The First Attempt at Affordable Zero Energy Houses

By
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Introduction

Affordable energy efficient zero energy houses (ZEH) is the grand challenge set forth by the Department of Energy Building Technologies Program. For the goal to have sustaining national focus the concept requires promise in a variety of different U.S. climates and all price ranges. This article specifically addresses affordable housing in a mixed, humid climate. The first research prototype described was the first attempt at low first cost near zero-energy houses, June 2002. The United States Department of Energy's (DOE) long-term goal is to create technologies that enable net-zero energy residences at low incremental cost by the year 2020. The initiative is to lead new homeowners and builders toward houses that will enable the integration of on-site power. [1.]

The features in the first attempt at a zero energy house (ZEH1) are listed in Table 1 and 2. The small very efficient houses including the cost for solar PV were constructed for under \$100K. The ZEH1 all electric house uses about 10,000 kWhr/year. The heat pump and ventilation require about 30%, heat pump water heater 15% of the total energy. Local electric rates at the time were \$0.063/kWh. This was the first house in Tennessee to sell solar energy to the grid. The solar system generates about 2000 kWh/yr. The net energy cost to the homeowner is under a dollar a day. [2.]

House Descriptions

This article focuses on the first of a series of four near net-ZEHs (ZEH1). The measurement period was during the first year of occupancy. A full years worth of data was available on ZEH1, but only fractions of a full year for the other 3 prototypes. This article focuses mostly on ZEH1. Some comparisons will be given to other houses referred to as ZEH2, ZEH3 and ZEH4. Table 1 shows envelope features and Table 2, mechanical features. Structural Insulated Panels (SIP) were used in all four test houses. These panels were premanufactured with either Expznded Polystyrene or Polyisocyanurate insulation, blown with pentane, sandwiched between two layers of Orientated Strand Board (OSB) and shipped to site with rough openings for windows and doors, as well as, channels for running electrical wiring.

Table 1 Envelope features

House	ZEH 1	Base House	ZEH2	ZEH3	ZEH4
Stories	1	1	1	1	2
floor ft^2	1056	1056	1060	1082	1200
Foundation	Unvented crawl	Vented crawl	Mechanically vented crawl with insulated	Unvented crawl with insulated	Walk out basement with

			walls 2 in polyisocyanurate boards (R-12)	walls 2 in polyisocyanurate boards (R-12)	insulated precast (nominal steady state R-value of (R-16)
1st Floor	6.5 in. SIPS 1#EPS (R-20) Structural splines	R-19 fiberglass batts (R-17.9)	R-19 fiber glass batts, ¾ in XPS boards installed on bottom side of 9 ½ in. I-joist (R-24)	R-19 fiber glass batts, ¾ in XPS boards installed on bottom side of 9 ½ in. I-joist (R-24)	Concrete Slab
Walls	4.5 in. SIPS 1#EPS (R-15) surface splines, house wrap, vinyl	2 X 4 frame with R-11 fiberglass batts, OSB sheathing, (R-10.6)	4.5 in. SIPS 2#EPS (R-15.5) structural splines, house wrap, vinyl	6.5 in SIPS 1#EPS (R-21), structural splines, house wrap, vinyl	2nd floor 4.5 in. SIPS polyiso., pentane blown (R-27), surface splines
Windows	9 windows 0.34 U-factor, 0.33 SHGC, sill seal pans	6-7 windows, U factor 0.538	8 windows 0.34 U-factor, 0.33 SHGC, sill seal pans	8 windows 0.34 U-factor, 0.33 SHGC, sill seal pans	10 windows, 0.34 U-factor, 0.33 SHGC, sill seal pans
Doors	2-doors, solid insulated, & half view	2-doors, one solid insulated, one half view	2-doors, one solid insulated, one half view	2-doors, one solid insulated, one half view	2-doors, one solid insulated, one full view
Roof	SIPS 1#EPS (R-28) surface splines	Attic floor blown fiberglass (R-28.4)	6.5 in. SIPS 2#EPS (R-23) structural splines	10 in SIPS 1#EPS (R-35), surface splines	8 in SIPS, polyiso., pentane blown (R-27), surface splines (R-48)
Roofing	Hidden raised metal seam	Gray asphalt shingles	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 ZEHs and Base house mechanical features

House	ZEH 1	Base House	ZEH 2	ZEH 3	ZEH 4

Solar system	48-43W amorphous silicon PV modules, 2.06 kWp	none	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	1-1/2 ton air-to-air HP, SEER 13.7, 2 speed ECM indoor fan	Unitary 2 ton HP, SEER 12	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	6" duct supplying fresh air to return side of indoor fan-coil	none	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	Inside conditioned space	Crawl space	Inside conditioned space	Inside conditioned space	Inside conditioned space
Water Heater	Integrated HPWH linked to unvented crawl	electric	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

Features in the first attempt at a ZEH (ZEH1) beyond those listed in Table 1 and 2 are, compact thermal distribution system, controlled mechanical supply ventilation, of 40 cfm, meeting ASHRAE 62.2-2003, compact florescent lights, Energy Star Appliances, heat recovery shower, insulated water pipes in the crawl space, and extended roof overhangs. ZEH1 is shown during construction in Figure 1. Figure 2 shows the completed house.

Figure 1 First attempt at a Habitat ZEH June 2002

Figure 2 ZEH1 showing the 48 roof mounted solar modules and south facade

Foundation

The ZEH1 3-bedroom, 1056 ft^2 house sits on an unvented crawl space with polyethylene ground cover. The floor of the house is 6 inch thick SIPS as shown in Figure 3.

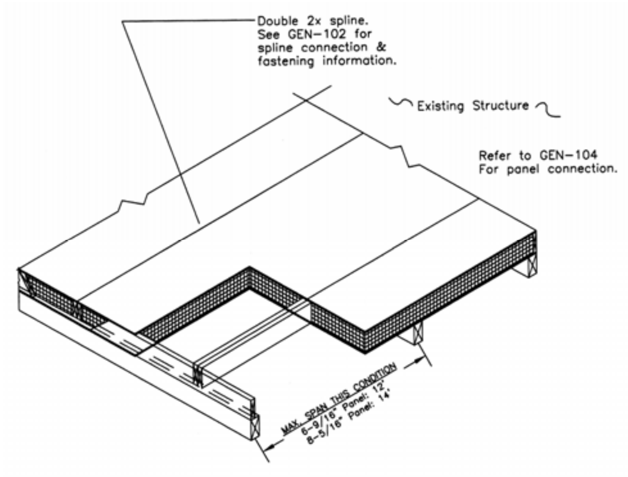

Figure 3 Shows the SIP floor construction

The floor SIPS have 22 mil white aluminum sheets laminated to the bottom surface as shown in Figure 4.

Figure 4 ZEH Crawl Space with 22 mil white sheet aluminum laminated to the bottom of the SIP floor

This metal laminate provides; nonabsorbent surface preventing wet SIPs, capillarity break from wet soils, termite barrier, daylight reflection from the access hatch into the crawlspace.

Figure 5 shows average daily crawl space temperatures for a full year. The space remains above 50 F throughout the winter. The coldest ambient temperature experienced in 2003 was zero. This earth coupled space not only leads to minimal winter time floor heat loss but also eliminates the risk of pipes freezing and provides a heat source for the HPWH.

Figure 5 shows the crawlspace air relative humidity. In July 03, the RH for several days in a row was near 80%. The highest wet bulb temperature observed in July was around 71 F. In Figure 5 the average daily interior temperature is also shown and in July the average inside air temperature was 76 F. This suggests that even if the bottom of the floor reached average inside air temperature it would still be well above the average wet bulb temperature experienced in this crawl space during the worst part of the year. Vented crawlspaces during this time are frequently saturated and experience lengthy periods of near 100% RH. Figure 6 shows the hourly average humidity ratio for a warm moist day in July of the crawl space air and the outside air. The humidity ratio in the crawl space remains slightly less than the outside air. Conditioning the crawl space by providing a very small amount (~20 cfm) of supply air might be considered if the floor did not have the metal laminate to restrict moisture uptake into the floor assembly. A second consideration would be to place a dehumidifier in the crawl space from June-August.

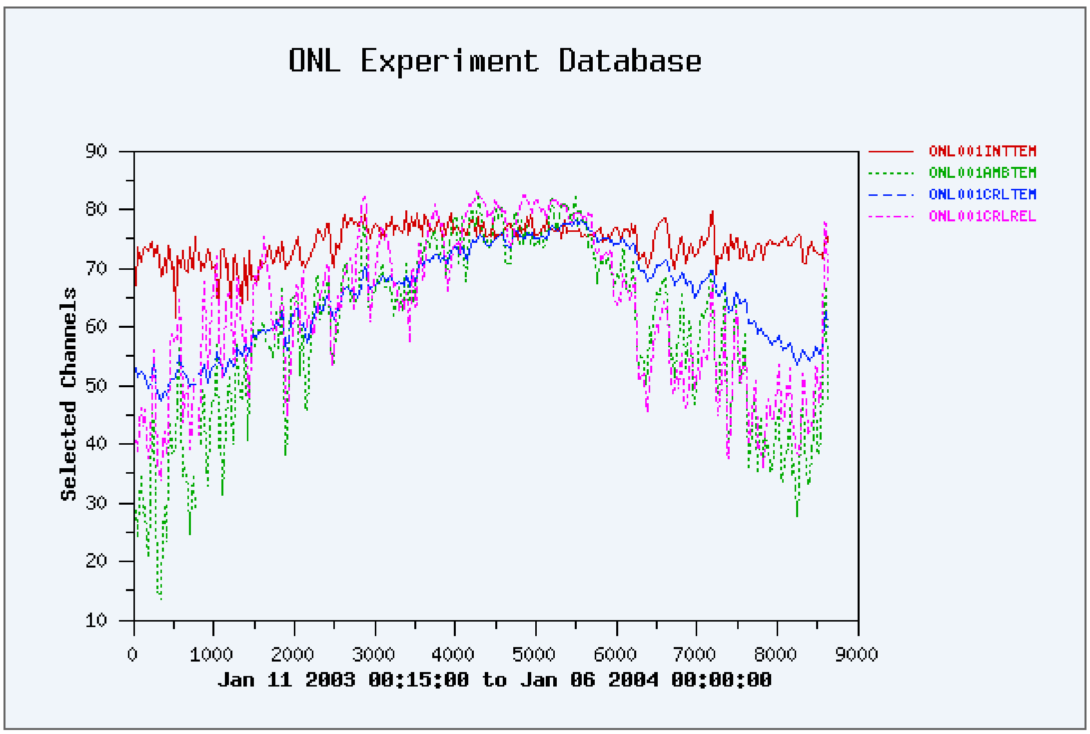

Figure 5 One year's worth of daily average crawl space temperature and relative humidity and inside air temperature measurements, Y axis equals ^{o}F for interior (INTTEM), ambient (AMBTEM), crawl space air (CRLTEM). Y axis equals %RH for crawl space relative humidity (CRLREL)

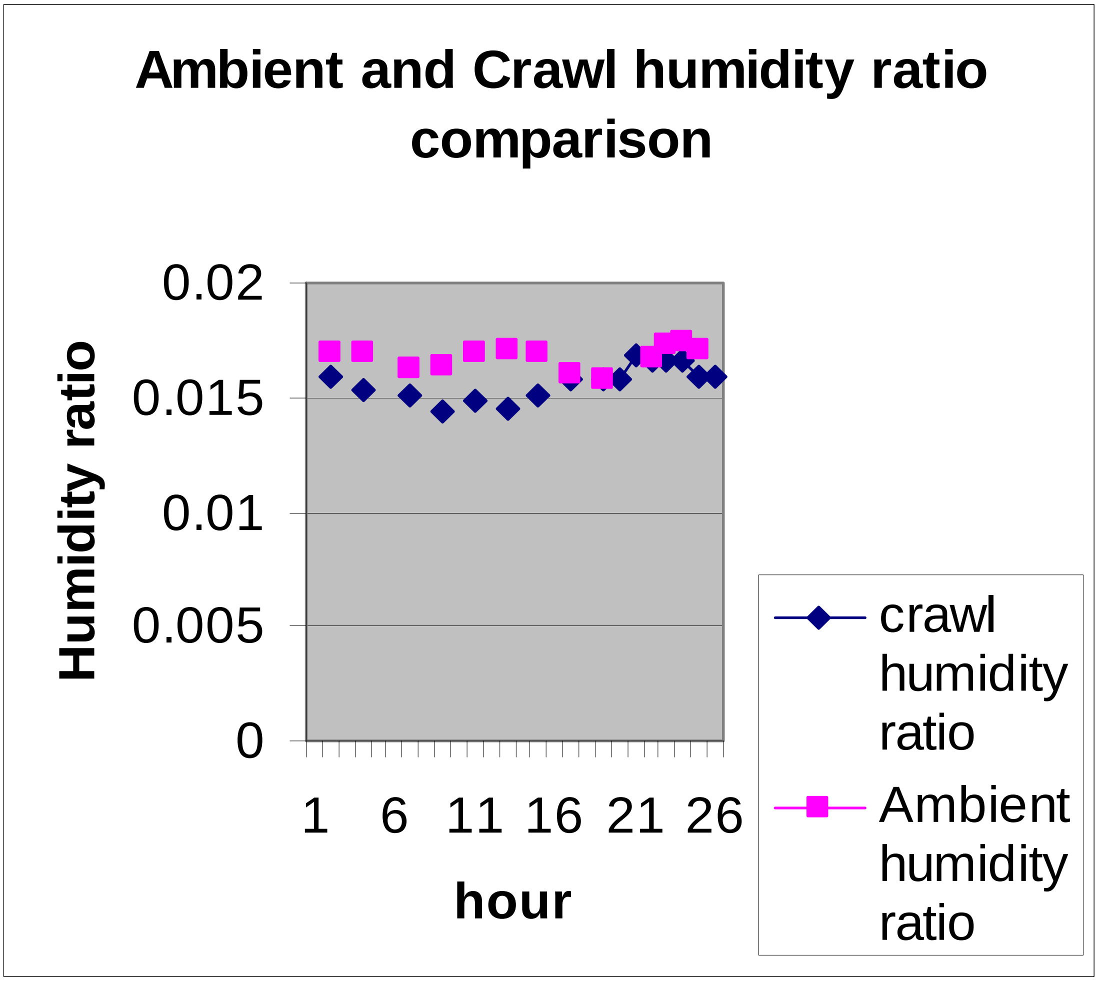

Figure 6 Ambient and crawlspace humidity ratio for July 8, 2003

Envelope

The house floor plan and cross section are shown in Figure 7 and 8. The house walls are 4.5 inch thick SIPS with 1 lb/ft^3 density expanded polystyrene between 7/16 inch OSB (Orientated Strand Board). The wall panels were fastened together using well sealed surface splines.

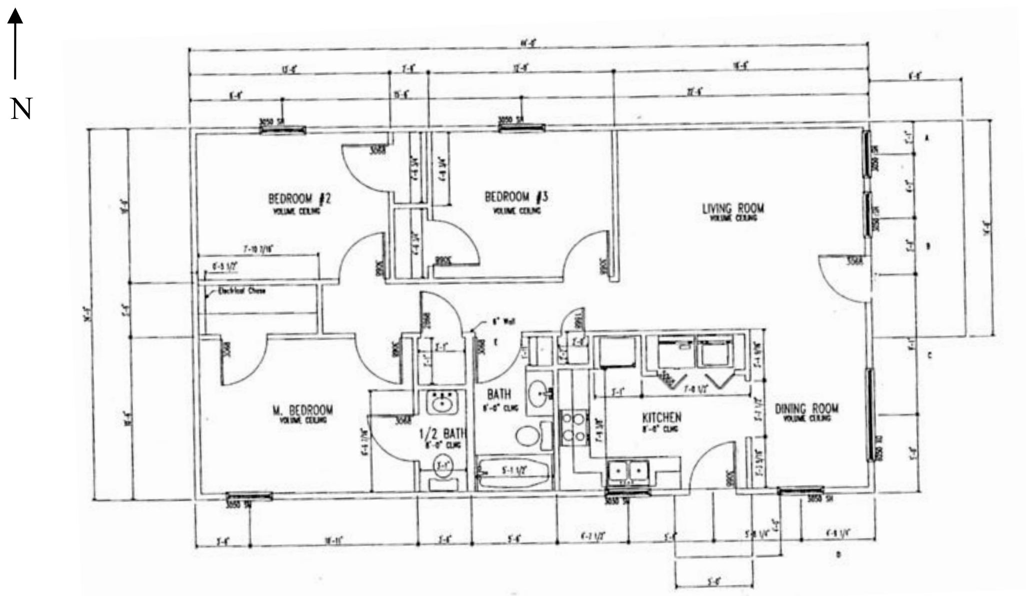

Figure 7 ZEH1 Floor Plan

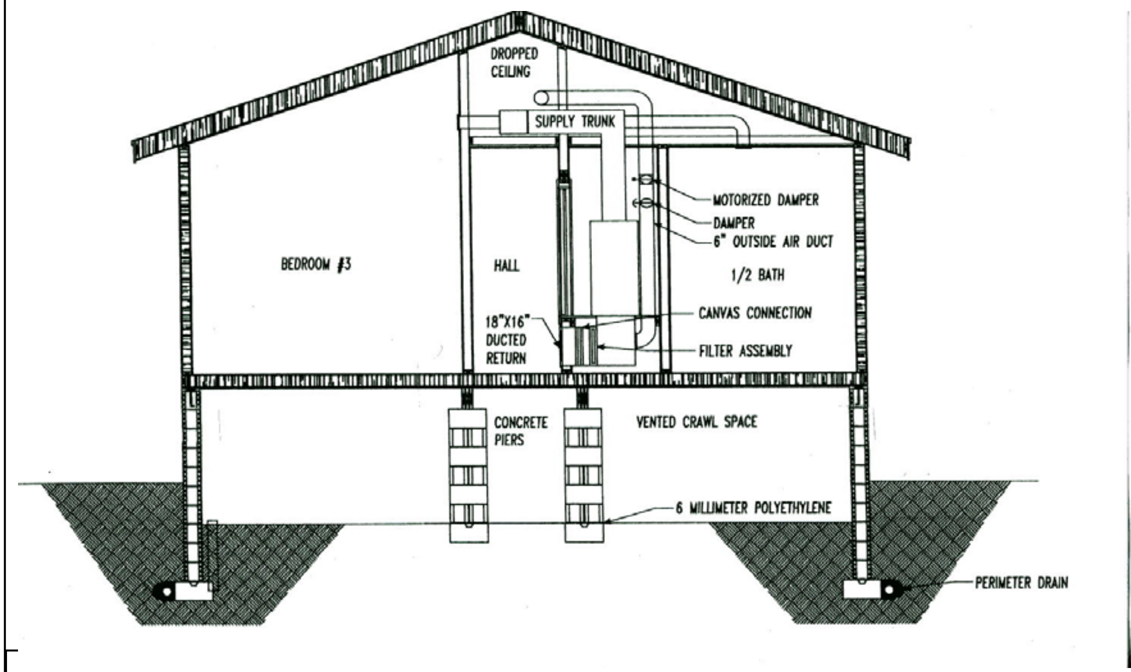

Figure 8 ZEH1 Cross section

The 4/12 pitch cathedral ceiling consisted of full length 4 ft wide panels, from ridge-to-eave, connected with surface splines. The roof system R-value is 28 h·ft²·°F/Btu @75°F. The windows were wood, vinyl clad, double-hung with National Fenestration Rating Council (NFRC) Labeled U-Factor of 0.34 and Solar Heat Gain Coefficient of 0.36.

Prior to selection of the opaque walls and roofs for ZEH1, two 12 ft by 12 ft by 8 ft high test rooms were constructed in the Laboratory. One of these rooms was constructed using 4.5 inch thick SIP walls with 10 embedded electrical boxes and connecting wires. The second room with identical inside floor space was constructed and tested in exactly the same manner. This room had 2 X 6 @16" on center frame walls with R-19 fiberglass batt insulation, a flat insulated roof with a layer of R-19 plus a second R-11 layer perpendicular to the R-19, the same window, door, and electrical wiring system. Air tightness tests were conducted on both test rooms. The data for the SIP test room is shown in Figure 9 as the line with the triangles "▲" pointing upward. The frame test room is displayed as the line in Figure 9 with the triangles "▼" pointing downward. This data is consistent with tightest and the leakiest of 6 nearly identical frame houses all built by the same contactor as all the houses described in Table 1 and 2. The tightest and leakiest frame house lines are shown in Figure 9 with "+" and "x" symbols. This confirms that the frame test room represents wood frame field conditions. At 50 Pascal of pressure across the envelope the SIP test room had an air leakage of 0.078 ft^3/ft^2 of floor area. The 2 X 6 test room had an air leakage value of 1.06 ft^3/ft^2 of floor area. The 2 X 6 frame test room was 14 times leakier than the SIP structure. These air tightness measurements encouraged the selection of a SIP envelope for ZEH1.

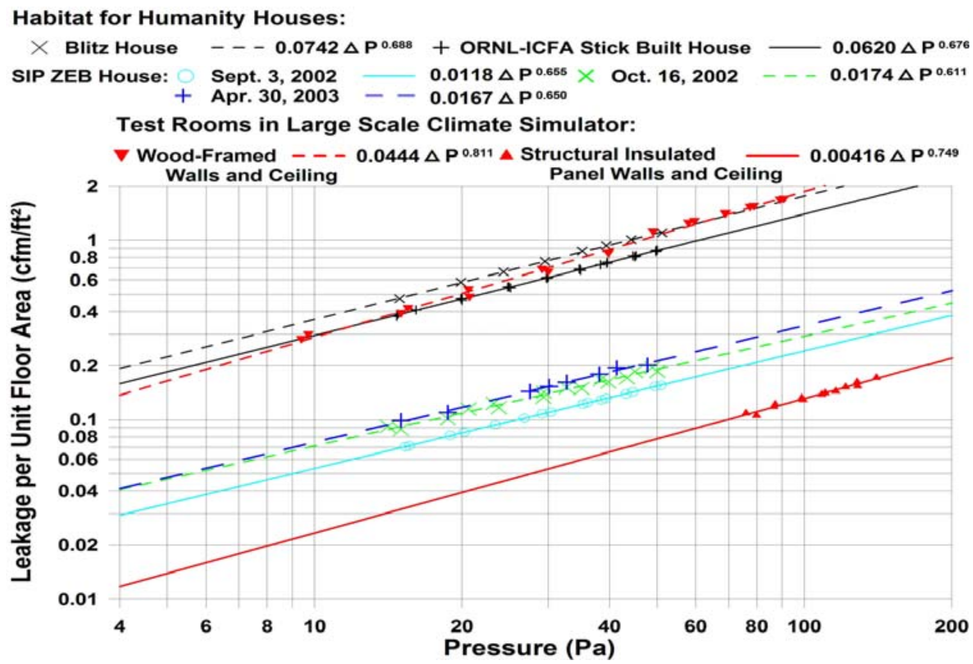

Figure 9 Air tightness of SIP structures compared to stick

A blower door analysis was run on ZEH1 prior to installation of the drywall, after the house was ready to be moved into and 6 months after occupancy. The line with the "o" shows the ZEH1 whole house leakage prior to drywall. The ZEH1 leakage per unit of floor area measured out at 0.15 cfm/ft2 at 50 Pascal. This can be compared to the wood frame base house of 0.87. The base wood frame house was 6 times leakier than ZEH1.

Domestic Water Heating (DHW)

ZEH1 is equipped with a domestic HPWH. The warmer the air source the better the HPWH's thermal performance. Also, to take advantage of the space cooling and dehumidification available from the HPWH, the unit is connected to the air space behind the refrigerator. When the house thermostat is set for cooling, motorized dampers allow the HPWH fans to pull air from behind the refrigerator into the evaporator coil of the HPWH. This air stream is cooled, dehumidified and directed back into the kitchen. When the thermostat is in the "off" or "heating mode", the ducts connecting the HPWH to the kitchen are closed and other ducts are opened to pull in earth tempered crawl space air and reject unneeded cold air outside. Since the crawl space is unvented it will go under a slight negative pressure. The crawl space access is not weather stripped and this crack allows make up air into the crawl. Figure 5 shows a full year of average daily temperatures in the crawl space. The space remains above 50^{o}F the entire winter.
The water heating usage measurements show the occupants used 72% of the DHW for showers and baths. The average daily usage was 40 gal/day. The measured daily energy consumption is 3.8 kWhr. The average HPWH COP was 1.62. With lower hot water usage the standby losses are a higher percentage of energy usage resulting in lower

COPs.   Because the HPWH and refrigerator were located on inside walls of the kitchen, long duct runs were required to vent to the outside and into the kitchen. The installed flex ducts generated excessive static pressure, restricting air movement away from the HPW. The optimized coupling with refrigerator, crawl space, space cooling and dehumidification was not attained in ZEH1. In ZEH2 the HPWH COP was measured closer to 2.0. This saves another 337 kWh/year ($0.06/day).   ZEH2 has a second generation hook up which consists of the refrigerator and the HPWH located adjacent to the outside wall and has all hard ducts, and short runs to and from the unit to minimize static pressure. Figure 10 shows the COPs in this unit from March 2004 until September 2004 averaged almost 2.0. The lower COPs in the winter are caused by a 155 F unintentional high HPWH standby temperature. The homeowner had intended to set the water heater at 130

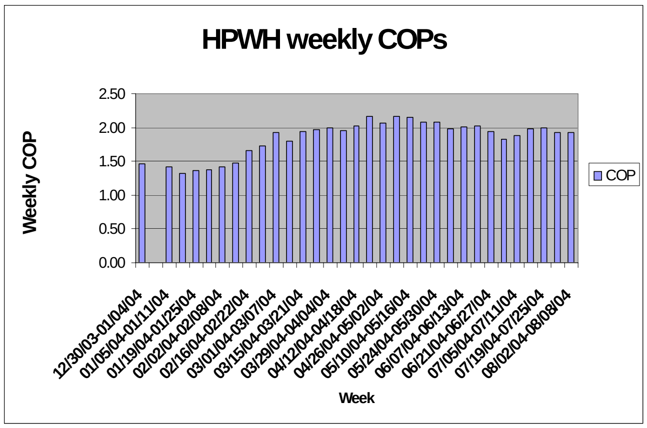

Figure 10 COP of HPWH in ZEH2

F.

Thermal Comfort

The conditioned space average hourly temperature and relative humidity for one complete year are shown in Figure 11. The thermostat temperature on average is kept around 75°F. No setback or setup schedules were programmed in this house. The occasional spikes in RH are due to window openings and 24/7 mechanical ventilation. The homeowners generally were not home during the summer weekday time periods. Even though the RH would tend to drift above 60% on some hot summer days the owners had no thermal comfort complaints. Because of the airtight envelope, well shaded low solar heat gain windows, and continuous mechanical ventilation the thermostat would occasionally not call for sensible cooling until after the RH rose above what would be considered acceptable in some situations. Later designs of the HVAC systems in ZEH2, ZEH3 and ZEH4 all tried to address this potentially unacceptable high relative humidity levels during the summer cooling period.

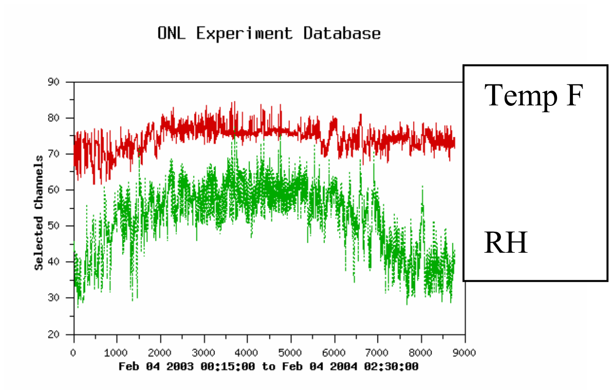

Figure 11 Interior temperature and RH for complete year

Total electric energy usage and cost

The ZEH1 all electric house, from March 1, 2003 until February 29, 2004, used 10,216 kWhr, as shown by Table 3. The heat pump and ventilation fan power required 2759 kWhr or 27% of the total energy. The HPWH used 1549 or 15% of the total. The rest of the energy loads in the building required 5907 kWh or 58% of the total. Prior to construction the Home Energy Rating System HERS rating was calculated to be 90.2, which converts to a 50% better than the International Energy Conservation Code (IECC). The electric rates in this area during the monitoring period were $0.63/kWh. This house sells green power to the electric utility. The utility pays the homeowner $0.15/kWh for all the solar power produced by the 2kWp PV system for 10 years. During this one year monitoring period the solar system generated 2006 kWh and a solar credit of $300. The net energy cost to the homeowner $343/year, or $0.94/day. In the winter of 2002-03 the homeowners used a bit less energy than the winter of 2003-04, during this annual period starting from November 2002 the cost would have been $0.82/day.

Figure 12 shows ZEH1 used 40% less total energy than the base house. The local electric utility certified the base house as a HERS 84 frame home (already 20% better than IECC).

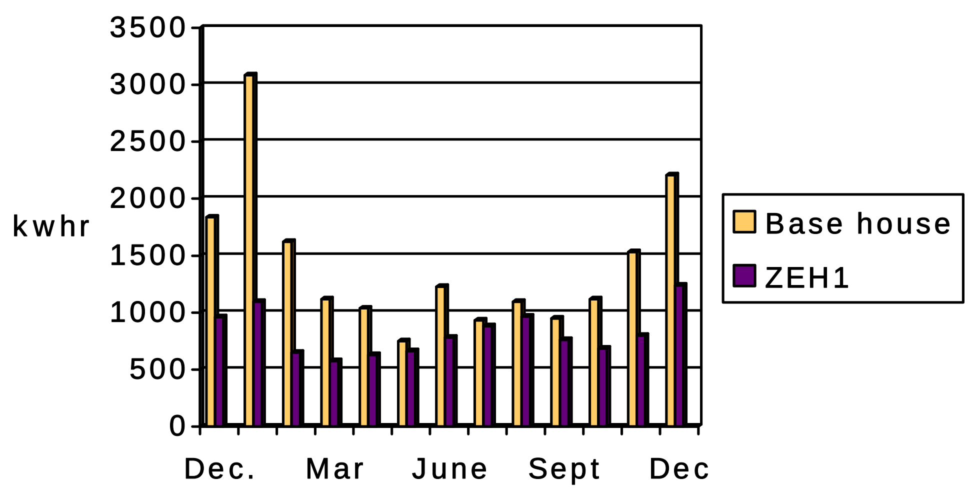

Figure 12 Monthly energy bills from base house show a 40% higher annual energy cost than ZEH1, from Nov. 2003-Dec.2004.

Energy Use

Table 3 shows monthly measured electric energy usage for ZEH1. The columns labeled, “space heat”, “space cool”, “hot water” and “other”, equal the values shown in “total electric”. The annual energy cost for space heating totals about $100, space cooling $74, domestic hot water $98, the “Other” equates to $372. The total cost is calculated by subtracting the solar credit at $0.15/kWhr or $301 from the total used, $644/yr.

Table 3 Energy breakdown and costs

Month	Space Heat (kWh)	Space Cool (kWh)	Hot Water (kWh)	Other (kWh)	Total electric (kWh)	Solar AC generated* (kWh)	Solar sold back (kWh)
March 03	127		124	325	575	167	91
April	64		146	419	629	195	100
May		94	109	460	663	188	90
June		204	87	490	781	213	88
July		314	74	494	882	209	79
August		359	70	536	966	219	76
Sept		187	82	491	760	195	95
October	34	17	117	518	686	159	77

November	141		138	518	797	121	45
December	401		187	650	1238	115	15
January	473		219	540	1232	120	23
February 04	344		196	466	1006	104	25
TOTAL	1584	1175	1549	5907	10216	2006	804
% total used	15.5%	11.5%	15%	58%		20%	
Cost ($)	-100	-74	-98	-372	-644	301	

*****Alternating Current

Table 3 shows the 2kWp PV system monthly generation in the column "Solar AC generated". The total solar annual generation was 20% of the total energy used. The last column shows the solar power generated on-site but at the time was not needed in the house and therefore sent to the grid. The estimated first cost of the ZEH1 solar system was $22,388, as shown in Table 3. The total installed solar system cost with the same capacity installed in ZEH2 and ZEH3 was $16,000. The installed cost in ZEH4 was under $15,000 and had 10% more capacity. Solar system first cost will have to continue to drop and PV utility incentives continue to rise. The buyback incentives could be going up to $0.20 kWhr and at market costs for this size solar system in late 2004 of around $13.7K the simple solar payback for this location and current residential electric rates is around 30 years. The total cost to build these 3 experimental houses is shown in Table 4 along with the base house.

About 40% of the solar power generation was not coincident with the house energy demand. This solar power for the most part is available during hot summer afternoon hours when utility electric grids values not only the reduction in load but the power to help meet peak period cooling demands. The PV system on this house on average reduced summer peak loads by 40% in the three summer months June-August.

Construction cost

These houses were all constructed by the Habitat for Humanity Loudon County Affiliate. Most of the construction was done with volunteer labor. Subcontractors were hired for plumbing, HVAC, foundation installation and site work, concrete pavement, and drywall installation. Volunteer hours were kept track of by a sign in/out book. The value assigned per volunteer hour was $5.50. The Habitat for Humanity affiliate's indicated that this rate represents local market value.

Table 4 shows a spread sheet for construction cost of ZEH 1, ZEH 2, ZEH 3 and the base house. The good news is that these near ZEHs cost only $100K. Because of the research aspects of these test houses the costs are higher than production units. Production units will result in lower material and installation cost reductions. Additional utility incentives are anticipated for future PV systems. It is hoped that this research will also result in incentives for solar water heating and geothermal systems, which could be converted to green labeled energy and made a part of the local utility green power program.

Table 4 Construction cost of research ZEHs and the base frame house

	Base House	ZEH 1	ZEH 2	ZEH 3
house	59,295	78,914	83,953	87,889
Land and infrastructure	14,500	14,500	14,500	14,500
Cost of solar	0	22,388	16,000	16,000
Total cost	73,795	115,802	115,953	122,329

Lessons learned

Table 3 shows that more than 75% of the heating energy for an air-to-air heat pump is consumed in the three coldest months, December, January, and February. ZEH2 and ZEH3 research houses used better envelopes, and better heat pumps. ZEH3, shown in Figure 13, used a direct exchange geothermal system for January and February 2004 demanded 19% less total house energy and produced 12% more solar power than ZEH1. The orientation of this house is a bit better and has a 6/12 pitched roof compared to ZEH1s 4/12. By the end of September 2004 and 9 months of measured performance the solar system on ZEH3 had generated the same amount of AC solar as that on ZEH1. The biggest energy savings in ZEH3 is believed to come from the geothermal heat exchanger, drawing heat from the surrounding earth which stayed above 50^{o}F in the winter and below 73^{o}F in the summer, compared to the much colder night time winter ambient air, and higher ambient PM cooling periods. The additional features of this second generation of near ZEH are listed in Table 1 and 2. The local electric utility auditors rated ZEH3 with a HERS = 93.9. Of course the 2020 affordability cost goal has not been met in these first prototypes.

Figure 13 ZEH3 has only 12 solar modules compared to ZEH1 48 and thicker SIP roof and walls.

Conclusions

ZEH1 had a rated HERS of 90. It used about 40% less energy than the base house with electric utility certified performance of HERS 84. The total cost to build ZEH1 including the market value for all the donated time and materials came to about $100K.. The total energy costs are under $1/day. The heating cost of ZEH1 using the local electricity rate of $0.063/kWh, was under $100/year, cooling under $75, and domestic hot water under $100.

The solar PV system generated about 2000 kWhr over first full year. This amounted to 20% of total energy load and 74% of HVAC load. The lowest average total energy cost less the solar credits came to $0.82/day. This was the first local electric generation utility's Green Power Switch Generation Partner. With the electric utility green power offering $0.15/kWh and the energy saving features this house experienced an annual energy cost savings of 65%. ZEH3 had been occupied for only nine months and with normalized occupancy the daily average energy cost is extrapolated for a full year to be $0.68/ day for ZEH3. The use of geothermal heat pump in the winter time was making a substantial step closer to net-zero. However it did add first cost. Ongoing research and development is leading to lower first cost reductions in the envelope, HPWH and geothermal heat pump.

Reference

1. DOE Building Technologies goal for zero energy buildings can be found at the following web site < http://www.eere.energy.gov/buildings/program_areas/zeroenergy.html>

2. Christian, J.E., Beal, D, Kerrigan, P., Toward Simple Affordable Zero Energy Houses, Performance of Exterior Envelopes of Whole Buildings IX International Conference Proceedings CD, Clearwater Beach, Florida, ASHRAE, December 2004.