Toward Simple, Affordable Zero Energy Houses

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ABSTRACT

A long-term goal of the U.S. Department of Energy is the creation of zero energy houses by the year 2020. This paper focuses on the first of a series of six near-zero-energy houses constructed in east Tennessee as part of a project to build a true net zero energy house by the end of 2005. The features in the first house included airtight floor, walls, ceiling, and structurally insulated panels (SIPS); compact thermal distribution system with all ducts positioned inside the conditioned space; controlled mechanical supply ventilation; high-efficiency windows with 0.34 U-factor and 0.33 SHGC; 14 SEER 1.5-ton heat pump with two-speed indoor circulating fan; heat pump water heater integrated with the refrigerator/AC/dehumidification; compact florescent lightbulbs and Energy Star appliances; reflective hidden metal seam roof; and grid-connected 2 kWp solar photovoltaic.

BACKGROUND

Energy-efficient zero energy houses and affordability today are at a crossroads. First costs of the full package of efficiency measures and on-site energy generation often rule out their incorporation into mainstream housing. However, the long-term vision of focusing research on affordable zero energy buildings has international appeal. The ultimate solutions will depend on many factors, one of which is climate. This paper specifically addresses housing in a mixed, humid climate that is affordable, practical, and available. The prototype described turns out to be the first attempt to design, build, and monitor a Habitat for Humanity near zero-energy house (ZEH1).

The United States Department of Energy's (DOE) long-term goal is to create technologies and design approaches that enable net-zero energy residences at low incremental cost by the year 2020. The current initiative is to lead potential new homeowners and builders toward houses that will enable the integration of on-site power. To meet the net-zero energy goal, the homes will be designed to incorporate energy-saving features to reduce loads by 70% below the International Energy Conservation Code and then satisfying the remaining energy demand with approximately 2 kilowatt peak (kWp) of site-generated power. On June 17, 2002, the chairman of the TVA, the largest electric utility in the U.S., announced the initiative to help develop net-zero energy test houses in east Tennessee. Research visions and incentives from these programs, coupled with Habitat's desire to build a cutting edge, energy-efficient home, led to the construction of ZEH1.

The features in the first attempt at a net zero energy house (ZEH1) are:

- Airtight floor, wall, ceiling, and structurally insulated panels (SIPS)
- Compact thermal distribution system with all ducts positioned inside the conditioned space
- Controlled mechanical supply ventilation
- High-efficiency windows with 0.34 U-factor and 0.33 SHGC
- 14 SEER 1.5-ton heat pump with two-speed indoor circulating fan
- Heat pump water heater integrated with the refrigerator/AC/dehumidification
- Compact florescent lightbulbs and Energy Star appliances

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- Reflective hidden metal seam roof
- Grid-connected 2 kWp solar photovoltaic

The ZEH1 all-electric house, from March 1, 2003, until February 29, 2004, used 10,216 kWh. The heat pump and ventilation fan power required 27% of the total energy. The heat pump water heater used 15% of the total. The rest of the energy loads in the building required 5907 kWh or 58% of the total. Local electric rates at the time were $0.63/kWh. This was the first house in Tennessee to sell solar energy to the electric grid. During the monitoring period the solar system generated 2006 kWh. The net energy cost to the homeowner results in an expense of $0.94/day. The ZEH1 has a gross floor area of 1056 ft^2. During this same period a nearby, 20-year-old, two-story house with 3032 ft^2, gas heat, and SEER 13 AC experienced energy costs of $7.82/day. The HVAC in this house was just replaced in 2002. On a cost per square foot of floor area per year, this is $0.94 compared ZEH1 at $0.32. Over a 30-year period, this house would save the homeowner more than $20,000 compared to the option of moving into an older house with new HVAC equipment with the same floor area. This saving grows to more than $75,000 compared to moving into that larger, less efficient house.

INTRODUCTION

In September 2003, the U.S. Environmental Protection Agency released national smog alert data. Tennessee was the third worst state in the nation, next to California and Texas. In the month of June 2003 ozone alerts were announced 25 out of 30 days in the Great Smoky Mountain National Park, which has more than 8.5 million visitors annually. Coal-fired power plants are the second largest source of this pollution, accounting for 14-21% of the total. Over one-third of this energy is used to power buildings. A healthy economy in east Tennessee is dependent on tourism; the availability of healthy, reasonably low-cost labor; industry leaders desiring to site new and expanded facilities; and a growing number of retirement communities. The process described in this paper is a roadmap for communities to transform their building industry from part of the problem to part of a solution by changing buildings from being energy consumer/polluters to being clean energy producers. In the case of Tennessee, air quality concerns have taken center stage. Pollution abatement equipment on coal-fired power plants is a major reason the Tennessee Valley Authority (TVA) in 2003 increased residential and small commercial electricity rates by 7.5%. If the air shed cannot safely disperse even low-emitting new pollutant point sources, fewer new businesses will be able to site in east Tennessee. The strongest response to electric utility incentives to conserve energy and pay for renewable power has been from the territory surrounding the Great Smoky Mountain National Park. Customers in this region appear willing to pay more for electric power generated from renewable sources because they have concluded that the path toward a cleaner, healthier environment and economy is to exercise affordable available options to take personal responsibility toward becoming better environmental stewards.

On June 17, 2002, the chairman of the TVA, the largest electric utility in the United States, announced TVA would launch an initiative to help develop net-zero energy test houses in East Tennessee, an area of the country that has not been aggressively encouraging building energy efficiency nor offering attractive subsidies for onsite solar energy production. Details of this announcement are available at: <http://www.tva.com/news/releases/0602netzero.htm>.

The long-term goal of the United States Department of Energy (DOE) is to create technologies and design approaches that enable net-zero-energy residences at low incremental cost by the year 2020. The current initiative is to lead potential new homeowners and builders toward houses that will enable the integration of on-site power. To meet the net-zero-energy goal the houses will be designed to incorporate energy-saving features to reduce loads by 70% below the International Energy Conservation Code and then satisfy the remaining energy demand with about 2 kilowatt peak (kWp) of site-generated power. The effort must be all-inclusive, including plug loads and occupant interaction, not stopping with space heating, cooling, domestic hot water, lighting, and major appliances.

DESCRIPTIONS OF THE TEST HOUSES

This paper focuses on the first of a series of six near net-zero-energy test houses (ZEH1). The project's goal is to build a true net-zero-energy house by the end of 2005. Some comparisons will be given to other houses built in this series. They are referred to as ZEH2, ZEH3, and ZEH4. Table 1 lists envelope features and Table 2 lists mechanical features of each of these test houses compared to the base house.

The features in the first attempt at a zero-energy house (ZEH1) are:

- Airtight floor, wall, and ceiling, structurally insulated panels (SIPS)
- Compact thermal distribution system with all ducts positioned inside the conditioned space
- Controlled mechanical supply ventilation to meet ASHRAE 62.2-2003
- 14 SEER 1.5-ton air-source heat pump with ECM (electronically commutated motor) two-speed indoor circulating fan
- Heat pump water heater integrated with the refrigerator/AC/dehumidification
- Compact florescent lightbulbs and Energy Star appliances
- High-efficiency windows
- Reflective hidden metal seam roof
- Grid-connected 2 kWp solar photovoltaic,
- Heat recovery shower, insulated water pipes in the crawlspace
- Extended roof overhangs

Table 1. ZEHs and Base House Building Envelope Features

House	ZEH1	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 walls 2 in polyisocyanurate boards (R-12)	Unvented crawl with insulated walls 2 in polyisocyanurate boards (R-12)	Walk out basement with 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 ¥ 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	two doors, solid insulated & half-view	two doors, one solid insulated, one half-view	two doors, one solid insulated, one half-view	two doors, one solid insulated, one half-view	two 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, 0.032 aluminum

Table 2. ZEHs and Base House Mechanical Features

House	ZEH1	Base House	ZEH2	ZEH3	ZEH4
Solar system	48-43 W amorphous silicon PV modules, 2.06 kWp	None	12-165 W multi-crystal silicon PV modules, 12.68% eff, 1.98 kWp	12-165 W multi-crystal silicon PV modules, 12.68% eff, 1.98 kWp	20-110 W polycrystalline, 2.2 kWp
Heating and cooling	1½ ton air-to-air HP, SEER 13.7, two-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	Supply to return side of coil	None	Supply to return side of coil, CO_2 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	Crawlspace	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	Desuperheater for hot water, EF.94	HPWH vented to ½ bath that is exhausted for ventilation

Figure 1 *First attempt at a Habitat ZEH, June 2002.*

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

A picture of ZEH1 is shown during the SIP roof installation in Figure 1. This was the first house in Tennessee to sell solar energy to the electric grid, beginning in May 2003. Figure 2 shows the house after construction.

Foundation

The three-bedroom, 1056 ft^2 house sits on an unvented crawlspace with a black 6 mil polyethylene ground cover with taped seams. The groundcover is fastened one foot up the uninsulated walls and pilasters with caulk and held in place with 1 × 4 pressure-treated furring strips using masonry nails. Four crawlspace vents were installed near each corner and sealed using 2-inch-thick extruded polystyrene XPS. Currently, vents are required by most code bodies, but the performance of the crawlspace in this house would support the argument that they are not needed if the crawlspace is properly designed and operated. The floor of the house is 6-inch-thick SIPS with two 2 × 6 wood structural splines embedded on 4-foot centers in the floor. Structural splines cut all the way through the insulated core as shown in Figure 3.

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

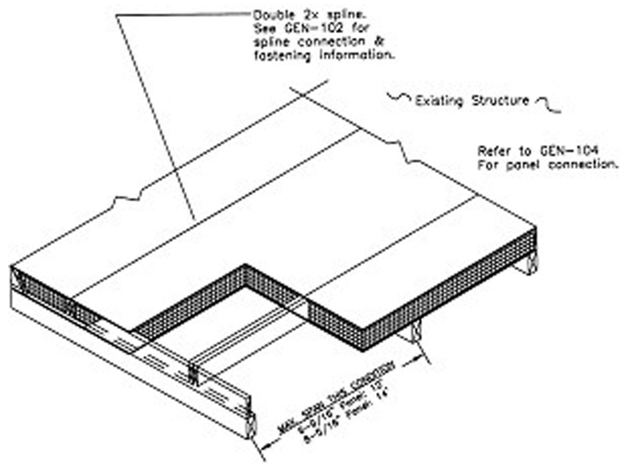

Figure 3 *Shows the SIP floor construction.*

Figure 4 *ZEH1 crawlspace with 22 mil white sheet aluminum laminated to the bottom of the SIP floor.*

This metal laminate provides multiple services. First, the metal provides a nonabsorbent surface for those times the surface temperature falls below the crawlspace air dew point, generating condensation that would otherwise wet the SIP. This could lead to mold, mildew, odors, and eventual decay of the orientated strand board (OSB). Prior to the installation of the ground cover in December 2002, condensation did form on the underside of the floor SIP, most heavily near the crawlspace corners. Once the ground cover was installed, no condensation formed. The second service this metal laminate provides is a capillarity break for any moisture that might migrate up from wet soils under the footer and adjacent to the crawlspace walls. A footer drain was installed around the entire structure and run to daylight on the southwest corner of the house. The third service this metal laminate provides is as a mechanical termite barrier. A fourth service is that the white surface reflects light from the open access hatch and the limited light fixtures installed, helping to illuminate the 5.5 ft high crawlspace.

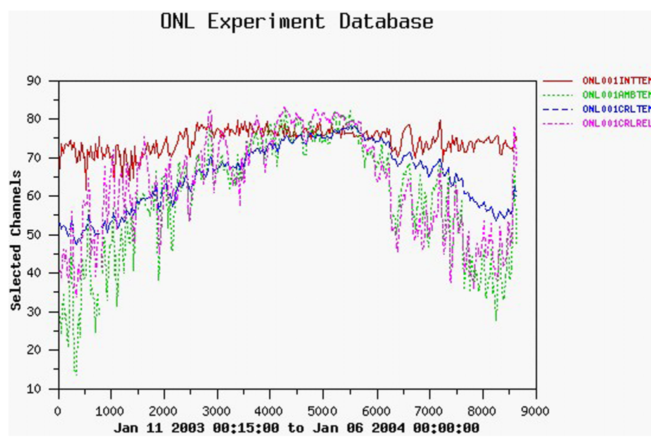

Figure 5 *One year's worth of daily average crawlspace temperature and relative humidity and inside air temperature measurements, y-axis equals °F for interior (INTTEM), ambient (AMBTEM), crawlspace air (CRLTEM). Y-axis equals %RH for crawlspace relative humidity (CRLREL).*

Figure 5 shows average daily temperatures measured in the crawlspace for a full year. The space remains above 50°F throughout the entire winter. The coldest ambient temperature experienced in 2003 was zero. Figure 5 also shows the average daily inside air temperature. The crawlspace air is, in general, warmer in the winter and cooler in the summer than the ambient air temperature. This earth-coupled space not only leads to minimal wintertime floor heat loss but also eliminates the risk of pipes freezing and provides an attractive wintertime heat source for the heat pump water heater supply air.

The only wood that had not been treated with preservatives exposed to the crawlspace is the central floor beam running the length of the house. Figure 5 shows the measured crawlspace air relative humidity. In July 2003, which experienced above average rainfall, 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 crawlspace 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 of the crawlspace air and the outside air for a warm, moist day in July. The humidity ratio in the crawlspace remains slightly less than the outside air. No conditioned air is provided in this crawlspace to further reduce the risk of unwanted condensation and high moisture conditions for generating mold and mildew.

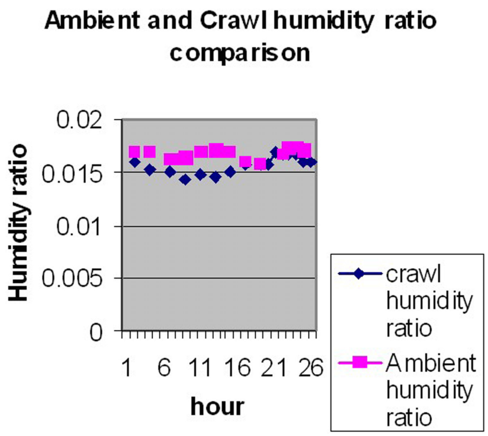

Figure 6 *Ambient and crawlspace humidity ratio for July 8, 2003.*

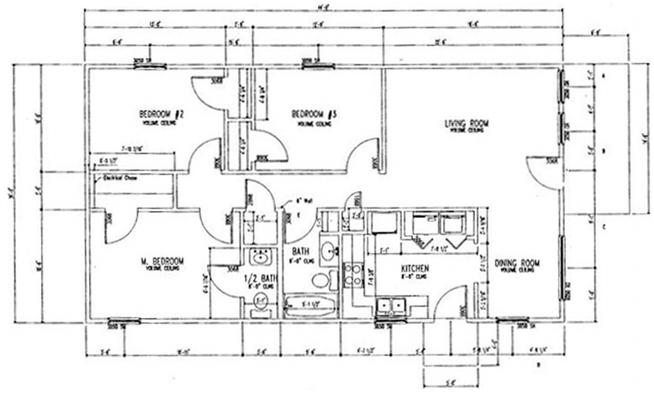

Figure 7 *ZEH1 floor plan.*

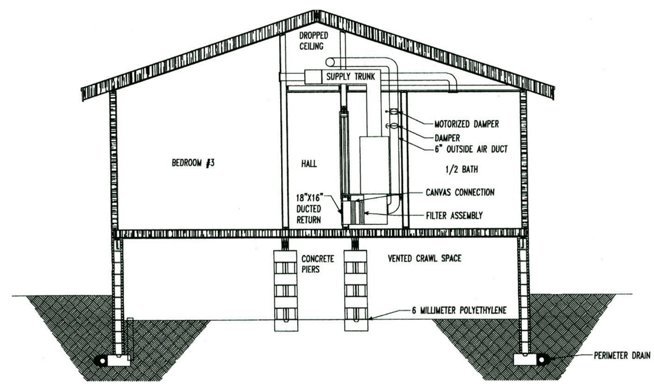

Figure 8 *ZEH1 cross section.*

Above-Grade Envelope

The house floor plan and cross section are shown in Figures 7 and 8. The house walls are standard 4.5 in. thick SIPS with nominal 1 lb/ft^3 density, expanded polystyrene sandwiched between two layers of 7/16 in. OSB (orientated strand board). The long wall panels were 8 ft high with various lengths on the eave walls, all sized to fit the pitched 4/12 gable on the front and back of the house. The panels were fastened together using surface splines that were well sealed using two different types of caulk. Each panel-to-panel connection was sealed at all contact surfaces, spline-to-foam, foam-to-foam, and on both surfaces where the OSB skins met. This totaled five caulk seals. The cathedral ceiling with a 4/12 pitch consisted of full-length 4 ft wide panels from ridge to eave. They were all connected with surface splines. This provides a roof system R-value of 28 h·ft^2·°F/Btu at 75°F. Two of these nominal 8 in. thick, 4 ft wide panels were fastened together on the ground and lifted to the roof with a crane. Two-thirds of the roof panels were supported by two full-height structural walls that served as partitions between the back two bedroom closets, shown in Figure 7, and hallway walls leading to the open dining living area. The open area in the front of the house was spanned by use of a laminated wood ridge beam. The windows were wood, vinyl clad and 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 in. thick SIP walls with 10 embedded electrical boxes and connecting wires. Several panel-to-panel joints were designed into the walls and sealed using manufacturer-recommended splines and caulking procedures for air sealing. The SIP test room had 4.5 in. SIPs and an 8 in. flat roof with a R-value of about 30 h·ft^2·°F/Btu @75°F. One double-hung window and full-view 36 in. wide door were installed in accordance with the manufacturer's recommendation for these flanged products. The inside walls and ceiling were dry-walled with one coat of mud. No house wrap was installed on the exterior. A ceiling fan with an electric heater was installed and used to condition the space at 74°F while the Large Scale Climate Simulator outdoor chamber was set at 0°F. The test was run long enough to reach steady state and measure the amount of energy needed to maintain the thermostat setting at mid-height in the test room.

The second room with identical inside floor space was constructed and tested in exactly the same manner. This room had 2 × 6 at 16 in. 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, and the same window, door, and electrical wiring system. The exterior OSB sheeting was attached with 3/16 in. space between sheets as recommended by the manufacture's installation guidelines. No house wrap was installed on either test room. The walls were insulated by a local insulation crew who were instructed to install just as they do in the field. This resulted in the electric wires compressing some of the fiberglass insulation, which is not according to manufacturer's recommended installation. The batts should be sliced and tucked around the wiring to avoid all

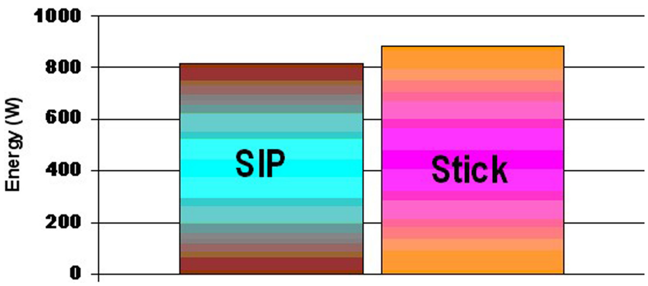

Figure 9 *At 0°F the SIP test room used 10% less energy to heat than the 2 × 6 frame.*

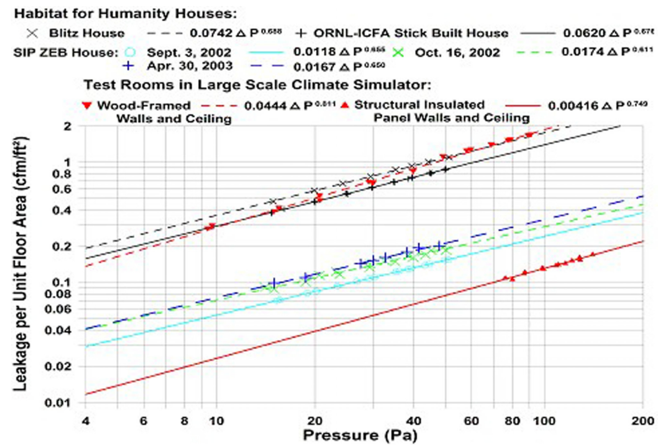

Figure 10 *Airtightness of SIP structures compared to stick.*

compression. The same SIP floor was used in both rooms. Its air-to-air R-value was estimated to be 17.25 h·ft^2·°F/Btu. Both ceilings were about R-30 h·ft^2·°F/Btu.

Figure 9 shows that the 4.5 in. SIP used 10% less energy, at 0°F ambient in the surrounding climate chamber and 74°F inside air temperature, to heat than the 2 × 6 wood frame test room. During this test in the Large Scale Climate Simulator, there was no intentional control of pressure other than the stack effect caused by the warm air inside the test rooms. The thinner SIP wall thickness results in the consumption of 20% less floor area than the 2 × 6 frame wall takes up.

A second set of tests were conducted on both test rooms to determined airtightness of the rooms. The data for the SIP test room are shown in Figure 10 as the line with the triangles pointing upward. This is the lowest line shown in Figure 10. The frame test room is displayed as the line in Figure 10 with the triangles pointing downward. These data are consistent with the tightest and the leakiest of six nearly identical frame houses all built by the same contractor as the base house, described in Table 1. The airtightness lines of the leakiest and the tightest frame house are shown in Figure 10 with "+" and "×" symbols. This provides confirmation that the frame test room was successful in representing airtightness field conditions found in the base case frame house. At 50 Pa 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 × 6 test room had an air leakage value of 1.06 ft^3/ft^2 of floor area. The 2 × 6 frame test room was 14 times leakier than the SIP structure. This impressive airtightness measurement encouraged the selection of an SIP envelope for ZEH1.

Since the SIP test room did not have all of the typical penetrations found in real house envelopes that so frequently compromise airtightness, the first test of ZEH1 was a blower door analysis. Tests were run prior to installation of the drywall, after the house was ready to be moved into and six months after occupancy. The testing prior to installing the drywall was an ideal opportunity to seal any significant unwanted leaks. The most significant was found in the front part of the house where the roof ridge beam met the front gable. The other leakage points were around the electrical outlets. Both sets of leaks were sealed and the blower door tests re-run. 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/ft^2 at 50 Pa. This can be compared to the wood-frame base house of 0.87. The base wood-frame house was six times leakier than ZEH1.

Mechanical, Electrical, and Plumbing

Domestic Water Heating. ZEH1 is equipped with a domestic heat pump water heater. The "drop-in" air-source heat pump water heater has the compressor and evaporator coil on top of the 50 gallon tank. The condenser coil is wrapped around the outside of the metal tank. Typically these units are installed in the conditioned space, in an unconditioned basement or unconditioned garage. In general, the warmer the air source surrounding the heat pump water heater the better the unit's thermal performance. A garage in southern Florida works well because the garage air is usually warm year-round. Another good location is in an unconditioned basement that needs dehumidification. Occasionally the units are installed in utility closets in conditioned space. This can cause the closet air to become cold, which is not always a bad thing, for example, a wine cellar or, in the case of the Habitat for Humanities field office, a convenient place to store semi-cold drinks for hard-working volunteers. However, when the conditioned air is used to heat the hot water during the winter, this heat may need to be made up by the space conditioning system.

To take advantage of the added cooling and dehumidification available from the HPWH and avoid taking valued heat from conditioned space, the heat pump water heater in this house is connected to the air space behind the refrigerator, which is laid out intentionally in the floor plan to be located next to the utility closet housing the heat pump water heater. When the homeowner has the house thermostat set for 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. This airstream is cooled, dehu-

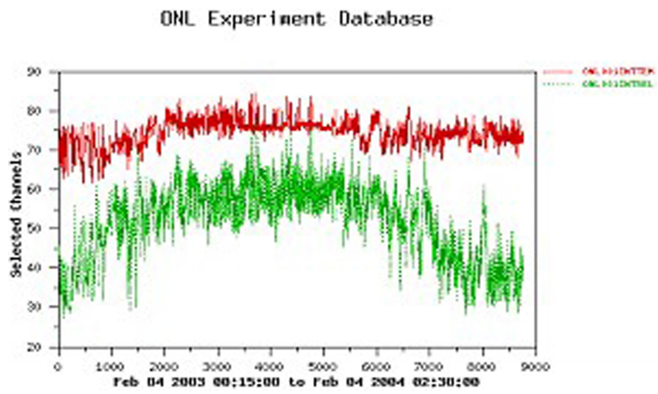

Figure 11 *Interior temperature and RH for complete year.*

midified, and directed back into the kitchen to help condition the house. When the thermostat is in either the OFF or heating mode, the ducts connecting the heat pump water heater to the kitchen are closed and other ducts are opened up to pull in earth-tempered crawlspace air and reject unwanted cool air to the outside. Since the crawlspace vents are sealed as well as the crawlspace floor, the crawlspace will go under a slight negative pressure when the HPWH fans are sucking from the crawlspace. The crawlspace access is not weather stripped, and this crack allows some makeup air into the crawl.

Figure 5 shows average daily temperatures measured in the crawlspace for a full year. The space remains above 50°F throughout the entire winter. During the winter the heat pump water heater does not remove desirable heat from the inside space. The airstream from the crawlspace, after passing through the heat pump water heater evaporator coil, is even cooler and directed outside by the water heater fans. The heat pump water heater fans were measured to blow 200 cfm through an unconstrained evaporator coil. When ducts are connected, the additional static pressure reduces this airflow.

The continuous water heating usage measurements found that the occupants used 72% of the DHW for showers and baths. The average daily usage was 40 gal/day, which is 43% less than found in the national HPWH field study by Tomlinson and Murphy at ORNL in 2003. The measured daily energy consumption is 3.8 kWh, which is 28% less than found in the national HPWH field study. The average heat pump water heater COP was 1.62. The monthly values ranged from a low of about 1.5 in the coldest winter months to almost 2 in the warmest summer months (1.52 to 1.88 from August 2003 to February 1, 2004). The national heat pump water heater study found an average COP of 2.0 (Tomlinson and Murphy ORNL 2003). This is with units installed in various locations with varying amounts of daily hot water usage. It is recognized that with lower hot water usage, as is found in this house, the standby loses are a higher percentage of energy usage and this results in lower COPs. Because the heat pump water heater and refrigerator were located on inside walls of the kitchen, rather long duct runs were required to vent to the outside and into the middle of the kitchen ceiling. These flex ducts were found to generate excessive static pressure, restricting air movement away from the heat pump water heater closet. It is believed that the optimized coupling with refrigerator, crawlspace, space cooling, and dehumidification was not attained in this house. If a heat pump water heater could reach a COP of 2.0, this house could have saved another 337 kWh/year ($0.06/day). ZEH2 has a second generation hookup, which consists of the refrigerator and the heat pump water heater located adjacent to the outside wall and has all hard ducts and short runs to and from the unit to minimize static pressure and restricted airflow. The COPs in this unit from December 2003 until October 2004 averaged almost 2.

Conditioned Space Thermal Comfort. The conditioned space average hourly temperature and relative humidity for one complete year are shown in Figure 11. The temperature on average is kept around 75°F. The occasional spikes in RH are due to window openings and 24/7 mechanical ventilation. The homeowners generally were not home during the summer daytime 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. The HVAC systems in ZEH2 and ZEH3 addressed this by changing the thermostat control logic. In one case a two-speed compressor was installed, and in the other a lower evaporator temperature was used for the direct exchange geothermal system.

Total Electric Energy Usage and Cost. The ZEH1 all-electric house, from March 1, 2003, until February 29, 2004, used 10,216 kWh, as shown by Table 3. The heat pump and ventilation fan power required 2759 kWh, or 27%, of the total energy. The heat pump water heater 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 of this house, the HERS was calculated to be 90.2, which converts to 50% better than the IECC. The electric rates in this area during the monitoring period were $0.63/kWh. The house is the first house to sell green power back to the largest public electric utility in the country. The contractual arrangement is that the utility will pay the homeowner $0.15/kWh for all of the solar power produced by the 2 kWp PV system for ten years whether they use it or not. During this monitoring period, the solar system generated 2006 kWh. Officially, this started on May 14, 2003. This house would have been given an annual credit of $300 if it was grid connected at the beginning of the monitoring period. The net energy cost to the homeowner results in an expense of $343 a year, a monthly average of $28.58, or $0.94 a day. In the winter of 2002-03, the homeowners used a bit less energy than in the winter of 2003-04. If the reporting period were from when they moved in (November 15, 2002) until November 15, 2003, the daily cost would have been $0.82/day.

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

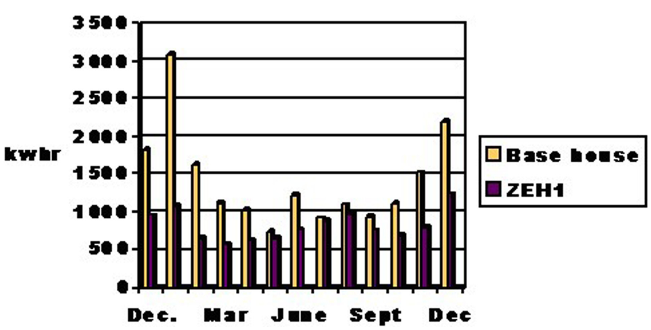

Figure 12 *Monthly energy bills from base house show a 40% higher annual energy cost than ZEH1, from November 2003-December 2004.*

The ZEH1 house has a gross floor area of 24 ft × 44 ft or 1056 ft^2. During this same period, a nearby 20-year-old two-story house with 3032 ft^2, gas heat, and SEER 13 AC experienced energy costs of $2853/yr or $7.82/day. The HVAC in this house was just replaced in 2002. On a cost per square foot of floor area per year, this is $0.94 compared to ZEH1 at $0.32. The ZEH1 requires 66% less energy expense. Over a 30-year period, this house would save the homeowner more than $20,000 compared to the option of moving into an older house with new HVAC equipment with the same 1075 ft^2 floor area. This saving grows to more than $75,000 compared to moving into that larger, less efficient house.

Figure 12 shows ZEH1 used 40% less total energy than the base house described in Tables 1 and 2. The local electric utility inspected and certified this house as a HERS 84 frame home (already 20% better than IECC) built by the same contractor and in the same neighborhood.

Closer Look at Energy Use. Table 3 shows the monthly measured electric energy usage for ZEH1. The first four 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, and the other electric uses in this all-electric house cost $372. The total cost is calculated by subtracting the solar credit, which is based on the electric utility’s rate of $0.15/kWh, or $301, from the total used, which came to $644/yr.

Table 3 also shows the 2 kW peak rated solar PV system monthly generation in the column labeled “Solar AC generated.” During this period the total annual generation came to 20% of the total energy used. The last column shows the solar power that was generated on site but at the time it was available was not used in the house and therefore sent to the electric grid. The estimated value of the ZEH1 solar system when installed in fall 2002 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 in summer 2003. Solar systems’ first cost will have to continue to drop. For ZEH1 to have met the net zero energy goal of producing on site what is consumed, the solar system capacity would have to have been 10 kWp. The cost of the energy-saving features in this house

Table 4. Construction Cost of Three Near 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

Figure 13 *ZEH3 has a smaller size solar collector field and much thicker SIP roof than ZEH1 shown in Figure 2.*

will also have to come down, as suggested by the numbers shown in Table 4, for the first three attempts at net zero and the base house.

It is also interesting to note that 40% of the solar power was not used by the house because at the time the solar was being produced, it exceeded the current house energy demand. This solar power for the most part is available during hot summer afternoon hours when utility electric grids welcome not only the reduction in load but the power to help meet the grid peak 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 test houses were all constructed by the Habitat for Humanity Loudon County Affiliate. Most of the construction labor is volunteer. Frequently a church or a civic group will commit to doing a house. This generally entails providing labor and in most cases a financial commitment. This particular affiliate has a paid staff consisting of an executive director, who is also a CPA and keeps the financial records; a logistics expert, who schedules all material deliveries and volunteers; and a construction supervisor. Critical subcontractors are hired for plumbing, HVAC, foundation installation and site work, concrete pavement, and drywall installation. Volunteer hours are kept track of by a sign-in and sign-out book. The value assigned to each volunteer hour is $5.50. This is about half of the average prevailing rates, but because of skill level and the social element of this activity, it is the Habitat's perception the assigned hourly rate is in the "ball park" of market value. Table 4 shows a spreadsheet for construction cost of ZEH1, ZEH2, ZEH3, and the average base house used in this paper to compare energy costs. Because the ZEHs are test buildings, some of the materials were donated or were funded by sources other than Habitat. The estimated value of all the features are reflected in the totals shown in Table 4. Because of the research aspect of these test houses, the costs are much higher than production units. The general agreement with the Habitat Affiliate is that the test houses will cost them no more than their current "conventional construction" costs, which they are held to by various grants and overarching requirements set forth by Habitat International.

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. The 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, ZEH3 demanded 19% less total house energy, and produced 12% more solar power than ZEH1. The orientation of this house is a bit better, and it has a 6/12 pitched roof compared to the 4 /12 of ZEH1, which increases winter time solar collection. The biggest energy saving is believed to come from the geothermal heat exchanger, drawing heat from the surrounding earth, which stayed above 50°F, compared to the much colder ambient air, particularly at night when the air-source heat pump must extract heat. A few of the additional features of this second generation of near zero-energy house are: 6 in. SIP wall, 10 in. roof, forest green cool pigmented roof (reflectivity of 0.23 instead of 0.17), 2 ton direct exchange geothermal heat pump with SEER of 16, desuperheater for DHW, more airtight than the ZEH1 with an ACH_4= 0.03 compared to 0.04. The local electric utility auditors rated this house with a HERS = 93.9. This represents a house almost 70% more efficient than IECC. In general, just meeting code would lead to a HERS rating of 80. Each point above 80 represents 5% energy savings beyond just meeting code. So a 94 rating is 14 points above 80, or 14 × 5% = 70%. It also meets the long-term energy savings goal of the DOE Building America Program. The cost goal was not met in this first prototype.

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 $116K. This included the estimated $14.5K for the infrastructure and lot. The actual cost to the Habitat Affiliate, not counting donated ZEH materials, was about the same as the base house they are currently building in the same development. The total energy costs are coming in under $1 a day. The annual heating cost of ZEH1, using the local electricity rate of $0.063/kWh, was under $100 a year, cooling under $75, and domestic hot water under $100.

The solar PV system generated about 2000 kWh over the first full year, which amounted to 20% of the total energy load and 74% of the HVAC load. The lowest average total energy cost, less the solar credits, came to $0.82/day. This was the first local electric 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%. ZEH2 and ZEH3 had been occupied for only two months at the time this paper was written. The use of a geothermal heat pump in the wintertime was making a substantial step closer to net zero. However, it did add to first cost as shown by Table 4. Additional cost reductions in the envelope and geothermal heat pump are ongoing at the time of this writing. However, it is apparent that the plug loads will have to be addressed to realistically meet the DOE's long-term goal. With plug loads at 60% of the total energy demand in ZEH1, this is an important issue. The homeowners have all expressed an interest in how much energy they are using. Real-time feedback and reliable automated shutoff controls are an obvious critical technology on the path to attaining zero energy at zero net cash flow over the life of the building.

REFERENCE

Murphy, R.W., and J.J. Tomlinson. 2002. Field tests of a "drop-in" residential heat pump water heater. Oak Ridge National Laboratory, ORNL/TM-2002-207, September.