Panels^3

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ABSTRACT

Engineering a small house that uses as much source energy as it produces on site during a year is intriguing to homeowners across the globe. The project objective is to create an affordable solar powered home that produces, on site, as much energy as it uses in a year. During the course of this project, five homes have been built and monitored to maximize affordable energy efficiency. These houses are located near Oak Ridge, Tennessee with 3500 HDD. This paper focuses on the fourth occupied house. It was built with well integrated envelope and equipment energy saving features. The envelope consist of eight inch thick insulated precast concrete foundation basement walls, 4.5 inch thick polyisocyanurate foam Structural Insulated Panel (SIP) walls upstairs; 8 inch polyisocyanurate SIP cathedral ceiling; and low U-factor and solar heat gain coefficient windows. The equipment consists of a heat pump water heater and a 17 SEER variable speed air-to air heat pump. The onsite renewable energy is generated by a 2.2 kWp roof mounted photovoltaic system. The precast insulated foundation panels were installed in 6 hours, the wall panels in 5 hours, roof panels set in 3 hours and the PV panels mounted on the roof in 2 hours. Thermal performance has been monitored with fifty sensors continuously for three years, gathering data every 15 minutes. Thermal couples monitor ambient, interior, air distribution, and hot water temperatures. Meters measure the flow of electricity to the air handler unit, water heater, compressor, inverter, refrigerator and incoming and outgoing electricity to the whole house. Water flow is also measured to collect hot water usage. Data provides detailed energy efficiency of various components of the house; the building envelope, water heater, space heat pump and whole house performance. The house performance is modeled and calibrated using the measured data. This model is used to extrapolate the performance in a Hot Humid Climate. The report concludes with some cost information. The house is served by an electric utility that offers solar credits which enable the average daily cost of all energy needs from off site for the first year of75 cents per day, and 41 cents per day for the second year. The benchmark house in this area is four dollars per day. The report concludes with how to get to zero energy cost a key steppingstone toward the ultimate goal of creating affordable zero energy.

INTRODUCTION

A net-zero-energy building is one that produces onsite as much source energy as it consumes on an annual basis. Tables 1 and 2 list building envelope and mechanical features used in the five near-zero-energy houses (Christian 2006c).

The power consumed by the household in 2007 costs the homeowner a flat rate of \$0.07/kWh and the roof top solar system generated a \$0.15 per kWh credit. Supply mechanical ventilation is provided in compliance with American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62.2 (ASHRAE 2004). The HPWH is more than twice as efficient as conventional electric water heaters (Christian 2006). An extensive moisture management package is provided to enhance the house durability and minimize the risk of moisture problems.

DESCRIPTION

Layout

ZEH4, shown in Figure 1, a two-story house, contains 1200 ft^2. It has a walk-out basement, opening on the south

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Table 1. Envelope Technology Packages in Test Houses

House	ZEH 1	ZEH2	ZEH3	ZEH4	ZEH5
Stories	1	1	1	2	2
floor ft^2	1056	1060	1082	1200	2600
Foundation	Unvented 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)	Walk out basement with exterior insulated block walls (nominal steady state R-value of (R-11)
1^{st} Floor	6.5 in. SIPS 1#EPS (R-20) Structural splines	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 with R-7.5 XPS 4 ft wide strip along the south wall	Concrete Slab, insulated underneath with R-10 XPS and exterior apron of R-10 XPS on south side
Walls	4.5 in. SIPS 1#EPS (R-15) surface splines, house wrap, vinyl	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	2^{nd} floor 4.5 in. SIPS polyiso., pentane blown (R-27), surface splines	6.5 in SIPS 1#EPS (R-21), structural splines-wood I-beams, house wrap, vinyl
Windows	9 windows 0.34 U-factor, 0.33 SHGC, VT=.55, sill seal pans	8 windows 0.34 U-factor, 0.33 SHGC, VT=.55, sill seal pans	8 windows 0.34 U-factor, 0.33 SHGC, VT=.55, sill seal pans	10 windows, 0.34 U-factor, 0.33 SHGC, VT=.55, sill seal pans	13 windows, 0.34 U-factor, 0.33 SHGC, VT=.55, 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	3-doors, one solid, one ½ view insulated, one full view (U=0.33, SHGC=0.27, VT=0.41)	3-doors, one solid, one ½ view insulated, one full view (U=0.33, SHGC=0.27, VT=0.41)
Roof	8 in. SIPS 1# EPS (R-28) surface splines	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, surface splines (R-48)	8 in SIPS 1#EPS plus 2 in XPS (R-35), surface splines
Roofing	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	15 in. Brown standing 24GA steel seam, 0.31 reflectivity

Table 2. Equipment Technology Packages in Test Houses

House	ZEH 1	ZEH 2	ZEH 3	ZEH 4	ZEH5
Solar system	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	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	2-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 17, variable-speed compressor, ECM indoor and outdoor fan	2 ton water-loop geothermal, R-410A, variable speed ECM indoor fan
Mechanical Ventilation	Supply to return side of coil	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	Supply to return side of coil, bath fan exhaust
Duct location	Inside conditioned space	Inside conditioned space	Inside conditioned space	Inside conditioned space	Inside conditioned space
Water Heater	Integrated HPWH linked to unvented crawl	Integrated HPWH, linked to crawl which has motorized damper	Desuperheat for hot water, EF .94	HPWH vented to ½ bath which is exhausted for ventilation	Solar Water Heater, 48 ft^2 collector area, PV pump, grey water waste heat recovery

Notes for tables 1 and 2: ECM = electronically commuted motor; EF = energy factor; EPS = expanded polystyrene; HP = heat pump; HPWH = heat pump water heater; HSPF = heating seasonal performance factor; OSB = oriented strand board; SEER = seasonal energy efficiency rating; SHGC = solar heat gain coefficient; SIP = structural insulated panel; XPS = extruded polystyrene

Figure 1 *ZEH4.*

side, which contains three bedrooms and a full bath. The construction drawings, specifications and assembly recommendations to build this house are found in Christian 2006d.

Basement/Foundation

The basement walls are four pre-cast concrete sandwich panels consisting of a single layer of polyisocyanurate insulation encapsulated by an interior and exterior layer of concrete. These walls are precast with electrical chases, receptacle boxes and fenestration rough openings. On below-grade surfaces, 60-mil waterproofing was sprayed and covered by 2-layers of ¾-in. fiberglass drainage boards. All but one small test area above grade is coated with a spectrally selective paint that helps keep the house cooler in the summer. The exterior insulated massive walls provide exterior insulated envelope thermal mass. They also aid thermal comfort and moisture management by providing a hygro-buffer.

The house has 30 ft south and north facing and 20 ft east and west facing walls. A four foot wide strip of 2 lapped ¾ in. thick layers of extruded polystyrene boards along the walk-out south side of the foundation minimize heat loss through the slab edge. The concrete sandwich panels were crane lifted into place, forming the first floor walls. These walls have a R-value of 16 h ft^2 ^oF/Btu, and were set on a sealing layer of bentonite and 9000 psi construction grout on ether side of the bentonite to prevent ground water from leaking inward and create a capillary break from moisture rising into the walls. The walls were welded to the foundation at the corners using embedded welding plates and at the center of the 30 foot sections. They were also welded to each other on the top of each corner. Each corner was set leaving a 3/8 inch gap at the seam; this gap was filled with backer rod and a polyurethane caulk on the outside and one part expandable foam on the inside. Total installation time of these insulated precast concrete walls was six hours.

Most of the above grade precast foundation wall was treated with a highly reflective paint. Figure 2 shows that the inside surface hourly temperatures behind the wall with cool exterior paint through out the cooling season remains about 3 ^oF cooler then the wall area without the reflective coating. Figure 2 shows hourly temperatures of the south basement wall interior surface temperatures with the exterior applied cool coating (the bottom line) compared the interior surface temperature at the same height on the south wall but without the cool coating.

Figure 3 shows for a very hot week in July 06 that the peak outside surface temperature that is covered with the cool coating is about 10°F lower than the test area with ordinary grey paint. On the inside surface behind the cool coated mass the wall always remains below the inside air temperature which means the wall is always providing sensible cooling whereas the portion of the wall that is not coated floats above the inside air temperature, which means it is a source of unwanted heat gain during this very hot week. The coating actually allows the wall mass to provide a heat sink through out the hot summer months.

Some of the additional benefits of these massive walls are no drywall is needed to attain Class 1 fire resistant surface. To finish the inside required only two coats of standard indoor latex paint. Also the window and door rough openings were precast with drip edges and beveled shelves for aiding moisture drainage away from the house. The windows were all inset inside the exterior surface drainage plane enhancing the durability of the windows and seal between the window and the wall. The exterior wall is finished to look like adobe and could have been stained a multitude of different colors and finished to look like brick or even natural stone.

Top Floor Walls

The SIPs used in the top floor are polyisocyanurate foam sandwiched between layers of OSB. A layer of flashing should be placed on top of the concrete wall prior to installing the metal floor hangers, setting the floor trusses and laying the ¾ inch glued and screwed plywood flooring that ran out flush with the exterior foundation walls. On top of the plywood floor decking under the exterior walls is a continuous bead of construction adhesive and a 2x4 base plate that runs around the entire perimeter. The 2x4 is set in from the edge of the plywood ½ inch so that the outer skin of the wall SIPS can rest on the structurally supported foundation. The 4.5 inch SIPS sit on top of the 2x4 base plates. The air seal between this base plate and the SIPS is not made during initial panel assembly. Rather the walls and the SIP roof are all installed to be straight and square without any sealing until the house is closed in. Then ½ inch holes are drilled from the inside of all wall SIPS every 8 inches and foamed using polyurethane foam. The SIP wall panels were put up in five hours with an inexperienced volunteer crew and two SIP technicians. One precaution that was taken during the air sealing procedure is not filling the electrical chases set in the SIPS at 14 and 44 inches from the floor. After the electrical wires and boxes are installed, those chases are foamed. The top floor SIP walls of the house were wrapped in a nonwoven house wrap.

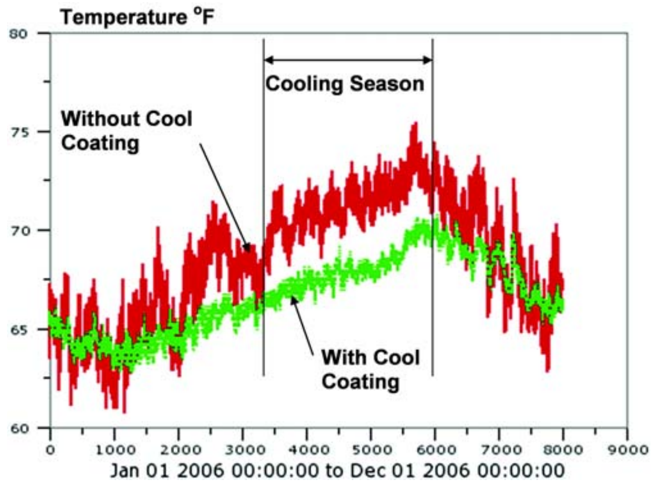

Figure 2 *Temperatures of the south basement wall interior surface with and without the exterior applied cool coating.*

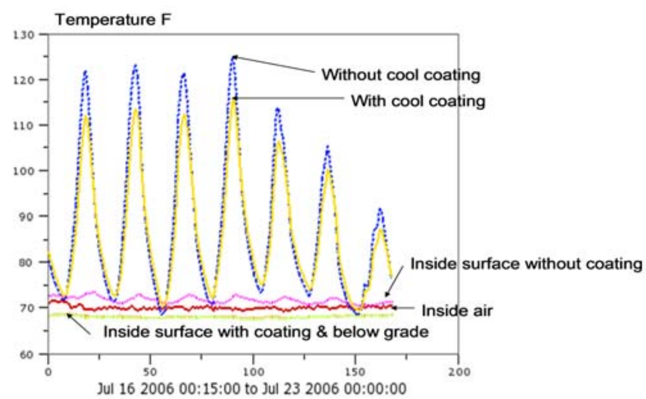

Figure 3 *Interior and exterior surface temperatures of the precast insulated foundation wall showing the cool coating keeps the mass of the above grade wall below the inside air temperature.*

The high efficiency windows and doors were installed using a single manufacturer's family of weatherization products to enhance material compatibility for maintaining the long term adhesion and general durability of this important sealing detail. The top floor house wrap was lapped about 3 inches over the top of the massive foundation wall. Vinyl siding is the cladding system used on this prototype house, however equal or better performance is expected from properly installed wood or cementations siding or brick. The SIP polyisocyanurate, pentane blown insulation was measured by ASTM C-518 test procedure at R-27 h·ft^2·°F/Btu in May 2004, R-26 h·ft^2·°F/Btu in December 2004 and in January 2007 R-24 h·ft^2·°F/Btu. This appears to be typical thermal aging of polyisocyanurate foam blown with Pentane. It was expected that this envelope package would out perform the previous ZEHs because of the integration of more interior thermal mass offered by the foundation walls and continuously circulating ECM interior fan bring in the required 40 CFM of ventilation air. The whole house was blower door tested. The ACH@50 Pascal rated at 1.64.

Roof

The roof is held up by a single ridge beam that runs the length of the house and the SIP eave walls. After the ridge beam was set in place the eight inch thick R-48 h·ft^2·°F/Btu, 4 ft wide ceiling panels (see Table 1) were lifted by crane onto the house and screwed into place. A layer of peel and stick tape is placed between the ridge beam and the SIPS to provide a second defense against air leakage. At the ridge and all other panel joints two part polyurethane foam is injected into the seams to air tighten the entire SIP envelope. The roof has extended two foot eave overhangs to allow shading of the upper windows during the summer on the south side and minimize impingement of wind driven rain on the walls. One layer of #15 felt covers the top surface of the roof SIPS. A single layer was used because it has relatively-high moisture permeability. If the SIPS should get wet, the felt will allow the roof to dry out. On the south side 16 standoffs were fastened to the OSB prior to installation of the metal panel roof (Christian 2006d). Roofing on this house is a light grey aluminum simulated tile, installed in long narrow sheets running the full length from ridge to eave. After the roofing was set solar module support hardware and solar modules were installed. On this house a 2.2 kWp PV system harvests energy from the sun using twenty-110 W Modules. There is room on the roof and in the inverter to add another column of 5 modules, increasing the capacity to 2.75 kWp.

Equipment

The heating/cooling system is a 17-SEER, 2-ton air-source heat pump with a two-speed compressor and ECM indoor fan motor. The water heater is a HPWH that draws warm air from around the refrigerator condenser and exhausts cool, dry air into the adjacent half-bath. The ventilation scheme for the house prevents the cool, dry HPWH exhaust from being a comfort issue during the heating season yet helps dehumidify in the summer. Every 20 minutes the fresh air inlet opens and the upstairs half-bath exhausts about 50 CFM for ten minutes. Figure 4 shows the seasonal variation of the incoming water temperature from 52°F in the winter to 75°F in the summer. The top line also shows that the HPWH temperature was set at about 142°F. This is too high, 120°F would have saved about 9 cents a day in energy cost. Figure 5 shows that the daily average hot water demand averaged about 50 gal/day in 2005 and about 40 gal/day in 2006. The house was build with 75% of the light fixtures equipped with fluorescent lights.

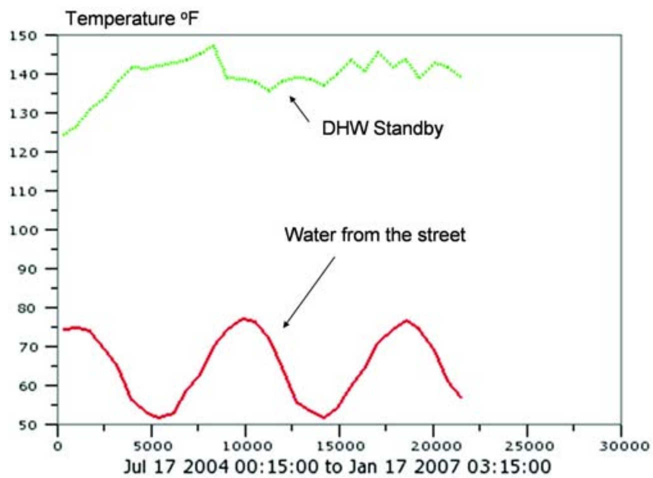

Figure 4 *Shows the seasonal variation of the incoming water temperature (bottom curve), HPWH standby temperature.*

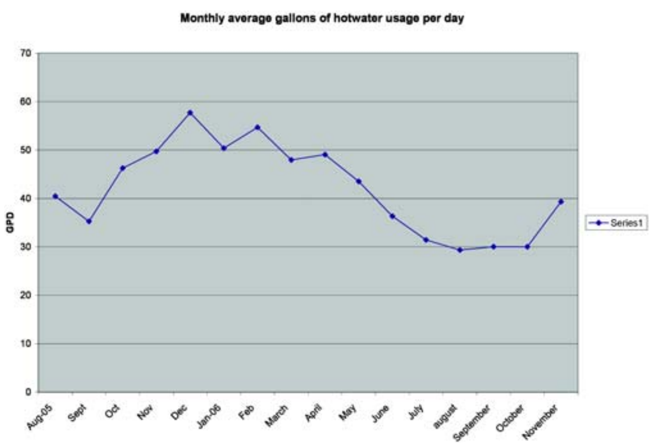

Figure 5 *Daily average hot water demand by month.*

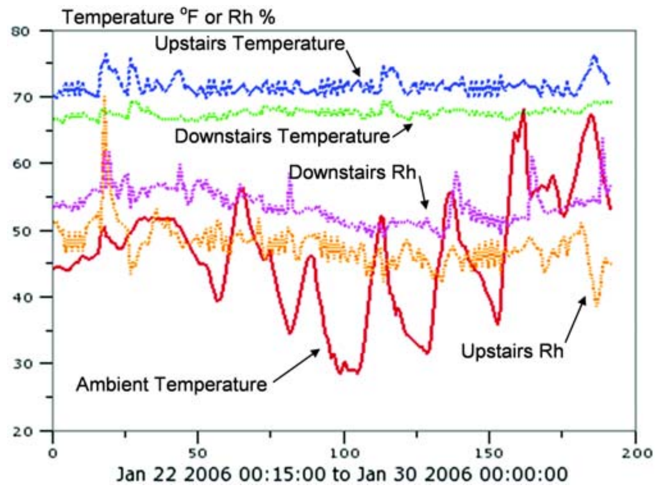

Figure 6 *Interior air temperature and relative humidity during the week of January 22, 2006 with ambient low temperatures below freezing.*

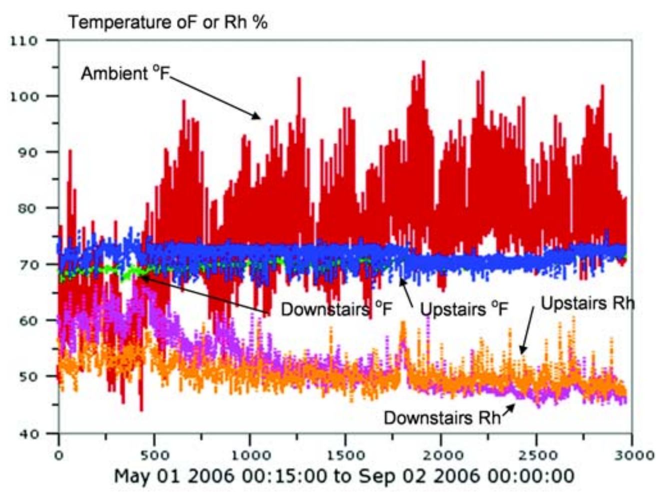

Figure 7 *Temperature and RH over 2006 summer.*

MEASURED INTERIOR TEMPERATURE AND RELATIVE HUMIDITY

Figure 6 shows the interior temperature and relative humidity during the week of January 22, 2006 with ambient low temperatures below freezing. The top line shows the upstairs air temperature is very steady around 71°F and down stairs are about 3°F cooler. The interior relative humidity is between 45-55%. The homeowner was encouraged to set the thermostat so the whole family would be comfortable.

Figure 7 is a similar plot for the summer of 2006. The air temperature averaged around 72 F which was 2 F below the thermostat setting mounted upstairs. The thermostat also had a desired relative humidity setting that was fixed at 55% which enabled the set point to be lowered 2 F. Throughout most of the summer the HVAC system operated at the lower set point. The average measured relative humidity was around 50% which is acceptable in light of the continuous mechanical ventilation in this house in a climate with hot and humid summers.

During the summer of 2005 the average relative humidity ran much higher, averaging 65% as shown in Figure 8. The lower RH after the second full summer is due to most of the concrete curing having taken place during the previous year. The entire bottom floor is surrounded on all sides, except the ceiling, with at least 4 inches of concrete inside the insulating layer, which equals approximately 19 cubic yards. The total moisture release to cure this much concrete is about 2772 pints. The curing process is just about complete after the first two years. If we assume all of the moisture uniformly comes out in the first year, this amounts to 7.6 pints per day. Respiration of 3 occupants is about 4 pints/day and typical cooking and cleaning adds another 4 pints/day. Thus it is possible that during the summer of 2005 the internal moisture load was double that experienced during the summer of 2006 during

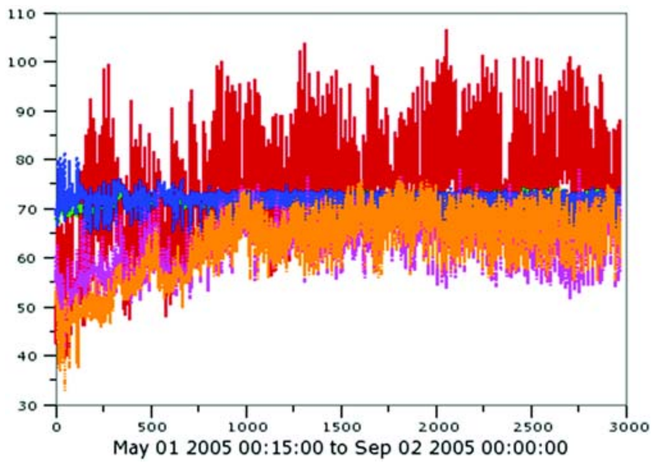

Figure 8 *Temperature and RH over summer of 2005.*

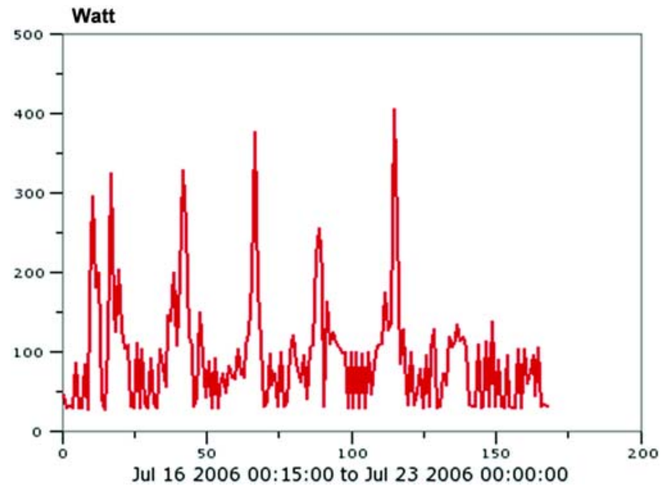

Figure 9 *Hourly internal circulating fan electric powers for hot week in 2006.*

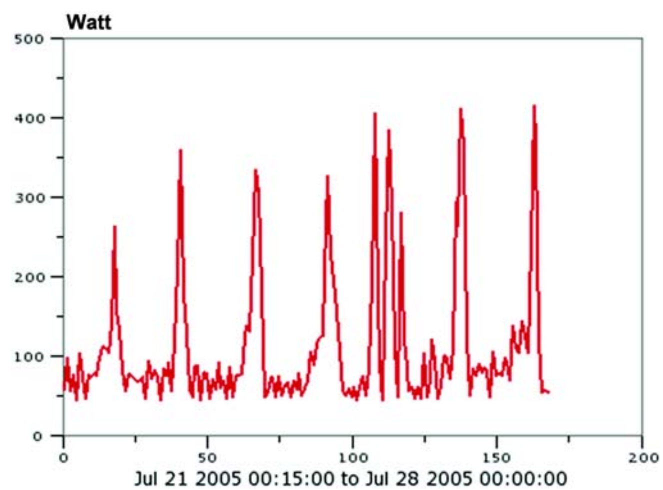

Figure 10 *Hourly internal circulating fan electric power for hot week in 2005.*

which the concrete would have been fully cured out. In the summer of 2005, a ventilation rate of 40 CFM in the Lenoir City climate converts to about 4.1 pints per day. The house had a blower door based natural air infiltration rate of 0.08 ACH, which converts to another 1.5 pints per day of moisture coming into the house. Adding the calculated moisture loads from all of these sources yields a summer 2005 internal moisture load of 21.2 pints per day, and a calculated moisture load of 13.6 pints/day in the summer of 2006, a 36% reduction in internal moisture production.

Figure 9 and 10 show that the air cycler is running continuously for two hot July weeks. This was just to confirm that the ventilation air source was not accidentally turned off during the 2006 season. Notice that the low point on this data shows that the low speed fan running for only 20 minutes pulls only about 45 watts on average for a full hour.

MONTHLY MEASURED ENERGY CONSUMPTION

ZEH4 occupants consumed a total of 9843 kWh from August 1, 2004, through July 31, 2005, and the solar system generated 2627 kWh. About 46% of the solar was collected at a time when it was not needed in the house. Table 3 shows the energy usage per monitored component. The net daily cost for off-site energy to power ZEH4 during the first year of occupancy was $0.75. The HVAC cost for ZEH4 with the SEER 17 air-source HP averaged $0.51/day. The solar energy collected on site amounts to 27% of the total electric demand.

The second year of measurement from December 1, 2005 until November 30, 2006, shown in Table 4, experienced much improved performance. The net average daily cost for this one year period was $0.41/day. This improvement was due to a number of factors; 1. 1000 kWh (-$0.19/day) drop in the "other" electric loads, attributable to a daughter moving out to attend college and the head of household being more conscious of energy after living in a near zero energy house for one year, 2. drop in hot water usage from 50 gal/day to 40 gal/day reduced the annual hot water energy by 167 kWh (-$0.03/day), 3. increase in solar PV generation from 2627 in 2005 to 2763 a 136 kWh difference (-$0.06/day), 4. a 367 kWh (-$0.07/day) reduction in space heating. The homeowner never turned off the heat pump nor opened any windows the first year. After the first year she learned how to better manage her heating, cooling and ventilation system with no impact on her family's thermal comfort, as supported by Figure 6. Both periods had similar HDD and CDD with warmer than normal winters and hotter than normal summers.

COMPUTER MODEL VALIDATION TO MEASURED DATA

Table 5 shows the annual energy usage per monitored component of the ZEH4 first year measured results compared to the prototype modeling predictions and a calibration model. The actual weather is not normalized in these comparisons. Over all, the model is reasonably close to the measured data.

Table 3. ZEH4 Measured Energy Use, August 2004—July 2005

Month	Space heat (kWh)	Space cool (kWh)	Hot water (kWh)	Other (kWh)	Total electric (kWh)	Solar generated (kWh)	Solar sold to utility (kWh)
August 2004	0	204	168	503	875	279	126
Sept	0	145	114	580	839	236	77
Oct	73	0	115	474	663	176	87
Nov	152	0	138	449	739	144	70
Dec	429	0	186	425	1041	146	62
Jan	438	0	190	441	1068	137	62
Feb	322	0	162	359	843	146	67
March	297	0	196	439	932	247	126
April	0	99	169	422	690	255	134
May	0	102	144	376	622	324	201
June	0	199	116	402	717	286	120
July 2005	0	267	120	427	814	251	87
Total	1711	1016	1819	5297	9843	2627	1219
% of total	17%	10%	18%	54%	100%		
Annual cost	$116[1]	$69[2]	$124	$360	$669	–$394	
Daily cost	$0.32[1]	$0.19[2]	$0.34	$0.99	$1.83	-$1.08	

[1] Heating days only
[2] Cooling days only

Table 4. ZEH4 Measured Energy Use, August 2005—November 2006

	Space Heat (kWh)	Space Cool (kWh)	Hot Water (kWh)	Other (kWh)	Total Electric (kWh)	Solar Generated (kWh)	Solar Sent to Grid Not Need at Time of Generation (kWh)
Dec	347		195	439	981	134	55
Jan-06	198		172	415	786	154	82
Feb	260		178	348	786	176	85
March	159		168	396	724	253	139
April	92		159	356	608	283	148
May		108	144	376	628	280	166
June		192	117	326	635	294	173
July		271	101	344	716	300	143
August		284	95	330	709	270	129
September		141	89	296	525	229	133
October	118		104	342	564	221	136
November	170		131	325	626	169	92
Sum	1344	996	1652	4293	8286	2763	1481
% of Total	16%	12%	20%	52%		33%	54%
Annual Cost	$91	$68	$112	$292	$563	$414	
Daily Cost	$0.25	$0.19	$0.31	$0.80	$1.54	$1.14	
				net cost per day	$0.41		

Table 5. Modeling Results for ZEH4 Are Compared to the Measured Data in 2005 and 2006

	Measured in 2005	Measured in 2006	Calibrated Model of Prototype to 2005 Measured Data	Difference of Calibration Model to 2005 from Measurement
	kWh/yr	kWh/yr	kWh/yr	%
Space Heating	1711	1344	1254	-27
Space Cooling	1016	996	1176	16
DHW	1819	1652	2283	25
Other	5297	4293	5073	-4
Subtotal	9843	8286	9786	-1
Solar generation	2627	2763	2627	0
Total	7216	5523	7159	-1

ENERGY SAVINGS COMPARED TO THE BENCHMARK

Lenoir City, Tennessee

Table 6 shows the modeling results following the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). ZEH4 has a net energy use of 5486 Wh/yr. ZEH4 has a solar fraction, 32% and has a source energy savings of 44% without the PV generation and 62% including the PV compared to the benchmark.

Figure 11 shows the ZEH4 source energy comparison of the benchmark compared to the ZEH4 prototype. The largest savings is due to space heating, followed by space cooling, domestic hot water, lighting, and the energy star refrigerator. No end use energy savings is assumed for the dryer, range, other appliances and plug loads.

Table 7 shows the percentage of source energy savings of the prototype compared to both the Building America Benchmark base and the Builder base house. The ZEH4 saves 71% of the heating energy used in the Benchmark, 65% cooling, 47% domestic hot water, 73% lighting and 36% refrigerator. ZEH4 benefited from a significant amount of internal mass resulting from the massive foundation system and the exterior insulated walk out basement. Sensitivity runs with the model suggested the added mass saves 135 kWh/yr, which is about 2.5% of the total annual energy usage of ZEH4.

New Orleans, Louisiana

Table 8 shows the result of simulating the ZEH4 in a hot humid climate like New Orleans. This climate has less heating demand with 1437 HDD. The ZEH proto type is a 64% saver in this climate. The solar generated is 2802 kWh 7% more than that generated in Tennessee. Using the local electric residential rate of $0.0963 the daily cost for this house would be $1.28/day with straight net metering and if the same buy back arrangement could be worked out so that the utility bought back the solar at $0.15/kWh the daily cost would be $0.77/day.

COST

The cost-effectiveness of near-net-zero-energy houses will vary with energy costs, climate, energy-consumption habits, utility, state, and federal incentives, and the cost of the selected technologies. The Tennessee electricity rate in 2007 was $0.07 per kWh, below the national average of around $0.10 per kWh. Energy cost savings would be greater in regions with higher electricity and solar credit rates.

The economic justification for net-zero-energy houses is that energy savings plus revenue from renewable energy sold to the utility grid help offset the added price of construction. For the first four houses, utility bills averaged from $1 to $0.41 per day after credit for the sale of solar. The fourth house built had an average daily cost for electricity of 75 and 41 cents per day for 2005 and 2006 respectively. Table 9 shows the Building America Benchmark house using national average electricity cost of $0.10/kWh would be $1458/yr. The ZEH4 prototype using the same $0.10/kWh rate and a solar buy back at $0.15 results in a total cost for energy of $417. This is an annual savings of $1041. Figure 12 shows the energy consumption of ZEH1, 2, 3, and 4, compared to the base house.

Table 9 shows the construction costs for all five houses and for a base house of similar size in the same locale. The costs of volunteer labor and donated materials are factored in. The base house cost is in 2002 dollars. Assuming the cost increased 3% per year would bring the base cost up to $78,223. ZEH4 in 2004 dollars has an incremental cost of $33,601. Assuming a representative solar buy down of $4.00/watt reduces this cost $8,800 reducing the differential to $24,801. This leads to a simple payback of 24 years. A substantial improvement in cost effectiveness is being demonstrated in ZEH5 which will be reported in 2008. The first cost on a per square foot basis is much less and the entire 2600 ft^2 house is being heated and cooled by the same 2 ton capacity unit as used in the smaller ZEH4.

Table 10 shows the ZEH4 subpackages that can be used to meet intermittent percentage energy savings. By using the envelope improvements and the SEER 17 heat pump upgrade

Table 6. ZEH4 End-Use for the Benchmark and Prototype

ZEH4	Annual Site Energy BA Benchmark	Annual Site Energy BA Prototype
End Use	(kWh)	(kWh)
Space Heating	3666	1057
Space Cooling	2336	813
DHW	2663	1399
Lighting	1131	304
Fridge	668	428
Dryer	833	833
Range	605	605
Other Appliances + Plug	2674	2674
OA Ventilation		
Total Usage	14576	8113
Site Generation	0	2627
Net Energy Use	14576	5486

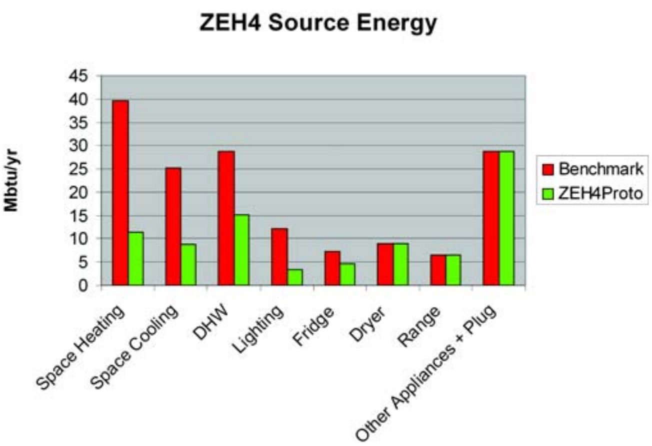

Figure 11 *ZEH4 source energy for the benchmark compared to the modeled prototype.*

a 30% energy savings is attainable in a mixed humid climate compared to the Building America benchmark house. This house does not have to employ its heat pump water heater nor PV Solar system to meet the 30% energy savings in Mixed Humid climates for 2006.

The complete technology package on ZEH4 results in an annual local energy cost savings of $798. The net daily cost for all the off-site energy to operate this house with the BA benchmark interior loads and schedules is only $0.48/day. If the local utility had a second tier rate in which it bought back solar power from these type houses of only $0.07/kWh more the net cost for all the off-site energy to run this house would be zero. In 2006 the critical peak power cost to the Tennessee Valley Authority, the electric utility that services this house, is about the same $0.22/kWh. Builders could distinguish themselves in the market by offering these houses that could be marketed at zero energy cost homes. The entire cost for the energy efficiency and solar technology as well as off site energy could be included in the mortgage.

The largest single energy efficiency saving technology is the heat pump water heater. The local energy cost savings per year is $88.

The ventilation strategy calls for at least 70 CFM for 33% of the time. The whole building computer simulation model was used to estimate the added energy needed to condition the ventilation air and run the fan. Table 11 shows the brake down of this additional energy. The added cost to condition the ventilation air is $37/yr in the ZEH4 prototype. A total of 81% of that cost occurs during the heating season. Only 13% is attributable to the added fan power.

SUMMARY

The ZEH4 prototype is compared to the Building America Research Benchmark House Definition, updated December 29, 2004 (NREL, 2004). This comparison shows that all electric house saved 44% energy compared to the Building America Benchmark. When the solar PV system generation is added to the near zero energy houses in the comparison to the Benchmark, which has no solar, the source energy savings goes up to 62%. The analysis shows that these prototypes could meet 30% energy savings criteria for a mixed humid climate without the heat pump water heater, and 2.2 kW peak solar PV systems.

Energy costs per day, based on measured data and November 2006 local residential electric rates of $0.07/kWh, for the ZEH4 was $0.75 for 2005 and $0.41 for 2006. These costs are based on an electric utility credit of $0.15/kWh for all

Table 7. ZEH4 Prototype Percentage of Source Energy Savings Compared to the BA Benchmark Base and the Builders Standard Base

ZEH4	BA Benchmark	BA Prototype	Percent of End-Use Savings
End Use	(Mbtu/yr)	(Mbtu/yr)	BA Base
Space Heating	40	11	71%
Space Cooling	25	9	65%
DHW	29	15	47%
Lighting	12	3	73%
Fridge	7	5	36%
Dryer	9	9	0%
Range	7	7	0%
Other Appliances + Plug	29	29	0%
OA Ventilation	0	0	
Total Usage	157	87	44%
Site Generation	0	28	

Table 8. Modeling Results for ZEH4 in New Orleans, Louisiana Compared to the Benchmark

	Benchmark	Prototype	Difference from Benchmark
	kWh/yr	kWh/yr	%
Space Heating	1044	210	-80
Space Cooling	4329	1492	-66
DHW	2290	1096	-52
Other	5910	4844	-18
Subtotal	13574	7642	-44
Solar generation	0	2802	0
Total	13574	4840	-64

solar AC power produced by the house. Based on measured data the percentage of total energy load supplied by the PV systems for these houses ranged from 27% to 32%.

Based on the whole house modeling using the Building America Benchmark comparison method, and local energy rates in November 2006 of $0.07 /kWh, and solar buy back of $0.15/kWh, the electricity cost per day is $0.48 for ZEH4. This is compared to the Benchmark of $4/day. The modeling prediction value is between the two measured one year average daily measured results of $0.75 and $0.41 for ZEH4. Modeling this house and its benchmark in New Orleans results in a daily cost of $0.77 for the ZEH prototype and $3.58 for the benchmark.

RECOMMENDATIONS

1. The energy performance of this house is impressive. The next step is to generate several model homes (1300 ft^2 one story to 2600 ft^2 two-story) that will perform as well or better than ZEH4, but have broad market appeal, beyond Habitat for Humanity, to obtain commercial construction costs to the level of detail available on energy costs as displayed in this paper. This will provide the data base need for a comprehensive life-cycle cost analysis.
2. To reach zero energy the plug loads must be addressed, a best guess is a savings of 1300 kWh, grey water waste heat recovery could cut about 60% from the hot water (using Table 4. 1652 X 0.6 = 991 kWh, cut the heating load by going to a geothermal heat pump by another 50% (using Table 4 1090 X 0.5= 545 kWh). This would get the demand after solar down to 2697 kWh/yr or 82% savings from the Building America Prototype shown in Table 9. This could be covered by doubling the size of the PV system. Not a cost effective solution in 2007 with the limited incentive package available in most of the Mixed Humid and Hot Humid Climates.
3. The use of exterior cool coatings on well insulated massive wall assemblies merits further study. The enabling benefit of extending the usefulness of the thermal mass for the entire cooling season uncovered by this paper is intriguing and should be explored in other high

Table 9. ZEH4 Individual Technology Energy Savings Using the Building America Benchmark Definition

ZEH4	Site Energy (kWh)	Est. Source Energy (Mbtu)	Savings %	National Average Energy Cost[1] ($/yr)	Savings (%)	Builder Standard (Local Costs)[2] Energy Cost ($/yr)	Savings (%)	Measure Value ($/yr)	Package ($/yr)
BA Benchmark	14576	157		$1,458		$1,020			
Builder Std Practice (BSP)	13879	150	5%	$1,388	5%	$972			
BSP + improved roof R-value	12794	138	12%	$1,279	12%	$896	12%	$76	$76
BSP+ improved wall R-value	12692	137	13%	$1,269	13%	$888	13%	$7	$83
BSP +tighter envelope	11665	126	20%	$1,167	20%	$817	20%	$72	$155
BSP+ extended roof overhangs	11600	125	20%	$1,160	20%	$812	20%	$5	$160
BSP ++ basement insulation and mass	11200	121	23%	$1,120	23%	$784	23%	$28	$188
BSP ++ LowE windows	10687	115	27%	$1,069	27%	$748	27%	$36	$223
BSP ++ SEER 17 Heat Pump	10185	110	30%	$1,019	30%	$713	30%	$35	$259
BSP ++ HPWH	8923	96	39%	$892	39%	$625	39%	$88	$347
BSP ++ Lighting	8114	87	44%	$811	44%	$568	44%	$57	$404
BSP ++ other appliances and Plug	8645	87	44%	$811	44%	$568	44%	$0	$404
Site Generation	2627								
BSP ++ PV	5487	59	62%	$417[3]	62%	$174	83%	$394	$798

[1]national average = $0.10/kWh
[2]local residential rate = $0.07/kWh, solar buy back = $0.15/kWh
[3]assume national average residential rate of $0.10 and utility buy back for solar of $0.15

Table 10. Construction Cost of Test Houses and Base House ($)

	Base 1060 ft^2	ZEH1 1060 ft^2	ZEH2 1060 ft^2	ZEH3 1060 ft^2	ZEH4 1200 ft^2	ZEH5 2600 ft^2
House	59,295	78,914	83,953	87,889	85,189	155,140
Land and infrastructure	14,500	14,500	14,500	14,500	14,500	14,500
Cost of solar	0	22,388	16,000	16,000	14,935	15,000
Incentives (Fed+TVA)		-2,800	-2,800	-2,800	-2,800	-2,800
Total cost	73,795	113,002	113,153	119,529	111,824	181,840
$/ft^2	69.62	106.60	106.75	112.76	93.18	70.00

Table 11. Energy Needed to Ventilate the ZEH4 Prototype

	ZEH4 Prototype (kWh)	Prototype with No ventilation (kWh)	Difference (kWh)	Percentage of Total	Annual Cost
Heating	941	562	379	71%	$27
Heating fan	116	64	52	10%	$4
Total heating	1057	626	431	81%	$30
Cooling	665	579	86	16%	$6
Cooling fan	148	132	16	3%	$1
Total cooling	813	711	102	19%	$7
Total	1870	1337	533		$37

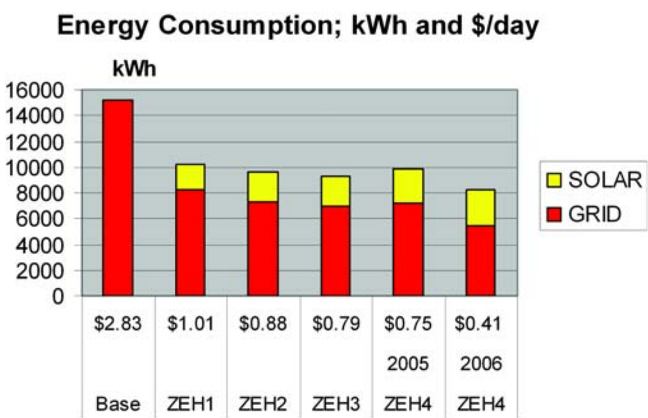

Figure 12 *Energy consumption of ZEHs.*

performance houses with mechanical ventilation systems.

4. The impact of concrete both as an unwanted first year increased moisture source and the hygrothermal buffer benefit should be further evaluated in near zero energy houses.
5. The pentane blown polyisocyanurate SIP used in the top floor walls and roof/ceiling assembly was measured to have thermal drift of about 11% over the 32 months since initial construction. A complete thermal aging curve should be developed for various panel thickness and facers, to properly account for the oxygen and nitrogen diffusing into the foam cells and the pentane diffusing out.
6. A concerted R&D effort should be focused on developing an affordable heat pump water heater. The unit used in this test house is no longer commercially available.
7. The two ton heat pump was the smallest SEER 17 available in 2004. Small highly efficient houses demand 1-1.5 ton units. These units need to be developed and at costs that are lower than the 2 ton, which is really oversized for the mixed humid climate with this level of envelope energy efficiency.

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