Small House; Construction Cost $100K, Total Energy Cost $0.88 a Day

Abstract

This paper describes a second step, initiated in 2003, toward development of an affordable net Zero Energy House located in Lenoir City, Tennessee. Affordable houses that generate as much energy as they use is the long term goal of the Department of Energy Building Technology Program. A Habitat for Humanity Family of three took occupancy in December 2003. This all-electric house has: air-tight structural insulated panels (SIPS), high efficiency windows with a 0.34 U-Factor and 0.33 Solar Heat Gain Coefficient, SEER-14 heat pump, space integrated heat pump water heater, and 1.98kWp grid-connected solar photovoltaic system. These features together lead to an annual total energy cost of $0.88 per day after utility solar credits and cost less than $100,000 to construct. Thirty two sensors were installed in the house to monitor thermal comfort, energy efficient technologies, and the rooftop photovoltaic system every 15 minutes for more than a year. Twenty three percent of the houses' total energy demand is satisfied by the solar photovoltaic system.

Introduction

This second prototype house, in a series of five, is on the pathway toward houses that will be so energy efficient that the integration of onsite power could potentially meet the remaining energy load on an annual basis. The DOE Building Technologies goal is to develop technology packages that result in energy efficient houses that save 70% of energy from the Department of Energy Building America Benchmark House, http://www.eere.energy.gov/buildings/building_america/pdfs/37529.pdf, and satisfies the remaining energy demand with about 2kWp rated output of solar collectors. An important secondary benefit of the zero energy houses is that they instill the occupants to save energy by reducing plug loads, day-lighting, purchasing more energy efficient appliances and turning off unused lights, computers, entertainment equipment, etc.

The second of five near zero energy test houses is referred throughout this paper as ZEH2. This house will be compared to the first house, ZEH1 as well as a few aspects of the next two houses, ZEH3 and ZEH4. Table 1 and 2 show the features of ZEH2 compared to the other houses discussed in this report.

Table 1 Envelope features

House	Base House	ZEH 1	ZEH2	ZEH3	ZEH4
Stories	1	1	1	1	2
floor ft^2	1056	1056	1060	1082	1200
Foundation	Vented crawl	Unvented crawl	Mechanically vented crawl with insulated walls 2 in polyisocyanurate boards (R-12 hft^2 ^{o}F/Btu)	Unvented crawl with insulated walls 2 in polyisocyanurate boards (R-12 hft^2 ^{o}F/Btu)	Walk out basement with insulated precast (nominal steady state R-value of (R-16 hft^2 ^{o}F/Btu)
1st Floor	R-19 hft^2 ^{o}F/Btu fiberglass batts (R-17.9 hft^2 ^{o}F/Btu)	6.5 in. SIPS 1#EPS (R-20 hft^2 ^{o}F/Btu) Structural splines	R-19 hft^2 ^{o}F/Btu fiber glass batts, ¾” XPS boards installed on bottom side of 9 ½ in. I-joist (R-24 hft^2 ^{o}F/Btu)	R-19 fiber glass batts, ¾ in XPS boards installed on bottom side of 9 ½ in. I-joist (R-24 hft^2 ^{o}F/Btu)	Concrete Slab
Walls	2 X 4 frame with R-11 fiberglass batts, OSB sheathing, (R-10.6 hft^2 ^{o}F/Btu)	4.5 in. SIPS 1#EPS (R-15 hft^2 ^{o}F/Btu) surface splines, house wrap, vinyl	4.5 in. SIPS 2#EPS (R-15.5 hft^2 ^{o}F/Btu) structural splines, house wrap,vinyl	6.5 in SIPS 1#EPS (R-21 hft^2 ^{o}F/Btu), structural splines, house wrap, vinyl	2nd floor 4.5 in. SIPS polyiso., pentane blown (R-27 hft^2 ^{o}F/Btu), surface splines
Windows	7 windows, U factor 0.538 Btu/ft^{o}F	9 windows U-0.34 Btu/ft^{o}F 0.33 SHGC, sill seal pans	8 windows 0.34 Btu/ft^{o}F U-factor, 0.33 SHGC, sill seal pans	8 windows 0.34 Btu/ft^{o}F U-factor, 0.33 SHGC, sill seal pans	10 windows, 0.34 Btu/ft^{o}F U-factor, 0.33 SHGC, sill seal pans
Doors	2-doors, one solid insulated, half view	2-doors, solid insulated, & half view	2-doors, one solid insulated, one half view	2-doors, one solid insulated, one half view	3-doors, one solid insulated, one half view, one full view
Roof	Attic floor blown fiberglass (R-28.4 hft^2	SIPS 1#EPS (R-28 hft^2 ^{o}F/Btu) surface	6.5 in. SIPS 2#EPS (R-23 hft^2 ^{o}F/Btu) structural	10 in SIPS 1#EPS (R-35 hft^2 ^{o}F/Btu), surface	8 in SIPS, polyiso., pentane blown (R-27 hft^2

	^{o}F/Btu)	splines	splines	splines	^{o}F/Btu), surface splines (R-48 hft^{2} ^{o}F/Btu)
Roofing	Gray asphalt shingles	Hidden raised metal seam	15 in. Green standing 24GA steel seam, 0.17 reflectivity	15 in. Green standing 24GA steel seam, 0.23 reflectivity	Light gray Metal simulated tile, .032 aluminum

Table 2 Near ZEHs and Base house mechanical features

House	Base House	ZEH 1	ZEH 2	ZEH 3	ZEH 4
Solar system	none	48-43W amorphous silicon PV modules, 2.06 kWp	12-165W multi-crystal silicon PV modules-12.68% eff, 1.98 kWp	12-165W multi-crystal silicon PV modules-12.68% eff, 1.98 kWp	20-110W polycrystalline 2.2 kWp
Heating and Cooling	Unitary 2 ton HP, SEER 12	1-1/2 ton air-to-air HP, SEER 13.7, 2 speed ECM indoor fan	Two speed compressor 2 ton air-to-air HP, SEER-14, HSPF-7.8, CFM cooling 700, variable speed ECM indoor fan	2 ton Direct exchange geothermal, R-417a, variable speed ECM indoor fan	2 ton air-to-air HP, SEER 14, variable speed compressor, ECM indoor and outdoor fan
Mechanical Ventilation	none	6” duct supplying fresh air to return side of indoor fan-coil	Supply to return side of coil, CO2 sensor, bath fan exhaust	Supply to return side of coil, bath fan exhaust	Supply to return side of coil, bath fan exhaust
Duct location	Crawl space	Inside conditioned space	Inside conditioned space	Inside conditioned space	Inside conditioned space
Water Heater	electric	Integrated HPWH linked to unvented crawl	Integrated HPWH, linked to crawl which has motorized damper	Desuperheat for hot water, energy factor (EF) 0.94	HPWH vented to ½ bath, ½ bath fan runs when fresh air is supplied to the house

The distinguishing features between ZEH2 and ZEH1 are all attempts at making ZEH2 closer to an affordable net zero energy house. The different features in ZEH2 are wall and ceiling SIPS with higher density and lower conductivity expanded polystyrene insulated core foam, R-10 $hft^2 \, {}^oF/Btu$ insulated-control ventilated crawlspace, 14 SEER- 2 ton air source heat pump with two stage compressor and variable speed ECM indoor circulating fan, 2nd generation integrated heat pump water heater, demand ventilation system based on CO_2 measurement, green standing seam steel roof, and more efficient grid connected 2kWp solar photovoltaic system.

Foundation

The 3 bedroom, 1060 ft^2 house sits on an unvented crawl space with insulated walls, using 2 inch R-12 $hft^2 \, {}^oF/Btu$ polyisocyanurate (PI) boards and a black 6 mil polyethylene ground cover. The ground cover was installed to decrease moisture load into the crawl space and reduce the risk of condensation. The 6 mil polyethelene is lapped and run up the crawl space block wall about one foot. The PI boards are installed over the top of this seam. The floor of the house over the crawl space is insulated with R-19 $hft^2 \, {}^oF/Btu$ fiber glass batts and ¾ inch extruded polystyrene (XPS) boards installed on the bottom side of 9 ½ inch wood I-Joist. The top side of the floor has ¾ inch tongue and grove plywood. The major difference in the crawl spaces of ZEH1 and ZEH2 is the addition of crawl space wall insulation in the latter. A second difference is a motorized damper installed in the south wall of ZEH2 separating the crawl space from the outside. This damper is normally closed, except in the winter when the heat pump hot water heater is recharging. A second motorized damper is installed in ZEH2 between the crawl space and the air-sealed insulated closet, where the HPWH is placed next to the refrigerator. Both dampers are operated the same way. These dampers open only when the thermostat is set in the heating mode and the HPWH is running.

The temperature in the crawl space tends to be 10-15^{o}F warmer in the winter and 4-7^{o}F cooler in the summer than the ambient air temperature. This is shown by the measured average monthly temperature for a complete year, in Figure 1. Figure 1 shows the monthly average temperature for identical crawl spaces but ZEH2 pulls in ambient air when the HPWH is running in the winter. ZEH 3 does not have a mechanical vent and as a result the winter temperature is slightly warmer than ZEH2. In both houses this earth coupled space not only leads to minimal winter time floor heat loss but also eliminates the risk of freezing pipes and provides a winter time heat source for the heat pump water heater supply air. It was felt that good HPWH air flow was attained in ZEH2 compared to the first attempt at linking the refrigerator exhaust heat and crawl space in the winter to the air source for a heat pump water heater.[1]

This is supported by the higher COPs of 2 measured in ZEH2, compared to 1.6 for the HPWH installed in ZEH1.

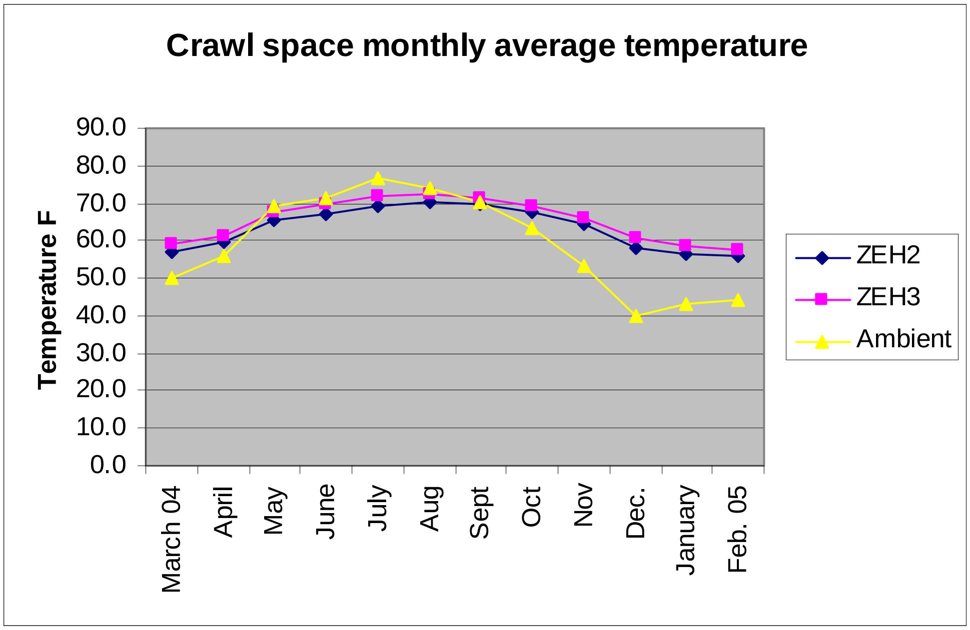

Figure 1 shows the average monthly temperature of ZEH2 and ZEH 3 crawl-spaces compared to outside temperature

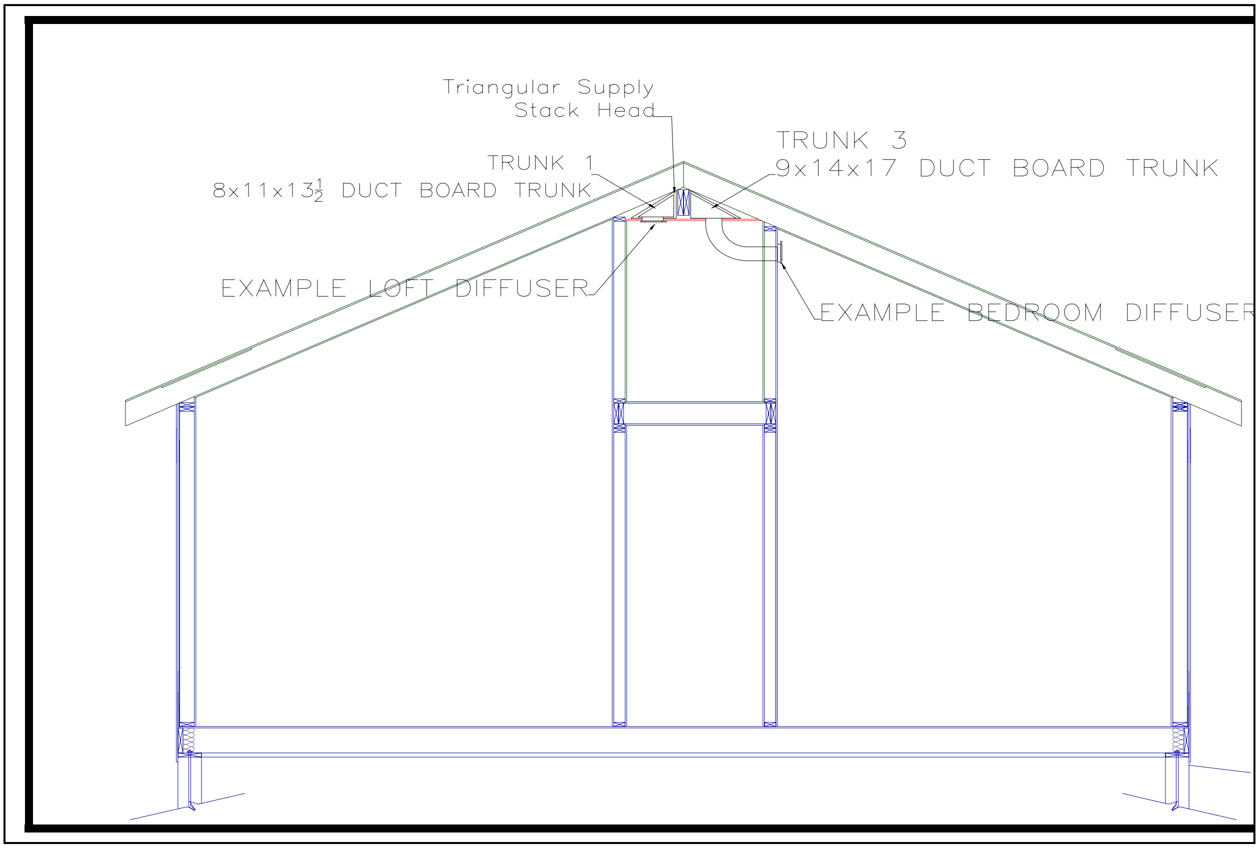

Figure 2, ZEH2 Cross Section

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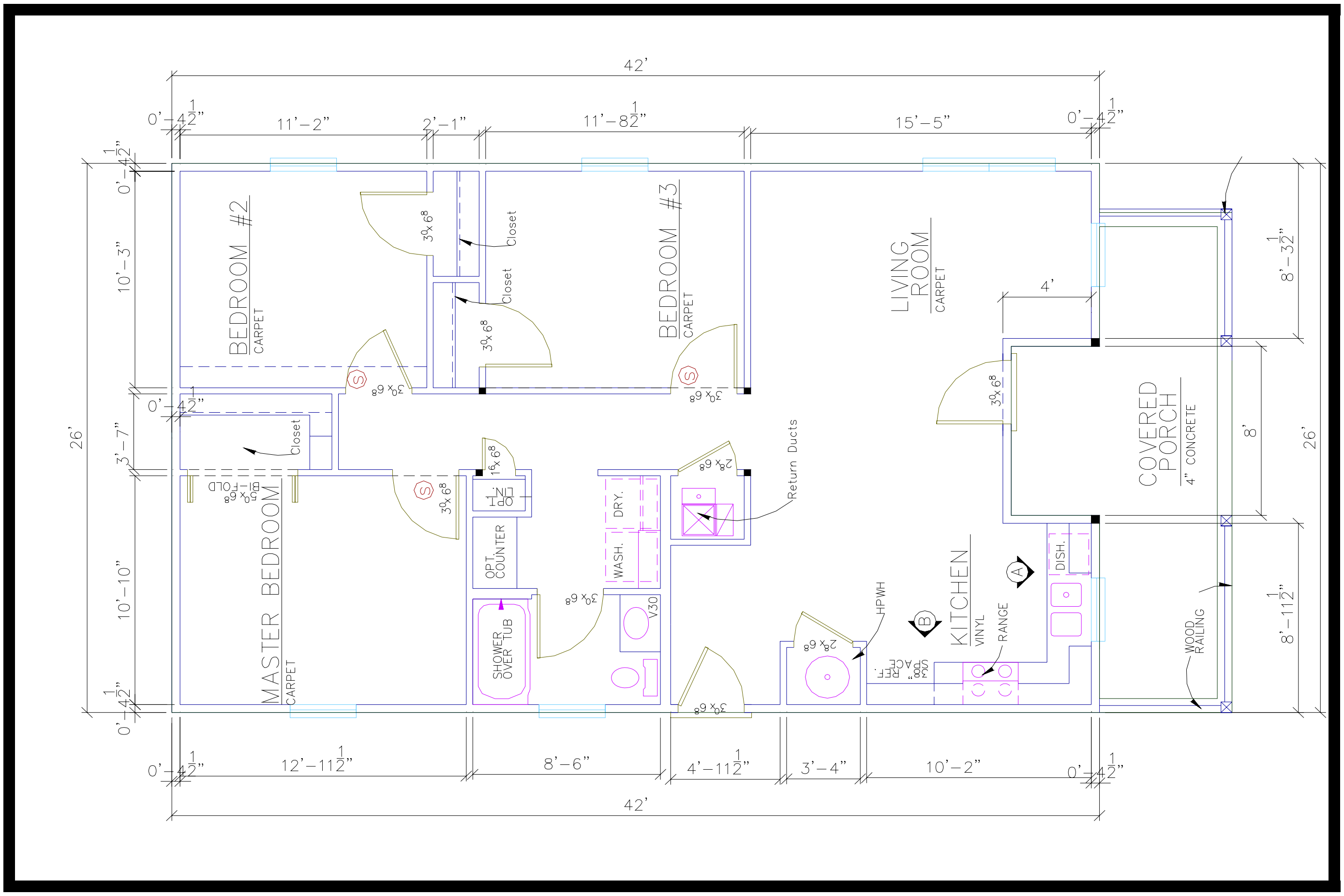


Figure 3, ZEH2 House Plan, the north façade is at bottom.

Above-grade Walls

The house cross section and floor plan are shown in Figure 2 and Figure 3. The main duct trunk line is located above the drop ceiling under the ridge beam. The house walls are 4.5 inch thick SIPS with 1.8 lb/ft^3 expanded polystyrene (EPS) sandwiched between two layers of 7/16 inch Oriented Strand Board (OSB). We used ASTM C518 procedure in the heat flow apparatus that yielded an R-value of 16.1$hft^2\,{}^oF/Btu$ for the 4.5 inch SIP (1.8 lb/ft^3 EPS). These panels were prefabricated off site with rough openings for windows and doors. The wall panels are 8 ft high and various lengths on the eave walls sized to fit the 6/12 gable on the front and back of the house. The 21 wall panels widths varied from 1 ft to 12 ft. Besides the eight corner joints another 13 wall joints were needed to enclose this house. Figure 4 shows ZEH2 during the SIP walls installation. The panels were fastened together using structural splines. Each panel-to-panel connection was caulked at all spline-to-foam contact surfaces. The 8 windows, one less than in ZEH1, in the house are wood vinyl clad doublehungs with the same National Fenestration Rating Council (NFRC) labeled U-factor of 0.34 Btu/ft^oF and Solar Heat Gain Coefficient of 0.33 as used in ZEH1, ZEH3 and ZEH4.

Figure 4 picture of the SIPS being installed in ZEH2

A blower door test was conducted on ZEH2 to determine its air-tightness. ZEH2 had an initial 0.07ACH, natural air change rate. The initial ACH for ZEH1 was 0.08. ZEH2 has a slightly better air-tightness than ZEH1 but both are significantly better than an ordinary wood frame house. As shown in Figure 5, a wood frame house constructed in 2000 by the same Habitat Affiliate had an initial 0.26ACH and a wood frame house constructed right next to ZEH2 in 2002 of 0.2ACH. The improvement in the second stick built house ACH is attributed to better general envelope sealing techniques and dropping the interior ceiling to accommodate ducts inside the conditioned space. Both of these construction practice improvements were learned from the Habitat Affiliates construction experience on ZEH1-3. This habitat Affiliate now builds 100% energy star house with certified >86 HERS rating.

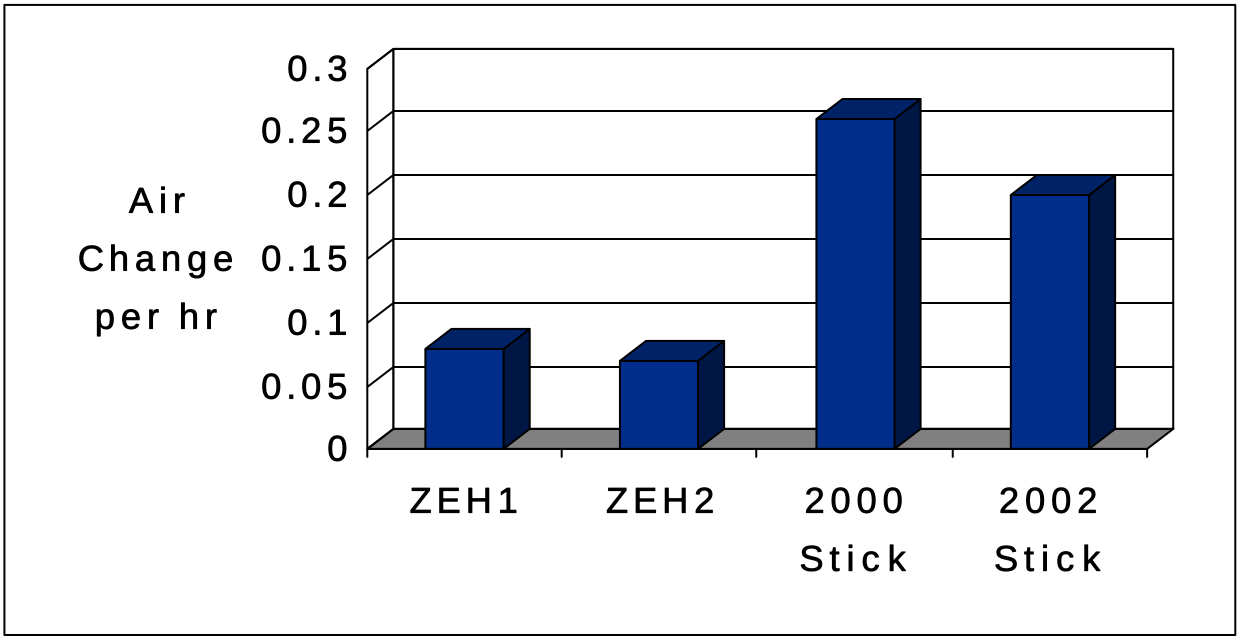


Figure 5 shows the blower door tests on ZEH1, ZEH2, a 2000 stick house, and a 2002 stick house.

Roof

The roof is 6.5 inches thick 4 ft by 16 ft SIPS with nominal 1.8 lb/ft^3 EPS installed to create a 6/12 pitch using structural splines for support. The entire roof contains 22 panels. The full porch could have also been covered with a SIP. This would have saved considerable construction time and cost compared to the stick built porch roof. The 6/12 pitch provided sufficient head room to design two small loft areas in the bedrooms on the southside of the house. This represents another 100 ft^2 of floor area and potential cost/ft^2 reduction of 10%. Peel and stick tape was used on all internal panel seams to help assure the building air-tightness. The roof was built to have a 1 ¼ ft overhang on both eves and 1ft on the gabled front and back of the house, it would have been preferable to extend the over hangs on the eves to 2 ft, like specified in ZEH1 and ZEH4, to better shade the south facing windows in the summer. On top of the SIPS is a heavy-duty underlayment. This product a coated woven synthetic is mechanically fastened. It was recommended by the metal roof manufacturer, because it provided a more reliable secondary waterproofing under their raised metal seam roof. On top of the white titanium roofing underlayment is a forest green 24-gauge steel roofing that has a reflectivity of 0.17. The forest green metal roof has 15-inch-on-center-standing seams making the PV system easier to attach without penetrating the roof. The panels were all cut to run from the ridge to the eave in one piece. A ladder was built on site from 2 X 4s and temporally nailed to the SIP roof to help install these panels.

Heat Pump Water Heating

The ZEH2 has a 50 gallon integrated heat pump water heater (HPWH) with a full year measured coefficient of performance (COP) of 2. The COP is the heating efficiency rating for hot water systems. The COP of the HPWH in ZEH1 was 1.6 meaning the HPWH in ZEH2 is more efficient than the one in ZEH1. Both of the HPWHs in the zero energy houses are more efficient than a standard electric resistance water heater with a typical COP close to 0.85. ZEH2's HPWH better efficiency rating saves $0.07 in energy cost per day compared to ZEH1. This family, of three, is using considerably less hot water than the national average of 80gal/day. During the one year measurement period the family used an average of 36 gal/day. The HPWH is losing more standby energy than a 30 or 40 gallon HPWH would lose in an average house of this size with one or 1 ½ bathrooms.

Figure 6 shows the HPWH located in a utility closet next to the refrigerator. The HPWH is linked by ducts and transfer grills to the crawl space and the air space behind the refrigerator. When the house thermostat is set to “cooling”, motorized dampers are energized to allow the heat pump water heater fans to pull air from behind the refrigerator to extract heat for domestic hot water production. The air stream is cooled and dehumidified as it is pushed through the evaporator coil on top of the HPWH and is directed back to the kitchen through the register above the clock in Figure 6. When the thermostat is set to “OFF” or heating mode the duct connecting the HPWH to the kitchen is closed and the duct connected to the crawl space is opened to allow the HPWH fans to pull from the earth-tempered crawl space and reject unwanted cool air to the outside. Taking air from the crawl space avoids stealing valued heat from a conditioned space in the winter. Over an entire year, water heating in this house used 961 kWh. At the rate of $0.068/kWh this totals $65.

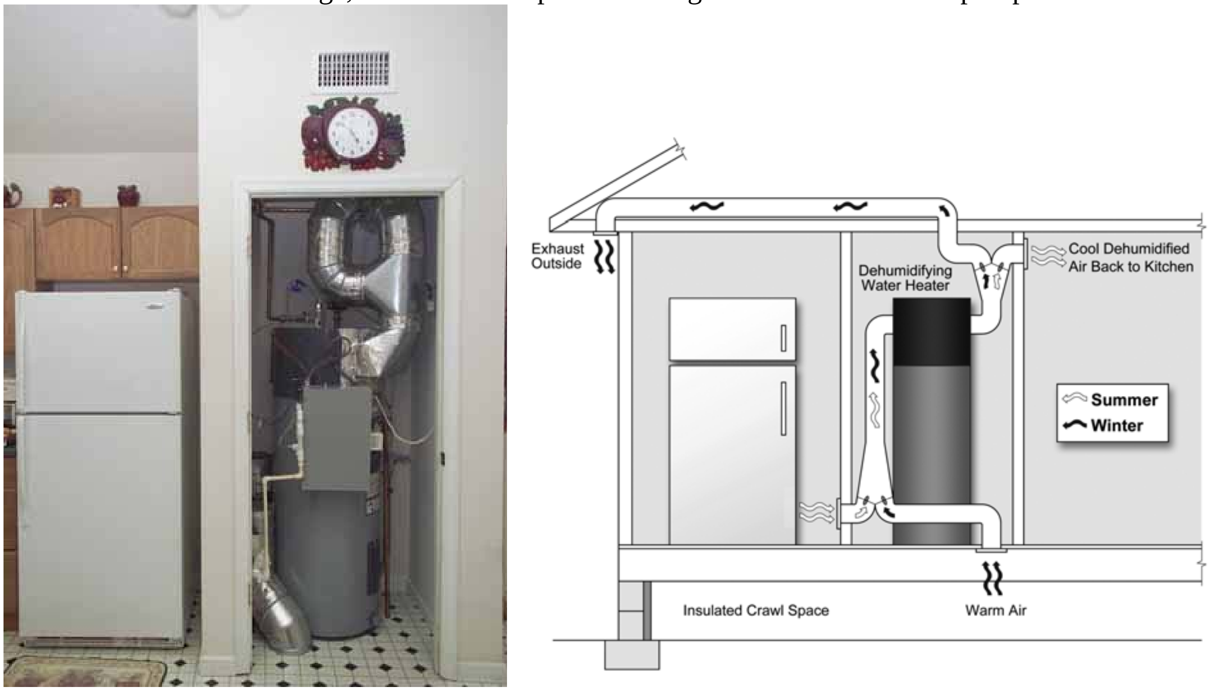


Figure 6 shows a picture of the ZEH2 integrated HPWH with the refrigerator.

In December 2003 the homeowner change the HPWH set point to 155^{o}F because they wanted hotter water than the original HPWH set point of 125^{o}F. Even after raising the set point to 155^{o}F the water in the shower was not any hotter; it was then noticed that there was a scorch protector on the shower faucet. This was causing even more cold water to mix with the hot water wasting energy by higher standby losses than necessary. This problem was fixed on February 23, 2004. The thermostat was set by the homeowner at 130^{o}F and has remained at this setting from February 2004 until May 2005. Figure 7 shows that the COP increased to about 2 after the set point was reduced from 158^{o}F to 130^{o}F. The annual reported energy demand for hot water did not include this problem since the performance period quoted above ran from April 1, 2004 until March 31, 2005.

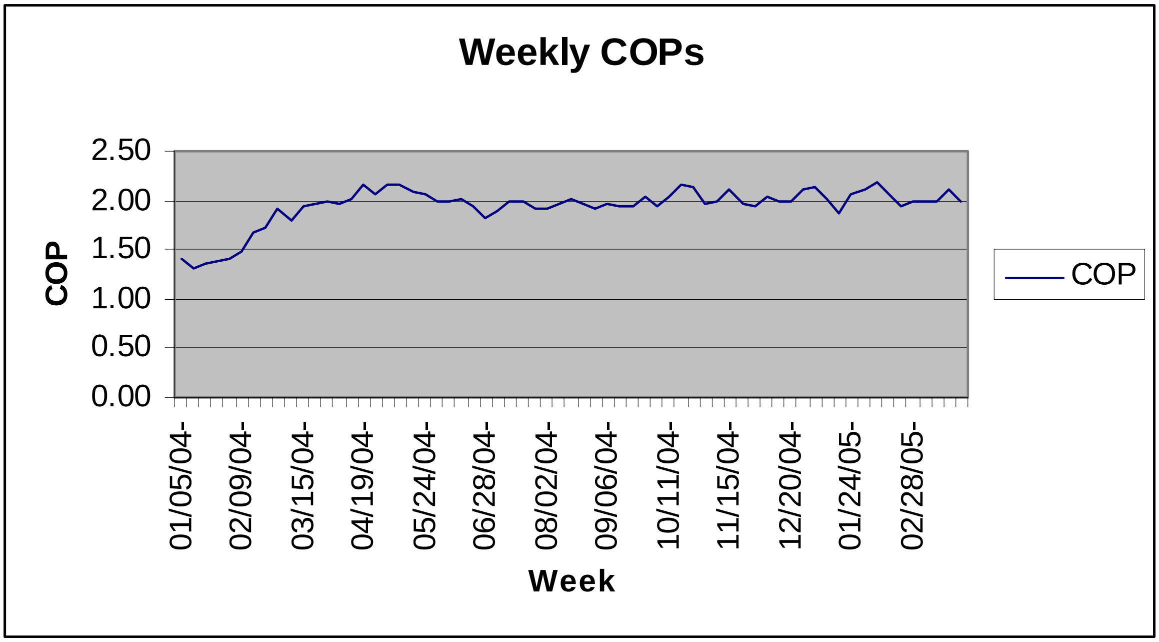


Figure 7 Weekly HPWH COPS show that once the HPWH temperature setting was corrected in late February the COP went up from 1.4 to 2.0.

Thermal Comfort

The conditioned space average monthly temperature and relative humidity from April 2004 to March 2005 are shown in Figure 8. The temperature is kept around 75^{o}F year around. Even with the mechanical ventilation system, the relative humidity stays at a comfortable level. During the hottest months of the year, the average relative humidity was near 60% and the maximum RH was 70%. The relative humidity tends to be higher during the day, but the family has had no thermal comfort complaints. A better job of controlling RH is needed. There are obviously times in which the indoor conditions are outside the thermal comfort range as defined by (ASHRAE handbook of Fundamentals 2005). The SEER-14 heat pump with a two speed compressor in this house was chosen to help with the July and August relative humidity problem first observed in ZEH1, which only had a single speed compressor.

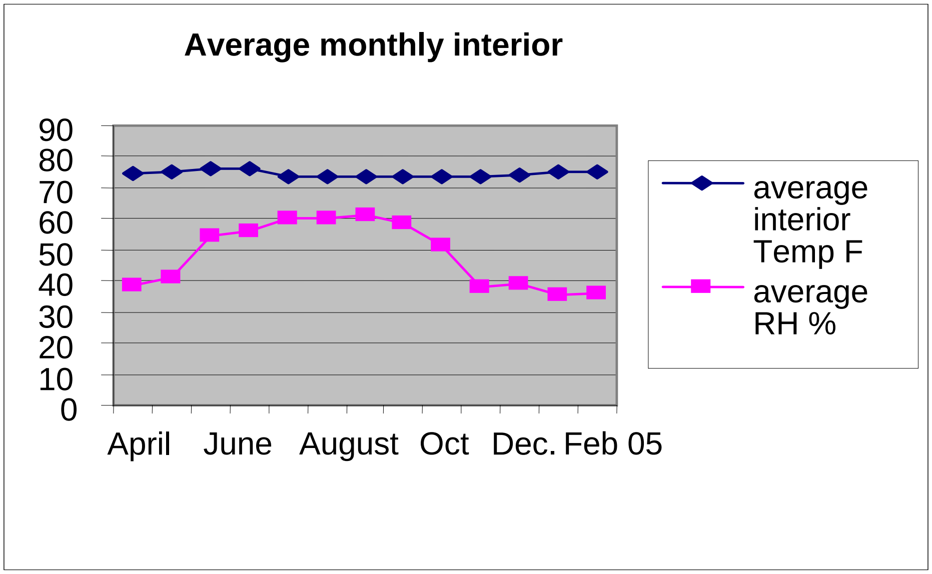


Figure 8 Average monthly interior temperature and relative humidity.

Air-Source Heat Pump

The house has a 2 ton heat pump with two speed compressor, SEER 14, EER of 7.8@47ºF and a COP of 2.3@17ºF. The heating capacity at 47º F is 20,880 Btu/hour and at 17ºF, 11,110 Btu/hr. The indoor fan was set at 700 CFM and in November 2003 this was measured and tuned to within 3% of the design air flow from all registers. The cooling capacity on the high indoor fan speed was 21,520 Btu/hr and at the low speed 11,860 Btu/ hr. The design sensible load was calculated by Manual J at 13,240 Btu/hr and the total load was 16, 460 Btu/hr.[2] This unit suffered from poor performance first noticed in the beginning of the 2004 cooling season, which lead to a refrigerant recharge. The unit appeared to operate fine throughout the summer of 2004 and in December 2004 sub performance was again noticed. Several requests for service led to a second recharge in late February 2005. Through out the 2004-2005 heating season a continued sub performance was evident from the data. Using the data base for January 17, 2005, the average heat pump supply and return temperature measurements, electrical measurement on the indoor air handling unit and the separate outdoor unit were used along with the measured indoor fan 700 CFM to calculate the COP. The average ambient temperature for this day was 22.6 F. At 17 F the manufacturers rated COP is 2.3. The measured value using the above 15 minute data was 1.1. This was 47% of rated performance.

Photovoltaic System

This house has a 1.98kWp photovoltaic system with only twelve-165W panels. These panels are 32.5 in. X 62 in.. The total solar module roof foot print is 168 ft^2. This is only 38% of the roof area required for the solar modules on ZEH1 (436 ft^2). This PV system was purchased from and installed by a local solar distributor in Tennessee. This house should have been producing as much, if not more, solar power as ZEH1 but ZEH2’s inverter initially did not perform to its specifications. ZEH2 and ZEH3 had their PV systems connected to the grid on the same day and have exactly the same PV system, yet in the first 7 months ZEH2 produced 1301kWh and ZEH3 produced 1491kWh. The inverter was replaced on May 17, 2004, and from that point on ZEH2 and ZEH3 generated almost identical AC from solar power. The loss of revenue to the homeowner amounted to $28.20, (188 kWh X $0.15). From May 4, 2004 until May 2, 2005 the average daily solar generated AC was 6.0 kWh for ZEH2 and 6.05 for ZEH3. Over this same period ZEH1 had a daily collection rate of 5.91 kWh/day.

Demand ventilation

CO_2 monitoring in this house proved that occupancy could be detected and operating changes to the building made to save additional energy. In this house the energy management controls were limited, but in future ZEHs that utilize the forced air distribution system to deliver fresh air with only one sensor can provide a lot of insight into occupancy behavior and potentially trigger additional energy savings by providing demand controlled ventilation. Since the houses are air-tight, fresh air is brought in mechanically. The amount of fresh air allowed into the house is fixed so that the entire house gets 40 CFM as long as the ventilation controller and heat pump are turned on. If the house has a lot of people, more fresh air may be needed. When the CO_2 reaches 1000 ppm the motorized damper opens to allow more than 40cfm of fresh air into the house. The CO_2 monitor can also be used to determine when no one is home, when everyone is sleeping, or even when they are having a party. This information is important to determine when the family is using energy and when unneeded appliances could be shut off. For instance, if no one is at home the energy consumption should be substantially lower then when it is occupied; if the house is still using energy, it is possible to tell if something was accidentally left on. Figure 9 shows two days in April 2004: one on the weekend and one during the week. During the work week, this family is not home during day-time. The graph in Figure 9 shows that the CO_2 level in the house drops when the family isn't home and then begins to rise when the family comes home around 5:00PM. The weekend day that is plotted shows a higher level of CO_2 in the house during the mid-day, suggesting that the house was occupied during those hours. On both days the CO_2 levels at night, show very stable CO_2 generation suggesting everyone is home.

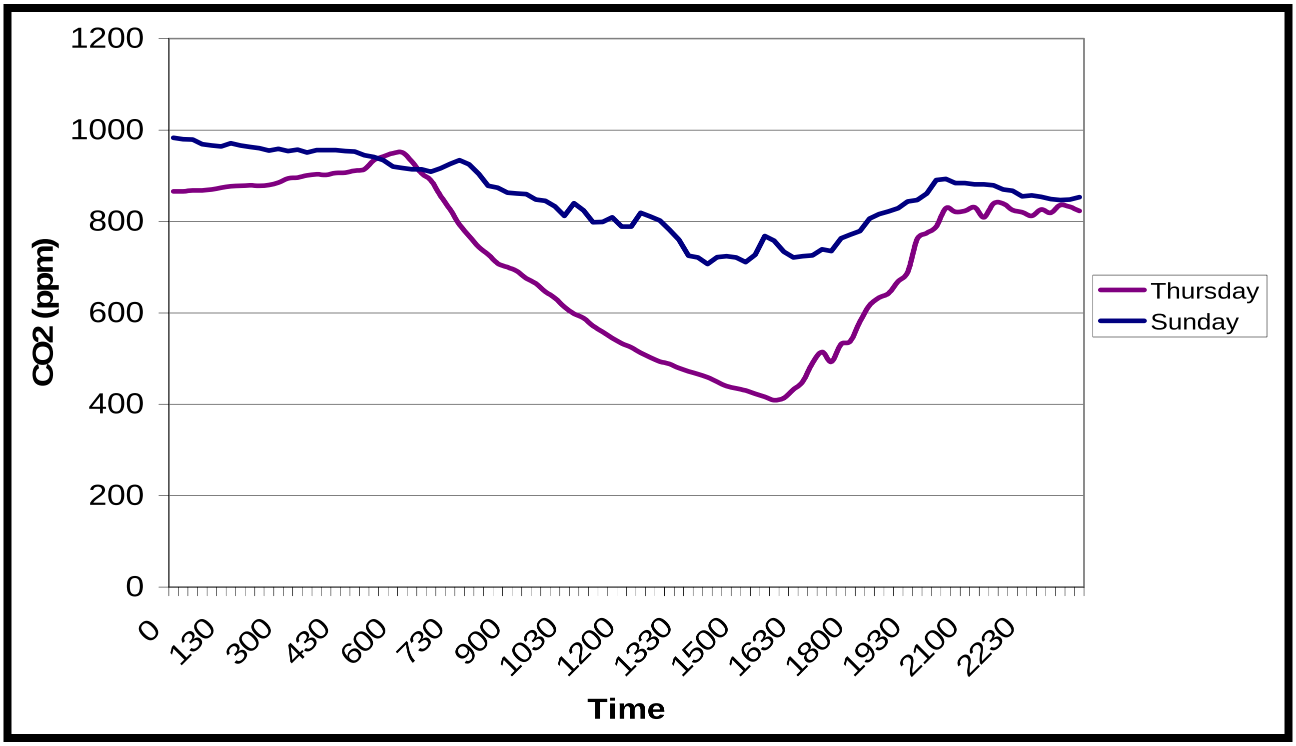


Figure 9 is a graph showing the amount of CO_2 in the house during two days.

On March 25, 2004 a large tour group of about 30 entered ZEH2 which generated the spike in the CO_2 concentration around 9:30 AM. The highest CO_2 level (1375 ppm) occurred during this event in March.

After the tour ended CO_2 concentrations fell to below 500. For comparison, a variety of more typical days are shown in Figure 10.

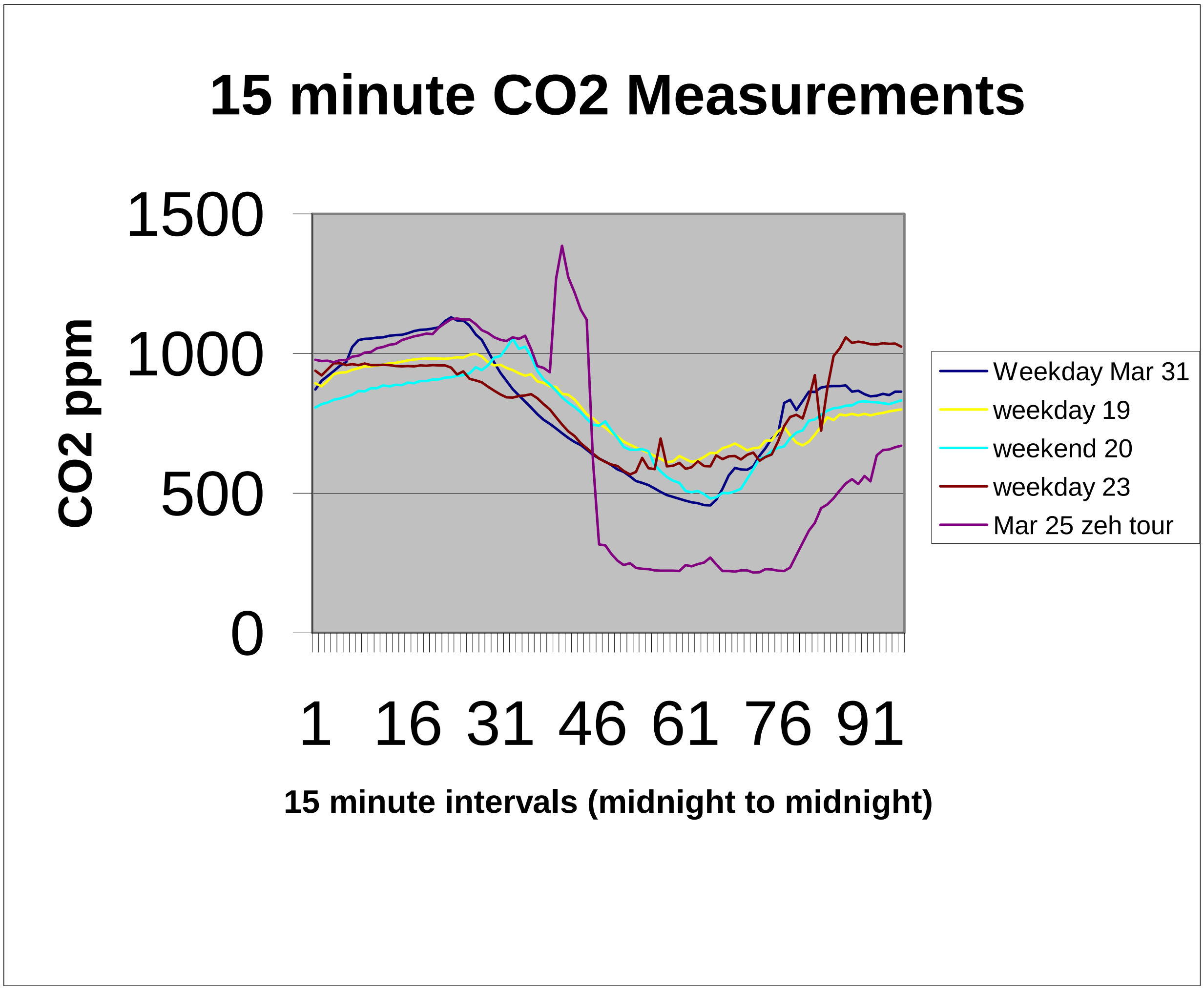


Figure 10 March 25 AM tour of 30 people is reflected in CO_2 readings triggering the increase in fresh air ventilation.

Data Acquisition System

Every 15 minutes 32 sensors in this house measure the performance of the energy efficient technologies; interior temperature, relative humidity, crawl space temperature and relative humidity, ambient temperature, water temperatures in the HPWH, the space heat pump, and the CO_2 level. Every morning at 2 AM, a computer calls the system and downloads the data. This information is ready to view on the Web the day after measurements are recorded. The data retrieved from the system is analyzed to determine the energy usage and overall house performance. Data collection period ran from December 2003 until August 2005.

Energy Usage and Cost

ZEH2 occupants consumed a total of 12207 kWh for one complete year from April 1, 2004 until March 31, 2005. The homeowners during this period paid \$0.068/kWh for their electricity. This house sells green power back to the local utility. The contractual arrangement is that the utility will pay the homeowner $0.15/kWh for all the solar power produced by the PV system for 10 years whether the homeowner uses it or not. During this same annual period the solar system generated 2305 kWh. Thirty four percent of the solar was collected at a time when it was not needed in the house. Table 3 shows the energy usage broken down into Heating, Cooling, Hot Water, and Other.

Table 3 ZEH2 monthly energy usage

Month	Space Heat (kWh)	Space Cool (kWh)	Hot Water (kWh)	Refrigerator (kWh)*	Other (kWh)	Total electric (kWh)	Solar AC generated (kWh)	Solar to the grid (kWh)
April		159	87	33	418	664	203	99
May		488	66	37	359	913	234	78
June		498	57	35	336	891	215	76
July		347	59	33	325	731	250	110
August		280	60	34	344	684	233	86
Sept.		246	56	31	299	601	217	102
October	280		70	32	346	696	159	65
Nov.	624		78	31	359	1061	145	30
Dec.	1420		109	32	403	1932	148	19
January	1392		118	33	382	1892	136	15
February	756		99	30	352	1207	142	34
March	442		102	33	391	935	223	81
Total	4914	2018	961	394	4314	12207	2305	795
Annual Cost	$334.	$137.	$65.	$27.	$293	$830	-$346	
Daily cost	$0.91	$0.37	$0.18	$0.07	$0.80	$2.27	-$0.95	

* included in other

The net daily cost for off-site energy to run this all electric house was $1.32. The coolant charge on the 14 SEER, two speed compressor with a variable speed, direct current, commutating fan motor was found to be low on two occasions, which resulted in higher space heating and cooling loads than should have been consumed with a properly charged heat pump. The heat pump was recharged on June 6, 2004 and a second time on February 23, 2005. This resulted in a daily HVAC energy usage of $1.30 per day. The HVAC cost on the ZEH3 with the geothermal HP came to only $0.44/day. The HVAC cost on ZEH1 with a 13 SEER single speed compressor using the same $0.68 per kWh electricity came to $0.52/day.

The measurement of the Heat Pump supply and return temperature, the separate kWh measurements on the heat pump indoor unit and outdoor unit along with ambient air temperature measurements were used to calculate the COP during January 17, 2005. It was found that the heat pump was delivering only 47% of the rated performance. Using this calculation the heating season HVAC power requirements from the beginning of the heating season until the unit was recharged in late February 2005 can be reduced assuming a properly performing heat pump. This results in a reduction, for October 2004 until the end of February 2005, of 2370 kWh or $161 per year. Leaving an adjusted daily HVAC cost of $0.47/ day and a total whole house daily energy cost after solar credits of $0.88. This can be compared to the first year's performance of ZEH1 using the same electric energy rate of $0.068/kWh of $1.01/day. With a properly functioning heat pump this all-electric house's fraction of solar energy collected on site amounts to 23% of the total electric demand of 9837 kWh/year. This is an improvement from the first house which attained 20% of total electric demand supplied by solar energy.

Construction Cost

Table 4 shows the detailed cost for ZEH2 and an average cost of constructing conventional houses of similar design by the same Habitat for Humanity (HfH) Affiliate. The top half of the cost table shows the out of pocket cost to the Habitat Affiliate. Both houses cost HfH about the same ($60K). The bottom half of the cost table shows market value donations specifically for each house.

The ZEH2 solar system installed cost ($16,000) was much less than ZEH1 ($22,388), however both systems generate the same AC power over an annual cycle. If the cost of solar panels continues to drop over the long run, the cost of future zero energy houses will become more affordable. In June 2002 solar module's were selling for an average of $5.65/watt in August 2003 this cost was about $5.13/watt, which is the same rate as found in May 2005.[3] The long-term goal of making these near-zero energy houses more affordable is counting on continued DOE R&D break throughs in PV and inverter technology.

The over all construction cost for the ZEH prototypes on one hand seem reasonable once the land and infrastructure costs are removed; about $100,000 as shown in Table 5. Although when one compares the equivalent cost for conventional stick built Habitat Houses constructed by the same crews in the same time frame the first cost increment of more than $43,000 is high. These are research prototypes so it is to be expected at this time that the first costs are high. In the ZEH5 plans more focus will be given to the affordability portion of the DOE long range goal of “affordable zero energy houses”. Removing the cost of solar PV system drops this differential to $27,000.

Table 4 Construction Cost of ZEHs and base frame house

	Average Stick House Cost	ZEH2 4" SIPS 2003
Expenditures:		
Site Preparation	2,500.00	3,671.48
Foundation/Porch/Pads	7,000.00	8,290.63
Termite Pre-Treatment	200.00	195.00
Framing and Decking	4,500.00	5,587.66
Trusses	1,300.00	0.00
Roofing Materials	1,000.00	195.19
Roofing Labor	0.00	0.00
Guttering	300.00	275.00
Windows	700.00	0.00
Bathtub and Water Heater	400.00	413.38
Exterior Doors	350.00	357.24
Siding	1,250.00	1,397.53
Plumbing Materials	1,200.00	1,798.12
Plumbing Labor	1,400.00	1,225.00
Toilets	100.00	78.22
HVAC	3,200.00	3,397.00
Insulation	700.00	301.21
Sheetrock Materials	1,000.00	1,154.31
Sheetrock Labor	1,400.00	2,152.89
Interior Doors	700.00	593.67
Paint	300.00	305.64
Trim Molding and Casing	200.00	245.56
Cabinets	1,400.00	1,581.65
Closet Maid	100.00	62.92
Flooring	1,500.00	1,286.74
Electrical Materials & Fixtures	1,300.00	2,030.32
Electrical Labor	0.00	0.00
Landscaping	200.00	842.83
Driveway	1,800.00	1,971.62
Final Grade	1,200.00	1,080.00
Storage Building	900.00	1,000.00
Land & Infrastructure	14,500.00	14,500.00
Miscellaneous	400.00	516.42
Closing Costs	200.00	12.00
Subtotal Expenditures	53,200.00	56,519.23
Construction Overhead	5,000.00	5,000.00

	Average Base Stick	ZEH2 4" SIPS 2003
Donations:		
Foundation Labor	1,000.00	622.50
Gutter installation	175.00	188.65
Windowsills	75.00	0.00
Flooring	0.00	100.00
Land & Infrastructure	4,000.00	3,991.00
Miscellaneous:		0.00
Labor	10,000.00	8,062.32
CenterPoint Flood Services	0.00	0.00
Campbell & Associates	0.00	0.00
Southeastern Title	345.00	345.00
SIPS Panels	0.00	15,000.00
Metal Roof	0.00	3,500.00
House Wrap	0.00	697.00
Andersen Windows	0.00	2,500.00
Solar Panels	0.00	16,000.00
Water Heater	0.00	930.00
GFX (Copper) Shower Recovery	0.00	0.00
Air Cycler	0.00	120.00
CO2 sensor		300.00
Geo Thermal equipment	0.00	0.00
additional HVAC equipment		3,500.00
Total Donations	15,595.00	55,856.47
Total House Value	73,795.00	116,875.70

Table 5 House cost with land and infrastructure removed

	Base House	ZEH2
House	55,304	82,385
Land and Infrastructure	18,491	18,491
Cost of Solar	0	16,000
Total Cost	73,795	116,876

Lessons Learned

In ZEH2 cracks are visible at the ceiling interior wall intersections. They have become more visible with time. These could have been caused by moisture trapped in the SIP roof before it was finished. The hypothesis is that during the first winter the top of the OSB had higher moisture content then the bottom layer and tended to expand. The bottom layer of OSB in the winter dried causing shrinkage. The result is a bowing upward of the SIP roof panels that pulled away from the interior partition walls which run all the way to the SIP ceiling. These cracks were not formed in ZEH1, ZEH3, or ZEH4. In the mid point of the 6 inch thick SIP roof span from the 15 ft ridge to the exterior wall the downward deflection was measured at 1.5 inches in November 2003.

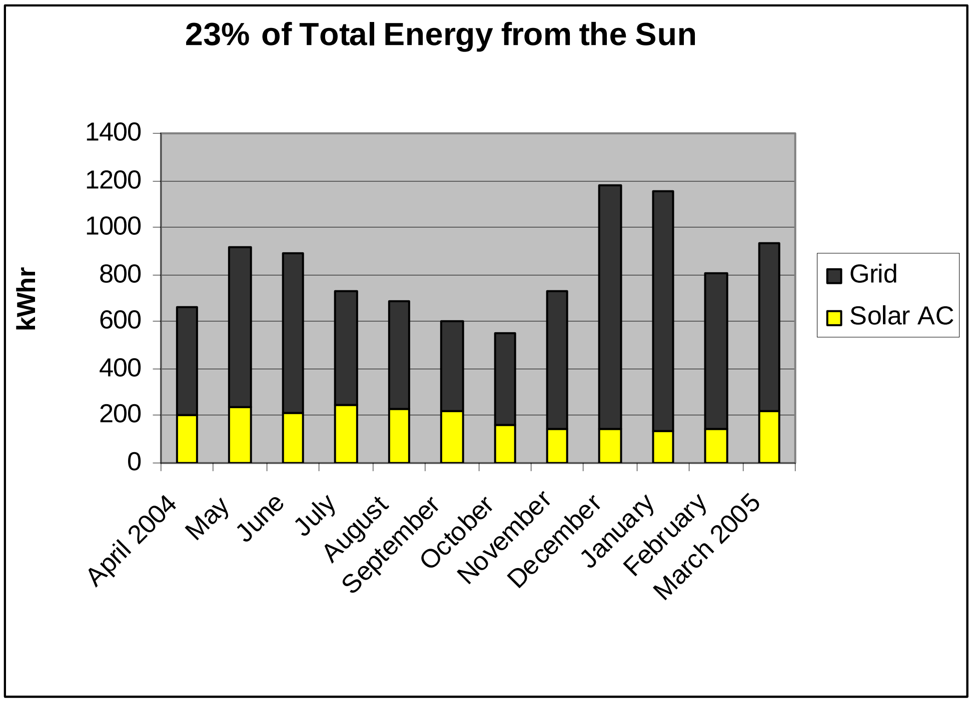
Another concern with the house is the metal roofing noise. The homeowners have complained about a series of loud popping sounds in the late afternoon. This is believed to be caused by thermal expansion of the metal roofing panels, creating a space between the SIP and the metal roofing. In the afternoon when the metal roof cools, contraction causes metal to snap down on to the SIP. This contraction is the likely source of the roof noise.

Another concern is with the high relative humidity measured in the crawl space and the conditioned space during July and August Mixed Humid climate. From January until May 2004, the average crawl space temperature was around 57°F and the average relative humidity was around 56%. The average temperature in the crawl space for June and July was 67°F and the relative humidity was 88%. This is a very high relative humidity and could have been caused by the unusual high amount of rainfall during those two months.

Six months after the house was occupied the air-to-air heat pump was found to have a low charge, noticed by the unit's inability to cool the house in the beginning of the summer. The unit was recharged on June 6th 2004 and through out the summer appeared to have lowered the energy usage of the heat pump. It is uncertain how long the low charge existed and some concern exists that it may have been low throughout the 2003-2004 winter. This lead to an extension of the performance monitoring of this house until the end of May 2005 in order to capture the full winter performance with the proper refrigerant charge. A second recharge was administered in late February 2005. The energy consumption of this heat pump was at least twice as high as it should have been with a properly charged unit.

As described earlier, the photovoltaic system initially was not performing to its capabilities. This poor performance was due to a defective inverter. During the middle of the day when the PV panels should have been producing the most energy, the inverter was cutting off and DC solar power was not being converted to AC, causing the data readings for the AC solar power to be lower than the actual amount of power the photovoltaic system was capable of producing. The inverter was replaced on April 27th, 2004 and the level of the solar immediately matched that of ZEH3, which is expected because they have the same PV system. Figure 11 shows the monthly solar produced as a percentage of the total energy used if the inverter and the heat pump had been working properly. The ZEH3's solar data was used for the months of April and May in place of ZEH2's solar data. A corrected HP electric power consumption is assumed for the months of October 2004 through February 2005. The measured HP power shown in Table 3 was reduced by 53% and the lower total monthly energy consumption recalculated for these five months shown in Figure 11. The total resulting annual energy for the house is 9836 kWh and the total AC solar is 2305 kWh. The solar fraction comes to 23% of total demand. To attain zero energy in this house the PV system would have to be 4 times larger; an 8kWp system.

Figure 11 Monthly solar produced as a percentage of the total energy used by ZEH2



This house does not have a dishwasher, which would actually save on energy usage. A University of Bonn study reported that washing dishes by hand uses more energy than using a dishwasher.[4] This study showed that washing dishes in a sink used 27 gallons (this seems high) of water and 2.5kWh for hot water. Cleaning the same dishes in an automatic dishwasher required only 4 gallons of water and between 1kWh and 2kWh of electrical energy to heat hot water. Using this study, having a dishwasher could be a way to save a kWh per day or another $0.068 in the case of this house.

The house initially had predominately incandescent light bulbs instead of compact fluorescent light bulbs. On October 15, 2004 10 CFL were installed which amounted to all except the lights over the kitchen table. According to Energy Star, compact fluorescent light bulbs (CFL) save two-thirds the energy used by an incandescent light bulb. CFL’s also last 8 to 10 times longer than incandescent lights. This could also have reduced the average daily energy use. In ZEH1 and ZEH4 about 75% of the house lights are CFL. A significant reduction in “other loads” was not noticeable in the data shown in Table 3. These lessons and observations will be taken into consideration with the design and construction of the future near zero energy houses.

Figure 12 ZEH2 draws a crowd as part of the 2004 National Solar House Tour

ZEH2, shown in Figure 12, had a Home Energy Rating (HERS) of 91.4. A HERS of 80 is considered to just meet minimum energy efficiency codes and standards. This house is 57% more energy efficient than a house with a HERS of 80. The total cost to build ZEH2 including the market value for all the donated time and materials came to $117K. This included the estimated $18.5K for the infrastructure and lot.

Over a one year measurement period the solar PV system generated 2305kWh and the total energy usage after correction for the faulty heat pump was 9836 kWh. The solar power fraction was 23% of the total energy usage. This is an improvement from the first house, ZEH1, which attained 20%.[1].

The actual net daily cost for off site energy to run this all electric house was $1.32. The coolant charge on the 14 SEER, two speed compressor with a variable speed, direct current, commutating fan motor was found to be low on two occasions, which resulted in higher space heating and cooling loads than should have been consumed with a properly charged heat pump. The heat pump was recharged on June 6, 2004 and a second time on February 23, 2005. This resulted in a daily HVAC energy usage of $1.30 per day. The HVAC cost on the ZEH3 with the geothermal HP came to only $0.44/day. The measurement of the HP supply and return temperature, the separate kwh measurements on the ZEH2 HP indoor unit and outdoor unit along with ambient air temperature measurements were used to calculate the COP for January 17, 2005. It was found that the heat pump was delivering only 47% of the rated performance. Using this as a correction factor the heating season HVAC power requirements from the beginning of the heating season until the unit was recharged in late February 2005 can be reduced assuming a properly performing heat pump. This results in a reduction for October 2004 until the end of February 2005 of 2370 kWh or $161 per year. This results in a daily HVAC cost of $0.47/ day and a total whole house daily energy cost after solar credits of $0.88. This can be compared to the first years performance of ZEH1 using the same electric energy rate of $0.068/kWh of $1.01/day.

Summary

Considerable lessons have been learned by this house. Future attempts at high performance small houses must address the occasional high humidity in the living space and the crawl space. Once all intermittent problems were corrected for in the analysis the solar fraction comes to 23% of total demand. To attain zero energy in this house the PV system would have to be 4 times larger; an 8kWp system. Some additional reductions in hot water usage and lighting energy have been identified. About 44% of the remaining energy to attempt to save in future affordable zero energy houses is other than space heating cooling and hot water in this house. The house has a certified Home Energy Rating (HERS) of 91.4. The total construction cost to build ZEH2 minus the utility infrastructure and lot is less than $100,000. Once the measured data was corrected to accommodate the know performance problems which occurred over a one year period, this house had a total daily energy cost after solar credits of $0.88. This can be compared to the first years performance of ZEH1 using the same electric energy rate of $0.068/kWh of $1.01/day.

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