the top of the insulation installed right above the garage drywall in this 18 in. floor truss area.

Figure 38. The GE Hybrid Electric Water Heater in the unconditioned garage.

The second level consists of three bedrooms with two full baths. The bonus room above the garage can also be considered a bedroom, but is considered to be a home office for this analysis to be consistent with the average American’s standard occupancy of three bedrooms. Note the two-story entry near the staircase, where balloon framing was used to take advantage of the double-height ceiling. The framing for the tray ceiling in the master bedroom adds an extra expense to construction costs. This space also poses potential insulation problems with extra measures necessary to ensure even coverage in CC1. In CC2 this is not an issue because the insulation layer is up under the roof sheathing, not on the attic floor.

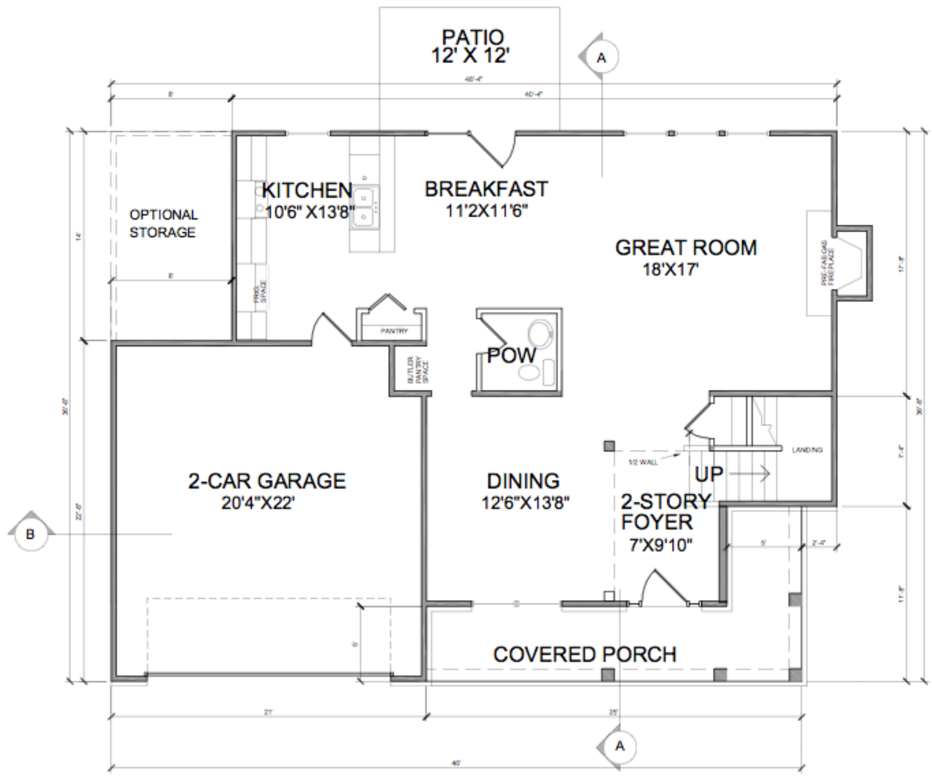


Figure 39. Ground-floor plan of CC1 and CC2.

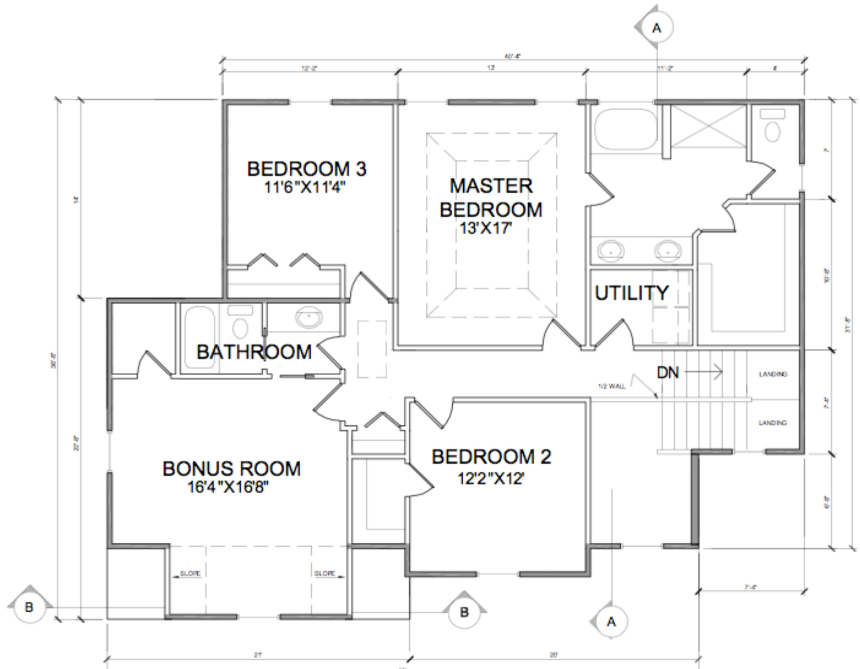


Figure 40. Second level floor plan of CC1 and CC2.

6.1.2.2 Elevations

Figures 41 through 44 show the four elevations of CC1 and CC2.

Figure 41. South elevation of CC1 and CC2. The area above the garage is a conditioned space, so extra attention is needed to ensure proper thermal air and moisture management between the garage and the space above it. No extra attention was given to this issue in either house, although the problems were carefully documented.

Figure 42. North elevation of CC1 and CC2, the ample window area provides an even balance of indirect sunlight into the main living spaces.

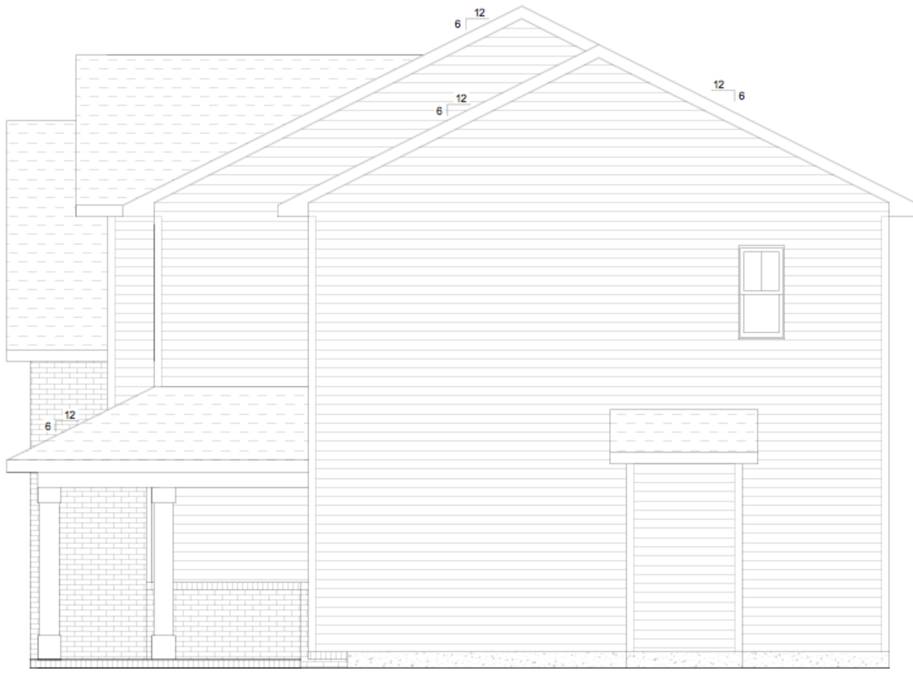


Figure 43. East elevation of CC1 and CC2. The front porch provides some shading to the windows in the first-floor living areas.

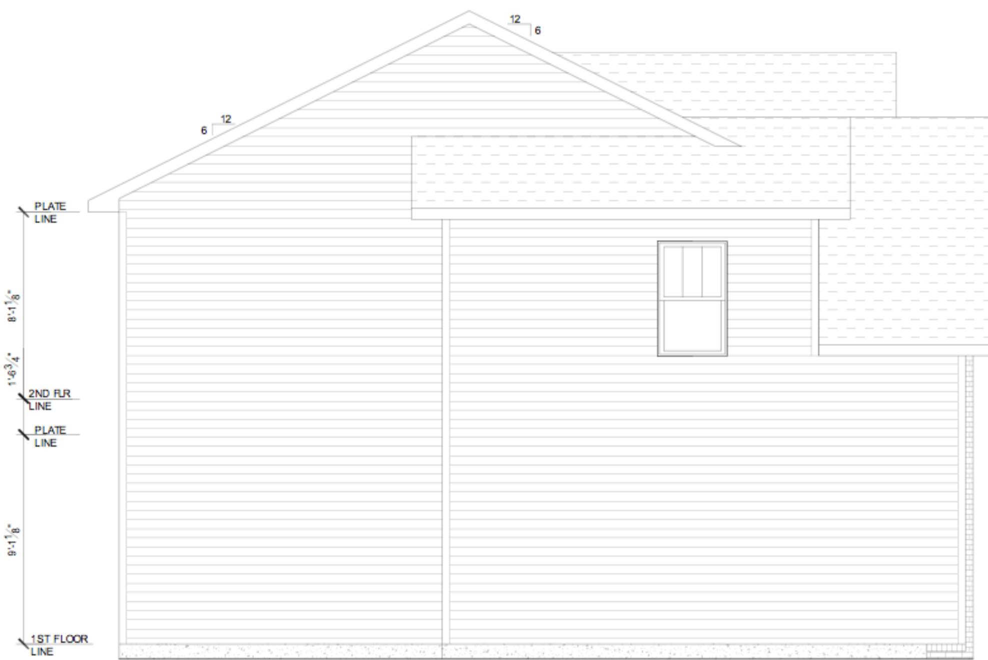


Figure 44. West elevation of CC1 and CC2. The lack of windows on the east and west elevations is to provide privacy, but because of the home's orientation also happens to minimize the harsh direct sunlight in the mornings and evenings that cannot be treated with overhangs nor shading devices of any kind. This same floor plan is also built in this subdivision with the heavily fenestrated back side facing west, which would have resulted in higher cooling energy needs relative to CC1.

6.1.2.3 Cross sections

Figures 45 and 46 show the cross sections of CC1 and CC2. The cross sections indicate the attic areas that were encapsulated into the conditioned space in CC2 by "cathedralizing" this space. The 18 in. floor trusses are primarily supported by the exterior walls except in conditions noted in the floor plans. Section B-B (Figure 46) shows the conditioned space above the unconditioned garage. Special attention should have been given to the installation of the R-19 batt insulation between the floor trusses to ensure proper coverage in both houses, but was intentionally not. The improper installation in CC1 was documented but left as it was to have a realistic house for comparison, and in the case of CC2 it was felt that in a typical retrofit, removal of drywall to properly back-seal and insulate these locations would be unlikely.

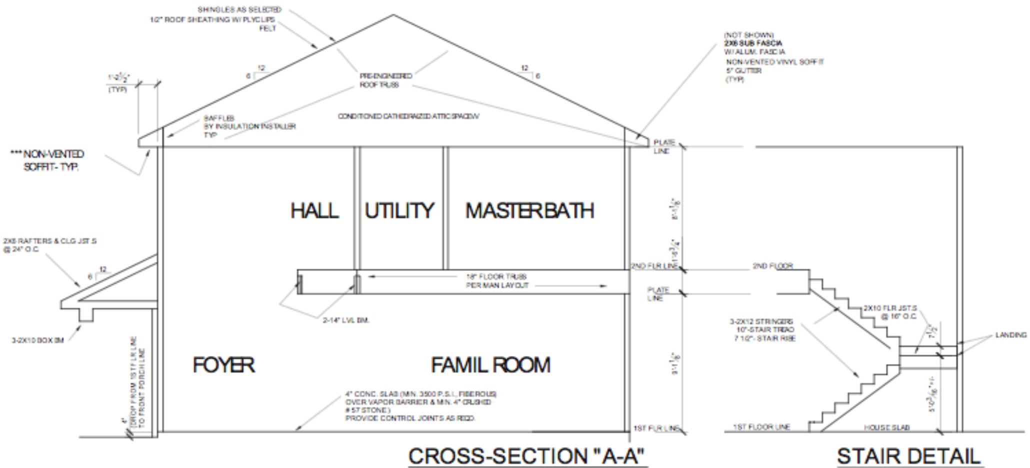


Figure 45. Section A-A and stair detail as marked on the floor plans.

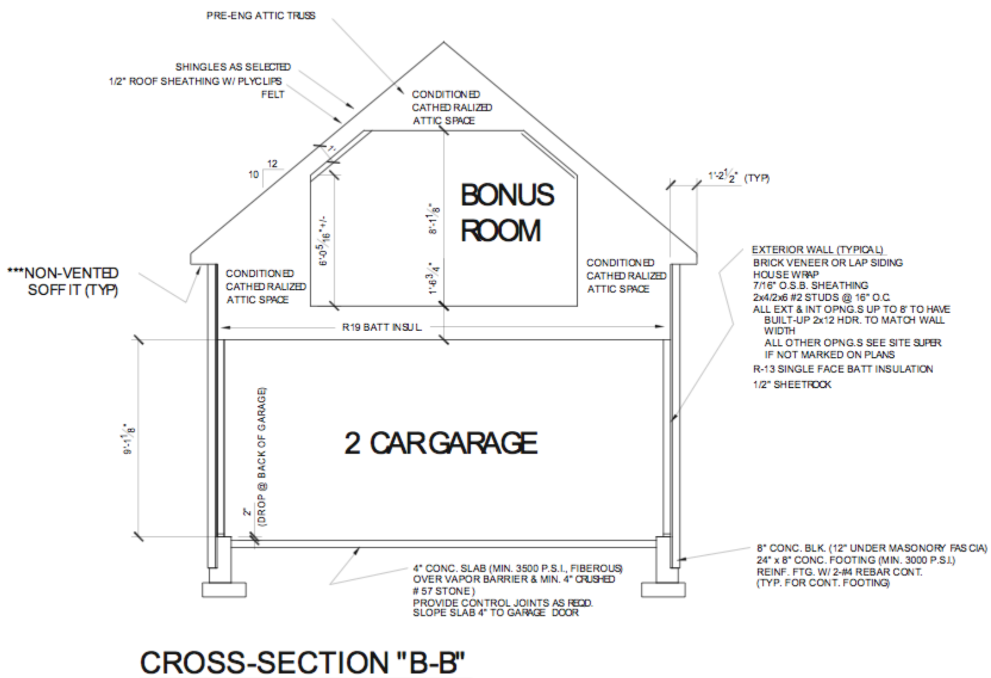


Figure 46. Section B-B as indicated on the plans.

6.1.3 Envelope Specifications and Performance

6.1.3.1 Foundation

Figure 47 shows the foundation detail of CC1 and CC2. A 1 × 24 in. extruded polystyrene board (XPS) is cut to wrap around the slab edge as well as horizontally under the slab except on the wall adjacent to the garage. The foam board seams are taped and mechanically fastened to the header block every 3 ft. The above-grade wall is attached to the foundation by anchor bolts through a 2 × 6 Borate-treated sill plate. During the slab pour the weight of the concrete occasionally opened a thermal short between the small horizontal strip of XPS resting on the shelf of the header block and the longer piece of XPS resting on the gravel. For this reason it is suggested not to use this detail, rather to place the longer piece of XPS vertically along the inside of the stem wall. This is what was done for CC3.

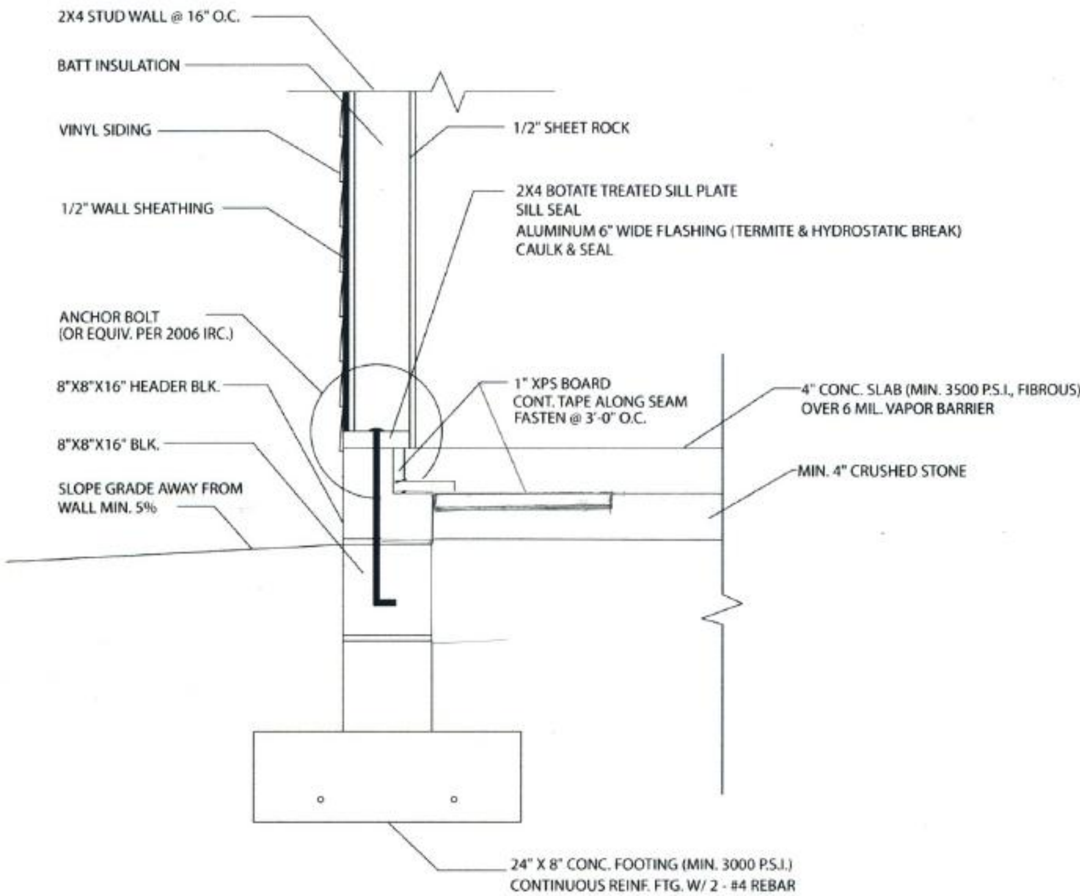


Figure 47. Foundation detail of CC2.

6.1.3.2 Walls

CC1 and CC2 are constructed with conventional 2 × 4 framing. The exterior walls are insulated with R-13 batt insulation with a framing factor of 0.23. Vinyl siding with a solar absorptance of 0.8 is the primary exterior finish. A few areas of the house, particularly the front wall of the garage and the lower level exterior wall below the front porch, use a brick veneer. In those cases 1 in. drainage planes are incorporated along with flashing and weep holes at the specified offsets. Balloon construction was used in the foyer to account for the double height of the entry rather than the platform construction used for the walls that are between levels.

Blower door tests to determine air-tightness of the houses identified excessive leakage around the patio and kitchen doors, which were tightened up, resulting in a June 9, 2009, test result of 3.43 ACH at 50 Pa.

6.1.3.3 Windows

The only retrofit to the vertical envelope on CC2 was an upgrade to U-0.35, SHGC 0.34 windows. No guidance was given to the window installers. In general the windows were installed using best practices. Both caulking and expanding foam were used around the windows prior to installing the drywall returns.

6.1.3.4 Sealed attic and roofing

CC2 roof includes sealing off the attic as a cathedralized, conditioned space as seen in Figure 37. The roof trusses are pre-engineered and sheathed with one-half-inch OSB plywood with ply-clips joining the seams. A layer of roofing felt is applied prior to application of the specified shingles. The attic is sealed with 2 in. XPS blocking along the soffits and insulated with BioBased® SPF insulation and topped with 2 in. of JM Spider™ to a total R-value of R-30.

6.1.3.5 Space conditioning equipment

Heating and cooling design loads were calculated using Manual J (eighth edition, Rutkowski 2004). The breakdowns for the heating and cooling design loads are shown in Table 18. These loads were cross checked with the EnergyGauge model for this house and were found consistent with the more detailed modeling imbedded in the DOE-2 model [which is the engine used in EnergyGauge version 2.6.06-09/-4/2007 (FSEC 2006)]. The total cooling load is estimated at 22,000 Btu/h. The heating design load is 33,000 Btu/h. With these calculations in hand the HVAC contractor elected to install a 3-ton split system.

Table 18. Heating and cooling design load breakdowns for the Builder House, calculated using Manual J

	Heating	Cooling
	Heat loss (Btu/h)	**Sensible gain (Btu/h)**
Vertical glass	5,654	6,504
Doors	1,034	368
Above-grade wall	10,766	3,941
Ceiling	2,429	1,352
Floor	4,728	213
Infiltration	6,630	1,447
Duct	0	0
Ventilation	1,815	528
internal gain	0	2,400
Latent heat	0	3,819
Totals	33,056	21,660

6.1.4 Equipment Specifications

6.1.4.1 SEER-16 air-to-air heat pump, ECM indoor fan, with two zones

The SEER-16 HVAC with single speed compressor is located within the conditioned attic space and serves both floors with a zone-control air-side system. It has an indoor ECM circulating fan and an SHR of 0.75 with a total cooling capacity of 36 kBtu/hr and HSPF of 9.5. The unit was sized at 2 tons according to Manual J, eighth edition, for the entire 2400-ft^2 house; however, based on Manual S guidelines and the HVAC subcontractor and the builder experience selected a 3-ton system, which compensated for the fact that the calculations do not take into consideration the typical construction practices in the area. The measured airflow with a flow hood is 989 CFM with two return registers, one centrally located on each floor.

6.1.4.2 Ducts inside the conditioned space

The ducts are all inside the conditioned space except for two supply run-outs in the garage ceiling leading to the bonus room above the garage. The ducts are zone-controlled to allow for separate operating conditions upstairs and downstairs. This allows for better management of the typically warmer upstairs spaces due to the rising of heat. The lower-level return vent is between the half-bath and the pantry, while the upstairs return vent is adjacent to the utility/laundry room in the hallway. Transfer ducts will eventually be placed between bedrooms and the hallway upstairs but were not installed during this first year test period. There is also no exhaust fan from the kitchen to the outside, which is considered another needed upgrade for proper moisture control.

6.1.4.3 Supply ventilation balanced with master bath fan exhaust

The mechanical fresh air system is a 6 in. duct running from a vent on the north-facing roof. A motorized damper is controlled with an "air-cycler" and a manual damper installed in series so that a planned average of 30 CFM could be pulled into the return side of the heat pump's indoor coil. Whenever mechanical ventilation is being supplied by the HVAC indoor fan the master bathroom exhaust fan is also turned on to help balance the air pressure inside CC2.

6.1.4.4 50 gal heat pump water heater

The GE Hybrid Electric Water Heater in CC1 is estimated to have a COP field performance of 2.35, which exceeds DOE's guidelines for Energy Star water heaters (2.0). This heat-pump water heater, which uses the heat in the surrounding air to heat water, is located within the unconditioned garage space. The Ge Geospring Water Heater[@] was installed in CC2 before it was commercially available (in March 2010), and has performed with a measured COP closer to 2.5 for more than a year. Figure 48 compares the energy consumption of the water heaters in the CC1 and CC2 on June 20, 2009, when the heat pump water heater achieved 63% energy savings in comparison to the standard unit in CC1 standard electric water heater with the same water consumption.

6.1.5 CFL

CC2 is equipped with 100% compact fluorescent (CFL) bulbs. The goal is to install all LEDs as they become available and affordable. Some ceiling fans more easily accommodate a compact fluorescent light than others. In CC2, fluorescent bulbs were used throughout the house, even around the bathroom mirrors. While these bulbs are now reasonably priced, more LED bulbs with even better lumens/watt continue to become available in 2010. A useful resource used to help select the

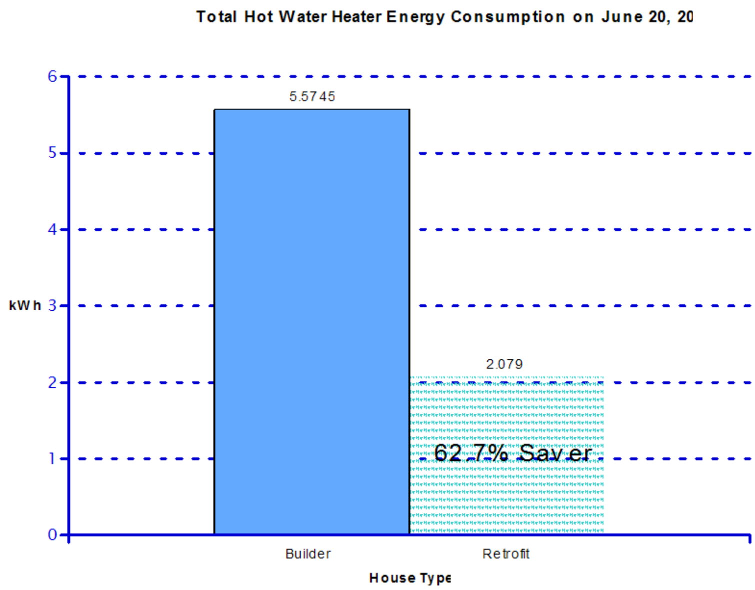


Figure 48. Comparison of energy consumption for hot water in CC1 and CC2.

lighting package in CC2 was the Energy Star Advanced Lighting Package specification web site: www.energystar.gov/index.cfm?c=fixtures.alp_consumers.

6.1.6 Energy Star Appliances

CC2 is furnished with all donated GE Profile™ appliances. GE supplied these for research purposes. These appliances are all running under simulated occupancy where the refrigerator and freezer doors open on a timed schedule, and the oven, dishwasher, clothes washer, and dryer run on timed cycles based on the day of the week. The program LabVIEW® by National Instruments controls the scheduling of all these appliances based on occupancy profiles established by BA (Hendron 2010).
Energy Star refrigerator, clothes washer, and dishwasher are part of the retrofit package. Refrigerators and clothes washer manufacturers have made significant energy savings improvements in the last decade. Future improvements in the retrofit package used in the research houses will include simulation of Energy Star entertainment center and home office equipment. For the first year of testing average energy consumption is assumed for these features. In the future LED or LCD screens rather than Plasma TVs and LED lighting will be installed and operated in a more energy conscious manner. The Energy Star ratings are updated periodically (available at www.energystar.gov), and options are often available that go beyond Energy Star standards.

6.1.7 Lessons Learned from Nonparticipatory Observed Construction

Spider needs to be sprayed perpendicular to the surface, if obstacles are in the way like ducts, shown in Figure 49, other methods were implemented; i.e., netting, hand packing; 2 in. of Spider gave us a total attic ceiling insulation level of in situ measured R-30. Other interesting lessons learned are shown in Figures 50–56.

Figure 49. Need 90 degree angle to spray Spider foam.

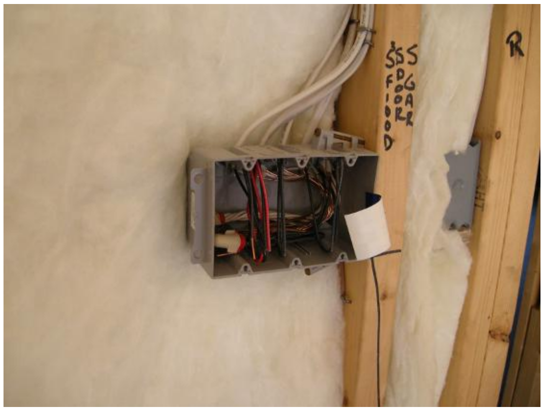


Figure 50. Switches on wall between garage; compressing insulation and no air seal.

Figure 51. Retrofit House batts not installed as well as CC1.

Figure 52. Front Porch Box Beam from the outside.

Figure 53. Box Beam runs right into the house.

Figure 54. Porch box beam on the inside; run right into the house.

Figure 55. Block cavity to prevent proper insulation in the wall.

Figure 56. Bath exhaust fans; painted open or shut in this house.

6.2 CC3

6.2.1 Major Features

The Campbell Creek CC3 south elevation is shown during construction in Figure 57. The back of CC3 faces 26 degrees west of true south.

Figure 57. The south elevation of CC3 during construction.

The floor plan has three bedrooms, two and a half baths, living room, dining room, kitchen, laundry room, and bonus room. The wall construction is optimum-value framing consisting of 2 × 6's on 24 in. centers, DOW SIS, 1 in. of closed-cell spray foam, and the remainder of the interior cavity shown in Figures 58–60 filled with Spider blown-in fiberglass.

Figure 59 shows the single laminated-veneer-lumber structural header, allowing longer window and door opening spans than standard dimensional lumber, as well as more insulation.

The cantilevered floor over the front porch was sprayed on all interior surfaces with at least 1 in. of foam and the remainder of this cavity space was filled completely with Spider (Figure 60) to avoid convective heat transfer. Also shown are the insulated header and wall cavities.

Figure 58. First-floor framing aligned with the second-floor trusses. Note single top plate.

Figure 59. Advanced header framing of CC3.

Figure 60. Insulation under the cantilevered floor.

Figure 61 shows the triple-pane windows used in CC3. These windows, provided by Serious Materials of California, have a U-value of 0.15 and SHGC of 0.26.

Figure 61. Triple-pane windows from Serious Materials.

6.2.2 Floor Plans, Cross Sections, and Elevations

6.2.2.1 Floor plans

Figure 62 shows the as-built first-floor plan for CC3. The kitchen, half bathroom, living room, utility room, and dining room are on the main level. Figure 63 shows the second floor's three bedrooms, two bathrooms, bonus room, and laundry room. The shaded areas on this drawing highlight the location of the added insulation and backing needed to seal the cavities behind the knee walls in the bonus room.

6.2.2.2 Elevations

Figures 64 through 67 show the four elevations of CC3 (produced by Larry Northcutt, River Chase Construction). CC3 has the same layout as CC1 except that two windows are relocated to the south (which saved 27 kWh/year). The additional 8 in. to the overhang on the south elevation saved 2 kWh/year. Exterior shading is a much smaller issue because of the high-performance windows on this house.

6.2.2.3 Cross sections

Figures 68 and 69 depict the cross sections of CC3. The structural support of the flooring on the upper level comes from the 20 in. deep engineered truss system. The trusses are constructed from 2×4-dimensional lumber and like the wall studs are placed on 24 in. centers and line up with each wall stud.

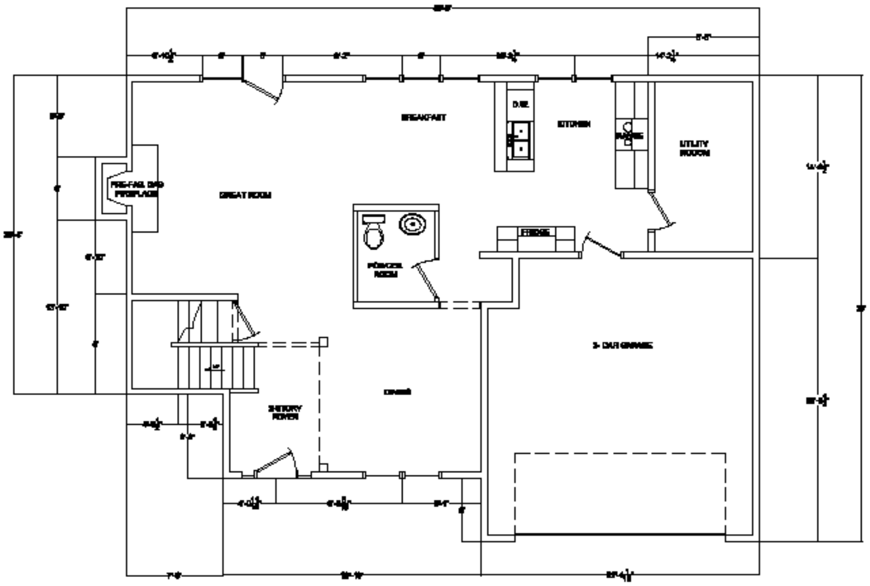


Figure 62. Main level CC3 floor plan.

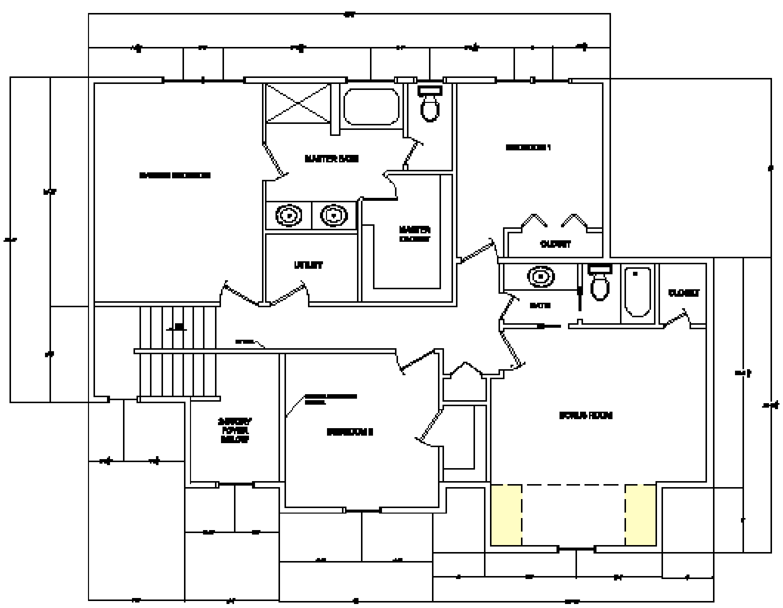


Figure 63. Second floor of CC3. Shaded areas are well-insulated knee walls to reduce the thermal convection from the unconditioned garage space.

Figure 64. North elevation of CC3. The space under the front porch is insulated with 1 in. of spray foam insulation and the remaining area with blown-in fiberglass (Spider).

Figure 65. South elevation of CC3. The solar thermal collectors for the solar water heater are on the left and the PV modules on the right of the south-facing roof. Most of the windows are on the south side, providing great daylighting. There remains sufficient space to double the number of 208-W PV modules on the roof to 24 (an increase from 2.5 kW_{peak} to 5.5 kW_{peak}).

Figure 66. East Elevation of CC3. One 3 × 5 window that was on the east side of CC1 design is moved to the south.

Figure 67. West elevation of CC3. One 3 × 5 window originally on the west side of CC1 design is moved to the south elevation.

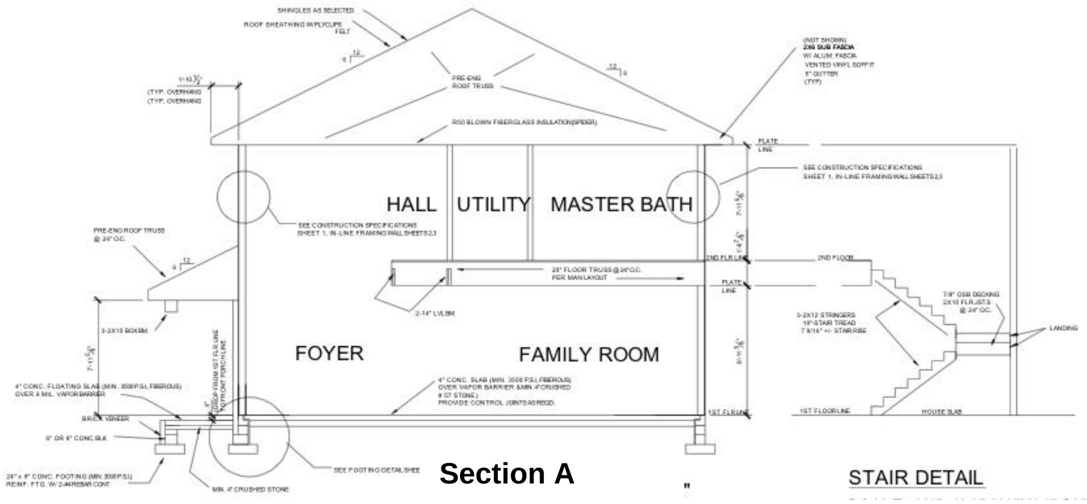


Figure 68. Longitudinal section through CC3.

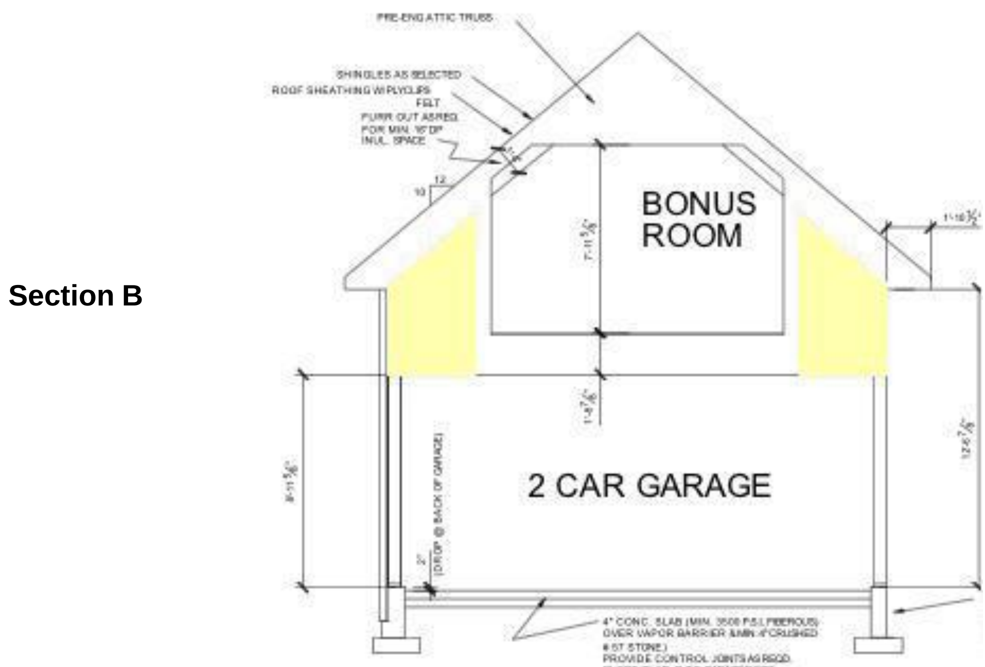


Figure 69. Basic building cross section.

6.2.3 Envelope Specifications

6.2.3.1 Foundation

Figure 70 illustrates the foundation detail used for CC3. A continuous 2 in. layer of XPS was placed on the inside of the foundation masonry wall from the top of the footing to the bottom of the slab, and another 1 in. layer continued from there along the slab edge and separating the slab from the header block.

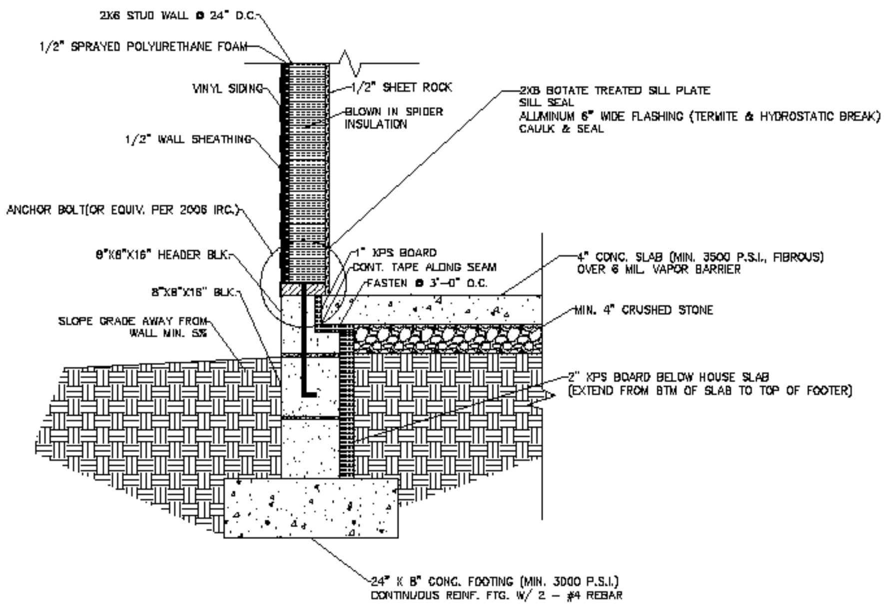


Figure 70. Foundation detail of CC3.

6.2.3.2 Walls—optimum-value framing R-22

Houses constructed of 2 × 6 framing at 24 in. centers allow for added insulation. Typically with 2 × 4 construction a whole-wall value of R-11 is attained, but with 2 × 6 construction a value of R-22 is achieved in this design. Two-stud corners not only allow for more insulation, but they also allow fewer thermal shorts than a three-stud corner. The insulation added to the wall cavities was 1 in. of BioBased closed-cell spray foam and then the remainder of the cavities filled with Spider™. Spider is a Johns Manville spray-in fiberglass insulation system. The advantage of this type of insulation versus batt insulation is that it minimizes insulation gaps and voids. With batt insulation, thermal shorts are easily created around receptacle and switch boxes, and around plumbing and wiring when not installed correctly. The sheathing used on the exterior walls is DOW SIS. With an R-value of 2.74 measured using ASTM C518 apparatus in the ORNL Buildings Technology Center, this structural insulated sheathing provides a greater resistance to heat flow than oriented strand board (R ~ 0.5). All seams were taped with DOW WEATHERMATE Construction Tape. DOW SIS also provides support for structural lateral bracing and transverse loads, and serves as a water-resistive and air barrier.

The installers that provided the insulation for CC3 are found at the following web sites:

- Johns Manville, http://www.specjm.com/index.asp
- DOW Building Solutions, http://building.dow.com/na/en/sis/index.htm
- BioBased foam, http://biobased.net/

6.2.3.3 Windows

The National Fenestration Rating Council recommends that windows for all-electric houses in mixed-humid climates and having energy costs around $0.09/kWh should have an R-value of at least 0.34 and a solar heat gain coefficient no higher than 0.33. The visible transmittance for the windows used in CC3 was 0.47. The warranty on the test house windows, which is not prorated, guarantees to the purchaser of windows installed as new construction or as replacements that Serious Materials, Inc. will repair or replace any defective materials for as long as the homeowner resides in the home. Serious Materials, Inc. (http://www.seriousmaterials.com/) specifically designed its 500-series single-hung vinyl windows with foam-insulated frames and triple-layer panes for the test houses. Serious Materials estimated installed cost of the 16-window package for CC3 at $10,000 in 2008. A more recent cost for the windows of $8.30/ft^2 above the cost of CC1 windows was obtained in September 2009. This is a $2,465 cost difference between the windows in CC1 compared to the triple layer window package in CC3. If interior window trim is used, jamb extensions should be ordered installed on the windows. This will speed the window installation on site.

The windows are installed after the DOW SIS sheathing is installed and the seams fully taped. The windows were installed as outlined below:

- Pan flashing installed at the base of every window and rough door opening.
- Flanged window is installed.
- Window centered in opening and shimmed, with close attention paid to the middle part of the window frame, so that shimming maintains uniform reveal of drywall returns.
- Window leveled and secured through the flange.
- Jamb flashings on both sides installed so as to cover the entire window flange.
- Top flashing installed over window weather lapping the jamb flashing.
- The interior between window and wall framing on all four sides sealed and insulated using low-pressure expansion foam or backer rod and caulk. This forms the air barrier at the window-wall interface
- The window installer on this project insisted that the windows be sealed at the bottom outside flange. This is not recommended practice since you want to enable any leaks into the window itself or the rough opening to drain to the outside.

6.2.3.4 Roof and ceiling—R-50

The roof of CC3 is constructed on a 2 × 4 truss system with three-quarter-inch OSB and LP Techshield Radiant Heat Barrier laminated to the underside. Next #30 asphalt-impregnated roofing paper was weather-lapped on the roof as soon as the sheathing was installed (ASTM 4869 Type II). The roofing system on CC3 is a 3-tab composite shingled roof. Figure 71 depicts the radiant barrier used under the roof sheathing. To help

Figure 71. LP Techshield radiant barrier roof sheathing.

limit solar gain through the top floor windows on the south elevation in the summer months, an extended 2-ft overhang was installed. The builder was told that there would be no extra cost for the longer roof trusses. The builder was billed for an extra $1000 truss package in CC3 compared to the Builder and Retrofit Houses. This did include the extra trusses used above the one-story, 112-ft^2 pantry off the kitchen.

Before ordering the truss system, design loads, roof transverse loads (live, dead, calculated wind load, and total), wind loads (basic wind speed, design wind loads for walls and roof uplift), and seismic design category must be provided. Also, it is imperative to include the weight of the solar modules for the PV system and the collectors for the solar hot water heater in the dead load calculations. In order to achieve true zero energy in the future, it may be advantageous to assume total south-facing roof area coverage with solar PV modules for dead load calculations.

6.2.3.5 Space conditioning equipment

CC3 in a mixed-humid climate is suitable for high efficiency split air source heat pumps, although 30% of the heat pump energy consumption was due to resistance backup heat in February 2010, 42% in January 2010, and 30% in December 2009. The unit operated the entire heating season at low compressor speed capacity. It is not clear how much more efficiently the unit would have operated if allowed to heat at the higher stage. A properly functioning air source heat pump would reduce the amount of backup resistance heat during the coldest months. The unit is going to be kept in for at least the beginning of the 2010–11 heating season to estimate how much resistance heating in the 2009–2010 season could have been reduced with the higher capacity available. A DC commutating fan motor could be used to meet ASHRAE Standard 62.2 ventilation air requirements using the low speed on the indoor circulating fan of the heat pump. This would be about a $500 solution. In this house a completely separate energy recovery ventilator with its own duct system is used for bringing in fresh air and recovering about 50% of the heat contained in the exhaust conditioned air. This is closer to a $3500 first cost solution. However eliminating the ERV would increase the resistance back up heating demand.

Manual J (eighth edition) was used to calculate the heating and cooling design loads for the whole house (Rutkowski 2004). Table 19 shows the breakdown of heating and cooling loads. One HVAC unit with a two-zoned distribution system was sized for the entire house. One thermostat-controlled motorized trunk served upstairs a second served the downstairs. These loads were cross-checked with the EnergyGauge model for this house and were found consistent with the more detailed modeling imbedded in the DOE-2 model, which is the engine used in EnergyGauge version 2.8.01-01/17/2009 (FSEC 2009).

6.2.4 Equipment Specification

6.2.4.1 2-ton SEER air-to air heat pump with two zones

CC3 is equipped with a 2-ton air source heat pump (Amana model# CAPF3636C6AA). The 2-ton system has a dual-speed compressor and a variable-speed electronically commuted motor (ECM), with an indoor fan. The unit sizing was found using the Manual J (eighth edition) load for the entire house of 2512 ft^2. The design heating load was 23,612 Btu/hr, and the design total cooling load was 15,729 Btu/hr. The estimated COP at peak was assumed to be 2.0 and the SEER, 16. In CC1 with 112 ft^2 less floor area a 2.5-ton heat pump is located in the unconditioned attic serving upstairs and a second 1.5-ton unit in the garage serves the downstairs.

Table 19. Heating and cooling design load breakdown for CC3, calculated using Manual J

	Heating	Cooling
	Heat loss (Btu/h)	**Sensible gain (Btu/h)**
Vertical glass	2,570	3,747
Doors	1,034	368
Above-grade wall	6,348	2,444
Ceiling	1,804	1,232
Floor	3,107	205
Infiltration	5,669	1,298
Duct	0	0
Ventilation	3,080	988
Internal heat gain		2400
Blower heat	0	222
Latent heat	0	2825
Totals	23,612	15,729

6.2.4.2 Ducts inside the conditioned floor joist space between floors

The blower equipment was located to allow for the shortest duct runs allowed by the fixed floor plan. All CC3 ducts are located in the conditioned space except for a 6-ft run going to the bonus room. This duct was well insulated and air sealed and resulted in zero Duct Blaster measured air leakage to the unconditioned space. The duct system in this house is zone controlled by an Aprilaire zoned comfort control system. Also, there is a Scuttle MERV 8 whole house air cleaner located on the return plenum in the utility room. This air cleaner removes airborne contaminants that enter the home through the return duct. The supply outlets are located near the exterior windows in the ceiling on the main level, and in the floor on the second floor. In the bonus room and each bedroom, 8 in. jump ducts have been placed in the attic connecting the often closed off bedroom space to the main hallway containing the single central return. Above the returns on the main and second levels, programmable thermostats were positioned. To complete this zone-controlled system, a 6 in. dump duct is run to the middle height of the two-story foyer. This duct always remains open to allow additional supply when only one of the zones calls for conditioned air.

ACCA's Manual D (ACCA 2006) was used in sizing the ducts for CC3. The modeled airflow in cubic feet per minute (CFM) for each room is shown in Figures 72 and 73. The airflow requirement for each room comes from the Manual J eighth edition room-by-room load calculation. The main supply trunk should be hard-piped and sealed with mastic. Insulated ducts lessen condensation risk. Short flex duct runs are used to connect the main supply trunk with floor and ceiling supply registers in every room, except in the laundry and bathrooms. In July 2010 the supply air flows were measured with a flow hood with the fan on high speed and both upstairs and down calling for conditioning. The air flow down stairs was only 5 CFM above the design and down 47 CFM below.

A Duct Blaster test was conducted on CC3 to measure the total air leakage of the duct system, along with the amount of air leakage to the outside. The results from this test showed 80 CFM of total leakage and 0 CFM of leakage to the outside. Total duct leakage of 9% is considered good, particularly when the ducts are inside the conditioned envelope as the case in CC3.

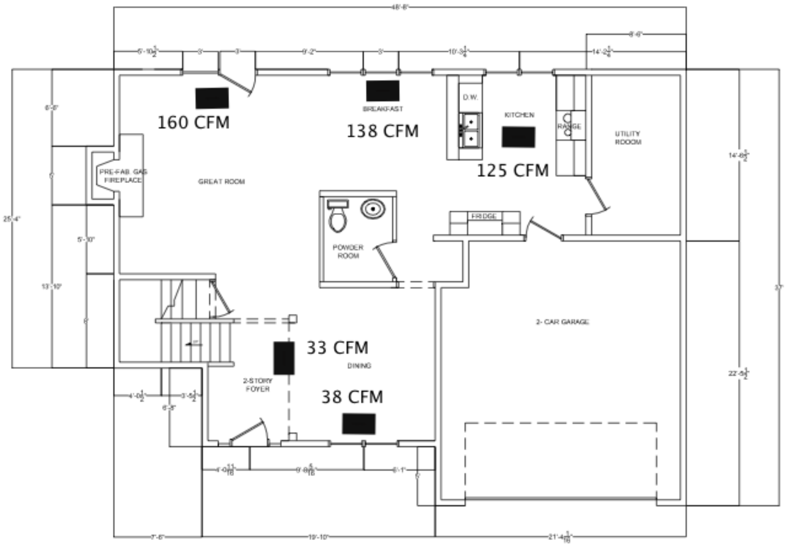


Figure 72. First-floor supply registers location and sizing.

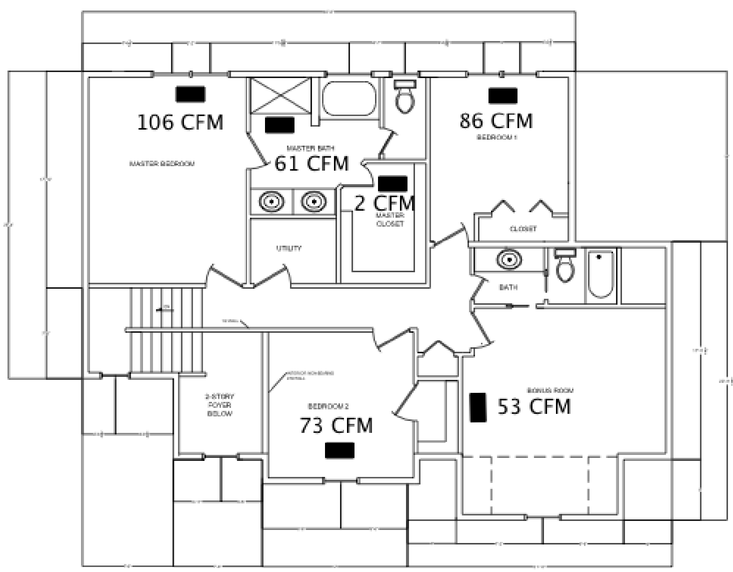


Figure 73. Second-floor supply registers location and sizing.

6.2.4.3   Energy recovery ventilator separate from heat pump space conditioning system

CC3 has an energy recovery ventilator that has six exhaust ducts and five supply ducts. The ERV is set to provide an automatic average of 30 CFM. Manual controls are located in each bathroom and the kitchen when additional ventilation is needed. The design was to meet the 2009 version of ASHRAE 62.2, which in the case of CC3 calls for the total ventilation and infiltration to be capable of providing 63.7 CFM. Figure 74 shows measured hourly average interior temperatures and relative humidity on June 19, 2009, for both floors. The average temperature for the month of February 2010 upstairs was 70.8ºF with a minimum of 69.9ºF. The average temperature for the same month downstairs was 70.9ºF with a minimum of 68.9ºF. These sensors are located near the thermostats on each floor. The HVAC system does an excellent job of maintaining the desired thermostat setting of 76ºF in the summer and 71ºF in the winter.

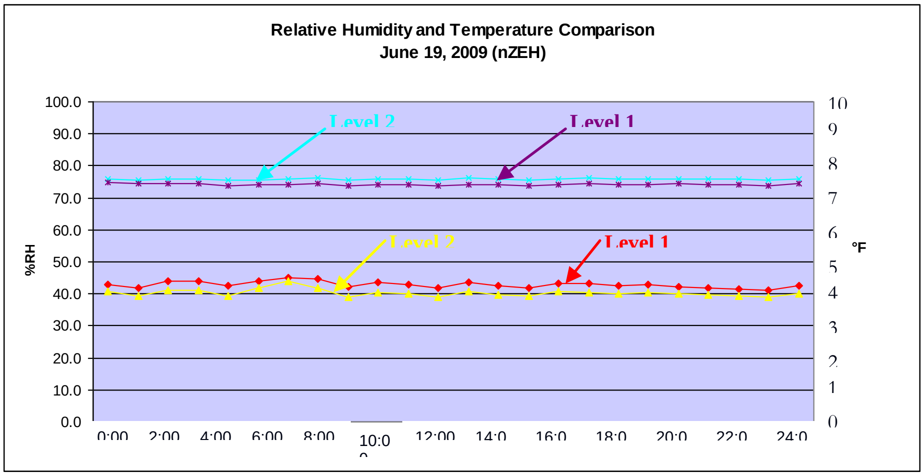


Figure 74. Interior temperatures and relative humidity for CC3 on June 19, 2009.

6.2.4.4 Drain back solar water heater with 85 gal storage tank

Figure 75 shows the solar water heater collectors that were installed on CC3 by Sustainable Future (http://sustainablefuture.biz/) of Knoxville, Tennessee. Including the cost of the 85-gal storage and drain back tanks, this system had a total cost of $10,333 in 2008. This two-panel system meets the Solar Rating and Certification Corporation standard. The two panels are angle mounted at 40^o to the composite shingled roof as shown in Figure 77. The roof slope is 23^o. Instead of using a smaller PV module to power the DC circulation pumps; this system uses a SolVelox heat exchanger pumping system to control the entire pumping operation. The storage tank used is an 85-gal electric water heater by Rheem Marathon, Model Number MR85245 B. This tank has an EF of 0.92.

Figure 75. Solar water heating system was installed by Sustainable Future, Knoxville, Tennessee.

6.2.5 100% Energy Star Lighting

In wood-frame construction, like that of CC3, the electric outlets are frequently a major residual leakage path after dedicated envelope air tightening. In CC3 the high-density spray foam insulation sealed the areas around the electric outlets.

CC3 is equipped with pin-based, Energy Star-rated, 100% florescent lighting. LED lighting was added after the first year test period in October 2010. For lighting fixtures, globe bulbs were used in the upstairs bathroom. Under-cabinet-mounted fluorescent lights are installed in the kitchen, which work very well. Even though CFL's are reasonably priced, LED bulbs have better lumens/watt and are expected to be available in the near future. The Energy Star Advanced Lighting Package specification (at www.energystar.gov/index.cfm?c=fixtures.alp_consumers) was used to assist the selection of a high performance lighting package. The actual cost of the pin-based fixtures and need for special orders from the builder's lighting supplies resulted in an actual incremental cost for lighting in this house of $2,506.38. This high cost actually made the efficient lighting not meet positive neutral cash flow. The incremental cost of CC2 lights compared to CC1 of $883.19, was assumed for the neutral-cash-flow analysis and still delivered the same lighting energy efficiency.

6.2.6 Solar Photovoltaic System

Homeowners are paid $0.12/kWh above the standard residential rate for all the AC solar power generated in a grid-tied arrangement by TVA's Green Power Switch Generation Partners program. A diagram of TVA requirements for a grid-tied PV system is shown in Figure 76. All interconnected equipment must be UL-listed to the appropriate standards. Figure 77 shows a picture of the 12 Sharp 208-W solar modules on the right side of the south-facing roof of CC3. There remains enough space on the south roof to double the solar PV capacity. The system must have a separate, accessible, and lockable disconnect along with a separate standard watt-hour meter (Figure 78). This meter measures the AC output of the generation system, and must be 1 ft from the billing meter. All items installed must meet the latest edition of the National Electrical Code (NEC) (ANSI/NFPA-70) compliance codes.

The 12-module PV system on CC3 was installed by Big Frog Mountain (www.bigfrogmountain.com/) on an aluminum UNIRAC rail system, bolted to 4-in.-high L-feet standoffs. These modules are designed for a maximum operating and storage temperature of 194°F. The 12 modules take up about 190–200 ft^2 of roof area. The manufacturer suggests a clearance of at least 4 in. under the module to permit air circulation and cooler operating temperatures. Elevated temperature not only lowers operating voltage; it

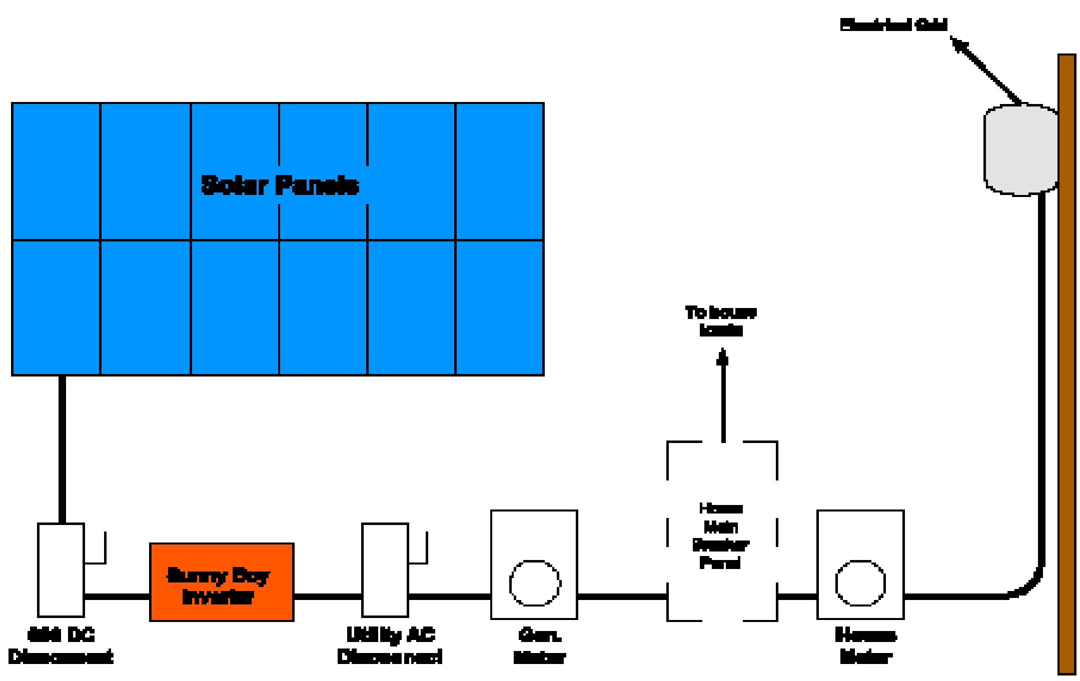


Figure 76. The arrangement required by the TVA distributor for tying solar systems to the grid.

Figure 77. Twelve 208-W PV modules installed on the south-facing roof by Big Frog Mountain.

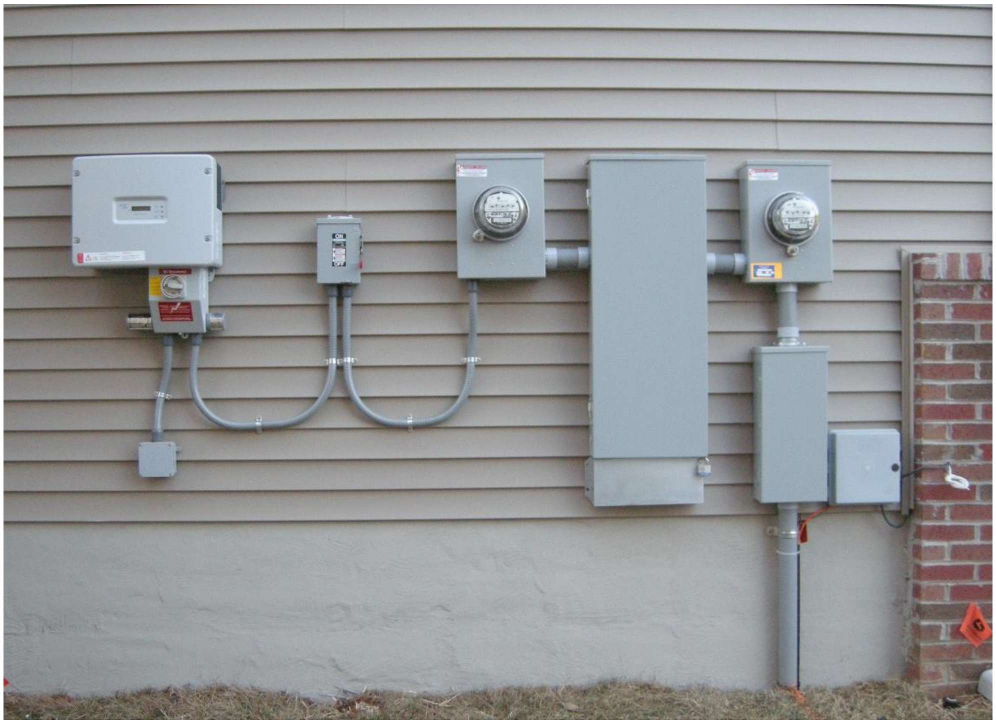


Figure 78. Dual meter, with Sunny Boy inverter on the far left.

also shortens service life. Each module is 37.5 in. × 61.8 in. and about 1.5 in. thick and weighs 40.1 lb. This amounts to an added dead load to the roof of 721 lbs. The south-facing roof of CC3 has a total area of about 796 ft^2. The added roof dead load attributable to the solar modules amounts to less than 1 lb/ft^2.

The January 2009 distributor cost for 12 Sharp 208-watt modules was approximately $10,400. The Sunny Boy 3000US/240 SBC w/LCD Inverter, AC and DC cutoffs, and module roof mounting hardware was $3,001.24, the module installation, $2002.41; and the electrician cost to wire the system and install the whole-house cutoff, $2,405.00. The total equipment and installation cost was $17,808. The prices of the PV modules and inverters are expected to fall in the future.

6.2.7 Energy Star Appliances

The dishwasher, refrigerator, and clothes washer in CC3 are all Energy Star® label, but the other appliances are not yet Energy Star-rated. In the last few years there has been several energy savings improvements made on appliances. If considering an entertainment center or a home office, look into Energy Star® rated equipment. Many manufacturers exceed the Energy Star® standards.

CC3 is furnished with the higher end GE Profile Energy Star® appliances that were available. Model numbers, energy guide label kWh and retail cost are provided in Table 20. GE donated these appliances for research purposes. These appliances are operated in accordance with the BA profile of three-person occupancy. The refrigerator doors are robotically controlled to open and close automatically in response to a daily schedule representative of typical users as defined by GE-provided market data. The dishwasher, clothes washer, oven, and clothes dryer are also simulated through various cycles. A program written with National Instrument's LabVIEW controls all of these appliances.

Table 20. General Electric appliance model numbers

Appliance	Retail ($)	Energy Guide Label (kWh)	Manufacturers description	House3 model #
Washer	$1,299	191	GE Profile™ 4.2 IEC Cu. Ft. Colossal Capacity Frontload Washer	WPDH8800J0WW
Dryer	$1,099		GE Profile™ 7.5 Cu. Ft. Colossal Capacity Electric Dryer	DPVH880EJWW
Refrigerator	$3,999	555	GE Profile™ 23.2 Cu. Ft. Stainless-Wrapped Side-by-Side Refrigerator	PSFW3YGXCGSS
Dishwasher	$1,549	324	GE Profile™ Dishwasher with SmartDispense™ Technology	PDW9980N20SS
Range	$1,849		GE Profile™ 30 in. Free-Standing Double Oven Range	PB970SM2SS
Microwave	$669		GE Profile Spacemaker® 2.0 Cu. ft. Over-the-Range Microwave Oven	PVM2070SM1SS

6.2.8 Lessons Learned and Relearned from Designing and Constructing a High Performance House in a Builder Spec Development

This section describes 12 lessons learned and relearned from the experience of designing and constructing a high performance house in a builder spec development. This was a group effort that grew from the experiences and vision of not only ORNL but also the builder, John Kerr, who had been a very successful builder for 20 years and a priceless sounding board and continual reality check as to the importance of keeping incremental construction cost marketable. His reputation is that of a very good builder who delivers a house at competitive rates in the Knoxville market. The author's conversations with many of the surrounding neighbors to the three research houses confirmed that he took care of call backs quickly and for the most part all were happy with their new home. In 2008 the majority of those looking for houses in this market were not asking for energy saving features beyond those required by local code, which was 2003 IECC at the time. Tim Carroll, owner of Carroll Heat and Air, served as the HVAC subcontractor for all three research houses. He felt that ERVs would eventually be required by local code and encouraged the design team to pursue a completely separate ERV system for CC3. Jody Webb, plumber subcontractor, felt that the future was heading toward more separate gray water collection systems with the pending water shortages and encouraged the design of the house to include separate gray water and black water collection in CC3. The TVA program manager David Dinse also provided considerable input and participated in regular planning meetings throughout construction of CC3 with a keen interest toward the impact of the design on not only annual energy usage but also peak. Dave also continuously reminded the authors not to alter the normal construction practices for all of CC1 and most of CC2 to observe current local base cases. Quietly documenting the good, the bad, and the ugly was extremely insightful for setting the design of CC3.

Lesson 1. OVE framing requires successful communication between the designer and the framing crew

The successful construction of cost savings from optimum value engineered framing requires the framing crew that has never built an OVE system to study and understand the design drawings, which show the details of stacked framing, 2-stud corners with drywall clips, single top plates with the use of 4 × 6 in. nailing plates, header design differences for spans of less than 3 ft (single regular 2 × 10 header on the outside), and 3 to 6 ft span openings (single LVL header on the outside). Uniformly applying the principle design strategies of OVE framing break down on 2 story balloon framed walls unsupported by the floor system. Straight and true 18 ft long, 2 × 6 boards are hard to find, are expensive, and usually do not provide sufficient structural support.

Lesson 2. Constructible insulated slab edge insulation

Cost effective slab edge insulation with no thermal shorts grew from the observation there is an urban legend that slab edge insulation was not needed adjacent to the garage, since it was not as cold in the winter as the outside. Secondly, it was observed during construction that when horizontal slab edge insulation is used between the gravel seam and the poured concrete pad, as shown in Figure 36 that occasionally the weight of the concrete and lack of carefully placed gravel near the foundation stem wall results in an insulation gap as shown in Figure 79. This lead to vertical placement of the XPS as shown in Figure 70.

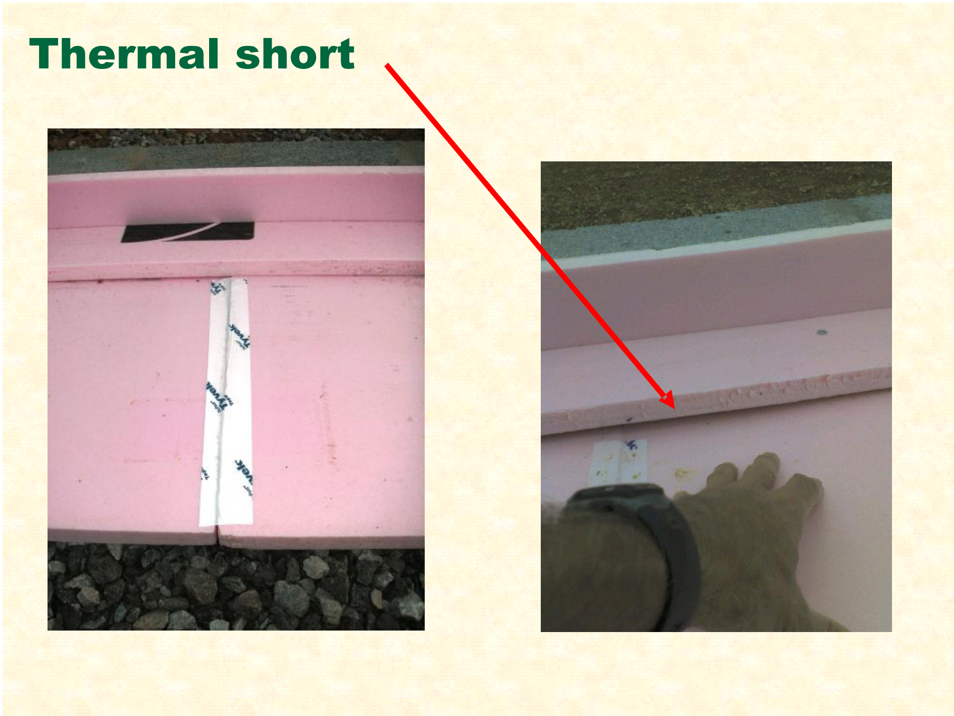


Figure 79. Slab insulation thermal short.

Lesson 3. Design and install a continuous air barrier; might just include a sill seal sandwich, knee wall blocking, behind tub and shower blocking, and second drywaller trip to block the common garage—house walls and backup wall air barriers.

Figure 80. Sill seal sandwich step one.

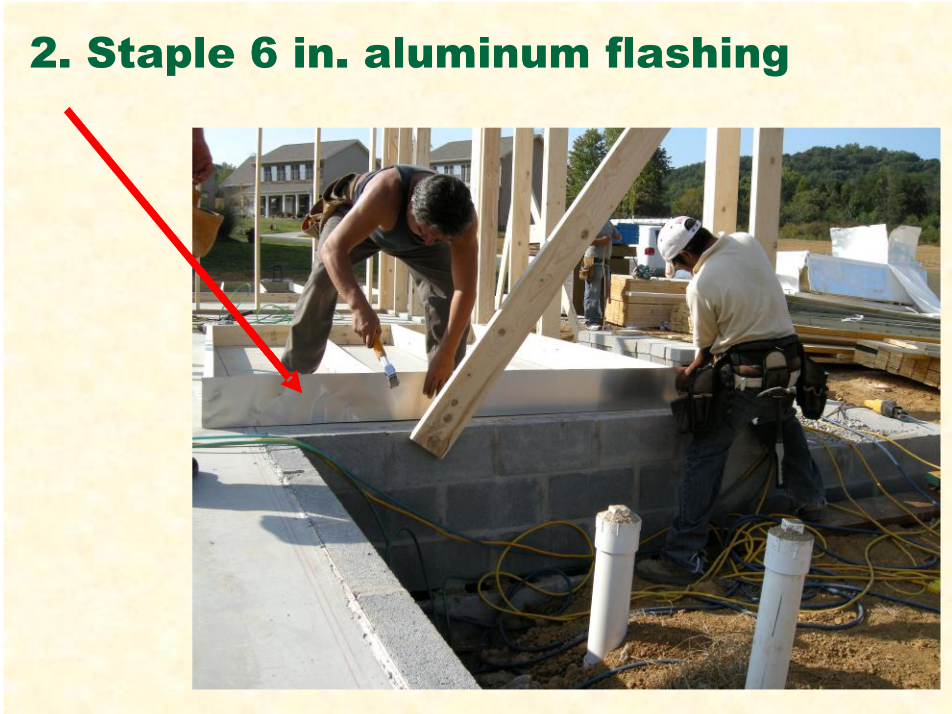


Figure 81. Sill Seal Sandwich step 2.

Figure 82. Sill seal sandwich step 3.

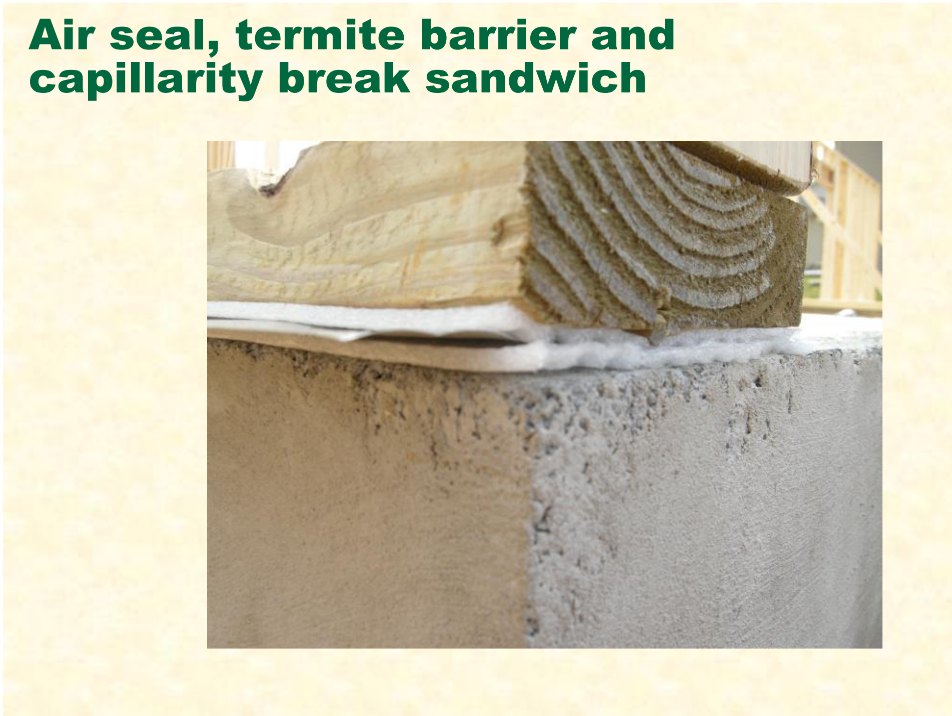


Figure 83. Sill seal sandwich.

Figure 84. Wall base plate flashing kickout.

Knee walls; Classic over sight

Figure 85. Knee wall begging for backing.

Bonus knee walls all foamed up ready for Spider

Figure 86. Foam sealed knee wall.

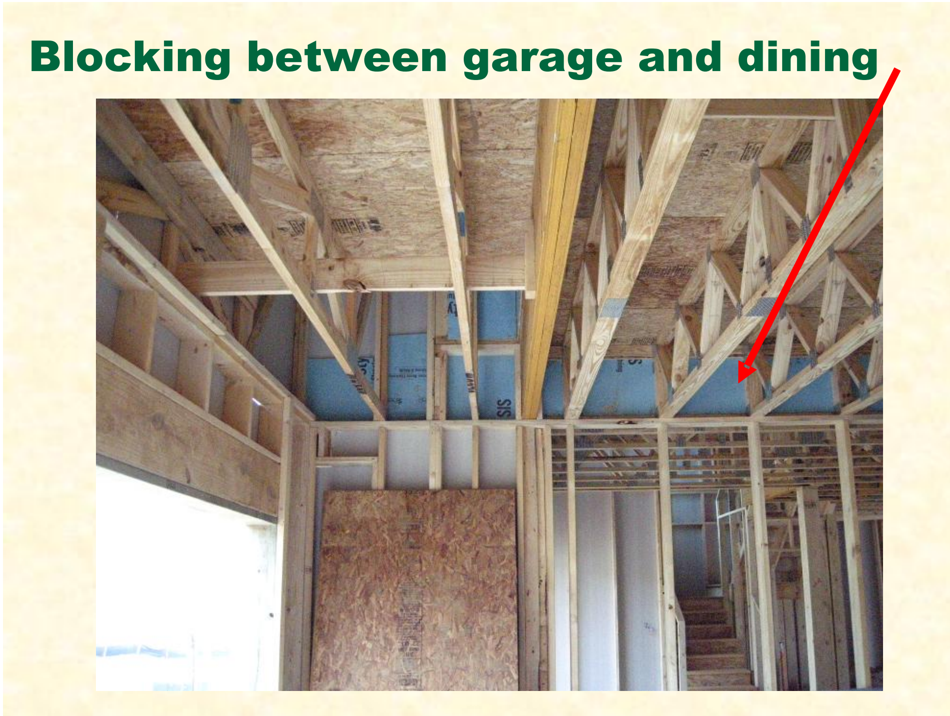


Figure 87. Floor joist blocking between the garage and conditioned space.

Lesson 4. Uniform and continuous insulation layer; might include a raised attic roof truss, foam in hard to reach places, redesign of structural solutions in complex roof systems, extended cathedral ceiling cavities.

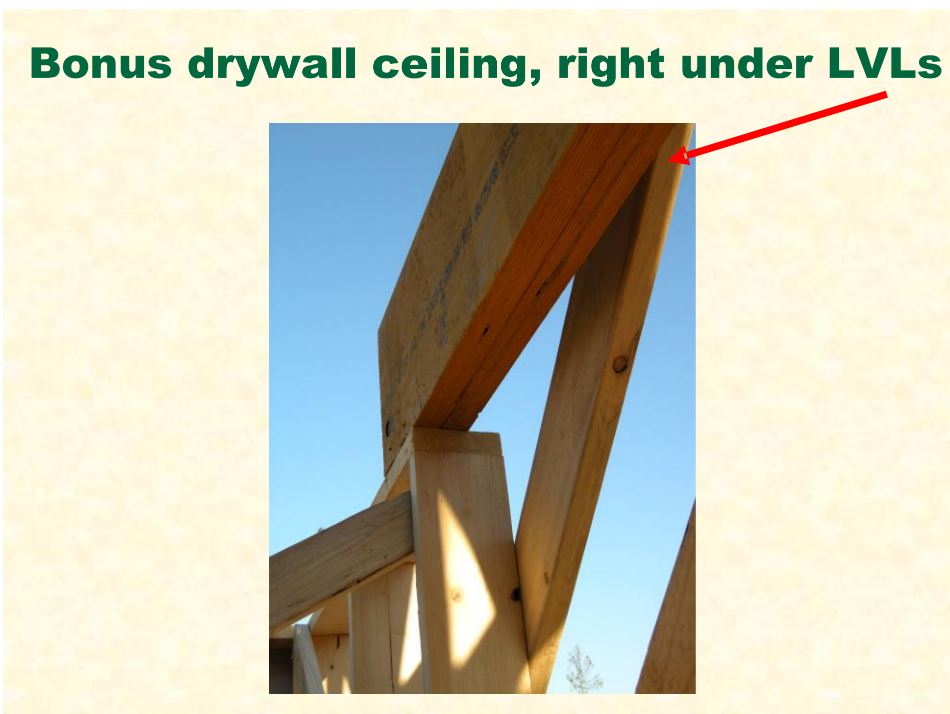


Figure 88. Hard to insulate thermal short caused by structural detail.

Figure 89. Foam helps in hard to get at potential air leakage point in Bonus room.

Figure 90. Cathedral ceiling cavity depth extensions allow for greater insulation thickness.

Lesson 5. If a fireplace is a must to sell the house than air seal and insulated right.

The construction sequence with the gas fireplaces is that the fireplace subcontractor comes in before the insulators. He installs a sheet metal fire block at the top of the fireplace chase before any insulation is installed. This sheet metal is not installed airtight. Once the insulators do arrive, they insulate both the fireplace chase except for the roof and the wall between the living room and the fire place chase. This leaves an uncontrolled air leakage path through the fireplace chase ceiling, through the leaky fireplace and into the living room. Several of the surrounding homeowners complained about the thermal discomfort in front of their fireplaces in houses similar to the Builder and Retrofit Houses.

Figure 91. Fireplace chase needs added airtightness and insulation consideration.

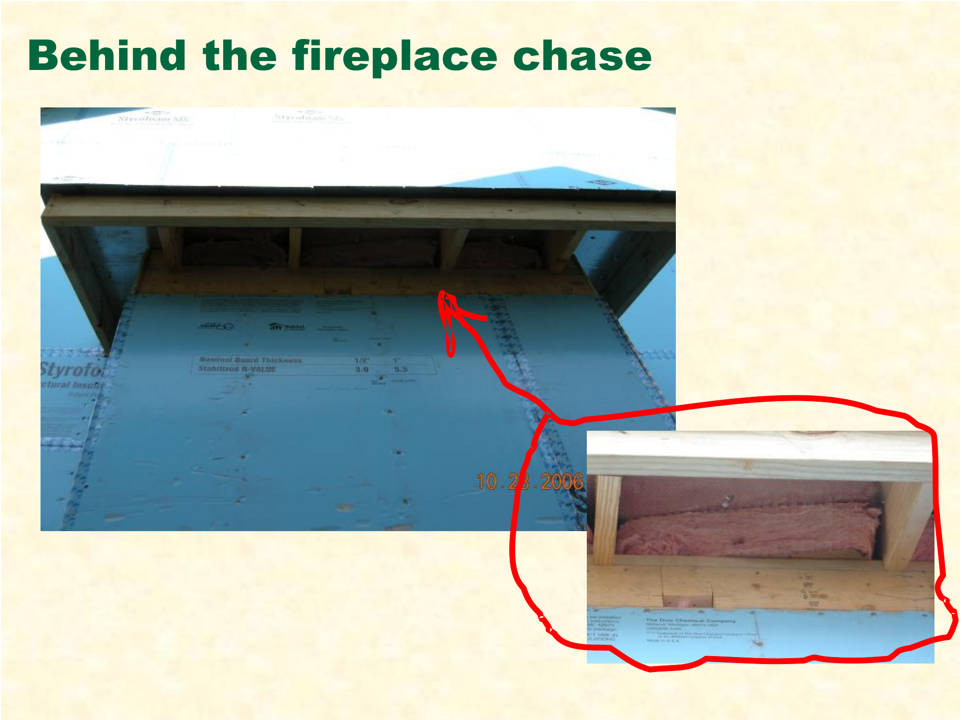


Figure 92. Looking up into the soffit of the fireplace chase with added insulation.

Lesson 6. Avoid the HVAC return register air gap.

Figure 93. Very common return duct installation bad practice.

Lesson 7. Optimum value floor joist duct design required.

Figure 94. Ceiling between floors coming out of the mechanical room in CC3.

Lesson 8. Backup insulating and air sealing duct runs in unconditioned spaces.

Figure 95. Proper insulation and air sealing in bonus room floor above the garage.

Lesson 9. Jump ducts yes but avoid air leaks into unconditioned attic spaces and discontinuity in uniform attic floor insulation.

Figure 96. Jump ducts relieve unwanted pressure imbalance when bedroom doors are closed.

Lesson 10. ERV hidden benefit could be to eliminate bathroom fan call backs.

Lesson 11. Plan for the future, waste heat recovery, grey water recovery and reuse, solar thermal, solar PV, additional electric circuits.

Lesson 12. Don’t forget about drywall stocking window.

7. THE MAKING OF A "ROBO-HOUSE"—OCCUPANCY SIMULATION

Comparing energy efficiency of 3 houses with almost identical floor plans cannot be done unless energy is being used. An un-occupied house is not sufficient to determine the energy efficiency of envelopes and technologies in the research houses because occupants add sensible and latent heat to the space that put a load on the HVAC system. Appliances, plug loads, and lighting also add sensible heat to the space as well as use energy. Some appliances such as washers, dryers, and dishwashers also add latent heat to the space. Occupants also create a load on the domestic hot water (DHW) system when showers or baths are taken and hands are washed.

If three families were put in these houses comparison would be difficult because each family would have different living habits. The answer to this problem is to simulate that people are living in the houses. The researchers have automated DHW draws, plug load draws, appliance use, and lighting use based on the BA Research Benchmark Update December 2008. In Table 21 details describing how this simulated occupancy is achieved is shown. The DHW is set at 60 gal/day for the shower only and it is mixed water temperature at the shower head recorded only when the shower temperature reaches 105°F.

Table 21. Simulated occupancy details

System	Control	Use CC1	Use CC2/CC3
Fridge Openings	LabVIEW®	24/day (12 sec each)	24/day (12 sec each)
Freezer Openings	LabVIEW®	6/day (12 sec each)	6/day (12 sec each)
Washer Cycles	LabVIEW®	6/week	6/week
Dryer Cycles	LabVIEW®	5/week	5/week
Dishwasher Cycles	LabVIEW®	6/week	6/week
DHW	LabVIEW®	60 gal/day	60 gal/day
Lighting Load	ZWave®	6597 W/day*	1505 W/day**
Oven	LabVIEW®	200 min/day	200 min/day
Plug Load (Sen. Heat)	ZWave®	8829 W/weekend day 8253 W/weekday***	7853 W/weekend day 7277 W/weekday***
Latent Load	LabVIEW®	NA	NA

* = 100% Incandescent, **= 100% CFL, ***=difference between these values for the different houses is because for CC2 and CC3 Plug in lights are 100% CFL (part of MEL load) and CC1 they are BA typical (84% incandescent and 16% CFL)

Table 21 describes the systems that are simulated and the controls used to automate the simulation. Two separate systems are used, a custom LabVIEW® virtual instruments, which uses a digital USB DAQ device to control relays at the different appliances to turn them on and off and control settings. A ZWave® based control system was installed by the local company Simple Controls, this system controls the lighting and plug loads.

An ftp server run from CC1 serves both the LabVIEW® and ZWave® systems with simulated occupancy profiles every night. This feature makes it very simple to populate both systems in all three houses with new profiles.

In March 2010 an alarm system was implemented in the research houses, which sends emails if values from data are out of a user defined range (see Table 22 and Figure 97). This was implemented to help catch failures of the simulated occupancy controls in a timely manner. Some alarms check data every hour and others once a day. The alarms were programmed in RTMC Pro software from Campbell Scientific. The program runs on the CC2 laptop as a server and continuously monitors data from all the houses. If an alarm is out of range an email is sent to Tony Gehl, Philip Boudreaux, and John Miller. Alarms can be seen by anyone by logging into the following website http://cchouse2.dyndns.org/.

Table 22. Alarm details

				CC1		CC2		CC3	
		Units	**Type of Meas.**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
LabVIEW	**Shower**	gal	Daily Total	55	62	55	62	55	62
	Range	Wh	Daily Total	1550	1625	1400	1550	1500	1550
	Dishwasher	Wh	Daily Total	700	925	975	1150	800	1250
	Washer	Wh	Daily Total	200	300	400	600	400	600
	Dryer (Sat, Sun)	Wh	Daily Total	7250	9000	5400	6750	5400	6750
	Dryer (Wed)	Wh	Daily Total	4125	5000	3000	5000	2500	3500
Simple Control	**Upstairs Heater**	Wh	Daily Total	3000	4000	2900	3500	2900	3500
	Downstairs Heater	Wh	Daily Total	6500	8000	6000	7000	6000	8000
	Bath Lights	Wh	Daily Total	2200	3050	790	950	250	375
	Bedroom Lights	Wh	Daily Total	1200	1375	400	550	350	475
	Gar and Ext Lights	Wh	Daily Total	700	900	300	550	175	273
	Level1 Lights	Wh	Daily Total	2400	3600	800	875	775	975
	Upstairs Heater	Wh	Hourly Total	50	300	50	300	50	300
	Downstairs Heater	Wh	Hourly Total	150	650	150	550	125	550
	Fan Tech	Wh	Daily Total					400	1100
	Master Bath Fan	cu. ft.	Daily Total	39000	50000	800	22000		
	DHW - Shower Temp	F	Daily Average	90	120	90	120	90	120
	LVL1 Temp	F	Daily Average	68	79	68	79	68	79
	LVL2 Temp	F	Daily Average	68	79	68	79	68	79
	NI-DAQ Monitor		counts	>	5	>	5	>	5

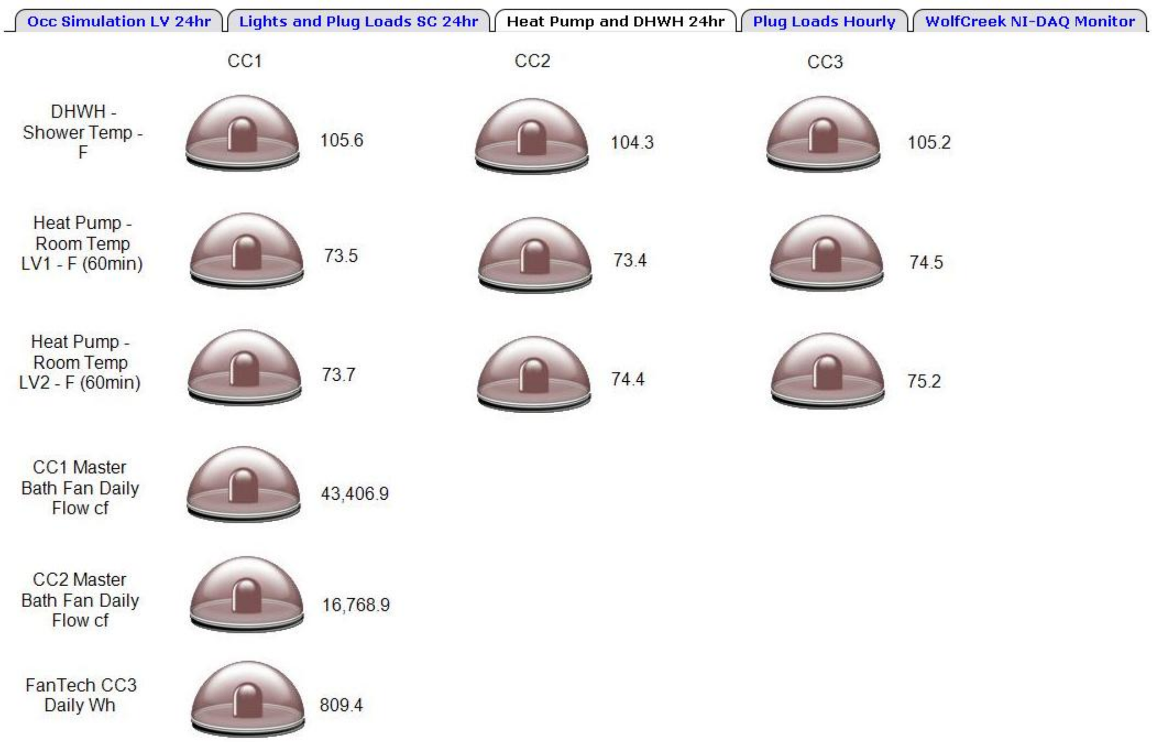


Figure 97. Screenshot of alarm front panel for heat pump and domestic hot water heater (DHWH) 24 hr.

Following is a breakdown of each system with details on building the profile and control schemes.

7.1 DOMESTIC HOT WATER

According to the BA Research Benchmark Update December 2008, the DHW usage of showers, baths, and sinks can be computed with the equations in Table 23.

Table 23. Water usage/day for end uses

End use	Water usage (gal/day)	Water usage for 3 bedroom	Average temp. (°F)
Shower	$14 + 4.67 \times N_{br}$	28.01	Mixed—105
Bath	$3.5 + 1.17 \times N_{br}$	7.01	Mixed—105
Sinks	$12.5 + 4.16 \times N_{br}$	24.98	Mixed—105

With three bedrooms in each of the research houses the total daily 105°F water use should be 60 gal. The daily use pattern can also be computed from the BA Benchmark. In Figure 98 the dishwasher and clothes washer daily use pattern is subtracted from the total DHW use pattern. The resulting black curve is the usage pattern that can be used for the shower to simulate showers, baths and sinks in the research houses. Because there was concern that very small draws of hot water would not tax the hot water heater sufficiently a revised use profile was created, see Table 24.

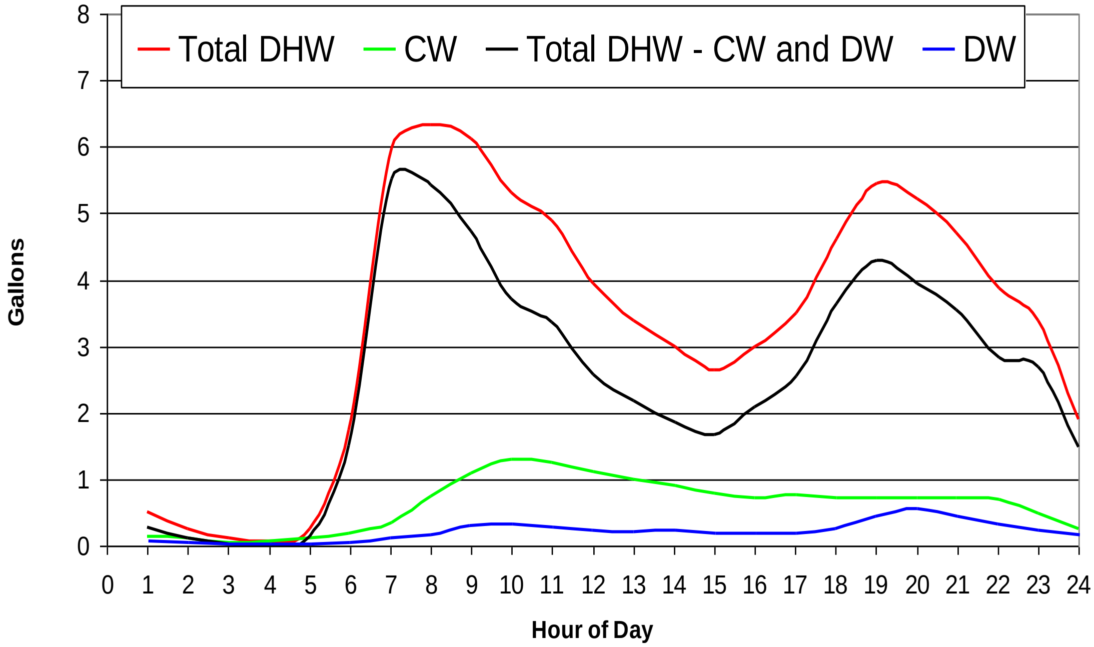


Figure 98. Net water use profile for Campbell Creek Houses.

Table 24. Revised water use schedule

Master shower start	Master shower gallons
7:00:00	20
8:30:00	5
12:00:00	5
17:00:00	15
21:00:00	15

The shower control is shown in Figure 99. A solenoid is used to turn the water flow on or off, a flow meter is used to monitor the flow rate and a thermister is used to measure the water temperature. Practical aspects of maintaining this system include adjusting the temperature of the mixing valve in the shower as the temperature of the cold water coming into the house changes with season. Also the flow seems to fluctuate so occasionally the times the shower runs is changed to try to keep a constant 60 gal dumping each day.

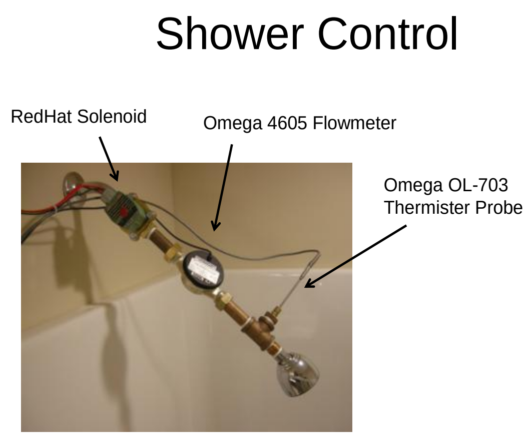


Figure 99. Shower control.

ORNL plans on adding in a temperature controller on the hot water supplied to the shower in CC3. ORNL speculates that at times a higher water temperature was being provided to the shower in CC3 than the other two houses.

7.2 CLOTHES WASHER AND DRYER

According to the BA benchmark model, the clothes washer cycles per year (CWC) can be given by Eq. (1).

$$CWC = (392) * \left(\frac{1}{2} + \frac{N_{br}}{6} \right) * \left(\frac{12.5 lbs}{W_{test}} \right) \tag{1}$$

In Eq. (1), N_{br} is the number of bedrooms and W_{test} is the maximum clothes washer test load weight found in *10 CFR part 430, Subpart B, Appendix J1*" and is a function of washer capacity. According to *Title 10 Code of Federal Regulations part 430, Subpart B, Appendix J1*, if house 1, 2 and 3, have washer capacities of 4.0, 4.2 and 4.2 cu. ft. respectively then W_{test} is 15.4lbs for all washers (Table 5.1, 2). Since all three houses have 3 bedrooms CWC is 318. If washers are run twice a day, 3 days a week then a CWC of 312 can be reached. A dry usage factor (DUF) of 0.84 can be applied to CWC to compute the dryer cycles per year (DC). In this case DC = 267. If the dryer is run once a day for five days a week then a DC of 260 is met. Table 25 describes the profile for washer and dryer control.

Table 25. Profile for washer and drying control

Washer start	Wash days	Dryer start	Dry days	Dryer mist (min)
7:00:00	4	19:00:00	4	240
17:00:00	4	9:45:00	17	192
8:00:00	17	11:35:00	17	157
10:00:00	17			

[a]Sunday =1, Monday=2,….Saturday=7.

Each house is equipped with GE washer and dryers. The mode selection on washer and dryer is not altered. The computer control (LabVIEW® and relays connected to washer and dryer control board) simply initiates a wash or dry cycle by turning on the appliance and issuing a start command. All user input for type of cycle is set manually at the appliance front panel. These become the defaults for all automated laundry cycles until we desire to change them again (manually)

Currently the washer controls in CC1 are set to:

- Load size = Large
- Load type = Heavy cottons
- Wash temp = Hot/Cold (Hot wash/cold rinse)
- Soil level = Normal *(options are extra light, light, normal, heavy, extra heavy)*

The dryer controls the Retro and nZEH house are set to:

- Cycle type = Normal/Mixed Loads Sensor Dry.
- Dry mode = Sensor Dry *(options are timer or sensor dry).*
- Dry level = Dry *(options are damp, less dry, dry, more dry, extra dry).*
- Dry temp = High *(options are extra low, low, med, high, anti-bacterial).*

Results of test runs with these settings show an average of 23 gal per cycle of DHW use; that is 138 gal per week using selected profile or an average of 19 gal per day.

The dryer mister is controlled by a relay and solenoid valve. It was recognized that the final higher spin cycle in the Energy Star washing machines take more water out of the clothes than the conventional washer in CC1. In September the load after washing in both washers was weighed. It was found that the same load of 10 towels after washing weighed less in CC2 and CC3 so the amount of mist added to towels in the dryers in houses 2 and 3 was reduced (see Table above). This results in the dryer energy savings in CC2 and CC3.

For the 28 day period from October 21 until November 16 the dryer in CC3 used 2.2 kWh/day compared to the dryer in CC1 of 3.24 kWh/day. The washer in CC3 uses a bit more electricity than in CC1; 237 Wh/day in CC3 compared to 179 Wh/day in CC1. The combination washer dryer in CC3 used 19% less energy than the conventional appliances in CC1. All the washing machines are using hot water consistent with the BA benchmark recommendations.

7.3 DISHWASHER

According to the BA benchmark model the dishwasher cycles per year (DWC) can be given by Eq. (2).

$$DWC = (215) * \left(\frac{1}{2} + \frac{N_{br}}{6} \right) \tag{2}$$

In Eq. (2), N_{br} is the number of bedrooms. Since all three houses have 3 bedrooms DWC is 215. If dishwashers are run 4 times per week then a DWC of 208 is reached. Table 26 describes the new profile for dishwasher control.

Table 26. Profile for dishwasher control

Dishwasher start	Operating days[a]
19:30:00	123456

[a]Sunday =1, Monday=2,….Saturday=7.

Currently the dishwasher controls in CC1 are set to:

- Cycle Mode = Normal Wash
- Options = Heated Dry

Results of test runs with these settings show an average of 6 gal per cycle of DHW use; that is 36 gal per week using selected profile or an average of 5.14 gal per day. All three dishwashers are loaded with settings for 8.

7.4 REFRIGERATOR

Only one reference for frequency of opening and closing refrigerator and freezer doors were found. The reference is from the *Code of Federal Regulations part 430, Subpart B, Appendix A1* and states that the refrigerator should be opened 24 times a day and the freezer 6 times with the doors staying open for 12 seconds. This citation though does not convey human occupancy habits but is rather a standard for testing refrigerator doors. Since no better citable reference was found these values will be used as a starting point. It might be beneficial to take some data in occupied houses to get this information. Table 27 shows the refrigerator and freezer door opening profile.

Both the freezer and refrigerator doors are opened and closed by a pneumatic system consisting of an air compressor, an electrically controlled valve and pneumatic piston with an arm and hinge for opening the doors. The electrically controlled valve is wired to a relay that is controlled with the LabVIEW® program. When the relay is open the door is closed; when it is closed the door is open. A picture of the refrigerator door opener is shown in Figure 100. This robotic refrigerator door opener has been very reliable and gets most of the attention from guests who are touring the research houses.

Table 27. Profile for refrigerator and freezer door openings

Fridge door open times	FridgDur(sec)	Freezer door open times	FridgDur(sec)
7:00:00	12	7:16:00	12
7:15:00		7:31:00	
7:30:00		18:16:00	
7:35:00		18:31:00	
7:45:00		18:46:00	
8:00:00		20:31:00	
8:02:00			
15:00:00			
15:05:00			
15:10:00			
17:00:00			
17:05:00			
18:15:00			
18:20:00			
18:25:00			
18:30:00			
18:45:00			
19:00:00			
19:15:00			
20:00:00			
20:30:00			
22:00:00			
22:15:00			
22:30:00			

Figure 100. Refrigerator and Freezer door opening apparatus.

7.5 RANGE

The range control was successfully implemented into the occupancy simulation routine by October 23, 2009. The following equation yields the kilowatt-hours per day that the range uses based on the number of bedrooms in the house. This equation was modified from the BA Research Benchmark.

$$W[kWh] = (302 + 101 * N_{br}) / 365 \quad (3)$$

With three bedrooms the energy use per day for the range is 1.657 kWh. It was found with the oven set to 350°F bake in CC1 it took about 200 minutes to use this amount of energy. So in each house the profile calls for 200 minutes of 350°F bake. Following is the range profile.

Table 28. Profile for oven control

Oven bake	Oven duration(min)	Oven days
12:00:00	40	1234567
16:00:00	160	1234567

It was found that the larger oven in the more expensive appliances in CC2 and CC3 used 64% more energy than the conventional oven in CC1 when comparing energy use for 200 minutes. After talking to GE about the issue, the researchers found that customers did not want to clean the bottom of the oven with the bottom heating element exposed so GE engineered the element placement underneath the liner. The single oven has a standard exposed bake element, and the lower oven in the dual cavity ovens in CC2 and CC3 are a “hidden bake” element (element is under a plate in the bottom of the oven). This accounts for the difference in performance. Ovens with the hidden bake element take longer to preheat and are less efficient yet GE customers like it because it is easier to clean and they do not see the element or the inefficiency.

After finding this issue, the simulation was changed to operate the smaller muffin oven compartment in CC2 and CC3. This change showed that the muffin oven uses the same amount of energy as the larger single oven in CC1. GE states that the smaller oven would heat up a kitchen space less than a large oven. A GE test of cooking a chicken in the upper oven compared to the lower used 588 less watts or 34% less energy. The chicken cooked in the small oven was ready to eat 4 minutes sooner than the one in the larger oven. So the kitchen does heat up less with the muffin oven compared to the larger often in CC2 and CC3 but not compared to the conventional oven with the exposed lower element like the one installed in CC1.

7.6 LIGHTING LOAD

ZWave switches are used to control the lighting in the research houses. A computer installed by Simple Controls of Knoxville is used to control when these switches are turned on and off. To determine the lighting schedule the BA benchmark is used. Figure 101 shows the fraction of total interior hard-wired lighting throughout the day.

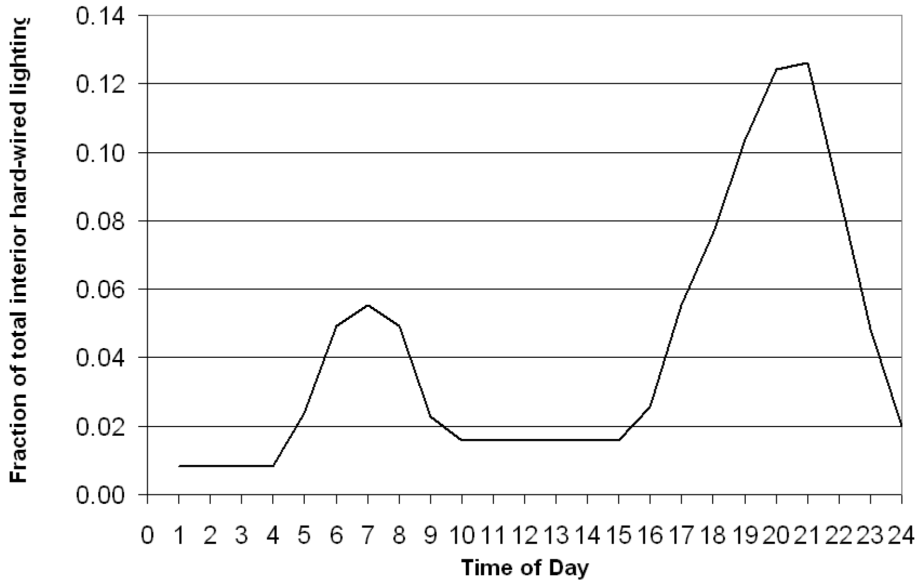


Figure 101. Lighting energy use pattern.

To compute the total interior lighting load (ILL) per year for house 1, which is 2400 sq. ft. and 100% incandescent, Eq. (4) is used, where FFA is finished floor area.

$$ILL = 1.12(0.8*(FFA*0.8+455)) \quad (4)$$

Using this we find that house 1 at Campbell Creek should have an ILL of 2128 kWh/year. We also need to compute the garage and exterior lighting load; according to the BA benchmark 100 kWh/year and 250 kWh/year are used for garage and exterior lighting in a house with 80% incandescent lights and 20% fluorescent. As we are using 100% incandescent, applying the 1.12 factor means an additional 280 kWh per year need to be added to ILL. So the total hard-wired lighting load that needs to be simulated at house 1 is 2408 kWh/year or 6.597 kWh per day. We can use this daily lighting load value and Figure 101 to make Table 29, illustrating how many watts per hour we need to simulate for lighting. Table 30 shows the energy used by the lights in CC1; this information along with Table 29 can be used to create the lighting schedule.

Table 31 shows the completed lighting profile with the times that each lighting fixture should be on throughout the day. These times are used in all three houses. Since CC2 and CC3 have 100% CFL lights the lighting load will be considerably less in these houses that in CC1. This current profile was implemented in October 21, 2009.

7.7 PLUG LOADS

The ZWave system also controls simulated plug loads. Two space heaters, one 1500W in the downstairs great room and one 500W ceramic heater in the master bath are controlled to simulate loads other than interior hard-wired lights and controlled appliances. This includes plug-in lights, miscellaneous loads, and sensible heat from occupancy. Since occupancy affects needed sensible heat simulation the weekday and weekend plug load profiles are different. Also since the simulation of the plug-in lights (100% fluorescent and opposed to 100% incandescent in CC1), the profiles for CC2 and CC3 will be different from CC1. The first step is to measure the wattages of the heaters installed at the three houses (see Table 32, measured December 2, 2009, with Campbell Scientific DAS).

Table 29. Energy per hour of lighting needed to simulate occupants in Campbell Creek Houses

Hour of the Day	Fraction of Total Lighting	Watts/hr
1	8.21E-03	54.13
2	8.21E-03	54.13
3	8.21E-03	54.13
4	8.21E-03	54.13
5	0.0236	155.69
6	0.0492	324.57
7	0.0554	365.47
8	0.0492	324.57
9	0.0226	149.09
10	0.0159	104.89
11	0.0159	104.89
12	0.0159	104.89
13	0.0159	104.89
14	0.0159	104.89
15	0.0159	104.89
16	0.0256	168.88
17	0.0554	365.47
18	0.0769	507.31
19	0.1036	683.45
20	0.1241	818.69
21	0.129	851.01
22	0.08818	581.72
23	0.049	323.25
24	0.02	131.94
Total	**1.000000**	**6597.00**

Table 30. Wattage of fixtures in CC1 that will be controlled

Room	Watt
Bed2	142
Bed3	142
breakfast	120
dining	312
foyer	522
Front porch	137
garage	106
great room	152
kitchen	292
master bath	332
master bed	162
office	142
outside back	185
outside` front	185
upstairs bath	292

Table 31. Lighting profile

New profile (102109)	Room	Bed2	Bed3	Breakfast	Dining	Greatroom	Kitchen	Master bath	Master bed	Office	Outside front	Upstairs bath	Front porch
	Watt	**142**	**142**	**120**	**312**	**152**	**292**	**332**	**162**	**142**	**185**	**292**	**137**
Hour of the Day	**Needed Watts/hr**												
1	**54.13**												23.71
2	**54.13**												23.71
3	**54.13**												23.71
4	**54.13**												23.71
5	**155.69**										50.49		
6	**324.57**							25.22			60.00		
7	**365.47**							60.00	12.40				
8	**324.57**	20.00	20.00	60.00			20.00		4.66				
9	**149.09**			13.72			5.00					20.00	
10	**104.89**									44.32			
11	**104.89**									44.32			
12	**104.89**									44.32			
13	**104.89**									44.32			
14	**104.89**									44.32			
15	**104.89**									44.32			
16	**168.88**	10.00		10.00		10.00	10.00			21.64			
17	**365.47**	30.00	29.35			60.00	15.00						
18	**507.31**				35.00	35.00	48.62						
19	**683.45**				60.00	31.36	60.00						
20	**818.69**			31.35	60.00	60.00	60.00						
21	**851.01**	60.00	60.00			60.00		17.35	10.00			60.00	
22	**581.72**					60.00		60.00				20.08	
23	**323.25**							43.78	30.00				
24	**131.94**												57.78
Total	**6597.00**												

Table 32. Heater wattages for use in simulating sensible load from people and miscellaneous electric loads

	Downstairs 1500 W	Upstairs 500 W
House 1	1440 W	494 W
House 2	1330 W	534 W
House 3	1374 W	542 W

Using the BA Research Benchmark the miscellaneous plug load [which will include fixed miscellaneous electric loads (MELs), variable MELs, and fixed gas electric loads] plus plug-in light sensible heat output can be computed for the whole day. The following equations give the total sensible heat from miscellaneous plug loads for one day and the plug-in lighting for one day.

$$MEL[kWh] = [0.12(469 + 77\,N_{br} + 0.122\,FFA) + 0.83(1281 + 196\,N_{br} + 0.345\,FFA)]/365 \quad (5)$$

$$PLL[kWh] = 0.2(0.8\,FFA + 455) \quad (6)$$

BA gives hourly fraction of total daily use profiles for MELs and plug-in lighting. This will be used and discussed later in building the final profile.

Next, the sensible heat added to the space from people should be computed. This will again be a function of the hour of the day. According to Eq. (17) in the BA Benchmark (Dec 2008), the number of occupants is equal to three. Table 33 is a combination of Table 19 in the BA Benchmark report and Eq. (7), where OS is occupants sensible heat added to space in W/hr, N_{oc} is the number of occupants, and Btu/person/hr is given in the table below.

$$OS[W/hr] = N_{oc}([Btu/person/hr]/3.412) \quad (7)$$

Table 33. Watts/hr for a house occupied with 3 people

Zone	Btu/person/hr	W/hr
Living Area Sensible Load	230	202
Bedroom Area Sensible Load	210	184

BA again gives hourly fraction of total people for living and bedroom areas and weekday vs weekend days that can be used to calculate the sensible heat from people added to the space depending on zone and time. The following two plots give the hourly fraction of total for occupancy depending on zone (Figure 103) and the MELs and plug-in lights (Figure 102).

To get the total sensible heat that we need to dump into the space we will arbitrarily add 25% of the non-people sensible heat from the upstairs heater (bedroom) located in the master bathroom and 75% from the downstairs heater (living) in the great room. To do this we will multiply the result from Eq. (5) by the yellow “Misc Elec Load” curve, and then multiply the result from Eq. (6) by the “Lights” curve. Then we will add these two resulting curves. Seventy-five percent of this resulting curve will be simulated by the downstairs heater and 25% by the upstairs heater.

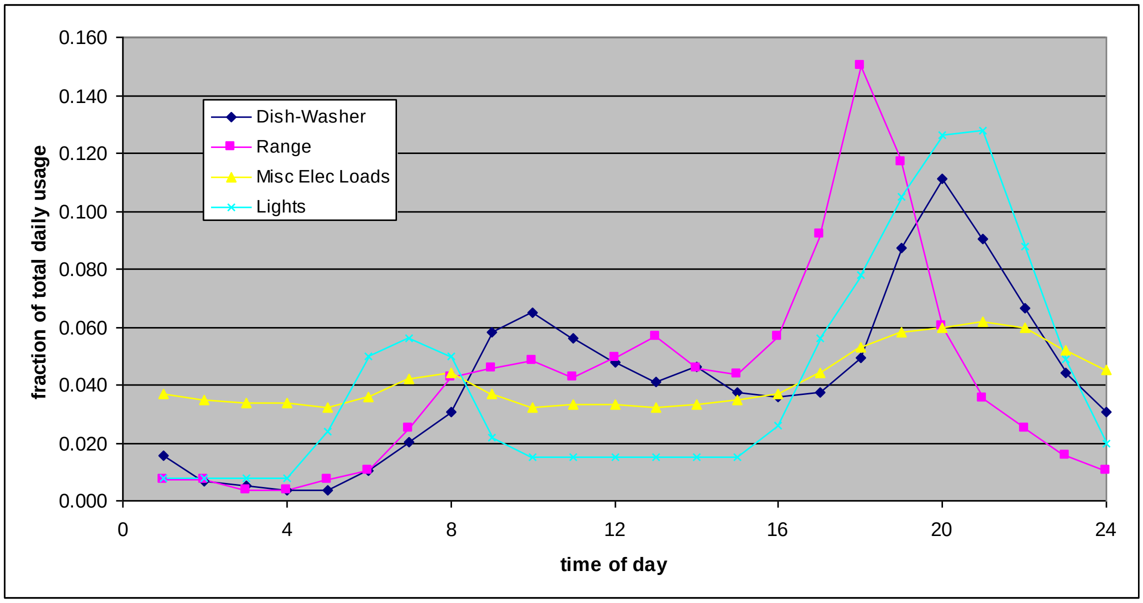


Figure 102. Appliance, MELs, and lighting use patterns (fraction of total daily use).

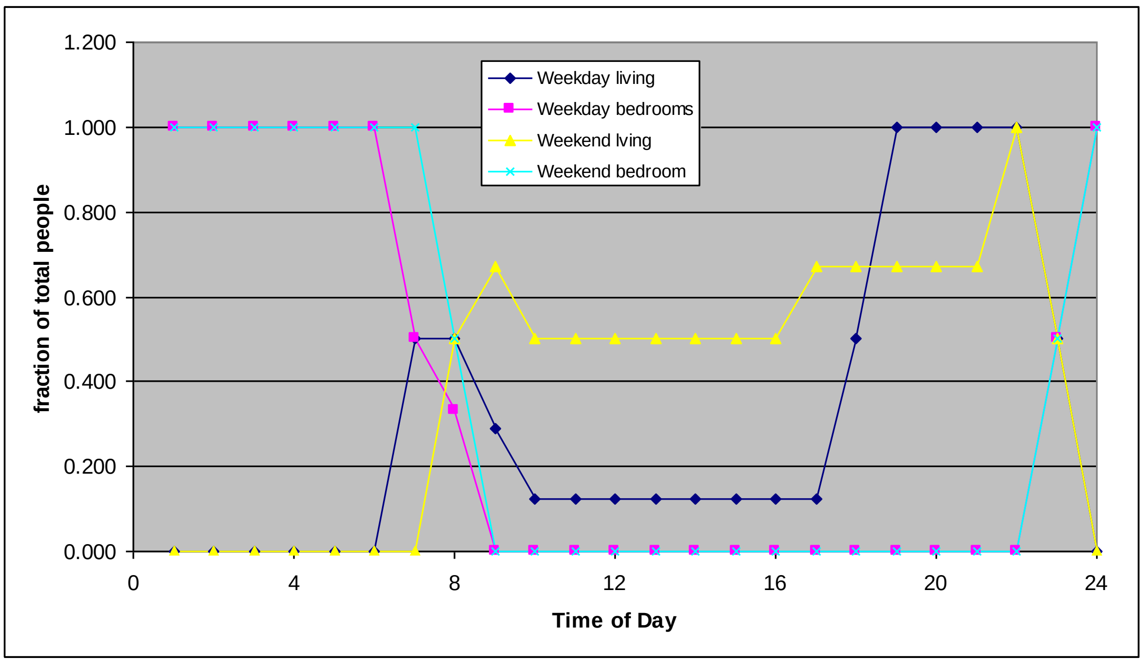


Figure 103. Occupancy patterns for 2 zones for weekday and weekend day.

Next we need to compute the sensible heat from the people. We will simply multiply the last column results in the table above with the appropriate curves, either "weekday living," "weekday bedrooms," "weekend living," or "weekend bedrooms." The final step is to add the sensible heat from people and MELs and plug-in lights according to zone. Note that there is not distinction between MELs and plug-in lights for weekday versus weekend. To get the time that the heaters should run for the profile we just divide the wattage needed for an hour by the measured wattage of the heater. The resulting value is the fraction of an hour that the heater needs to run to get the needed sensible heat output. We then multiply this number by 60 to convert fraction of hour to minutes. Table 34 shows the results for CC1. The results for CC2 and CC3 are not shown, but the plug-in light sensible heat is less because it is assumed that they are 100% CFL, so 25% of the energy from CC1 is used in CC2 and CC3 for plug-in lighting.

Table 34. Sensible heat generator profile

CC1	Total wattage for Sensible Generation per zone, time of week, and hr of day.				Time (minutes)			
Hour of Day	Weekday living	Weekday bedrooms	Weekend living	Weekend bedroom	Weekday living	Weekday bedrooms	Weekend living	Weekend bedroom
1	82.1	247.0	82.1	247.0	3.4	30.0	3.4	30.0
2	72.4	243.8	72.4	243.8	3.0	29.6	3.0	29.6
3	67.5	242.2	67.5	242.2	2.8	29.4	2.8	29.4
4	67.5	242.2	67.5	242.2	2.8	29.4	2.8	29.4
5	73.5	244.1	73.5	244.1	3.1	29.7	3.1	29.7
6	118.2	259.1	118.2	259.1	4.9	31.5	4.9	31.5
7	254.3	178.4	153.2	270.7	10.6	21.7	6.4	32.9
8	258.1	148.3	258.1	179.7	10.8	18.0	10.8	21.8
9	154.4	66.9	231.2	66.9	6.4	8.1	9.6	8.1
10	89.9	56.6	165.8	56.6	3.7	6.9	6.9	6.9
11	94.7	58.2	170.6	58.2	3.9	7.1	7.1	7.1
12	94.7	58.2	170.6	58.2	3.9	7.1	7.1	7.1
13	89.9	56.6	165.8	56.6	3.7	6.9	6.9	6.9
14	94.7	58.2	170.6	58.2	3.9	7.1	7.1	7.1
15	104.4	61.4	180.3	61.4	4.4	7.5	7.5	7.5
16	124.9	68.2	200.8	68.2	5.2	8.3	8.4	8.3
17	188.1	89.3	298.3	89.3	7.8	10.8	12.4	10.8
18	329.0	111.0	363.4	111.0	13.7	13.5	15.1	13.5
19	480.7	127.8	414.0	127.8	20.0	15.5	17.2	15.5
20	510.9	137.9	444.2	137.9	21.3	16.7	18.5	16.7
21	522.6	141.8	455.8	141.8	21.8	17.2	19.0	17.2
22	473.8	125.5	473.8	125.5	19.7	15.2	19.7	15.2
23	295.9	192.2	295.9	192.2	12.3	23.3	12.3	23.3
24	132.6	263.8	132.6	263.8	5.5	32.0	5.5	32.0

7.8 LATENT HEAT

The latent heat generator is still being worked on by EPRI and ORNL and is expected to be running by October 2010.

7.9 CHANGES TO THE OCCUPANCY SIMULATION OVER THE PAST YEAR

Since the Experimental Test Plan dated August 8, 2009, some changes have been made to appliance control, plug load, and lighting schedules. Beginning October 23, 2009, the ovens were being turned on using relays and LabVIEW®. On November 5, 2009, the oven schedule was fine tuned to run 200 minutes total during the day, every day of the week. This uses about 1.6 kWh a day for CC1. At the same time the oven started being controlled the plug load sensible heat/wattage was reduced because we where emulating the oven with these heaters. This is also when we noticed that the heaters varied in wattage so we took this into account when computing times for heaters to stay on.

The lighting schedule was changed slightly October 21, 2009, because the neighbors of CC3 were complaining that the back flood was coming on in the middle of the night, shining through their bedroom window, and waking them up. The profile was changed to turn on the front floods instead of the back floods. The lights were changed in all houses both weekday and weekend for consistency.

7.10 SUMMER LOAD FACTOR ANALYSIS

In October TVA requested the monthly load factors for the three CC houses. Table 35 shows that the average monthly load factor for the months from July –September is 0.21 for CC3 compared to 0.34 for CC1. The electric utility company has fixed costs for connecting each house to the grid; distribution lines, transformers, and substations. The higher the load factor the more quickly this fixed cost gets paid back. For high performance houses like CC3 to be considered a more valuable asset to the electric grid higher load factors are a desirable goal. The peak capacity for CC3 however is only 4.8 kW compared to 6.1 kW for CC1. This represents a reduced capacity of 21%. The load factor increase is 38%. If the fixed cost for generation capacity is 17% more than the fixed cost for transmission and distribution than the fixed cost to the utility is a wash.

Table 35. Summer time load factors

	Campbell Creek load factor (including PV)					**Campbell Creek load factor (excluding PV)**					
	Peak (kW)	**Monthly total (kWh)**	**Days in month**	**Average kW**	**Load factor**	**PV at peak (kW)**	**Time of peak**	**Monthly PV to grid total (kWh)**	**Peak without solar (kW)**	**Monthly PV total (kWh)**	**Load factor w/o PV**
CC1											
June	8.0	2042	30	2.8	0.35						
July	6.0	1564	31	2.1	0.35						
August	6.3	1607	31	2.2	0.34						
Sept	6.0	1354	30	1.9	0.31						
Average (July–Sept)	6.1				0.34						
CC2											
June	8.0	1427	30	2.0	0.25						
July	5.3	1136	31	1.5	0.29						
August	5.6	1143	31	1.5	0.27						
Sept	5.1	901	30	1.3	0.25						
Average (July–Sept)	5.3				0.27						
CC3											
June	5.6	1162	30	1.6	0.28	0.09	06/07/0800	25	5.7	364	0.37
July	4.4	912	31	1.1	0.26	1.20	07/13/1300	63	5.6	345	0.29
August	5.0	795	31	1.0	0.19	0.42	08/21/1300	83	5.4	360	0.27
Sept	4.9	695	30	0.9	0.18	0.93	09/21/1600	73	5.8	253	0.21
Average (July–Sept)	4.8				0.21						0.25

Ways to reduce the peak hourly demand is obviously one way of increasing the load factor. In August the peak hour occurs on August 21, 2009, at 13:00 the peak shown in the above table shows 5.052 kW. However when you add in the solar generation (0.420 kW) and subtract what is not needed in the house and sent to the grid (0 kW) it comes to 5.472 kW. The next question is exactly what contributes to that load. For openers the dryer demands 3.426 kW or 63% of the peak load during this hour. The electric dryer is a very obvious target for demand response, which will be influenced by the varying time of use rates under serious discussion at most electric utilities in 2010. This is simple, pass a law that all-electric dryers can run anytime other than in the summer between the potential electric system peak hours of 12:00–18:00. The next largest fraction is the heat pump, which at this time is demanding 1.170 kW or 21% of the peak load. The lights and plug loads result in 0.681 kW or 12%. The washer tops this off with the remaining 3%.

8. MAJOR MEASURED PERFORMANCE COMPARISONS

8.1 SLAB EDGE; TO INSULATE OR NOT TO INSULATE

Energy code inspections for the first time will begin on October 1, 2010, in Knox County, where the Campbell Creek research houses are located. The IECC 2006 will be enforced, which will for the most part require at least R-5 of slab foundation insulation.

CC1 and CC2 both have 1 in. of XPS horizontally placed around the perimeter except for the garage wall. Figure 104 is showing the slab temperature differences 8 in. away from the drywall of the dining room and garage wall. At times the difference is greater than 3°F. Cold surfaces can generate moisture condensation and cause thermal discomfort of the occupants.

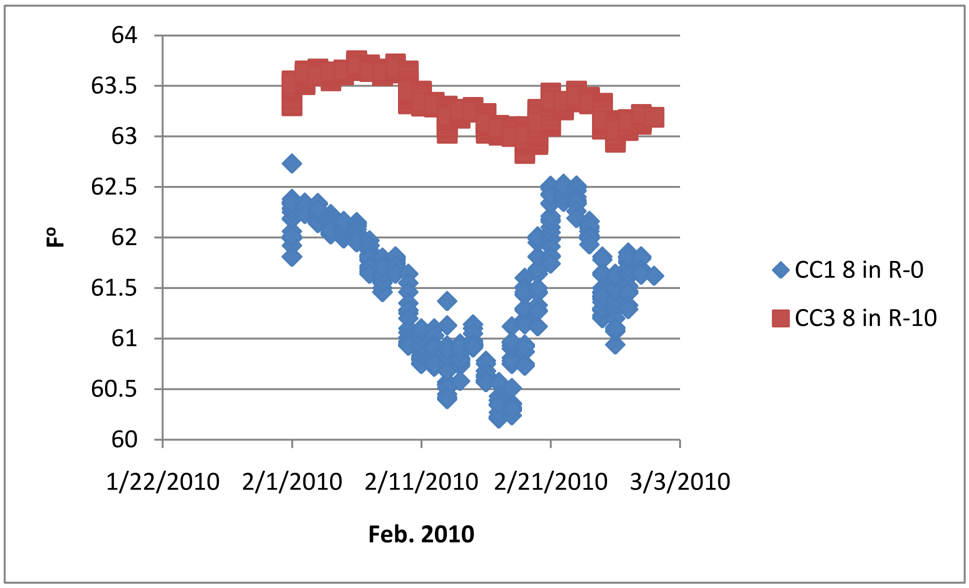


Figure 104. Slab temperature 8 in. from garage wall of CC1 with no insulation compared to CC3 with R-10.

Figure 105 shows the slab surface temperature differences 28 in. from the east wall of CC1 with R-5 slab horizontal insulation as shown in Figure 79 and the same relative location in CC3 with vertical R-10 foam board insulation. It is very apparent how much more stable the interior slab temperature is in CC3 and that at times the differences are as much as 6.5°F.

The modeling results of CC3 indicate that from no slab insulation to R-10 results in a 375 kWh space heating cost savings. The incremental first cost is $400, which would suggest a 12-year simple payback. Retrofitting slab insulation on the outside of a house is very challenging and since this would require a cover board of some sort the incremental cost is likely to be much more than $400. A recent ASHRAE publication (ASHRAE 1481 RP, May 2009) suggests the incremental cost for R-10 Slab insulation is $924.4. This discussion leads to the conclusion that slab insulation should be added from a thermal comfort and moisture control perspective. The ASHRAE 1481 RP confirms that if you have to do at least R-5 the incremental cost of going to R-10 is only $264.3. So it is recommended to go with R-10 in the TVA region in new construction. If an existing home is going for a deep retrofit it may be time to dress up the foundation with cultured stones and than why not slip some insulation in the mix.

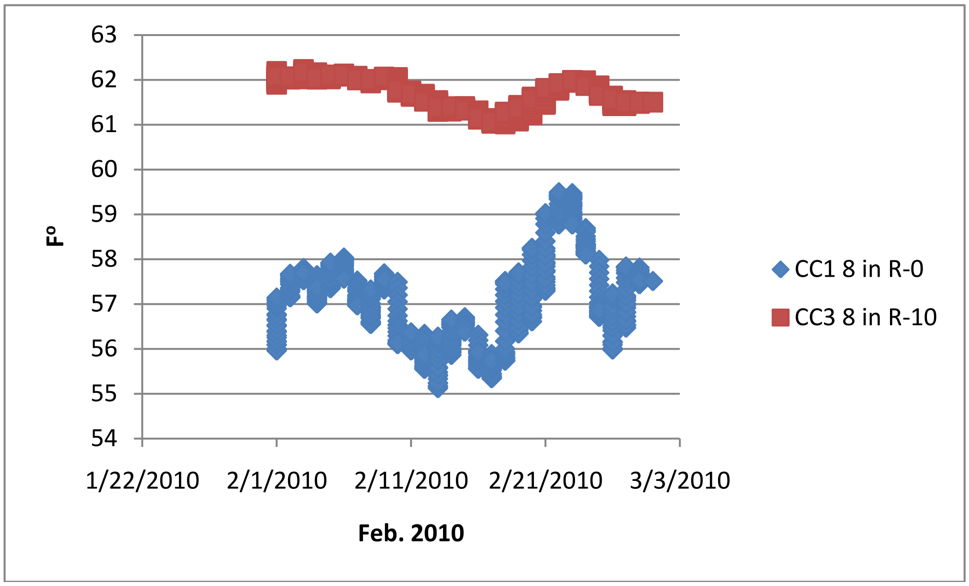


Figure 105. Slab surface temperature 28 in. from east wall in CC1 with R-5 horizontal insulation compared to R-10 vertical in CC3.

8.2 2 × 4 AT 16 IN. FRAME WALL WITH R-13 CAVITY FIBERGLASS BATTS VS 2 × 6 AT 24 IN. OPTIMUM VALUE ENGINEERED FRAMING; R-22 WITH R-2.74 STRUCTURAL INSULATED SHEATHING, SPRAY FOAM FLASHED AND SPIDER SPRAYED

Two heat flow transducers were set up in cavities on the second floor, one in the south, the other the north wall. Figure 106 shows the heat flux for the two coldest months at the two cavity locations. The monthly sum of the heat flow from CC1 is twice the flow from CC2. The monthly average temperature differences measured in these cavities at the same location are shown in Figure 107. The exterior north wall surface is colder than the south since the low angle of the sun in the winter does not warm up the northern face of

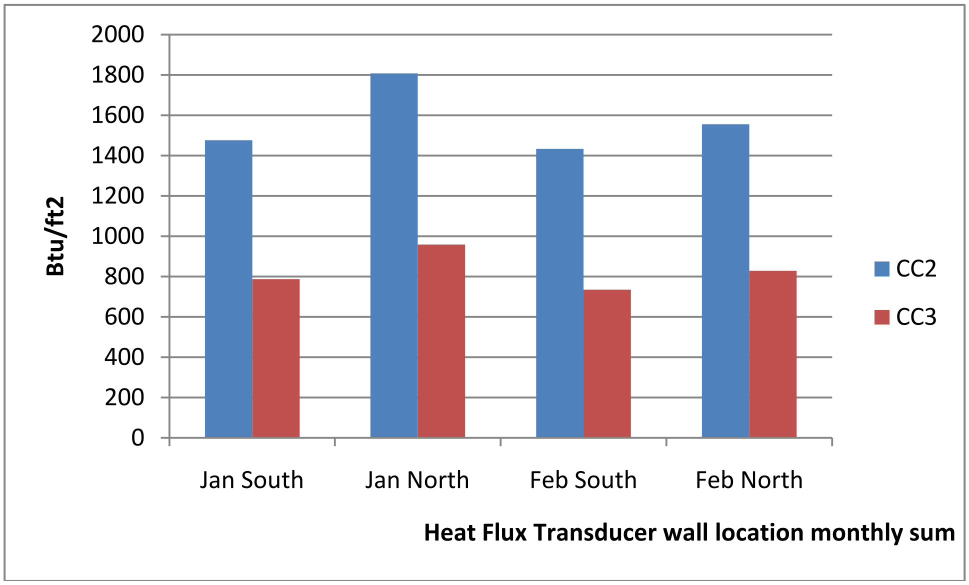


Figure 106. Monthly total heat flow through above grade wall cavities in winter months.

the houses. With the thermostats set at the same 71°F in both houses and the vertical temperature differentials very similar the inside wall surfaces are very similar. The average monthly interior surface temperature during these two coldest months of the year at mid height where the heat flux transducers are located is 68°F on the north and 69°F on the south.

Equation (8) can be used to take the measurements displayed in Figure 106 and Figure 107 to find the R-value of the insulation in the cavities. CC1 and CC2 have nominal manufacture listed R-13 Kraft faced batts. CC3 has about 1 in. of high density spray foam and the remainder of the cavity filled with Spider.

$$\text{R-Value} = \frac{\text{temp difference across the cavity insulation (Figure 107) X \# of hours in the month}}{\text{Heat flow (Figure 106)}} \qquad (8)$$

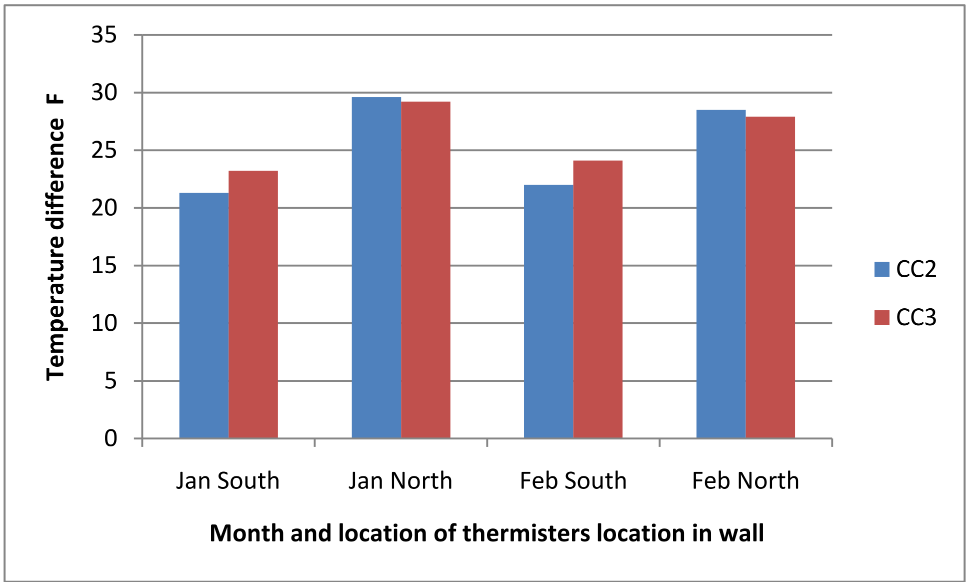


Figure 107. Temperature differences across the insulation in the above grade walls.

Figure 108 shows that the in situ measured cavity R-value is 23 for CC3s 5.5 in. cavity compared to 11.7 in CC2s, with a 3.5 in. cavity. The ASTM C518 measurement of the DOW SIS was 2.74. The measured center of cavity R-value for this wall is 25.7 h ft^2 °F/Btu. The whole wall hot box measurement, which accounts for the framing materials was R-22. The thickness of the foam and Spider does vary some. A pin probe analysis of the spray foam in CC3's walls found an average thickness of 1 3/16 in. This thickness is similar to the 8 ft by 8 ft test specimen constructed on site for testing in the Buildings Technology Center hot box.

Using the measurement based whole wall R-value in the Energy Gauge Model results in an energy saving for the CC3 OVF wall of 888 kWh/year. If the walls took the air tightness savings of 2.4 compared to 5.7 ACH at 50 Pa this would add another 311 kWh/year. This leads to a $112/year energy savings. Getting a handle on efficient construction to keep the installed cost down should make this very low risk assembly investment in new construction. You really only get one chance to get the wall air tightness right it seems prudent to consider a wall system that is only 2 in. thicker than a standard 2X4 wall while doubling the R-value.

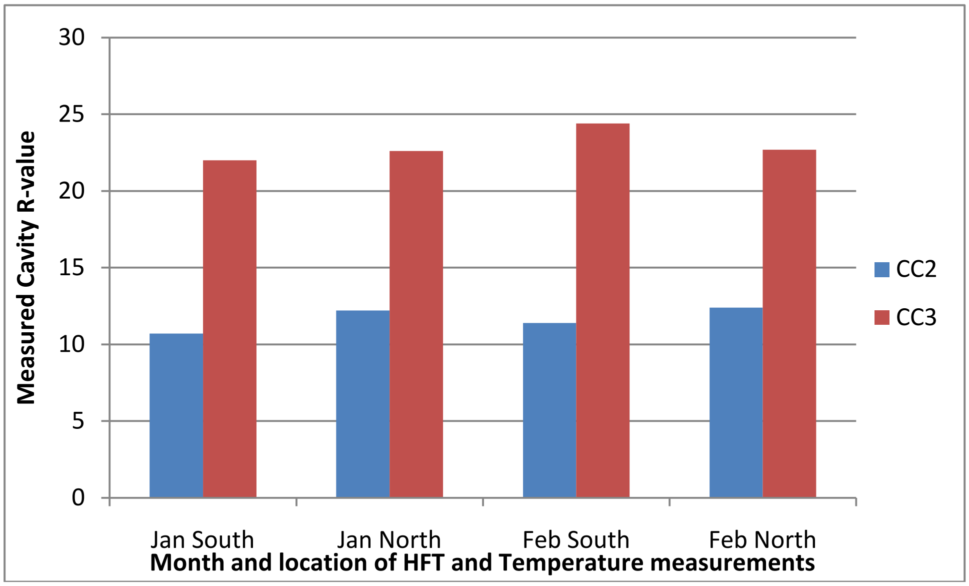


Figure 108. Measured center of cavity R- values in CC2 and CC3.

8.3 TRIPLE LAYER WINDOWS VS LOW-E GAS FILLED VS 2 PANE "NOTHING"

A rake of 5 thermistors with black ping pong balls were placed 2 ft from a south and a north bedroom window in all three houses. These sensors were measuring the mean radiant temperature from the ceiling to the floor in a location that would most likely be a reading chair. Occupants would usually be sedentary in this location and appreciate the better windows. The goal was to measure the thermal comfort benefits of the higher performance windows. The analysis of this data was inconclusive. There were no statistically significant measured differences that correlated with window type. It is recommended that additional instrumentation be added to 6 windows in October 2010 for the next test period.

8.4 INSULATED AND SEALED ATTIC VS R-50 VENTED WITH REFLECTIVE UNDER SIDE ROOF DECKING VS R-30 VENTED

One of the most interesting findings in the attics is how stable the indoor air and humidity conditions are in the insulated and sealed CC2 attic. The air temperature and RH do not vary much form the rest of the house. In fact the highest temperature found in the summer was only 82°F and an RH of 60%.

A second interesting finding is that the vented attic with R-50 in CC3 runs colder in the winter than the attic in CC1. Two explanations one is heat loss from the ducts and indoor unit located in the attic of CC1, second is less solar gain in the winter as a result of the radiant barrier adhered to the bottom of the roof sheathing.

A third discovery is that the CC1attic has an average measured loose fill fiberglass R-value for the December (41.5), January (47.6) and February (43.5) of 44.2 not 30 as was originally invoiced to the builder. The R-value measured in CC3 in the same manner and the same relative location was 51.1 very close to the requested R-50. These values were calculated by using the same mentioned procedure and data base for the wall cavity analysis above. A calibrated HFT was placed on the attic floor in a clear open space between two attic trusses along with a thermistor. The attic air temperature was measured at mid height in all three attics with a Vaisala sensor. Figure 109 shows the monthly maximum air temperatures in the Attics of CC1 and CC2. Notice that the maximum temperatures in the attic off CC2 never went above 83°F. There is no dedicated space conditioning supply or return ducts servicing the CC2 attic space. The maximum hourly air temperatures in CC1 vented attic is 133°F.

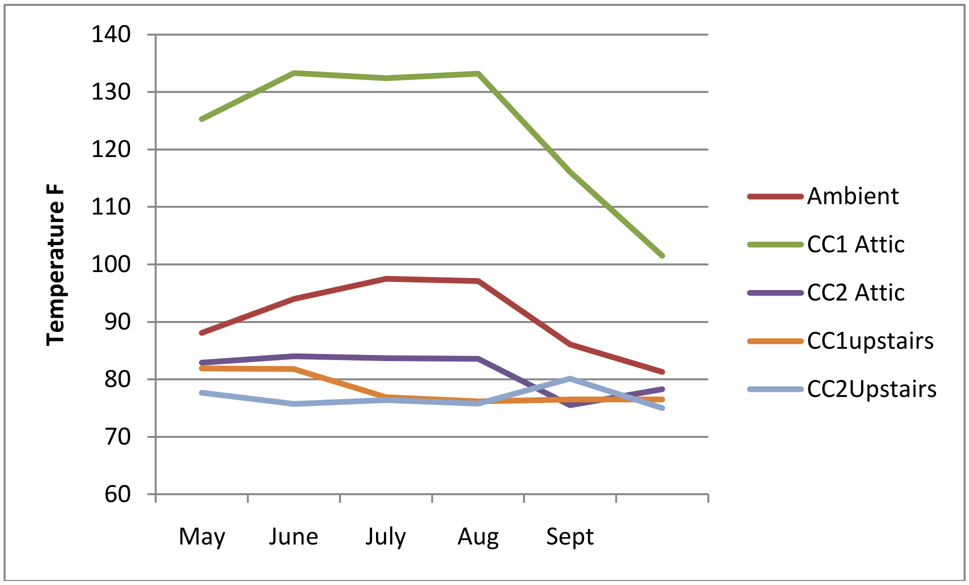


Figure 109. Maximum monthly attic air temperatures in CC1 and CC2 compared to the Maximum Ambient temperature and the maximum top floor inside air temperature.

Figure 110 shows the average monthly temperatures of the attic air spaces in CC1 and CC2, along with the average ambient temperature and the top floor space temperature. Notice that on average the attic in CC2 with the insulation and sealed space behaves almost like the interior. Notice on average in the winter the attic in CC1 is always warmer than the ambient conditions. This is in part due to the heat loss from the ducts as well as the house. The attic in CC3 actually has more heat loss from the ceiling of the top floor with R-50 than the attic in CC1 with less insulation.

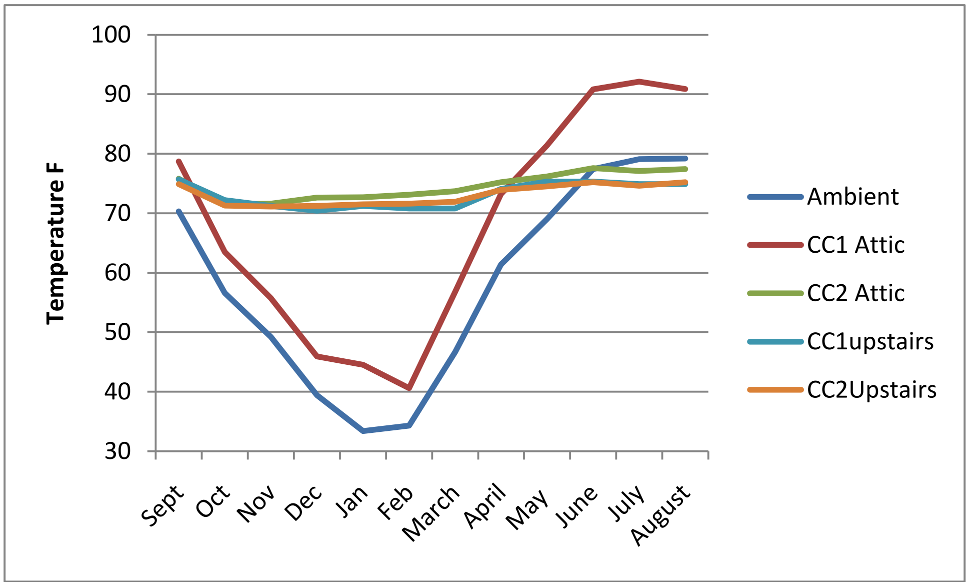


Figure 110. Average monthly attic, ambient, and top floor air temperatures measured in CC1 and CC2.

In CC2 there are two heat flux transducers with thermocouples buried in the foam underneath the roof sheathing. The same procedure for in situ R-value measurement as described for the attic insulation in CC1 and CC2 was followed in the roof of CC2. Using data for the February and tossing out those hours in which the there was reverse heat flow when the sun is shining brightly on the roof the north slope location has an R-value of 31.7 and the south slope location a R-value in situ measurement of 30.4. These measurements confirm the estimation based on pin probing the insulation thickness and laboratory specimen testing in ASTM C518 apparatus in the ORNL Buildings Technology Center.

8.5 WHOLE HOUSE BALANCED ERV VS SUPPLY VENTILATION TO RETURN HVAC PLENUM WITH BATH FAN VS BATH FAN CONTINUOUS EXHAUST VENTILATION

Figure 111 shows the average CFM of fresh air measured by month for the period from September 2009 until August 2010. Since February 8, 2010, the plan was to mechanically ventilate all three houses the same 30 CFM. This is relatively easy for CC1. Running the master bathroom exhaust fan 24/7 delivers 30 CFM. For CC2 there is a manual damper that needs to be adjusted at least every month with some anticipation of how much the heat pump will be at high indoor air fan speed. The indoor fan pulls air through the fresh air duct in the attic at different rates depending on the speed of the fan. If more conditioned air is delivered at the indoor fan high speed for a given month, than more fresh air is pulled into the house during that month than one that has most of the delivery of conditioned air at the low speed fan. It is clear that during the summer season this needs to be open up some more. The Fantech ERV in CC3 has been running pretty steady at around 42 CFM, which is probably ok since this house is so much tighter than the other two.

Evaluation of the ERV for February the inlet average temperature was 41°F this air stream of 40 CFM got on average heated up to 63.9°F the return air from the wet rooms arrived near the ERV at an average temperature of 67.6°F and was cooled to 47.6°F. This results in the fresh air being warmed on average about 21°F or 62°F. The full temperature lift needed is 30°F to reach the thermostat set point of 71°F. That indicates that the system during February was recovering about 70% of the exhaust heat leaving the house.

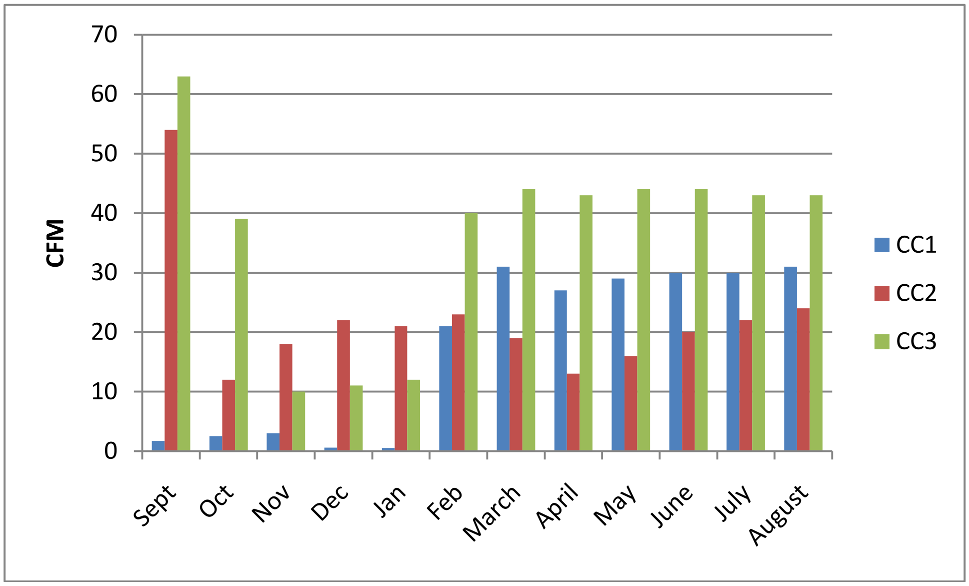


Figure 111. Average CFM of fresh air intake.

8.6 SINGLE SPEED SEER 13 HEAT PUMP VS SEER 16, ECM FAN SINGLE SPEED COMPRESSOR VS SEER 16 TWO SPEED COMPRESSOR

The data collected on air temperatures of the indoor space confirm that all three houses maintain a very good match to each other as they heat to the thermostat settings of 71°F in the heating season and 76°F in the cooling. Once the data base was adjusted for known problems with the systems it is felt that the reported energy savings of the higher performance heat pumps is a reasonable indicator of their relative performance. In the first 2 months or so of the heating season it was discovered that the CC3 heat pump was never allowed to go into the high speed compressor capacity mode. This resulted in more back up resistance heat than would have been called for particularly at the colder ambient conditions. A reasonable correction for this problem was not developed to reduce the energy consumption of CC3. It is felt that this leaves the relative performance differences between CC3 and CC1 a bit on the conservative side. One offering of a suggested correction is the average HDD at 65°F per day is 30 for both months. In January, when the high speed compressor was not available, 15 kWh/day were used for back up heat. In February the thermostats were replaced and the high speed capacity was available the backup heat needs were only 8.3 kWh/day. If that same rate was applied in January a 208 kWh savings would have occurred. This reduces the cost of energy for CC3 of about $20.

8.7 SOLAR WATER HEATER VS HEAT PUMP WATER HEATER VS ELECTRIC RESISTANCE WATER HEATER

The reported hot water energy savings in CC2 and CC3 account for not only the enhanced technology of heat pumps and solar heat but also the 14 gal per day of hot water savings resulting from the more energy efficient dishwasher (0.6 gal/day savings) and the Energy Star clothes washer, which was operated using hot water (13.4 gal/day savings). If CC1 had the same efficient appliances as CC2 and CC3 its water heating energy would drop from the reported 3424 kWh/year to 2980. This results in the heat pump water heater savings of 56% and the solar drain back water heater system of 64%. Obviously what this points out is that the payback on heat pump water heaters and solar water heaters would be quicker if Energy Star appliances are not used in the home. However it is best to reduce loads first.

Electric and solar water heaters in general are pretty quite. Heat pump water heater fans have a higher sound level, and some care should go into the location of these units to avoid unwanted noise in bedrooms, studies and entertainment areas in the home. The HPWH in CC2 is located in the garage and since these homes are unoccupied there is relatively little accumulation of garage "stuff" to dampen sound. On September 15, 2010, at 8:30 AM until about 9:30 AM sound level measurements were made in the center of the garage about 12 ft from the unit and 12 in. from the inlet grill in the back of the HPWH shroud. The highest sound recorded was when fan 1 was at high speed, 3900 RPM of 78.6 DB, 12 in. from the back of the fan coil inlet grill. The sound in the center of the garage, 12 ft from the unit at the same 5 ft height off the floor was 68.7 DB. The HPWH unit was run through all fan modes form low speed single fan operation to two fans both at high speed, 3200–3900 RPM. The measured sound level 12 in. behind the unit ranged from 65.5 to 78.6 DB. The measured sound level in the middle of the garage ranged from 59 to 68.7 DB. The background sound level with the unit shut off was 58 DB 12 in. behind the unit and 53.8 DB in the center of the garage.

8.8 HOME RUN VS TRUNK AND BRANCH PIPING

Home run plumbing performance measurements were made to give some indication of the energy and potential water savings. In all three houses an experiment was conducted that included running the master bathroom hot water fixture for the sink and time how long it takes to measure the arrival of hot water. Since the volume of water that has to be moved to reach the sink in the branch and trunk system is larger than the home run plumbing system it should take longer. This would be an indication of the potential energy and water savings. On September 16, 2010, at the master bath sink in each house the hot water faucet was open with a thermocouple positioned 1 in. from the spout outlet. Hot water arrived in 32 seconds in CC3 with homerun plumbing. In the other two houses with conventional trunk, branch and twig plumbing it took 52 to 76 seconds for hot water to arrive. The distance from the hot water heater to the bathroom sink in the house with homerun plumbing was 50 ft compared to only 30 ft in the houses with conventional plumbing. This supports the fact that homerun plumbing reduces distribution loses by saving both water and the energy to heat the water.

8.9 ENERGY STAR WASHER AND DRYER

The energy savings differences between the Energy Star Laundry set in CC2 and CC3 have been reported as only the electric savings of the appliances themselves to account for the energy to heat the water will increase these savings. The recalculated laundry energy accounting for hot water energy in CC1 increases to 1985 kWh from 1048 kWh, CC2 to 909 from 810 kWh, and CC3 to 878 from 795. Thus the overall energy savings of the Energy Star laundry equipment is 55%.

8.10 SEPARATE HEAT PUMP FOR EACH FLOOR VS SINGLE UNIT DOUBLE ZONED SYSTEM

Both systems were able to provide good thermal comfort in these homes. It was expected that this was the case but it was also expected that a first cost savings would be reaped from the single unit system. The experience with this project that the cost savings from the second unit went back into the increased duct work, two motorized dampers, control card and apparently added commissioning of the unit by the HVAC subcontractor. This appears to be an opportunity to take a closer look at the optimized cost of well designed single system applications serving multiple story houses with high performance envelopes in new construction and more importantly replacing two older units with a single much higher efficiency system to serve the multiple zones in retrofit applications.

9. INTERESTING FINDINGS AND LESSONS LEARNED

A ten thousand dollar incremental first cost 30%–40% whole house energy efficient retrofit package can be installed on a very common house type in the TVA service territory and deliver a positive cash flow (monthly energy bill savings > 10-year retrofit loan at 6%) to the homeowner in today's market.

Typical new houses build in the TVA service area have air leakage rates around 6 ACH at 50 Pascal of pressure. Careful retrofit air tightening should be able to cut that to about 3 ACH at 50 Pa. Two very important paths needed to attain this desirable level of air tightness; air tight ceiling/roof plane of the house and HVAC ducts inside the conditioned space.

A well built typical "Builder Spec" new all-electric 2400 ft^2 home built in the 2000–2010 time frame in the TVA service territory with average internal homeowner energy usage patterns has daily energy costs of around $5. With a well integrated energy package designed into Tennessee homes, the average daily cost for all the energy services can be less than $1/day. This is with an added $30,000 to the 30-year mortgage (at 5.23%), which can have a neutral cash flow to the homeowner after TVA, federal, and Tennessee state incentives.

The annual peak load of conventional all-electric homes with heat pumps occurs on very cold winter mornings. The average one hour peak demand for CC1 was 14 kW. Cost effective 30%–40% whole house energy savings retrofits can cut this peak demand by a third. Well designed and built new all-electric homes in the Valley can cut this peak in half. The annual load factor for all three test houses is 0.16–0.17. This means that the return on the electric power infrastructure investment for all three homes is the same. Annual load factor is defined as the average hourly electric demand for the whole house divided by the peak hour.

In the future the customers that will be first to "deep" retrofit or build new homes will also have PHEVs in the garage. During the one year study period it was shown that at least one PHEV available in 2009 doing a 32 mile round trip commute 5 days a week can deliver load factors greater than typical all-electric homes in the TVA region during both peak winter and peak summer months.

As the residential market transforms toward much more energy efficient houses, all-electric homes will gain market share in the TVA region. Secondly this transformation will result in the electric dryer becoming a much more important contributor toward peak monthly load demand. This study has shown that as houses get more efficient the dryer tends to dominate the peak load profile not only in the cooling months but also the summer. Other than clothes lines heat pump dryers appear to be a most attractive technology for TVA to encourage development. Several units are available internationally and it is suggested that one be installed in CC2 or CC3 for the next test period.

The solar water heater did use slightly less energy than the heat pump water heater but from the cost effectiveness perspective the GE heat pump was the clear winner. It is recommended that the heat pump water heater in the garage of CC2 be placed inside the conditioned space for the next test period. This will provide needed documentation of cooling and dehumidification benefits in the cooling season and over all space heating impacts during the winter.

The best mechanical ventilation system is clearly the ERV in CC3, but work needs to be done to reduce the $3500 installed cost for the TVA service territory, or potentially CC3 can be used to gather IAQ benefits during the next test period to demonstrate to homeowners the benefits to their health. The second bests method of bring in fresh air is via duct run to the return side of the heat pump. However it is necessary to develop a better controller with multiple speed indoor fan blowers. This study documented that the mix of time the fan is on high or low speed drastically alters the delivered average CFM of fresh air to the house. It is recommended that a better controller be installed or developed to control fresh air in CC2 during the next test period.

This study has lead to a one year long side-by-side field comparison between an Energy Star washer and dryer compared to economy grade appliances. Working with statistics from GE on average number of clothes washing per week of 7 for the simulated occupancy of 3 we found a hot water savings of 13.4 gal/day. Apparently the number of people that use hot water wash today is somewhere between 20 and 50%. It would seem that with the detergents that are now available today for cold water washing and the large water and energy usage that additional savings could be attained by only plumbing cold water to the laundry room.

Prior to determining paybacks of advanced water heating systems an important variable is calculation of hot water usage, which on average can vary from 66 to 54 gal of hot water per day depending on clothes washing technology and homeowner operating practices.

The incremental cost of low-E gas filled windows compared to builder installed regular two pane windows in 2008 was only $0.85/ft^2 of window area.

When a thermostat is changed out the entire heat pump system should be recommissioned to make sure the sequence of operation is optimized for the particular installation. When does the unit go into high speed indoor fan, or high capacity compressor operation, or resistance heating . . . ? What levels of fresh air are provided at the different modes of operation? Homeowners should be educated on real energy savings from thermostat temperature operation winter time setback at night and during hours of no occupancy and thermostat setup during the summer. General rules of thumb are not sufficient. The answers to these questions could be attained by some simple homeowner set of diagnostics that could be run through the thermostat. Real time HVAC energy consumption available at the stat for both homeowner feedback and adaptive learning by the equipment would lead to substantial retrofit energy savings.

By far the largest retrofit energy savings found in these houses with ducts outside the conditioned envelope is to get them inside the conditioned space and tighten the envelope at the same time. Converting the attic to a conditioned mechanical room with spray foam comes with a cost of about $5–6K. Finding the optimum installed cost of sufficient foam to avoid moisture problems and the remaining needed R-value of lower cost fiberglass or cellulose is needed for the Tennessee mixed humid climate. Another approach would be to go to a variable refrigerant flow ductless (zoned) system.

Solar PV system had zero problems after 2 years of operation. ORNL and TVA have been testing these TVA generation partner compliant systems since 2002 and with properly installed and commissioned systems have had zero faults.

The solar drain back water heater equipment on CC1 had no problems after the first year of operation. With durability issues still an occasional concern it is best to continue testing this equipment for at least the next test period.

This report describes a 75% energy savings compared to the BA Benchmark. Compared to the benchmark house of 136, CC3 has a HERS rating of 34. Without the PV system, CC3 maintains a 65% energy savings over the benchmark.

The measured solar photovoltaic fraction for this West Knoxville, TN house was found to be 30%.

The cost to construct CC3 including all market-valued donations and labor is $353.570, $141/ft^2, including the installed cost of the 2.5-kWp solar PV system and solar water heater.

One of the uses of this report is to aid builders and homeowners in making the “right” decisions in building a high performance house. The detailed drawings, specifications, and lessons learned from the construction process are presented. Also, provided is the analysis of the 121 sensors monitoring the performance of CC3. This information is specifically helpful for those considering 2 × 6 optimum-value framing, solar water heating and solar PV systems. The 90 sensors in CC2 have led to useful information to those designing deep energy efficiency retrofits for their homes.

The HPWH in CC2 was taken out of service and replaced on March 22, 2010, with a commercial unit that has a more efficient compressor and has resulted in higher field performance COP than the pre-commercial prototype we had been testing at about 2.2 compared to ~2.4.

In January 2010 CC1 two heat pumps make up the largest fraction of energy usage, 66% of the total. A total of 1998 kWh were used by the two heat pumps in January. The resistance back up heaters required 862 kWh or 43%. The resistance heaters required 28% of the whole house energy demand in January 2010. A total of 1608 kWh were used by the two heat pumps in February. The resistance back up heaters required 438 kWh or 27%. The resistance heaters required 16% of the whole house energy demand in February 2010.

In CC3 in January the single heat pump makes up the largest fraction of energy used, 65% of the total. A total of 1486 kWh were used by the single heat pump in January. The resistance back up heaters required 615 kWh or 41% of the space heating energy. The resistance heaters required 27% of the whole house energy demand in January 2010. A total of 1216 kWh were used by the single heat pump in February. The resistance back up heaters required 394 kWh or 32% of the space heating energy. The resistance heaters required 21% of the whole house energy demand in February 2010.

The 2 ton heat pump in CC3 for January uses by far the largest fraction of energy, 88%. A total of 1089 kWh were used by the single heat pump in January. The resistance back up heaters required 455 kWh or 42% of the space heating energy. A total of 809 kWh were used by the single heat pump in February. The resistance back up heaters required 234 kWh or 29% of the space heating energy. These resistance heat fractions were larger than they would have been if the 2 ton heat pump was allowed to go into the compressor high capacity mode. A thermostat change out to provide remote control prevented the unit from optimum performance for a period of time in the winter of 2010.

An analysis of the CC3 heat pump demand finds that heating balance point is 54°F. In general no heating is needed in the house until the outdoor temperature is 17°F below the thermostat setting of 71°F.

The heating season months from October through April cost for CC1 was $713 compared to the net cost for CC3 of $219. That is an energy cost savings of 69%. The costs are based on the LCUB actual monthly residential rates.

The AC Solar generation from the 2.5 kW_{peak} solar system on CC3 generated 9 kWh/day for this one year test period. The energy cost savings from the builder to CC3 is $844 due to energy efficiency and $666 from the solar credits.

TVA hit an all time daily energy generation record on January 8, 2009, 701,387 megawatt-hours. The average daily use per hour for the day was 29,224 megawatt-hours. On January 8 CC1 used 152 kWh, CC2 113 kWh, and CC3 76 kWh. The peak hour for CC1 and CC2 was 7:00 to 8:00 AM. The peak on January 8 for CC1 was 11 kWh, 8.64 for CC2 and 7.42 for CC3.

The incremental cost after incentives of this $1/day house above the same "builder house" in the same development was $31,000. The technologies in the house will continue to be tinkered with until 2012 getting ever closer to maximum affordable energy efficiency with the mixed humid climate serviced by TVA.

This report has described a cost-effective retrofit package for a typical new home that has a predicted 42% energy savings and achieves neutral cash flow based on electricity rates of $0.93/kWh, a 10-year mortgage at 6% interest, and available federal and utility incentives in 2010. This three-bedroom two and a half bath, 2400-ft^2 house has a HERS rating of 68 after retrofit and 101 before retrofit.

Based on measured data from almost 100 sensors and a computer simulation of CC2 with typical occupancy patterns and energy services for three occupants, energy for this all-electric house is predicted to cost only $3.76/day. By contrast, CC1 would require $6.46/day. Based on a full year of measured data with the houses operated under simulated occupancy CC2 is predicted to use an average of 39.5 kWh/day. The $10,000 incremental cost of the retrofit package described in this report, assuming that new windows, heat pump, and water heater are in need of replacement, has a positive cash flow to the homeowner. With the base house being an average new home built in 2008 and local electricity rates more than $0.02/kWh lower than the U.S. national average, the 42% whole-house savings should be exceeded in most other homes originally constructed prior to 1990.

10. RECOMMENDATIONS FOR YEAR TWO RETROFIT OF CC2 AND CC3

10.1 CC2

The following set of retrofits are suggested for CC2.

10.1.1 HVAC

Install an eight zoned mini split system. This will require added instrumentation to monitor the temperature, RH and energy consumption of each zone served by a separate indoor unit.

Install an ERV that is a lower cost than the completely separately ducted FanTech in CC1.

10.1.2 Water Heating

Move the GE heat pump water heater from the garage from the inside of CC2.

10.1.3 Envelope Air- tightness

Repair the known thermal short and leak above the fireplace in CC2 after taking infrared image.

Foam the thermal short left under the kitchen counter after taking infrared image.

Go into the ceiling of the front porch and block the wall into the floor joist area above the dining room windows after taking infrared image.

Retrofit a seal of the front porch box beam intersecting the stairwell after taking infrared image.

10.2 CC3

The following set of retrofits are suggested for CC3.

10.2.1 HVAC

Install the Daikin Skyway 2 ton VRF Heat Pump in replace of the Amana 2 ton unit that has been servicing the space conditioning in CC3. This system will have only one indoor unit and will use the existing duct system in CC3.

10.2.2 Lighting

LED lighting will be installed in the kitchen, master bath, and dining room; 6 ft T-5 liner fluorescent tubes will be installed in the great room and the bed wall of the master bedroom.

10.2.3 Envelope

The ceiling plane will be resealed from the interior. This will include recaulking the eight penetrations caused by the jump ducts running from the upstairs hallway with the central return and each of the bedrooms and the bonus. The penetrations caused by all the upstairs lighting fixtures will also be resealed.

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APPENDIX A. MONTHLY DASHBOARDS

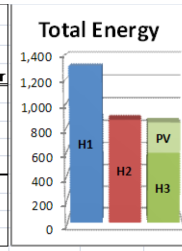
The dashboards represent the actual data collected after each month. They do not reflected the “cleaned up” with adjustments reflecting know events that did not reflect the intended performance as a result of our simulated occupancy not performing correctly, DAS malfunctions, or other known problems that have occurred over the first year of side by side monitoring. The adjustments to the raw data are all documented in the earlier sections of this report. The blue bars in each of the dashboards represents CC1, the red bars CC2 and green CC3. All units are kWh unless noted otherwise in the dashboard.

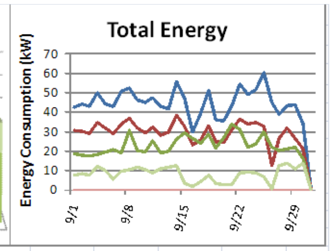
Dashboard Report

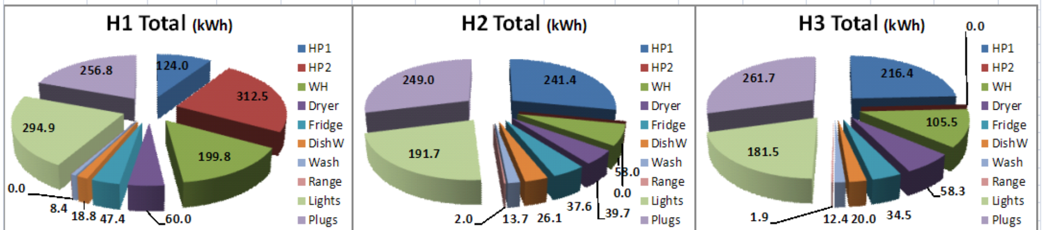
House Name	Total[1]	PV[1]	Net[1]	Cost[2]	PeakHr[1]	Average[1]	Ld Factor
	09/01/09		to		9/30/09		
H1	1,311	0.00	1,311	$109.71	6.04	1.88	0.31
H2	871	0.00	871	$72.85	5.14	1.25	0.24
H3	849	253.09	596	$19.46	4.86	0.97	0.20

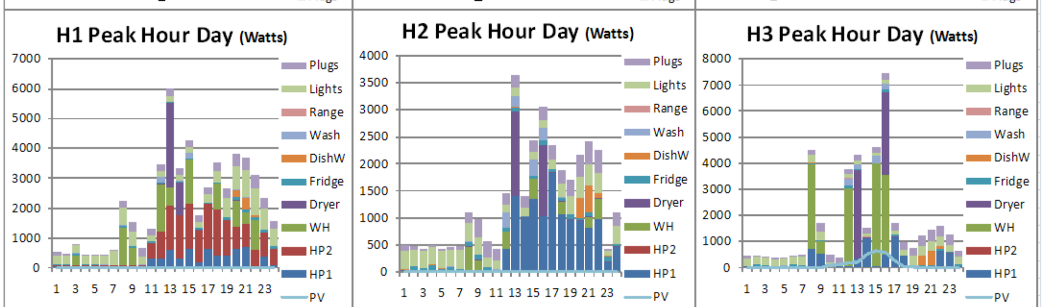
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour	
H1	100.00%	100.00%	100.00%	100.00%	9/25	9/14	13:00
H2	66.40%	85.04%	66.40%	66.40%	9/14	9/14	13:00
H3	64.72%	80.49%	45.42%	17.74%	9/21	9/21	16:00

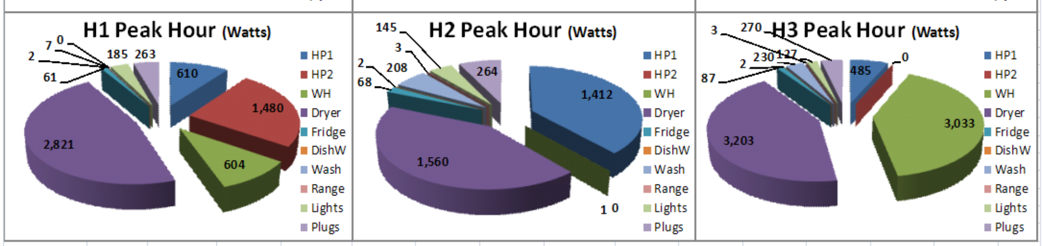
[1] Energy in kWh throughout unless otherwise noted

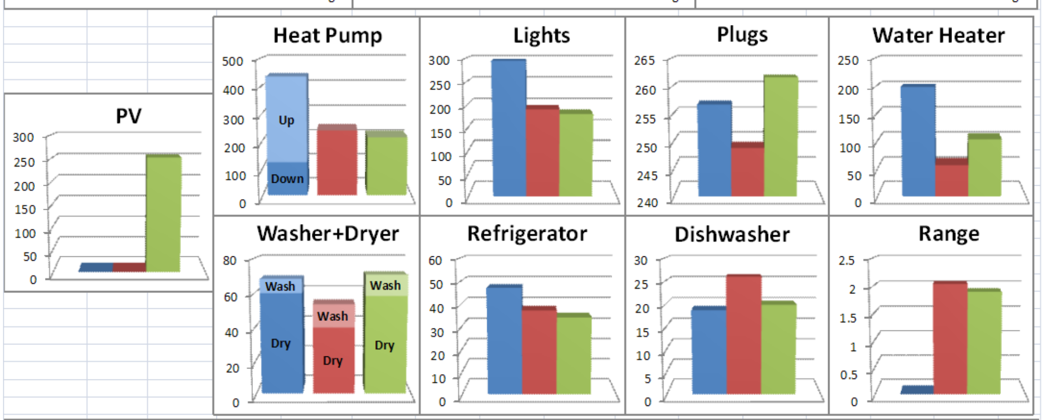


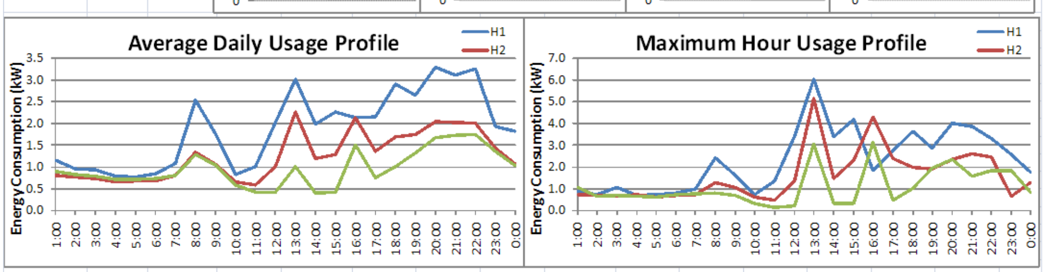












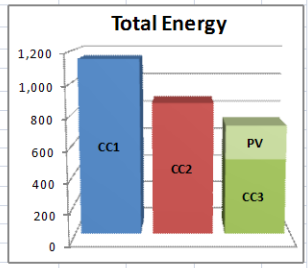
Dashboard Report

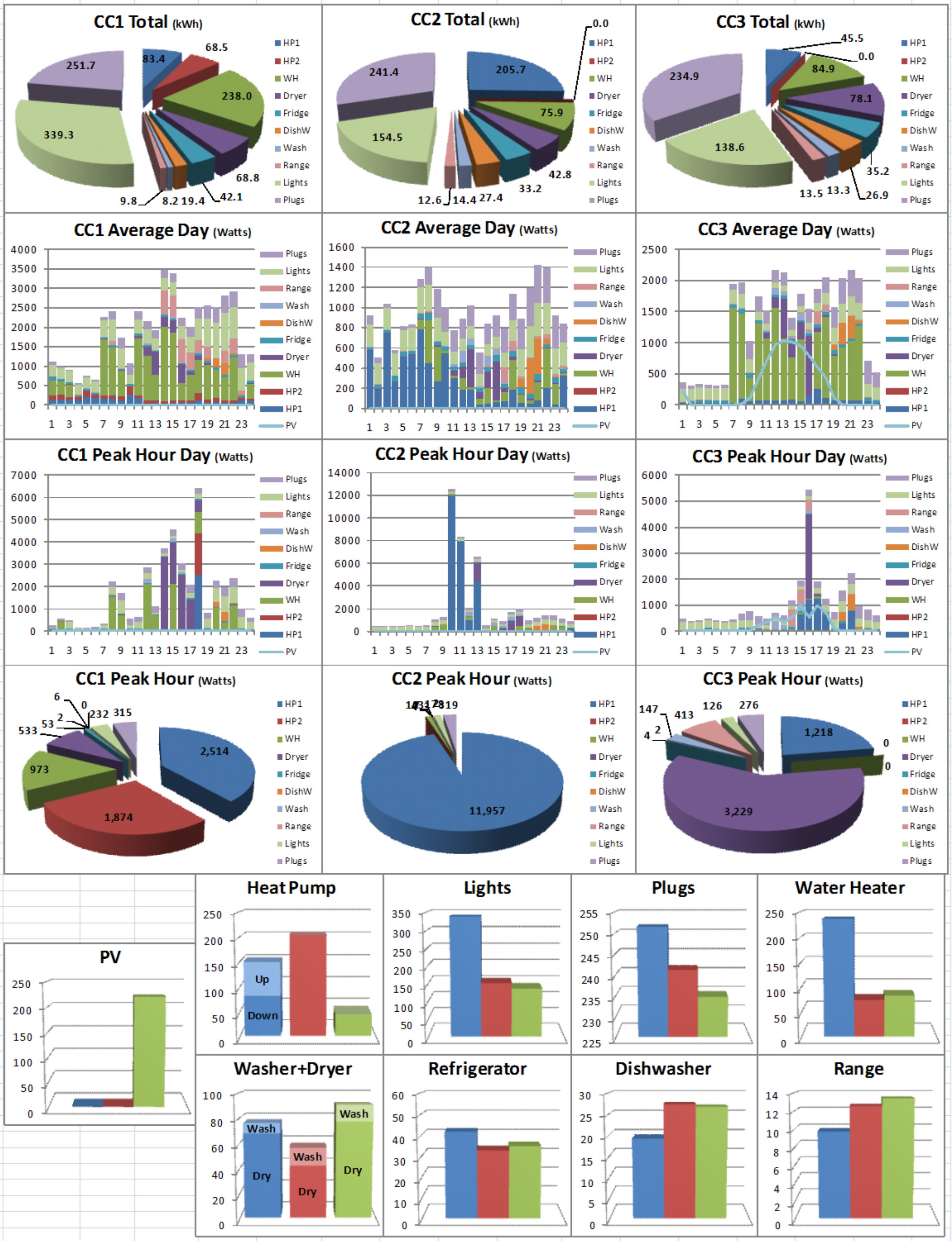
10/1/09 to 10/31/09

House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	kWh/MBTU	SolarFrac
CC1	1,149	0.00	1,149	$101.33	6.58	1.62	0.25	0.551	431.921	-0.474
CC2	867	0.00	867	$78.26	12.64	1.22	0.10	0.182	417.769	-0.425
CC3	721	221.07	500	$21.63	4.93	0.84	0.17	0.491	173.026	0.410

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	10/20	10/23	18:00	100.00%	100.00%
CC2	75.47%	192.14%	75.47%	77.23%	10/20	10/20	10:00	32.97%	96.72%
CC3	62.71%	74.98%	43.48%	21.34%	10/6	10/9	16:00	89.05%	40.06%

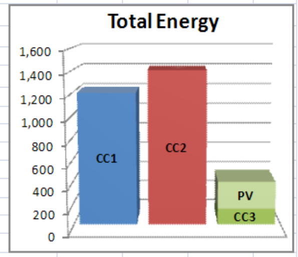
[1] Energy in kWh throughout unless otherwise noted

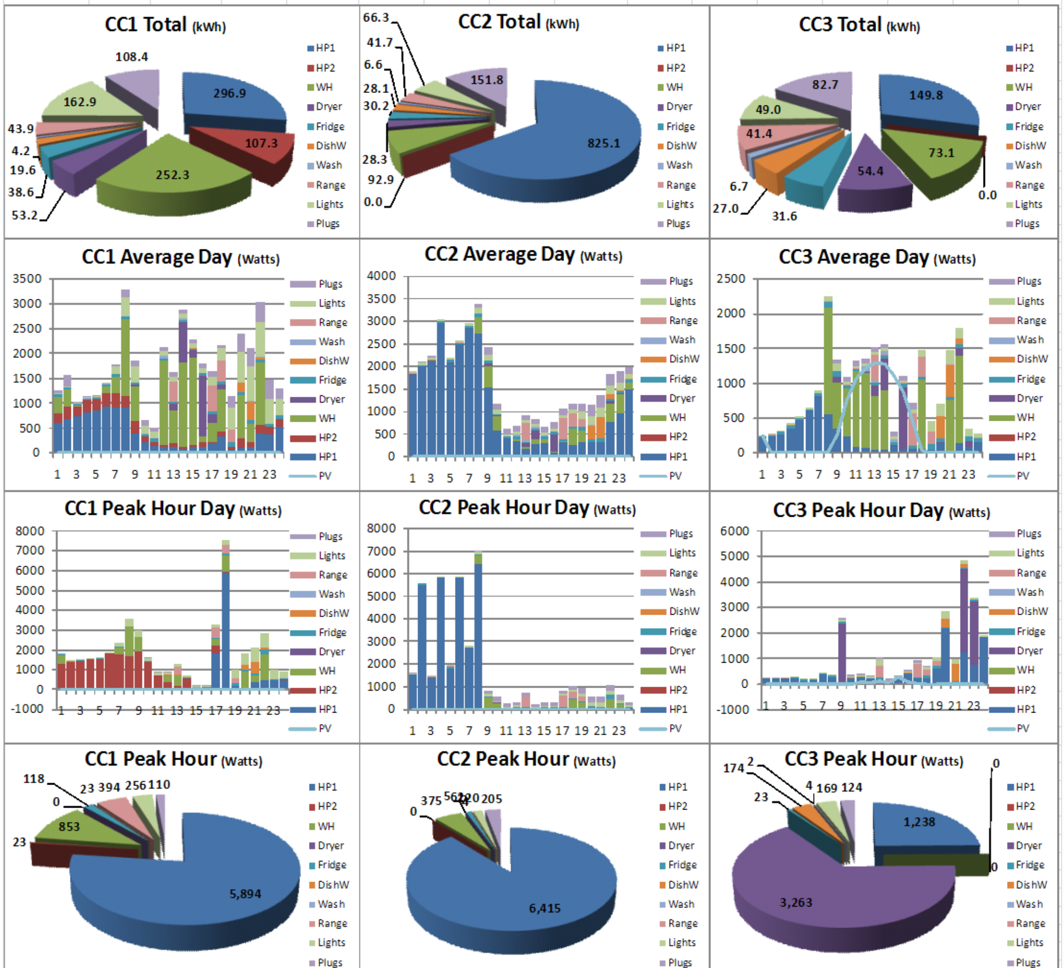


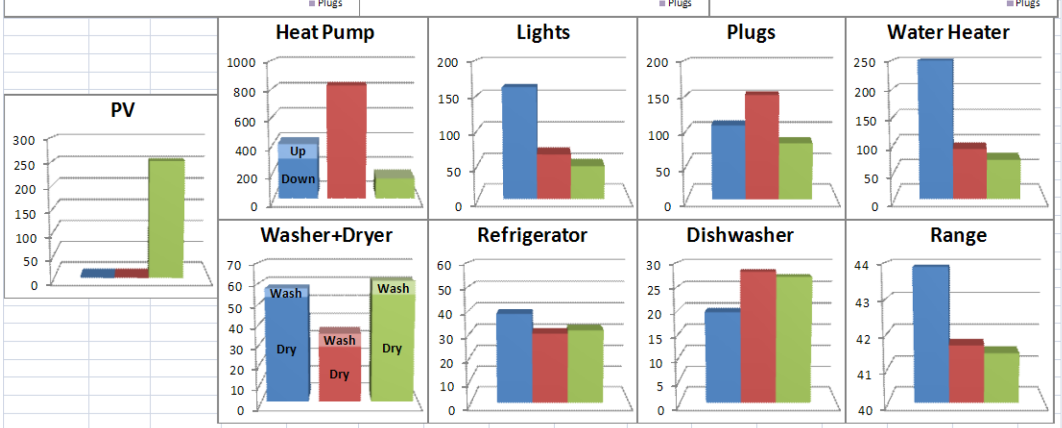


Dashboard Report										
			11/1/09		to	11/30/09				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,209	0.00	1,209	$104.93	7.68	1.68	0.22	0.586	430.661	-0.469
CC2	1,409	0.00	1,409	$121.12	7.45	1.96	0.26	0.194	478.931	-0.634
CC3	398	251.14	147	-$11.00	5.18	0.76	0.15	0.567	129.022	0.560
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	11/6	11/29	18:00	100.00%	100.00%	
CC2	116.57%	96.94%	116.57%	115.42%	11/22	11/7	8:00	33.11%	111.21%	
CC3	32.95%	67.46%	12.16%	-10.49%	11/30	11/30	22:00	96.74%	29.96%	

[1] Energy in kWh throughout unless otherwise noted

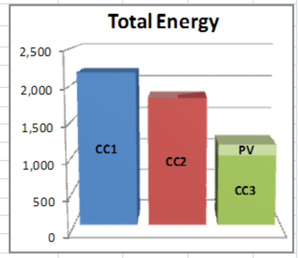


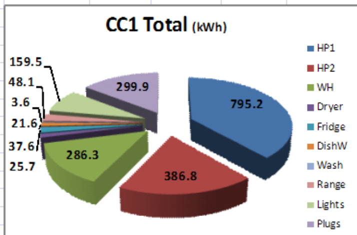


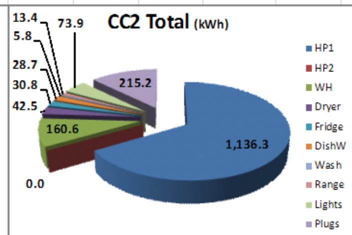


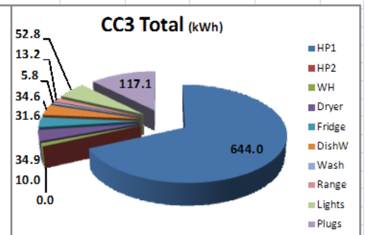
Dashboard Report										
			12/1/09		to	12/31/09				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	2,172	0.00	2,172	$174.75	8.68	2.94	0.34	0.648	441.706	-0.507
CC2	1,818	0.00	1,818	$147.51	7.39	2.47	0.33	0.503	319.280	-0.089
CC3	1,163	155.85	1,007	$66.19	5.68	1.47	0.26	0.268	37.375	0.872
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	12/11	12/12	8:00	100.00%	100.00%	
CC2	83.74%	85.14%	83.74%	84.41%	12/11	12/11	8:00	77.58%	72.28%	
CC3	53.53%	65.42%	46.36%	37.88%	12/26	12/26	11:00	41.39%	8.46%	

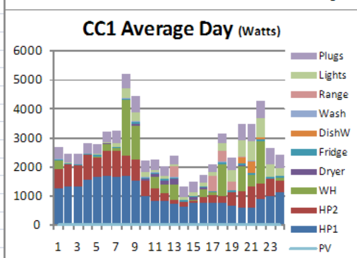
[1] Energy in kWh throughout unless otherwise noted

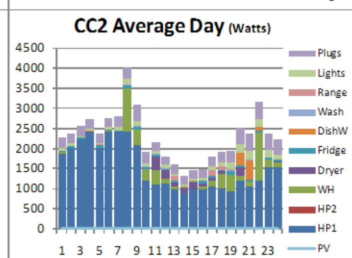


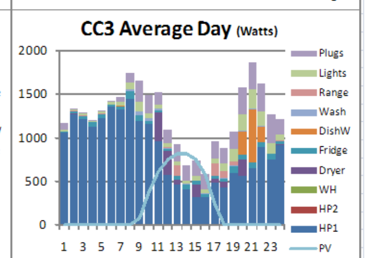


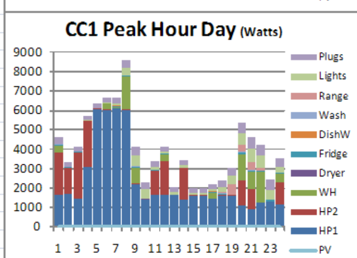


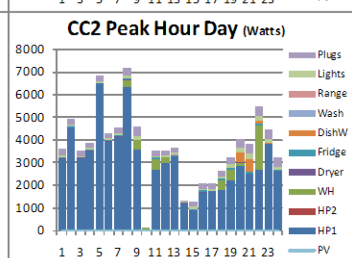


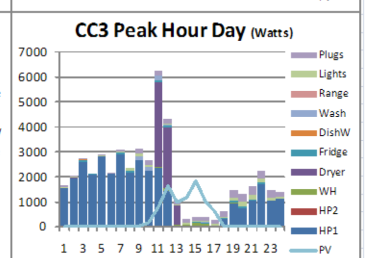


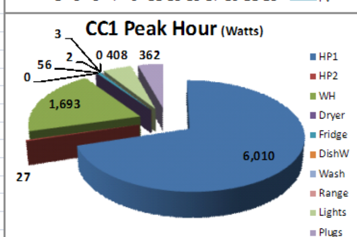


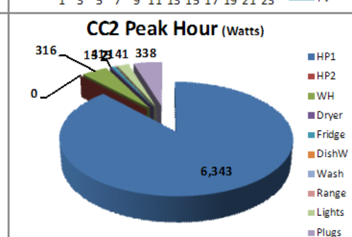


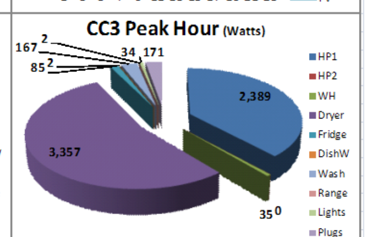


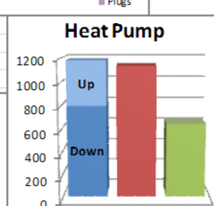


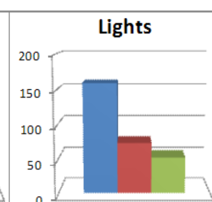


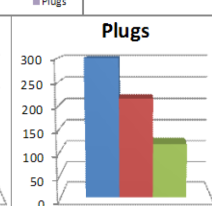


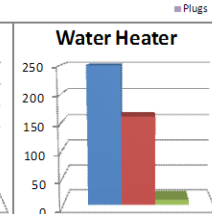


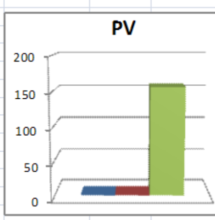


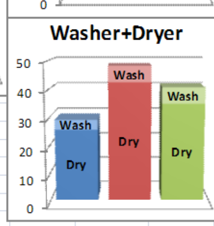


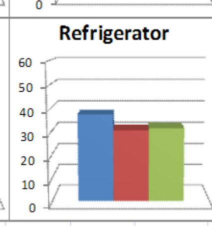


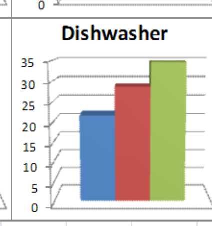


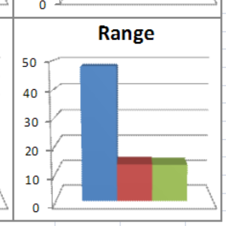












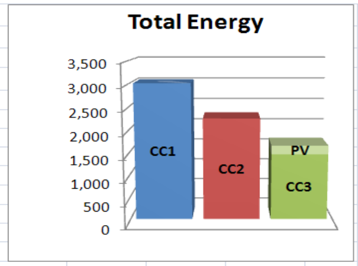
Dashboard Report

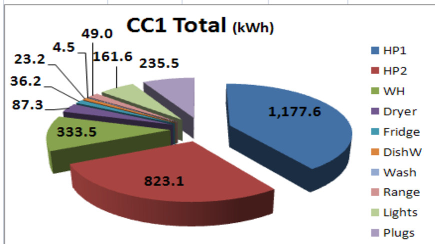
1/1/10 to 1/31/10

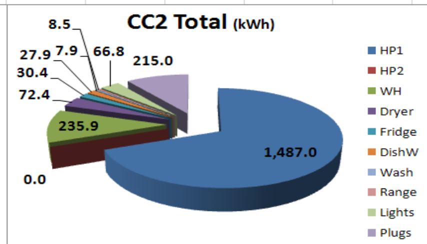
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
CC1	3,042	0.00	3,027	$287.45	14.65	4.09	0.28	0.778	428.630	-0.462
CC2	2,283	0.00	2,262	$217.48	9.88	3.06	0.31	0.571	413.039	-0.409
CC3	1,683	194.19	1,467	$121.07	7.42	2.09	0.28	0.349	34.464	0.882

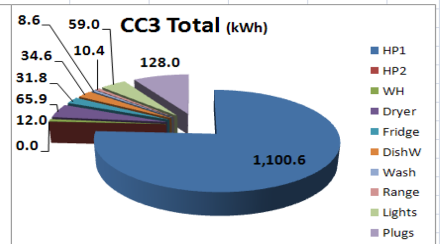
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	1/9	1/4	9:00	100.00%	100.00%
CC2	75.03%	67.43%	74.73%	75.66%	1/3	1/9	7:00	73.42%	96.36%
CC3	55.32%	50.62%	48.48%	42.12%	1/9	1/8	8:00	44.81%	8.04%

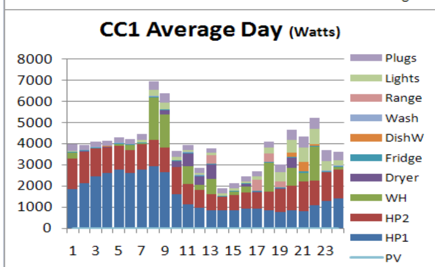
[1] Energy in kWh throughout unless otherwise noted

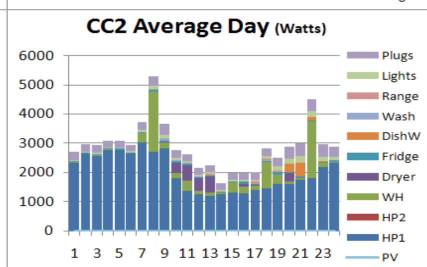


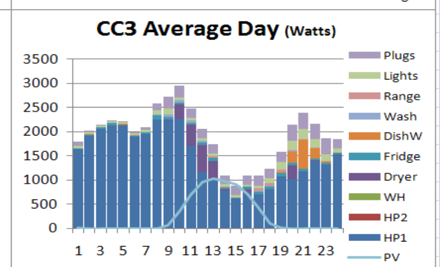


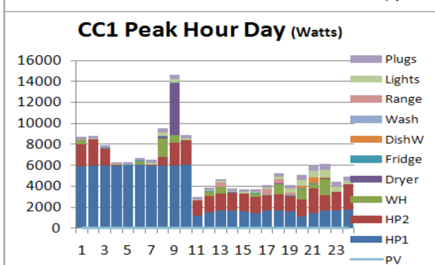


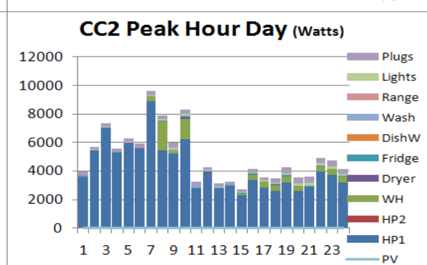


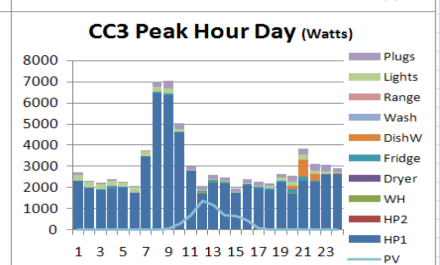


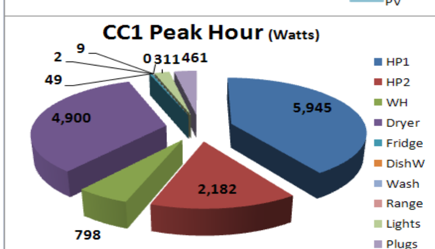


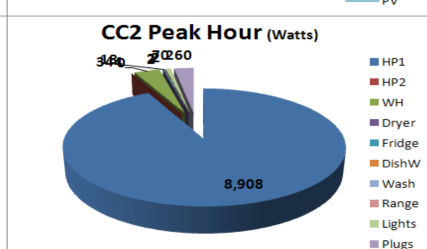


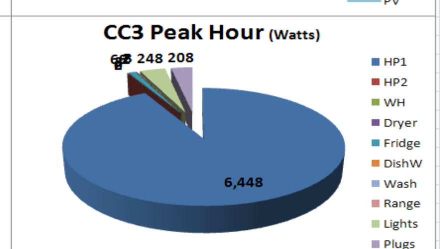


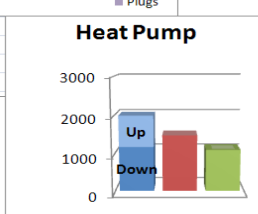


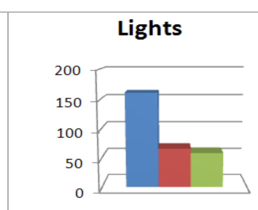


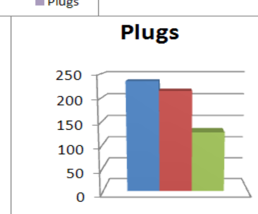


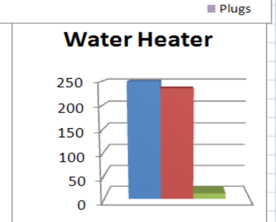


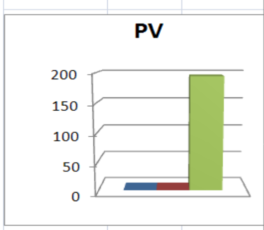


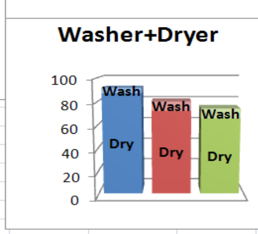


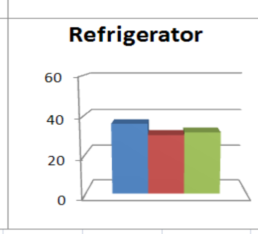


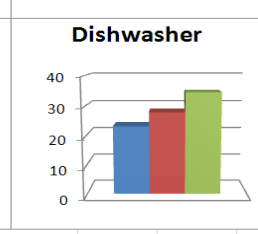


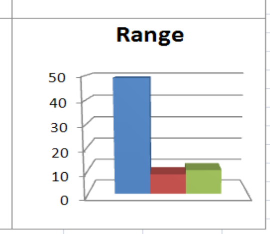






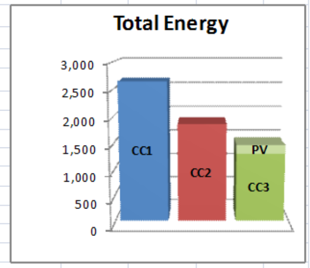


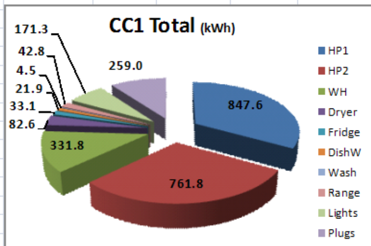


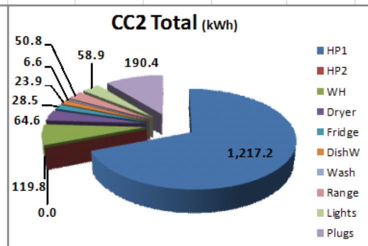


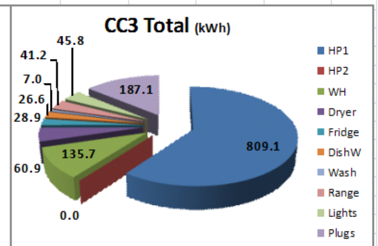
Dashboard Report										
			2/1/10		to	2/28/10				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	2,664	0.00	2,648	$252.62	11.12	3.96	0.36	0.939	352.852	-0.204
CC2	1,882	0.00	1,858	$180.54	7.51	2.80	0.37	0.619	193.310	0.340
CC3	1,508	167.49	1,295	$110.58	7.05	2.08	0.29	0.618	219.773	0.250
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	2/10	2/10	8:00	100.00%	100.00%	
CC2	70.62%	67.50%	70.20%	71.47%	2/10	2/17	20:00	65.93%	54.79%	
CC3	56.59%	63.39%	48.91%	43.77%	2/28	2/10	20:00	65.76%	62.28%	

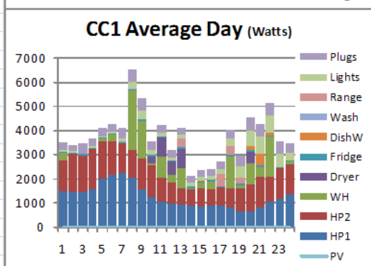
[1] Energy in kWh throughout unless otherwise noted

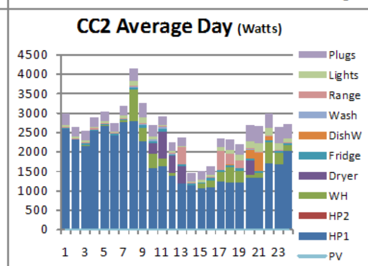


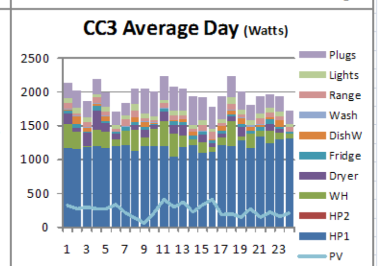


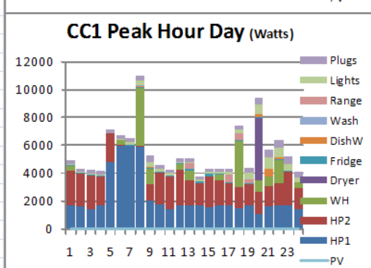


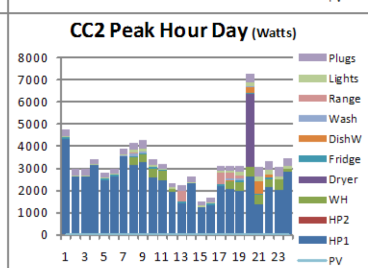


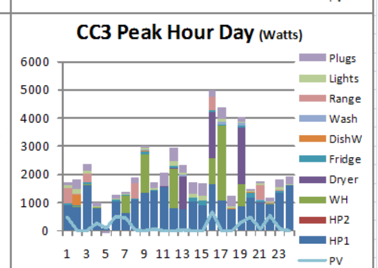


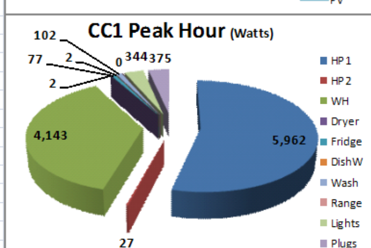


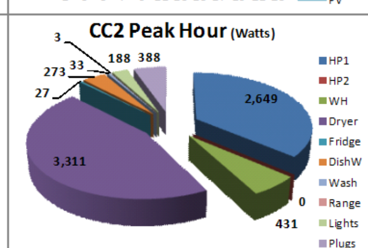


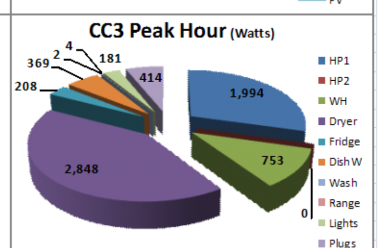


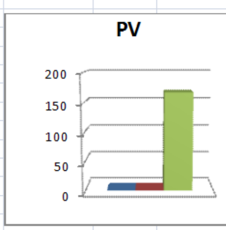


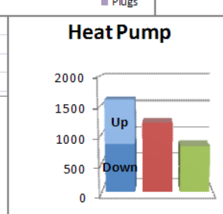


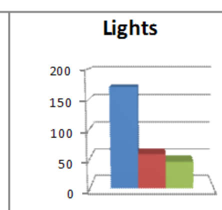


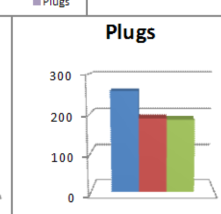


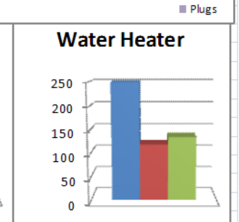


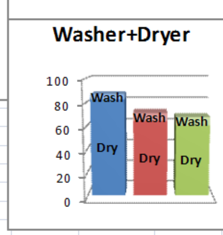


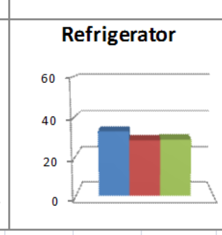


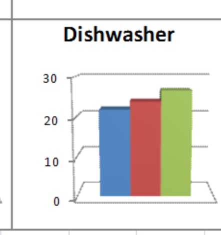


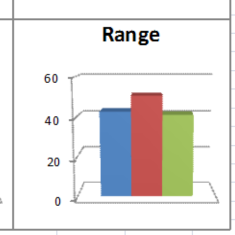






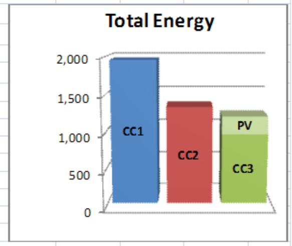


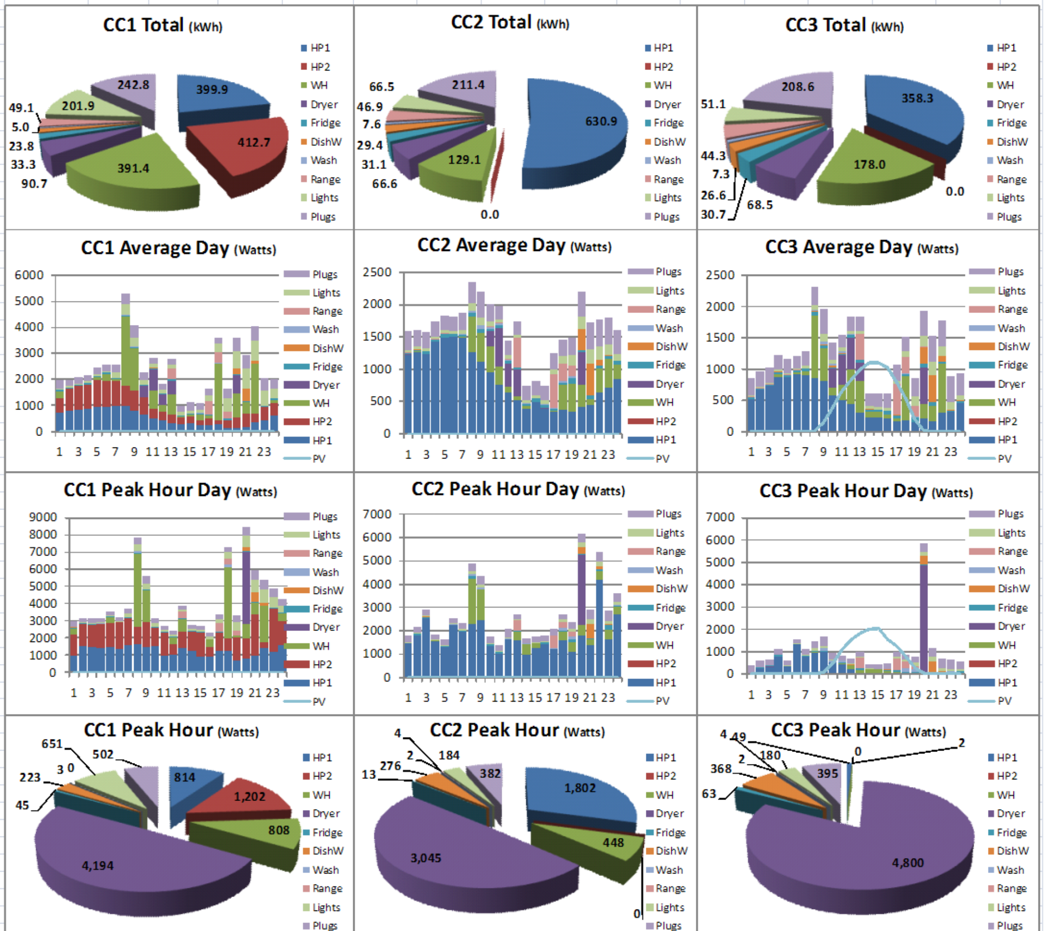


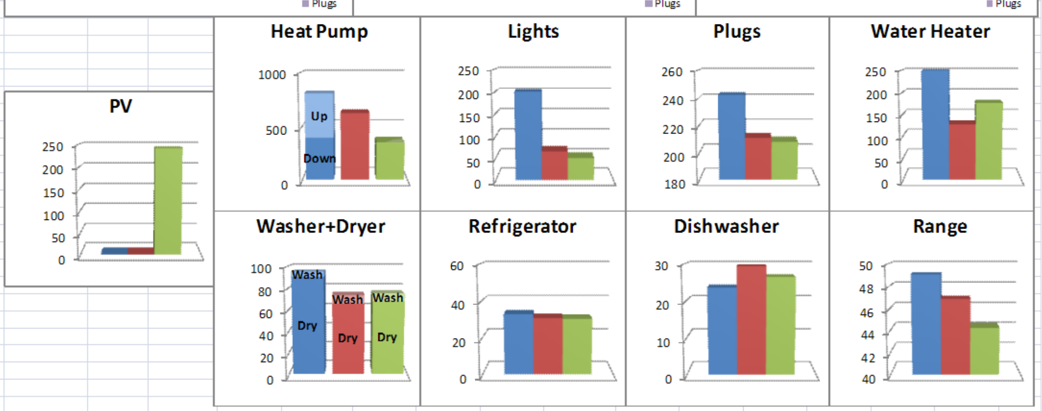


Dashboard Report										
			3/1/10		to	3/31/10				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,977	0.00	1,960	$189.33	8.60	2.65	0.31	1.166	335.619	-0.145
CC2	1,348	0.00	1,332	$131.38	6.35	1.81	0.29	0.992	130.071	0.556
CC3	1,177	242.24	958	$64.31	7.22	1.41	0.19	0.874	203.789	0.305
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	3/3	3/3	20:00	100.00%	100.00%	
CC2	68.17%	73.76%	67.93%	69.39%	3/3	3/3	20:00	85.09%	38.76%	
CC3	59.56%	83.87%	48.87%	33.97%	3/3	3/24	20:00	74.90%	60.72%	

[1] Energy in kWh throughout unless otherwise noted





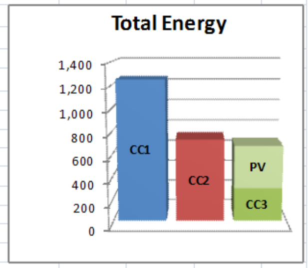


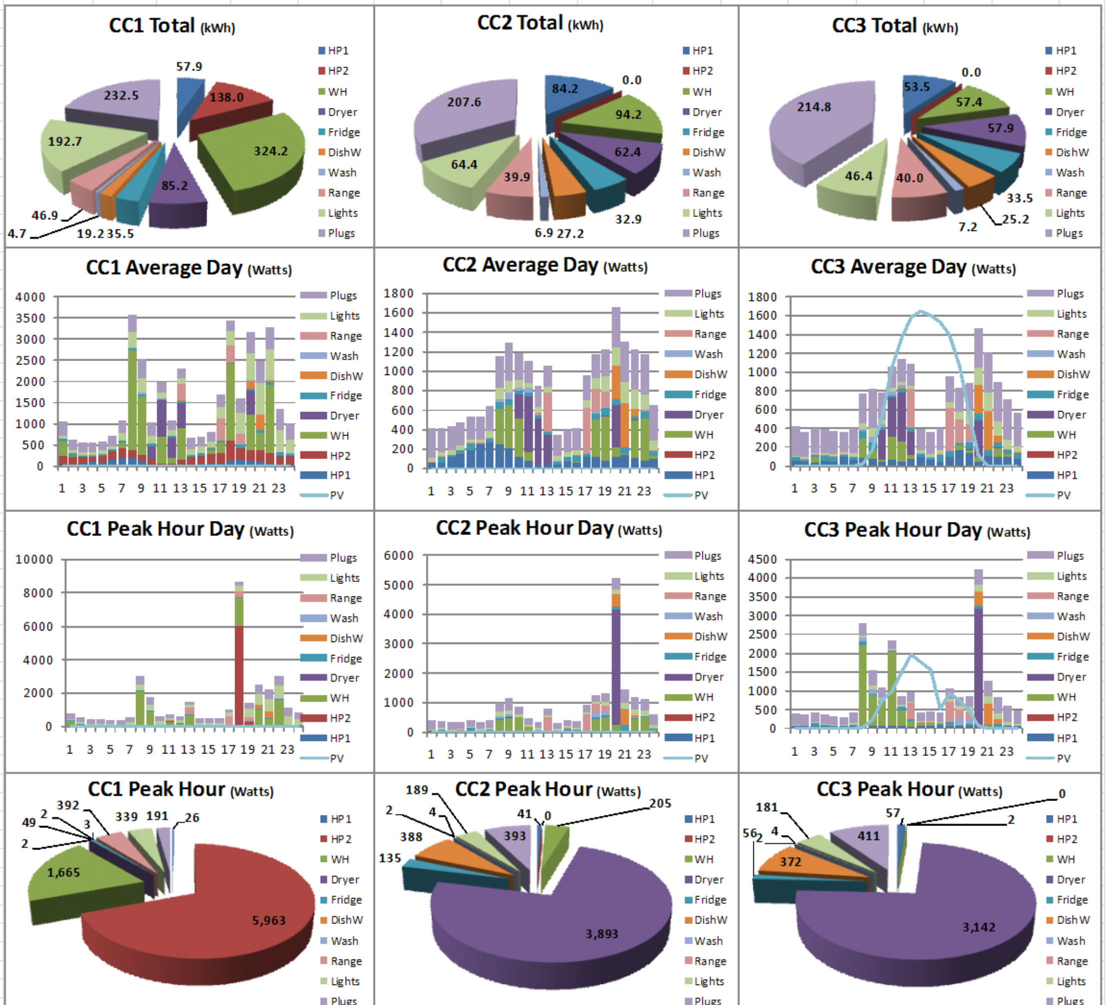
Dashboard Report

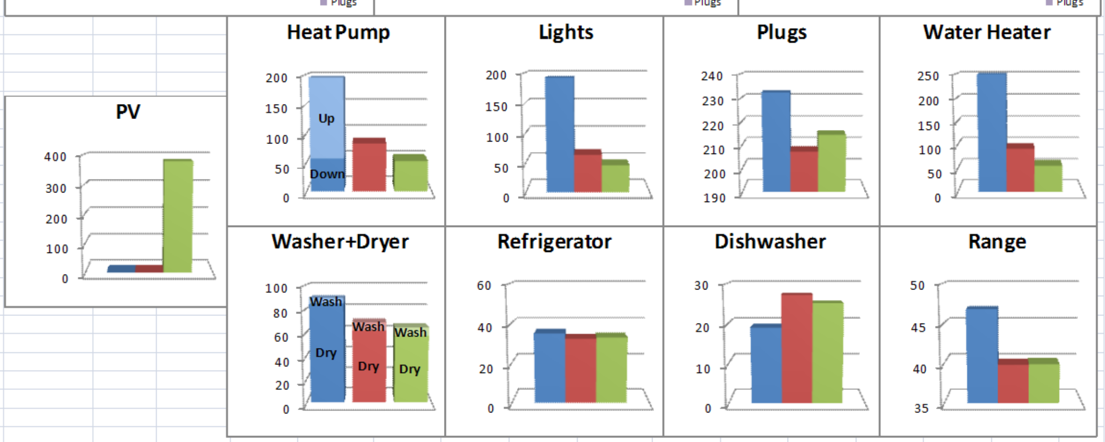
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	Water Heater MBTUs	Water Heater kWh/MBTU	Water Heater SolarFrac
			4/1/10		to	4/30/10				
CC1	1,267	0.00	1,253	$117.00	8.81	1.76	0.20	0.969	334.391	-0.141
CC2	745	0.00	730	$71.78	5.45	1.03	0.19	0.817	115.334	0.606
CC3	692	379.75	295	-$11.24	4.41	0.72	0.16	0.871	65.904	0.775

House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU
CC1	100.00%	100.00%	100.00%	100.00%	4/25	4/27	18:00	100.00%	100.00%
CC2	58.80%	61.89%	58.29%	61.35%	4/10	4/21	20:00	84.23%	34.49%
CC3	54.66%	50.10%	23.56%	-9.61%	4/24	4/21	20:00	89.81%	19.71%

[1] Energy in kWh throughout unless otherwise noted

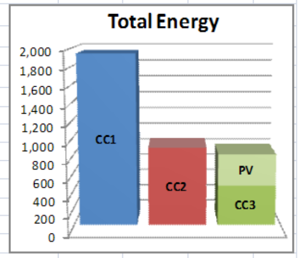


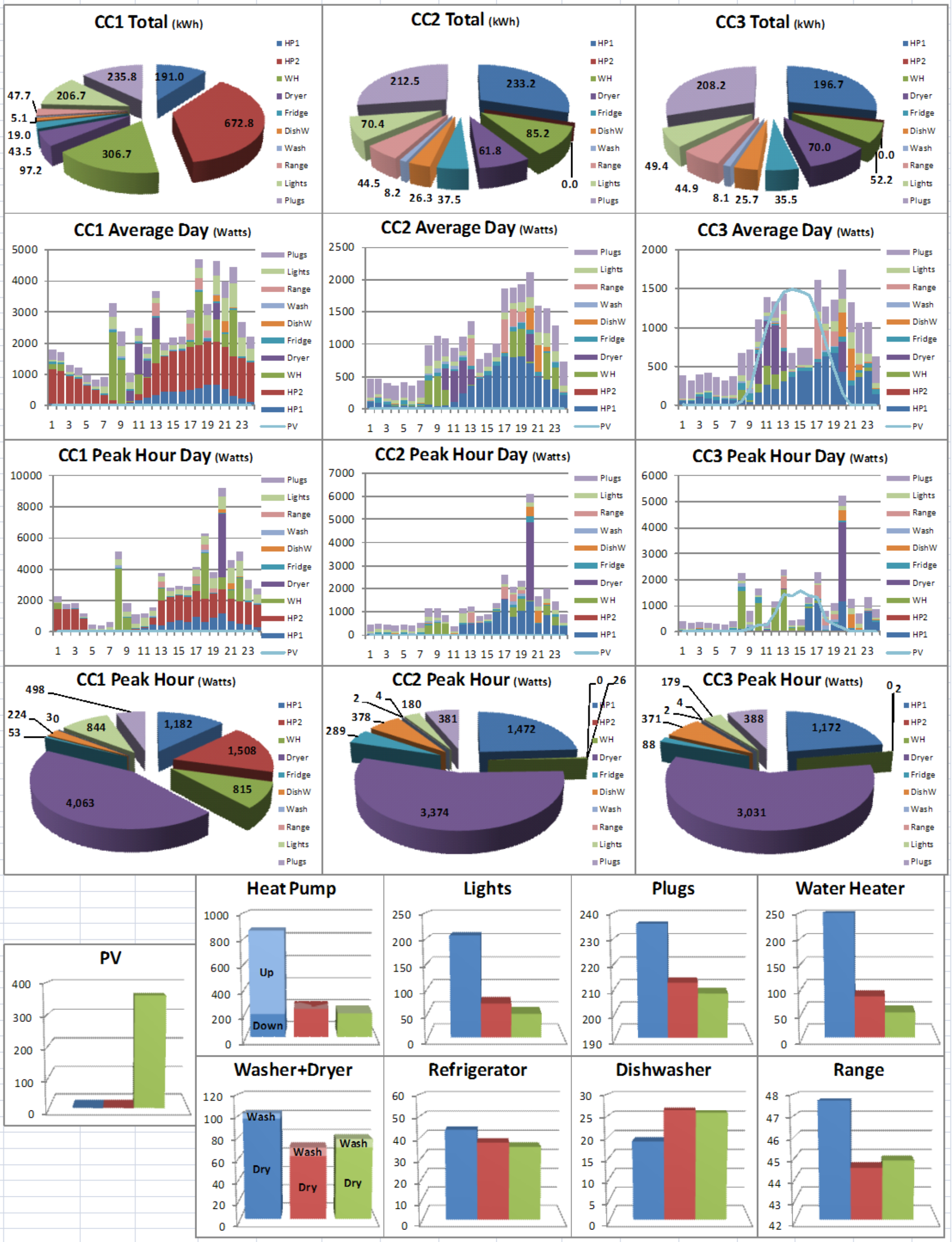




Dashboard Report										
			5/1/10		to	5/31/10				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,946	0.00	1,946	$168.17	9.37	2.63	0.28	0.915	335.237	-0.144
CC2	893	0.00	893	$81.14	6.30	1.22	0.19	0.764	111.480	0.620
CC3	819	360.25	459	$1.97	5.37	0.83	0.15	0.803	65.015	0.778
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	5/30	5/26	20:00	100.00%	100.00%	
CC2	45.92%	67.16%	45.92%	48.25%	5/23	5/26	20:00	83.50%	33.25%	
CC3	42.10%	57.26%	23.59%	1.17%	5/2	5/12	20:00	87.76%	19.39%	

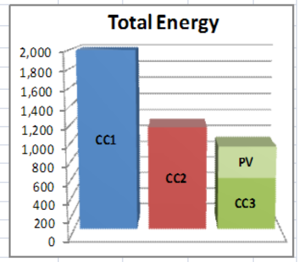
[1] Energy in kWh throughout unless otherwise noted

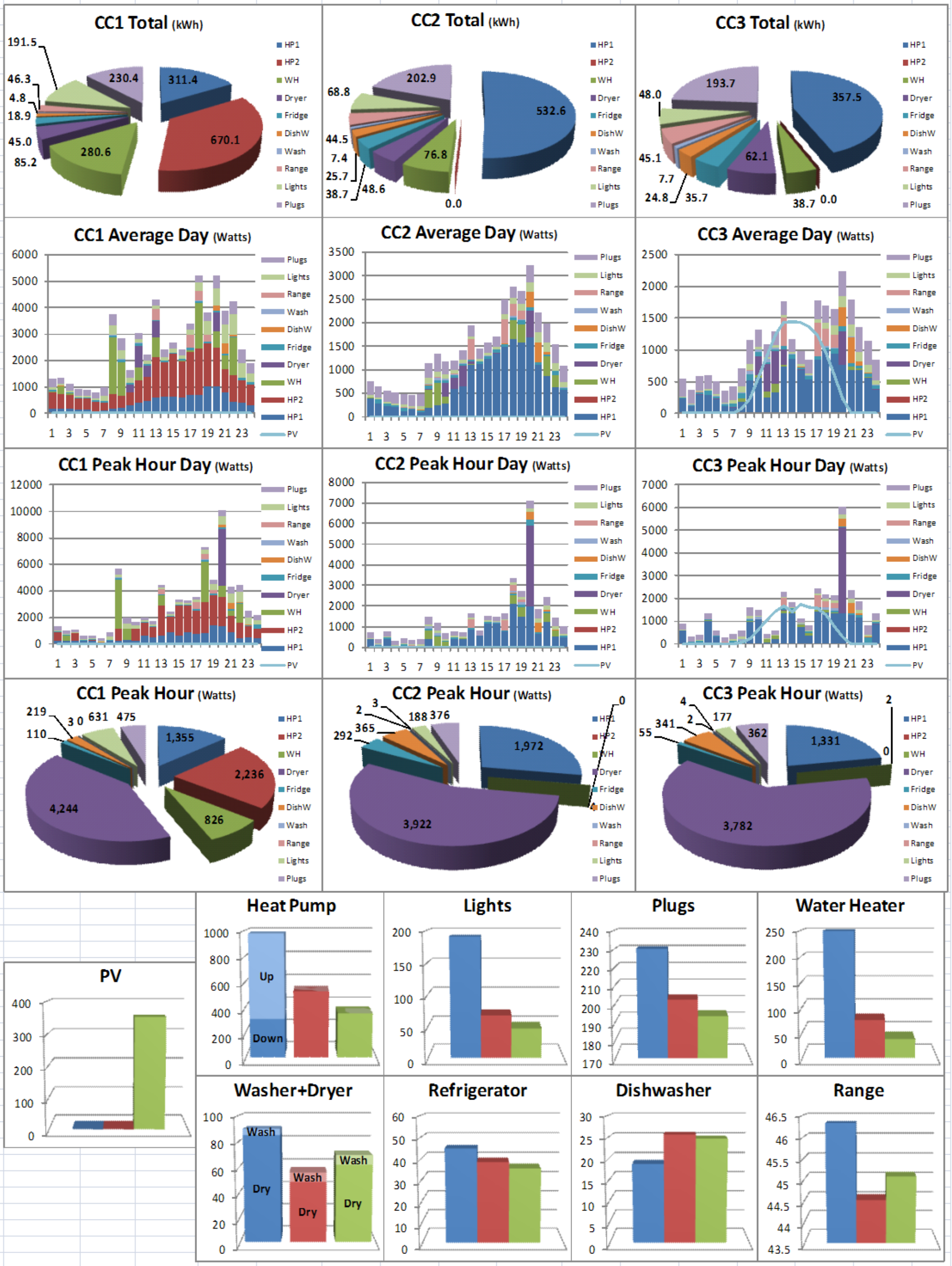




Dashboard Report										
			6/1/10		to	6/30/10				
								Water Heater		
House Name	Total[1]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,996	0.00	1,996	$180.24	10.27	2.79	0.27	0.834	336.404	-0.148
CC2	1,154	0.00	1,154	$107.20	7.31	1.62	0.22	0.707	108.678	0.629
CC3	937	352.91	584	$15.51	6.05	0.97	0.16	0.731	52.864	0.820
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	6/6	6/23	20:00	100.00%	100.00%	
CC2	57.78%	71.15%	57.78%	59.48%	6/27	6/30	20:00	84.73%	32.31%	
CC3	46.93%	58.86%	29.26%	8.60%	6/5	6/23	20:00	87.69%	15.71%	

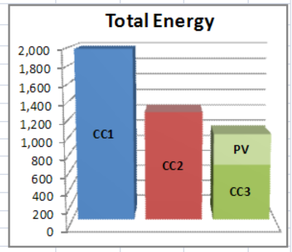
[1] Energy in kWh throughout unless otherwise noted

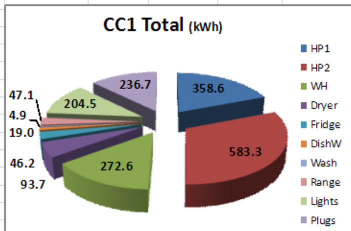


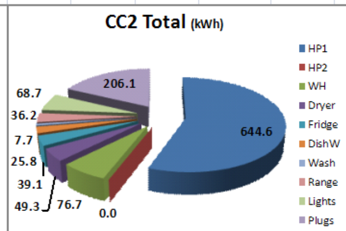


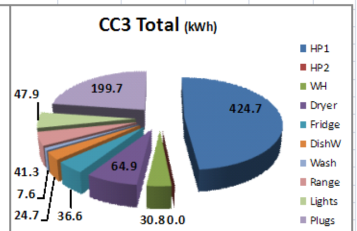
Dashboard Report										
			7/1/10		to	7/31/10				
								Water Heater		
House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,983	0.00	1,983	$173.15	10.40	2.68	0.26	0.800	340.860	-0.163
CC2	1,265	0.00	1,265	$113.08	8.05	1.72	0.21	0.673	113.912	0.611
CC3	1,010	356.81	653	$19.09	5.78	1.02	0.18	0.730	42.197	0.856
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	7/25	7/7	20:00	100.00%	100.00%	
CC2	63.79%	77.47%	63.79%	65.31%	7/25	7/7	20:00	84.20%	33.42%	
CC3	50.94%	55.60%	32.95%	11.03%	7/31	7/10	11:00	91.24%	12.38%	

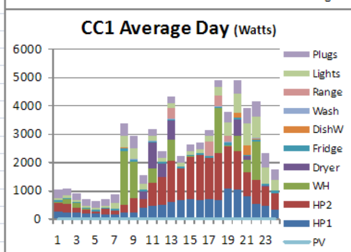
[1] Energy in kWh throughout unless otherwise noted; [2] Total corrects for DAS load

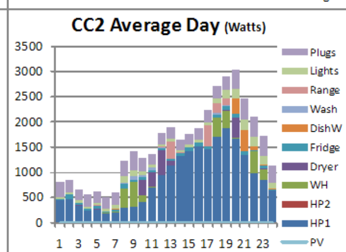


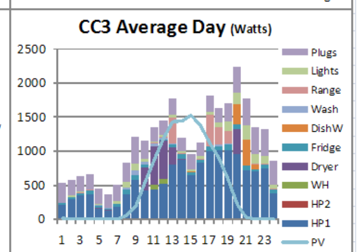


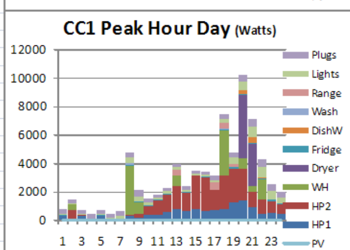


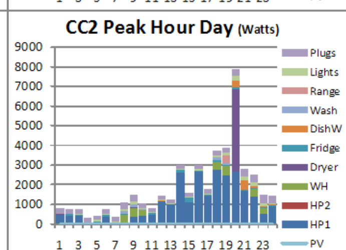


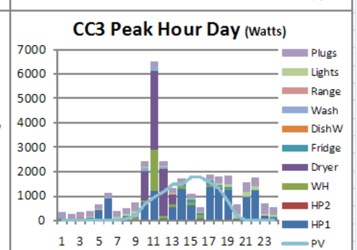


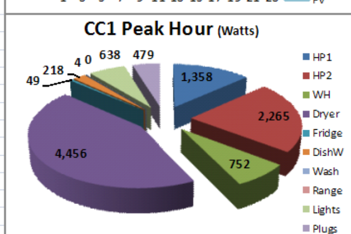


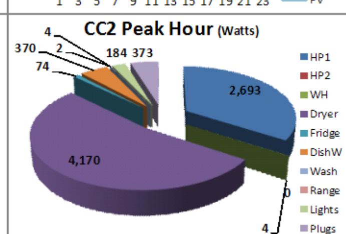


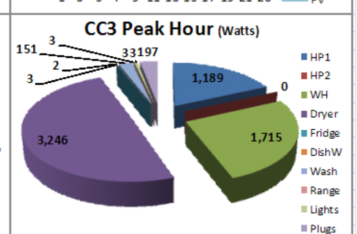


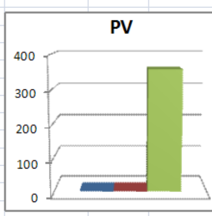


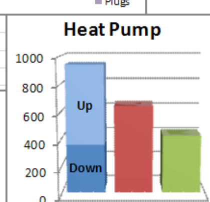


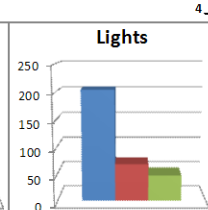


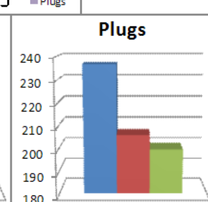


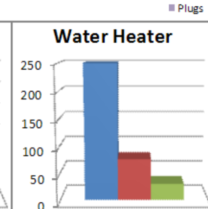


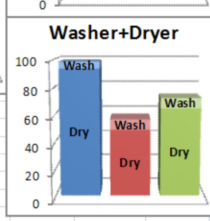


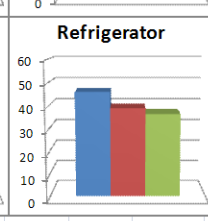


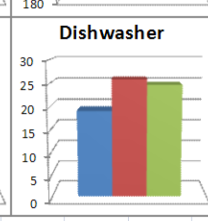


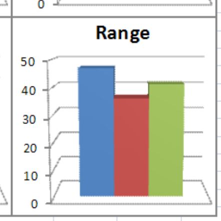












Dashboard Report										
			8/1/10		to	8/31/10				
								Water Heater		
House Name	Total[1,2]	PV[1]	Net[1]	Cost	PeakHr[1]	Average[1]	Ld Factor	MBTUs	kWh/MBTU	SolarFrac
CC1	1,990	0.00	1,990	$173.72	10.01	2.69	0.27	0.832	337.819	-0.153
CC2	1,269	0.00	1,269	$113.44	8.52	1.73	0.20	0.673	125.772	0.571
CC3	1,022	348.91	673	$21.68	5.46	1.06	0.19	0.715	42.742	0.854
House Name	Total	PeakHr	Net	Cost	Peak Day	Peak Hour		MBTUs	kWh/MBTU	
CC1	100.00%	100.00%	100.00%	100.00%	8/15	8/11	20:00	100.00%	100.00%	
CC2	63.79%	85.09%	63.79%	65.30%	8/22	8/11	20:00	80.85%	37.23%	
CC3	51.35%	54.53%	33.82%	12.48%	8/14	8/11	20:00	85.89%	12.65%	

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