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Building a 40% Energy Saving Home in the Mixed-Humid Climate

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Buildings Technology Center

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Contents

Abbreviations, Initialisms, and Acronyms

CFM	Cubic feet per minute
DOE	U.S. Department of Energy
ECM	Electronically commuted motor
EF	Energy factor
EPS	Expanded polystyrene
HDP	High density polyethylene
HP	Heat pump
HPWH	Heat pump water heater
HSPF	Heating seasonal performance factor
kWp	Peak PV solar system rating in kW
ORNL	Oak Ridge National Laboratory
OSB	Oriented strand board
PV	Photovoltaic
SEER	Seasonal energy efficiency rating
SHGC	Solar heat gain coefficient
SIP	Structural insulated panel
SWH	Solar water heater
TVA	Tennessee Valley Authority
XPS	Extruded polystyrene

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Executive Summary

This report describes a home that uses 40% less energy than the energy-efficient Building America standard — a giant step in the pursuit of affordable near-zero-energy housing through the evolution of five near-zero-energy research houses. This four-bedroom, two-bath, 1232-ft^2 house has a Home Energy Rating System (HERS) index of 39 (a HERS rating of 0 is a zero-energy house, a conventional new house would have a HERS rating of 100), which qualifies it for federal energy efficiency and solar incentives. The house is leading to the planned construction of a similar home in Greensburg, Kansas, and 21 staff houses in the Walden Reserve, a 7000-unit "deep green" community in Cookville, Tennessee. Discussions are underway for construction of similar houses in Charleston, South Carolina, Seattle, Washington, Knoxville and Oak Ridge, Tennessee, and upstate New York. This house should lead to a 40% and 50% Gate-3, Mixed-Humid-Climate Joule for the DOE Building America Program.

The house is constructed with structurally-insulated-panel walls and roof, raised metal-seam roof with infrared reflective coating, airtight envelope (1.65 air changes per hour at 50 Pascal), supply mechanical ventilation, ducts inside the conditioned space, extensive moisture control package, foundation geothermal space heating and cooling system, ZEHcor wall, solar water heater, and a 2.2 kWp grid-connected photovoltaic (PV) system. The detailed specifications for the envelope and the equipment used in ZEH5 compared to all the houses in this series are shown in Tables 1 and 2.

Based on one years worth of 50 sensor detailed 15 minute measured data a computer simulation of ZEH5 with typical occupancy patterns and energy services for four occupants, energy for this all-electric house is predicted to cost only \$0.69/day (\$0.86/day counting the hookup charges). By contrast, the benchmark house would require \$3.56/day, including hookup charges (these costs are based on a 2006 residential rates of \$0.07/kWh and solar buyback at \$0.15/kWh). The solar fraction for this home located in Lenoir City, Tennessee, is predicted to be as high as 41%(accounting for both solar PV and the solar water heater). This all-electric home is predicted to use 25 kWh/day based on the one year of measured data used to calibrate a whole-building simulation model. Based on two years of measured data, the roof-mounted 2.2 kWp PV system is predicted to generate 7.5 kWh/day.

The 2005 cost to commercially construct ZEH5, including builder profit and overhead, is estimated at about \$150,000. This cost — for ZEH5's panelized construction, premanufactured utility wall (ZEHcor), foundation geothermal system, and the addition of the walkout lower level, and considering the falling cost for PV — suggests that the construction cost per ft^2 for a ZEH5 two-story will be even more cost-competitive. The 2005 construction cost estimate for a finished-out ZEH5 with 2632 ft^2 is \$222,000 or \$85/ft^2.

The intention of this report is to help builders and homeowners make the decision to build zero-energy-ready homes. Detailed drawings, specifications, and lessons learned in the construction and analysis of data from about 100 sensors monitoring thermal performance for a one-year period are presented. This information should be specifically useful to those considering structural insulated panel walls and roof, foundation geothermal space heating and cooling, solar water heater and roof-mounted, photovoltaic, grid-tied systems.

1. Introduction

1.1 Background

This report provides information to help you build a small, affordable, energy-efficient house that will achieve 40% whole-house energy savings using a commercially available technology package in the mixed-humid climate region. This technology package and method of integration were used in ZEH5, the fifth in a series of near-zero-energy test houses (ZEHs).

This information includes floor plans, cross sections, and elevations. Technical specifications are provided for site characteristics, house orientation, envelope components (foundation, above-grade walls, windows, and roof), lighting, appliances, solar water heater, space conditioning systems, including mechanical ventilation, heating, cooling, dehumidification, water heating and grid tied roof mounted solar Photovoltaic system.

We also present construction cost, measured energy consumption for a one-year period, and predict energy consumption for a typical weather year and average United States residential internal energy services for a house this size. The predictions are based on a validated computer model of the house using the measured data and than simulating the house performance inputting typical occupancy and energy services of an occupied house for a one-year period with and without a roof-mounted 2.2 kWpeak photovoltaic (PV) solar system. This report contains lessons learned and advice on key construction and commissioning steps for this zero-energy-ready home.

The lessons learned come from experience gained from designing, building, and monitoring five affordable energy-efficient houses through a collaboration of Habitat for Humanity Loudon County, the U.S. Department of Energy (DOE), Oak Ridge National Laboratory (ORNL), Tennessee Valley Authority (TVA), State of Tennessee and the Southeastern Alliance for Clean Energy (SACE). The houses were designed by ORNL and DOE Building America (BA) teams and constructed by Habitat volunteers in Lenoir City, Tennessee.

This report mainly focuses on the 1232-ft^2, one-story ZEH5, which was the fifth in the series of test houses built in the same development, as shown in Figure 1. For one complete year ZEH5 was monitored while heating and cooling only the upstairs, while the walkout lower level was left unconditioned and performed as an 8-ft-high unvented, insulated crawlspace. There are no steps between the upstairs and down so that the house would qualify as a single-floor, four-bedroom Habitat for Humanity home. This is the largest house allowed within the Habitat for Humanity International guidelines.

Figure 1. Layout of development with five ZEHs.

1.2 The 40% Energy Saving Test House

The construction methods, building products, appliances, and equipment that were used resulted in low energy use, approaching “net zero energy,” in this all-electric, single-family house. (A net-zero-energy home is one that produces as much energy as it consumes on an annual basis.) Data collected on the thermal performance of ZEH5 was used to develop the guidelines presented in this report.

ZEH5 was instrumented for 94 performance measurements to record electric sub-metered usage, temperature and relative humidity (ambient, indoor, and crawl space), hot water usage, heat pump operation, and other data. We have accumulated 15-minute-interval data for one year from January 1, 2006, through December 31, 2006. The data were analyzed to determine component performance and energy consumption and to validate computer models. The models predicted that this house, with assumed typical occupancy and the same 2.2-kWpeak solar PV system as measured on ZEH4, would consume total off-site energy averaging a cost of $0.69/day. The current hook-up charges would add another $0.20/day, totaling $0.89/day. Hook-up charges are fees a utility requires from customers that are connected to the grid or pipe line even if they do not use a single kWh or therm of natural gas.

The actual construction cost for this house built in 2005 was $122,000, including the cost of the rooftop grid-tied 2.2 kWpeak solar PV system. Federal and electric utility incentives are included in this cost but the land and development infrastructure are not. The cost of an unfinished but very well insulated, waterproofed, and drained 8-ft-high unfinished walkout lower level is included (except for the two doors and three windows). This is the principal reason that the estimated cost per square foot of floor area is higher for ZEH5 than for the other four near-zero-energy houses (shown in Table 8). The cost of materials and value of materials and labor donated were tracked during construction. There is some uncertainty in the cost of labor other than for plumbing; heating, ventilating, and air conditioning (HVAC); excavation; and foundation subcontractors. The above-grade envelope can be assembled quickly with a SIPs technician and crew that have good general carpentry skills. The interior framing is a bit more extensive due to the cathedral ceiling compared to a flat ceiling system under roof trusses. Table 9 shows the cost breakdown for ZEH5 with an unfinished walkout lower level. The rows with a phase code shown in the first column in Table 9 are supported by actual invoices.

1.3 Technologies

Tables 1 and 2 list building envelope and mechanical features used in ZEH5, the other four near-zero-energy houses, and a baseline Habitat house used for comparison (Christian 2006c). The baseline house was rated using the Home Energy Rating System (HERS) and achieved a rating of 84. This indicates about 20% better performance than a typical American house of the same size and layout built in 2004 or 2005 (RESNET 2002).

ZEH5 has a rooftop solar water heater, but the grid-tied PV system with a rating of 2.2 kWp is actually mounted on the roof of ZEH4 directly across the street, which has the same slope and orientation as ZEH5 and very similar and limited tree shading patterns. To be connected to the TVA Green Power Generation Program, the houses must be equipped with two electric utility meters, one to track PV system generation and a net meter which shows in real time whether the house is using more energy than it is producing, or vice versa. The net meter allows the surplus energy to flow into the utility grid when a house is using less electricity than the PV system produces (usually on sunny summer afternoons). The power consumed by the household and generated by the PV system is metered separately, and the homeowner is credited $0.15 per kWh by the utility for all the solar power produced. The sum of these two meters, read once a month, represents the actual household energy consumption.

Table 1. Envelope technology packages in test houses

House	Baseline House	ZEH 1	ZEH2	ZEH3	ZEH4	ZEH5
Stories	1	1	1	1	2	1
floor ft^2	1056	1056	1060	1082	1200	1232
Found-ation	Vented crawl	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 lower level with insulated precast (nominal steady state R-value of (R-16)	Walk out unconditioned lower level with exterior insulated block walls (nominal steady state R-value of (R-11)
First floor	R-19 fiberglass batts (R-17.9)	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	Concrete Slab, insulated underneath with R-10 XPS and exterior apron of R-10 XPS on south side
Walls	2 x 4 frame with R-11 fiberglass batts, OSB sheathing, (R-10.6)	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	2nd 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	6-7 windows, U-factor 0.538	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 (3 are in the "crawlspace"
Doors	2-doors, one solid insulated, one half view	2-doors, solid insulated, & half view	2-doors, one solid insulated, one half view	2-doors, one solid insulated, one half view	3-doors, one solid, 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 (in the "crawl") (U=0.33, SHGC=0.27, VT=0.41)
Roof	Attic floor blown fiberglass (R-28.4)	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 (R-27), surface splines (R-48)	8 in SIPS 1#EPS plus 2 in XPS (R-35), I-joist splines
Roofing	Gray asphalt shingles	Hidden raised metal seam	15 in. Green standing 24GA steel seam, 0.17 reflectivity	15 in. Green standing 24GA steel seam, 0.23 reflectivity	Light gray Metal simulated tile, .032 aluminum	15 in. Brown standing 24GA steel seam, 0.31 reflectivity

Table 2. Equipment technology packages in test houses

House	Base House	ZEH 1	ZEH 2	ZEH 3	ZEH 4	ZEH5
Solar system	None	48-43W amorphous silicon PV modules, 2.06 kWp	12-165W multi-crystal silicon PV modules-12.68% eff, 1.98 kWp	12-165W multi-crystal silicon PV modules-12.68% eff, 1.98 kWp	20-110W polycrystalline 2.2 kWp	20-110W polycrystalline 2.2 kWp (actually on ZEH4 roof)
Heating and Cooling	Unitary 2 ton HP, SEER 12	1-1/2 ton air-to-air HP, SEER 13.7, 2-speed ECM indoor fan	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, comparable SEER 16.6	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 EER 19.2
Mechanical Ventilation	None	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	Crawl space	Inside conditioned space	Inside conditioned space	Inside conditioned space	Inside conditioned space	Inside conditioned space
Water Heater	Electric	Integrated HPWH linked to unvented crawl	Integrated HPWH, linked to crawl which has motorized damper	Desuperheat for hot water, EF .94	HPWH vented to ½ bath which is exhausted for ventilation	Solar Water Heater, 40 ft^2 collector area, PV pump, grey water waste heat recovery (not modeled)

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

Supply mechanical ventilation is provided in compliance with American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62.2 (ASHRAE 2004). ZEH5 is the first of the five test houses to use a solar water heater. An extensive moisture management package, is provided in all five test houses; capillarity break between the footer and foundation wall, below grade waterproofing covered with insulating drainage board, footer drain on both sides of the footer, extruded polystyrene placed under the walkout lower level slab to minimize condensation by increasing the inside slab surface temperature, air tight construction, balanced mechanical ventilation, insulated ducts inside the conditioned space, panned windows and door openings, transfer grills and jump ducts reliving pressure differences within the house when private bedroom doors are shut, windows properly installed with shingle style flashings, roof and wall drainage planes (both above and below grade, extended roof overhangs to minimize wind driven rain envelope penetration, minimum roof membrane penetrations, peel and stick tape on all interior SIP seams in 3 of five ZEHs, right sized HVAC (Manual J edition 8, Manual D), final grade sloped 5% at least 6” for 10 feet away from the foundation, whole house commissioned prior to occupancy which included a blower door envelope air tightness test, duct blaster duct tightness test, supply and return CFM measured and balanced with Manual D design specifications, HERS index estimate.

1.4 Energy Cost

The cost-effectiveness of a house like ZEH5 will vary with energy rates, climate, energy-consumption habits, utility, state, and federal incentives, and the cost of the selected technologies. The local electricity rate in 2006 for ZEH5 was $0.07 per kWh, below the national average of about $0.10 per kWh. Energy cost savings would be greater in regions with higher electricity and solar credit rates.

For ZEH 1, 2, 3, and 4, utility bills averaged less than $1 per day after credit for the sale of solar-generated electric power. ZEH5 would have an average daily electricity cost of $0.69/day ($0.89/day counting utility charges of $0.20 just to have available typical residential electric service) assuming the PV system on ZEH4 is on the roof of ZEH5. The Building America Benchmark house of the same size and in the same community as ZEH5 would be expected to average $3.36 per day for electricity ($3.56 with hook up charges). Figure 2 shows the energy consumption and solar generation of ZEH1, 2, 3, 4, and 5 (one-story) compared to the benchmark house.

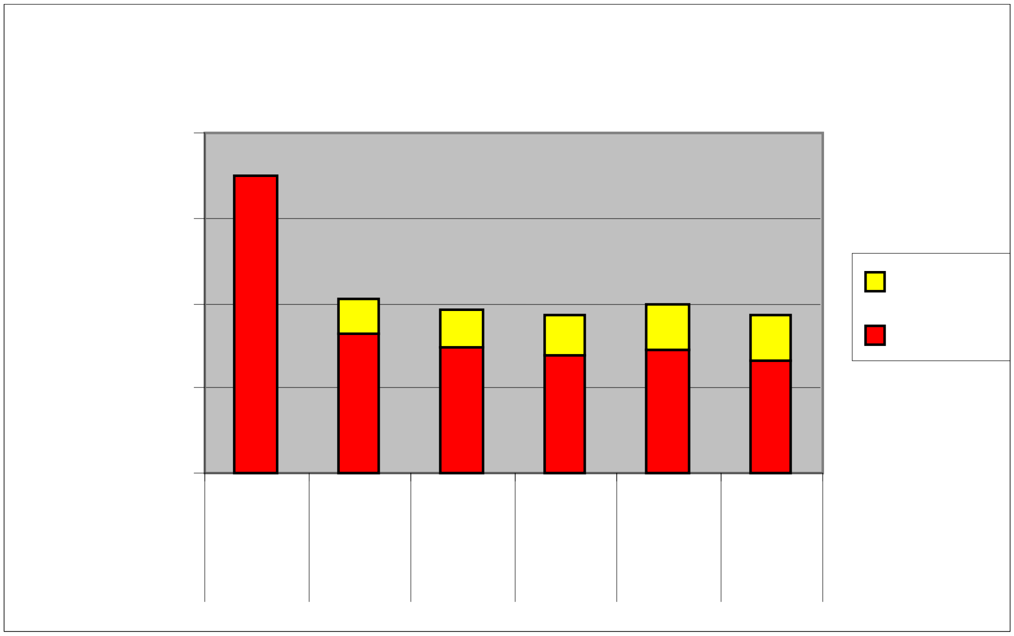

Figure 2. Energy consumption of ZEHs.

The monthly energy consumption values in Table 3 are based on a combination of measurements and modeling. This was necessary because the house was occupied as an office rather than a residence. The actual “other” loads were 54% higher than those defined by the BA benchmark (Hendron 2007). Therefore, measured readings for space heating and cooling were adjusted slightly to account for less heat from the other loads in the house. This raised the heating energy 339 kWhr, or 57%, and lowered the cooling energy by 285 kWh or 14%. The other loads shown in Table 3 were estimated using the procedure outlined in the BA Benchmark modeling procedure (Hendron 2007).

Table 3. ZEH5 energy use, January 2006 – December 2006

Month	Space heat (kWh)	Space cool (kWh)	Solar water heating; from Energy Gauge	Other; from Energy Gauge	Total electric (kWh)	Solar generated (kWh)	Daily cost
Jan-06	195	0	136	515	846	154	
Feb	237	0	90	465	792	176	
March	118	0	62	515	695	253	
April	0	284	29	499	812	283	
May	0	91	20	515	626	280	
June	0	242	9	499	750	294	
July	0	321	4	515	840	300	
Aug	0	579	10	515	1104	270	
Sept	0	217	21	499	737	229	
Oct	92	0	36	515	643	221	
Nov	91	0	84	499	674	169	
Dec	172	0	117	515	804	110	
Total	905	1734	618	6066	9312	2697	
Annual cost	$63	$121	$43	$425	$652	-$405	
Daily cost				$1.16	$1.79	-$1.10	$0.69

The hot water loads were derived from Energy Gauge modeling of the solar system installed in ZEH5. The house was used throughout 2006–2007 to test a variety of different water heating options. The house was equipped with a programmable controller that varied water usage from 45 to 100 gallons per day. The solar water heater was tested periodically throughout the year. In June of 2007 the solar water heater was tested for a 23-day period, with hot water consumption averaging 63 gallons per day. During the test, backup electricity of 11.0 watt-hours (Wh) per gallon of hot water delivered was required. The Energy Gauge simulation of the same house delivering the same 63 gallons of hot water per day estimated that backup electricity of 12.7 Wh per gallon of hot water delivered would be required for the month of June. This calibration indicates that the measured performance of the solar water heater is about 13% better than predicted by the model. We used the June performance to adjust the predicted energy required to back up the solar water heater in ZEH5 as follows:

$$709 \text{ kWh} \times 0.875 = 618 \text{ kWh} = 36 \text{ Wh/gal}$$

This is a 76% energy savings compared to an electric resistance water heater with an EF of 0.88 using 150 Wh/gallon.

The electric energy collected by the PV panels amounted to 29% of the total energy consumed. No solar panels are installed on ZEH5; the data on PV energy produced was measured on the 2.2 kWpeak PV system on ZEH4 in 2006. If we assume that the solar water heater displaced 76% of the electric resistance water heating, we have another 1987 kWhr/yr of solar savings, for a total solar fraction of 41%. The solar fraction is the amount of the house total energy demand satisfied by the sun.

1.5 Energy savings compared to the Building America Benchmark

Using the Energy Gauge program, we constructed a benchmark model following the Building America Definition (Hendron 2007) to compare the one-story ZEH5. ZEH5 required 62% less off-site energy than the Building America benchmark house. Without the solar PV system, the one-story ZEH5 is a Building America 47% energy saving house. This house has a HERS index of 39 and would qualify for the $2000 federal tax credit for the builder. The Benchmark house has a HERS index of 107. Table 4 shows where the improvements in the home were made to lower energy usage. The heating and cooling loads were the two largest reductions, followed by the water heater and the lighting. The only other energy savings reported is from the Energy Star refrigerator. The plug loads and all the remaining appliance energy usages are assumed to be the same in ZEH5 and the Benchmark house, as called for in the Building America energy savings methodology. The remaining appliance and plug loads represent 62% of the total energy consumption of this all-electric house. Compared to the smaller total after subtracting the onsite PV generation, this amounts to 87% of the energy needed from off site. ORNL is working with several major appliance manufacturers to substantially reduce these loads.

Table 4. Building America site energy consumption

	Annual Site Energy (kWh)	
End Use	**BA Benchmark**	**BA Prototype**
Space Heating	5148	1388
Space Cooling	2559	945
DHW	2709	901
Lighting	1155	322
Appliances + Plug	5950	5756
Total Usage	17521	9312
Site Generation	0	2697
Net Energy Use	17521	6615

Tables 5 and 6 show the envelope and equipment features used to generate the computer model comparison of ZEH5 and the Benchmark house. Table 7 shows the energy and dollar savings from individual components of ZEH5. The entire package of features saves almost $1000 per year with the PV generation and the $0.15/ solar kWh buyback. For this house to attain a DOE Building America 40% saver status, all but the solar PV features are needed. This includes the geothermal heat pump and the solar water heater.

Table 5. Envelope technology packages in test houses

	Benchmark House	ZEH5
Stories	1	1
Floor ft^2	1232	1232
Conditioned volume ft^3	12,689.6	12,689.6
Foundation	Insulated unvented crawl same volume as ZEH5, R-9.46	Walk out unconditioned, unvented crawlspace (walkout lower level with no interior steps to top floor) with exterior insulated block walls (nominal steady state R-value of (R-11) Concrete slab, insulated underneath with R-10 XPS and exterior apron of R-10 XPS on south side
First Floor	No insulation in the floor	No insulation in the floor
Walls	2 x 4 frame, Ins R-value 13.16, framing factor of 0.23, sheathing with 0.5 R-value, vinyl siding with solar absorptance of 0.5	6.5 in SIPS 1#EPS (R-21), structural splines-wood I-beams, framing fraction for north wall=0.026, east=0.06, south=0.04, west=.02, house wrap, vinyl siding with solar absorptance of 0.5
Windows	55.45 ft^2 window area on each of 4 walls totaling 221.8 ft^2, U-factor and SHGC of 0.58, no overhangs	10 windows, 138 ft^2 of total window area, 0.34 U-factor, 0.33 SHGC, VT=.55, sill seal pans
Doors	2-doors, one solid insulated, one half view both with U-value of 0.2	2-doors, one solid, one ½ view insulated, both with U-value of 0.2
Roof	Attic floor (R-27.78), framing fraction of 0.11	Cathedral ceiling, 8 in SIPS 1#EPS plus 2 in XPS (R-35), I-joist splines, framing fraction of 0.013
Roofing	0.75 solar absorptance, composition shingles , attic ventilation ration 0.0033 (1 to 300)	15 in. Brown standing 24GA steel seam, 0.31 reflectivity
Infiltration	SLA = 0.00057, ACH(50)= 8.16	SLA=.00012, ACH(50)= 1.65

Table 6. Equipment technology packages in test houses

House	Benchmark House	ZEH5
Heating and cooling	Unitary 2 ton HP, SEER 10, SHR= 0.75,cooling capacity = 23.3 kBtu/hr, 699 CFM, HSPF=6.8, heating capacity=38.8 Btu/hr,	2 ton water-loop geothermal, R-410A, variable speed ECM indoor fan EER 18.8, cooling capacity 24.7 kBtu/hr, 700 CFM, no desuperheat recovery, COP=4.4,heating capacity 21.7 kBtu/hr
Thermostat settings	76 F in summer, 71 F in winter	76 F in summer, 71 F in winter
Mechanical Ventilation	None	Supply to return side of coil, bath fan exhaust, fixed run time of 33%, supply ventilation rate = 63.7 CFM, exhaust ventilation = 36 CFM
Duct location	Crawl space, R-5, Supply area 332.64 ft^2, Return area 61.6ft^2, duct air leakage=15%	Supply Inside conditioned space, return in crawl, duct air leakage= 9.45%, R-5, Supply area 250 ft^2, Return area 40 ft^2,

Air handler location	Crawl space	Crawl space
Water heater	Electric, 50 gal capacity, EF=0.86, usage= 47 gal/day, set temp=120F	Solar Water Heater, 80gal, EF =0.88, set temp = 120F, 40 ft^2 collector area, PV pump, usage= 47 gal/day, set temp=120F
Lighting	20% fluorescent, 80% incandescent,1154 kWh/yr	100% fluorescent, 322 kWh/yr
Solar PV system	None	20-110W polycrystalline 2.2 kWp

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

Table 7. ZEH5 individual technology energy savings using the Building America Benchmark definition

				National average energy cost*		Builder standard (local costs)**			
	Site energy (kWh)	Est. source energy (Mbtu)	Savings %	($/yr)	Savings (%)	Energy cost ($/yr)	Savings (%)	Measure value ($/yr)	Package ($/yr)
BA Benchmark	17,521	188.9		$1,752		$1,226			
Benchmark + improved roof R-value & reflectivity	17,519	188.9	0%	$1,752	0%	$1,226	0%	$0	$0
Benchmark + improved wall R-value	16,969	183.0	3%	$1,697	3%	$1,188	3%	$39	$39
Benchmark +foundation R-value	16,959	182.9	3%	$1,696	3%	$1,187	3%	$1	$39
Benchmark + high performance windows & smaller window area	15,829	170.7	10%	$1,583	10%	$1,108	10%	$79	$118
Benchmark + lighting	15,032	162.1	14%	$1,503	14%	$1,052	14%	$56	$174
Benchmark +energy star fridge	14,854	160.2	15%	$1,485	15%	$1,040	15%	$12	$187
Benchmark + tighter envelope, mechanical ventilation, &smaller ducts	13,517	145.7	23%	$1,352	23%	$946	23%	$94	$280
Benchmark + geothermal	11,154	120.3	36%	$1,115	36%	$781	36%	$165	$446
Benchmark + solar WH	9,312	100.4	47%	$931	47%	$652	47%	$129	$575
Site Generation	2,697								
Benchmark ++ PV	6,615	71.3	62%	$527	70%	$247	80%	$405	$979

*national average = $0.10/kWh

**local residential rate = $0.07/kWh, solar buy back = $0.15/kWh

***assume national average residential rate of $0.10 and utility buy back for solar of $0.15

1.6 First Cost

Table 8 shows the costs for all five houses and for a base house of similar size in the same locale. The market value of volunteer labor and donated materials are factored in. The costs of building the five study houses (not including the cost of ZEH5 two-story) ranged from about \$93 to \$114/ft^2. The base house cost was about \$70/ft^2. The fifth house with a walk-out unfinished, unconditioned, and insulated walkout lower level (ZEH5 one-story) is \$114/ft^2. In 2007 the walkout lower level of ZEH5 was conditioned making the house a 2632-ft^2 two-story. The estimated cost to finish this of was \$24,139. This reduced the construction cost to \$62/ft^2. The national average cost of finishing a walkout lower level reported in *Remodeling Magazine* in 2001 was \$30/ft^2, which would be about \$42,000 for ZEH5. Using this higher estimate would result in a cost for the larger house of about \$70/ft^2.

Table 9 has a detailed cost breakdown for ZEH5. A 20% overhead and profit margin was added to the estimated total cost to approximate the added expense of having a builder construct the house. This results in an overall estimated cost of \$172,000, which represents an estimate of the market sale price for this house with a lot cost of about \$22,200 and construction cost of about \$150,000. We believe this is a reasonable estimate with very low-cost finish details.

Table 8. Construction cost of test houses and baseline house (\$)

	Base (1060 ft^2)	ZEH1 (1060 ft^2)	ZEH2 (1060 ft^2)	ZEH3 (1060 ft^2)	ZEH4 (1200 ft^2)	ZEH5 one-story (1232 ft^2)	ZEH5 two-story (2632 ft^2)
House	59,295	78,914	83,953	87,889	85,189	109,788	133,927
Land and infrastructure	14,500	14,500	14,500	14,500	14,500	18,500	18,500
Cost of solar	0	22,388	16,000	16,000	14,935	15,000	15,000
Incentives (Fed+TVA)		-2,800	-2,800	-2,800	-2,800	-2,800	-2,800
Total cost	73,795	113,002	113,153	119,529	111,824	140,488	164,627
\$/ft^2	69.62	106.60	106.75	112.76	93.18	114.03	62.55

Table 9. Detailed construction costs (estimates) for the ZEH5 test house, configured with one story and two stories ($)

Phase code	Phase description	ZEH5 — 1 story	ZEH5 — 2 story
001	Site Preparation	4,591.01	4,591.01
003	Foundation	13,794.88	13,794.88
004	Termite Pre-Treatment	200.00	200.00
005	Framing and Decking	7,708.71	7,708.71
006	Trusses	–	–
007	Roofing Materials	133.06	133.06
008	Roofing Labor	–	–
009	Guttering	325.00	325.00
010	Windows	250.00	250.00
011	Bathtub and Water Heater	720.68	720.68
012	Exterior Doors	303.50	830.50
013	Siding and Scaffolding	1,794.04	1,794.04
014	Plumbing Materials	2,000.00	2,717.39
015	Plumbing Labor	1,700.00	2,606.25
016	Toilets	157.53	157.53
017	HVAC (this is not the total cost see below)	450.00	450.00
018	Insulation	–	–
019	Sheetrock Materials	1,167.17	167.17
020	Sheetrock Labor	1,871.03	1,871.03
021	Interior Doors	926.69	926.69
022	Paint	286.59	286.59
023	Trim Molding and Casing	–	–
024	Cabinets	2,297.08	2,297.08
026	Closet Maid	–	–
027	Flooring	1,600.00	1,600.00
029	Electrical Materials & Fixtures	1,800.00	2,218.28
030	Electrical Labor	–	–
031	Landscaping	647.38	647.38
032	Driveway	2,260.32	2,260.32
033	Final Grade	1,000.00	1,000.00
037	Storage Building	900.00	900.00
039	Land & Infrastructure Costs	14,500.00	14,500.00
040	Miscellaneous	300.28	300.28
050	extra excavation for geo loop and labor to install walkout lower level floor insulation	715.16	3,215.16
055	Closing Costs	100.00	100.00
	Overhead	5,000.00	5,000.00
	Total construction expenditures	**69,300.11**	**73,569.03**
	Private-sector donations		
003	Foundation Labor	467.00	467.00
009	Gutter installation	136.00	136.00
010	Windowsills	–	–
027	Flooring	200.00	200.00
039	Land & Infrastructure Costs	4,000.00	4,000.00
045	Miscellaneous:	–	–

Phase code	Phase description	ZEH5 — 1 story	ZEH5 — 2 story
	Labor	6,000.00	10,000.00
	Campbell & Associates	–	–
	Southeastern Title	345.00	345.00
	Total private-sector donations	**11,148.00**	**15,148.00**
	Total, construction and private donations	**80,448.11**	**88,569.03**
	ORNL donations		
	SIPS	17,000	17,000
	Andersen Windows	2,900	3,830
	Andersen Patio door	0	1,000
	Englert roof (2006 costs)	6,950	6,950
	Solar water heater	2,400	2,400
	Solar water heater installation	800	800
	DuPont tyvek and window install	1,200	1,200
	HVAC (City Heat and Air), labor	1,500	1,500
	WaterFurnace equipment and piping	4,000	4,000
	Coil install	1,500	1,500
	Aircycler	150	150
	Tremco foundation system	7,000	7,000
	Gordon Myers, donated time and equipment	1,300	1,300
	Dow XPS	1,100	1,100
	Pipe insulation	40	40
	PV system	15,000	15,000
	Total ORNL donations	**62,840**	**64,770**
	Walkout lower level finishing		
	Interior wall framing		2,400
	Drywall		2,000
	Steps to upstairs		3,000
	HVAC ducts		655
	Flooring materials		1,600
	Flooring labor		1,000
	Bathtub		300
	More plumbing		800
	Interior doors		500
	More electrical wiring		1,300
	Bathroom cabinets		1,200
	Total, walkout lower level finishing		**14,755**
	Total costs, construction and donations	**$143,288.11**	**$168,242.03**
	Total with 10% contingencies	**$157,616.92**	**$185,066.23**
	Total with 10% contingencies and 20% builder markup	**$189,140.31 (\$152.53/ft^2)**	**$222,079.48 (\$84.38/ft^2)**
	Total with 20% builder markup and no contingencies	**$171,945.73 (\$138.67/ft^2)**	

2. Floor Plans, Cross Sections, and Elevations

2.1 ZEH5 Introduction

Figure 3. Picture of east elevation of ZEH5 from the street.

ZEH5 is a 1232-ft^2 one-story dwelling with a walkout lower level (Figure 3). The ultimate design intent for this house was to have the walk-out lower level completely finished and conditioned. For this report, however, we will only consider the top floor. The floor plan (shown in section 2.2) has four bedrooms, living-dining room, kitchen, laundry room, and two bathrooms. The walls and roof are made of 6.5-in. and 8-in. structurally insulated panels (SIPs), respectively (Figure 4).

Figure 4. SIP panels for ZEH5 come numbered to match the panel cut drawings. SIPs should be stacked in the order in which they will be installed.

The SIPs used on ZEH5, shown in Figure 4, are made of expanded polystyrene insulation (EPS) sandwiched between two 7/16-in. sheets of oriented strand board (OSB). Two inches of XPS are added on top of the 8-in.-thick SIP roof before installing the metal roofing. The XPS is framed with 2 X 4s along the gable and eve edges of the roof as shown in Figure 5.

Figure 5. Two inches of XPS is laid directly on top of the 8-in.-thick SIP roof panels.

A blower-door test of ZEH5 measured 1.65 air changes per hour (ACH) at 50 Pascal. The HVAC unit is a 2-ton geothermal horizontal water-loop with a variable-speed indoor circulating fan. The geothermal ground loop was installed without having to do additional excavation beyond what was needed to construct the foundation and connect the buried utilities.

Hot water for ZEH5 is provided by a solar water heater with electric resistance backup. The solar water heater collectors and the 11-W PV panel to power a 12V DC pump are shown in Figure 6. The two solar collectors have a total net area of 37 ft^2. The roof is an infrared reflective brown 24-gauge standing seam steel roof with a 4/12 pitch. The energy use of ZEH5 is modeled to include the same PV system as the one installed on ZEH4, which has twenty 110-W modules and is rated at 2.2 kWp.

Figure 6. Solar water heater collectors.

2.2 Floor Plan

The floor plan for ZEH5 as built is shown in Figure 7. The kitchen, main bathroom and laundry room are fixed since they are connected to the 12-in.-thick ZEHcor (Utility) wall. However, the remainder of the layout is extremely flexible since none of the interior walls are structural. This allows multiple options with 1, 2, or 3 bedrooms. Placing the master bedroom where bedrooms 2 and 3 are located and opening up the rest of the plan along with the cathedral ceiling makes this small house feel spacious.

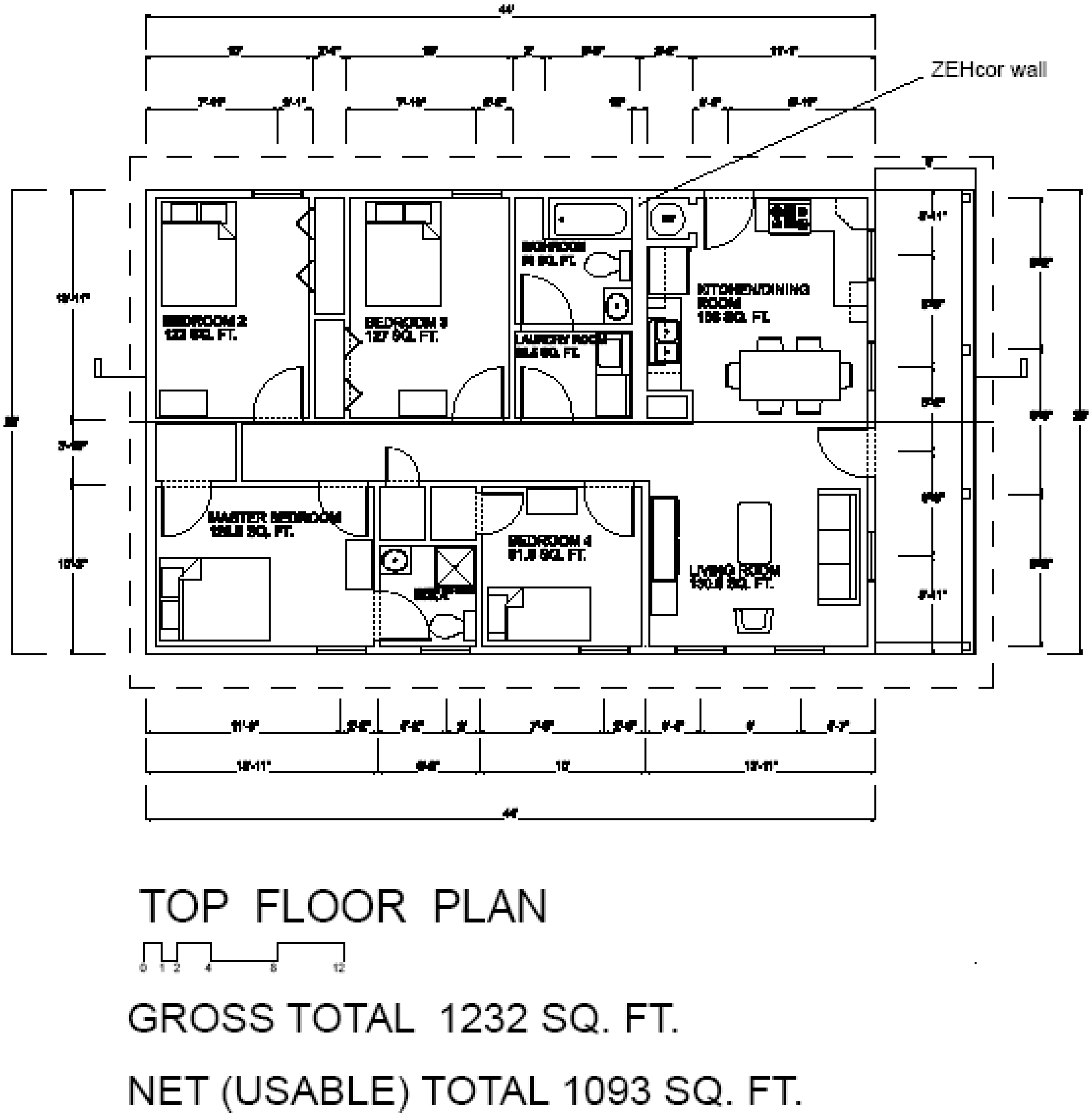

Figure 7. Floor plan of ZEH5.

2.3 Elevations

Figures 8 through 11 show the four elevations of ZEH5, which meets the criteria for a simple, affordable Habitat for Humanity house.

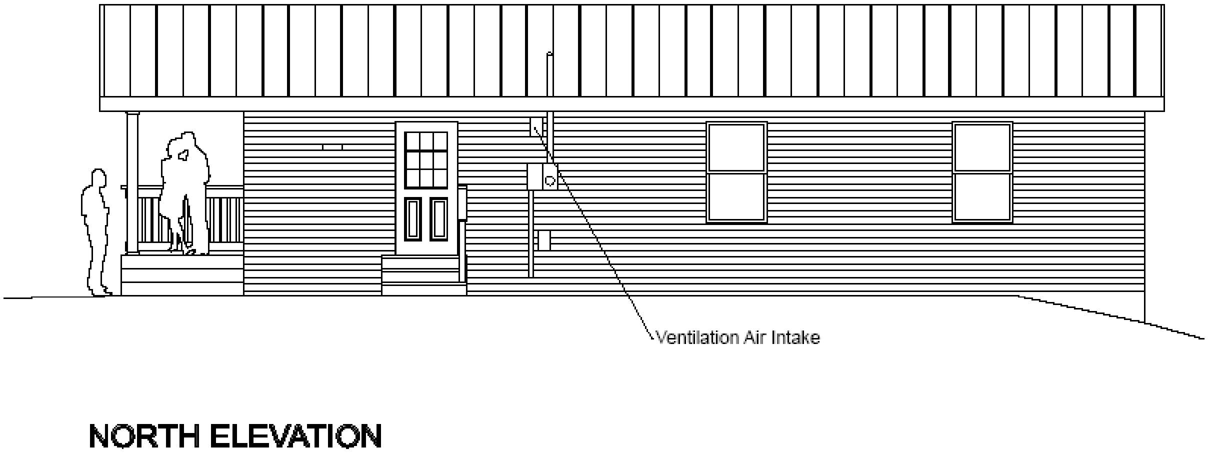

Figure 8. North elevation of ZEH5. Notice that the electric power feed into the house, ventilation air intake (high), and drier outlet (low) line up with the utility wall located between the kitchen, bathroom, and laundry room.

Figure 9. South elevation of ZEH5. The collector area is to scale. Most of the windows are on the south side, providing very pleasant daylit space. The garage door into the walkout lower level was to accommodate the Habitat for Humanity Affiliate which used this space for tool and construction material storage during the two-year testing period prior to making it available to a family. The garage door, patio door, and three windows in the unconditioned walkout lower level are not included in the cost or energy modeling for the one-story house.

Figure 10. East Elevation of ZEH5. The full-length porch on the front is covered with SIPs that are run out from the rest of the house. The space under the front porch is a full 8 ft high and is surrounded with R-10 board insulation on all exterior surfaces, including the bottom of the porch floor. Pouring a concrete porch on top of XPS insulation board requires careful tie-downs to make sure the boards do not float out of place during the pour, which happened on this job and required a call back of the masons to refinish the porch edge detail.

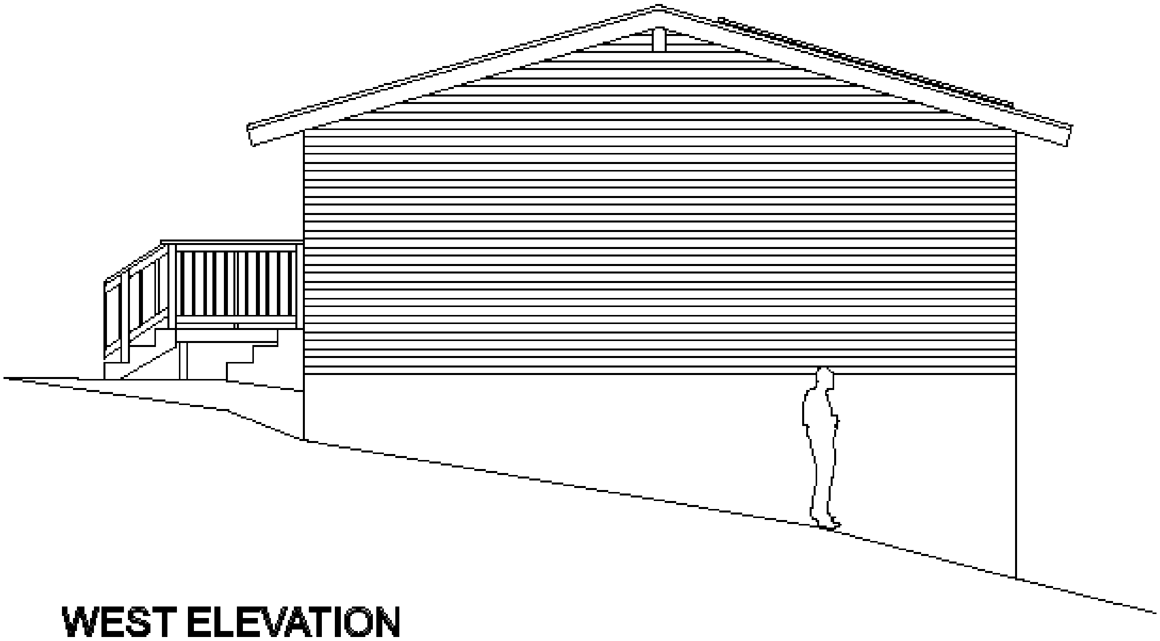

Figure 11. West elevation of ZEH5. The absence of windows is due to the limitations placed by Habitat for Humanity in this development on the number of windows allowed per house. Modeling indicates that as many as four additional 3-0 X 5-0 high-performance windows (with U-values of 0.35 Btu/hr ft^2 ^{o}F) in this house would have very minimal impact on peak or annual energy loads.

2.4 Cross Sections

Figures 12 and 13 show the cross sections of ZEH5. The 52-ft ridge beam shown in Figure 13 was site assembled with four 2 X 12s glued and bolted together to make a full-length beam that extended from the outside face of the west wall all the way to the outside edge of the front porch east gable overhang. Raising this beam into place must be done with a well-thought-out, safe lifting plan, considering the proper rigging, crane, and crew. It is recommended that glulam or other type of engineered ridge beam be considered rather than site assembly with dimensional lumber. Of course, solid lumber post and beam construction is another option for a more upscale version of this house.

Figure 12. Longitudinal section through ZEH5, location marked on the floor plan in Figure 7.

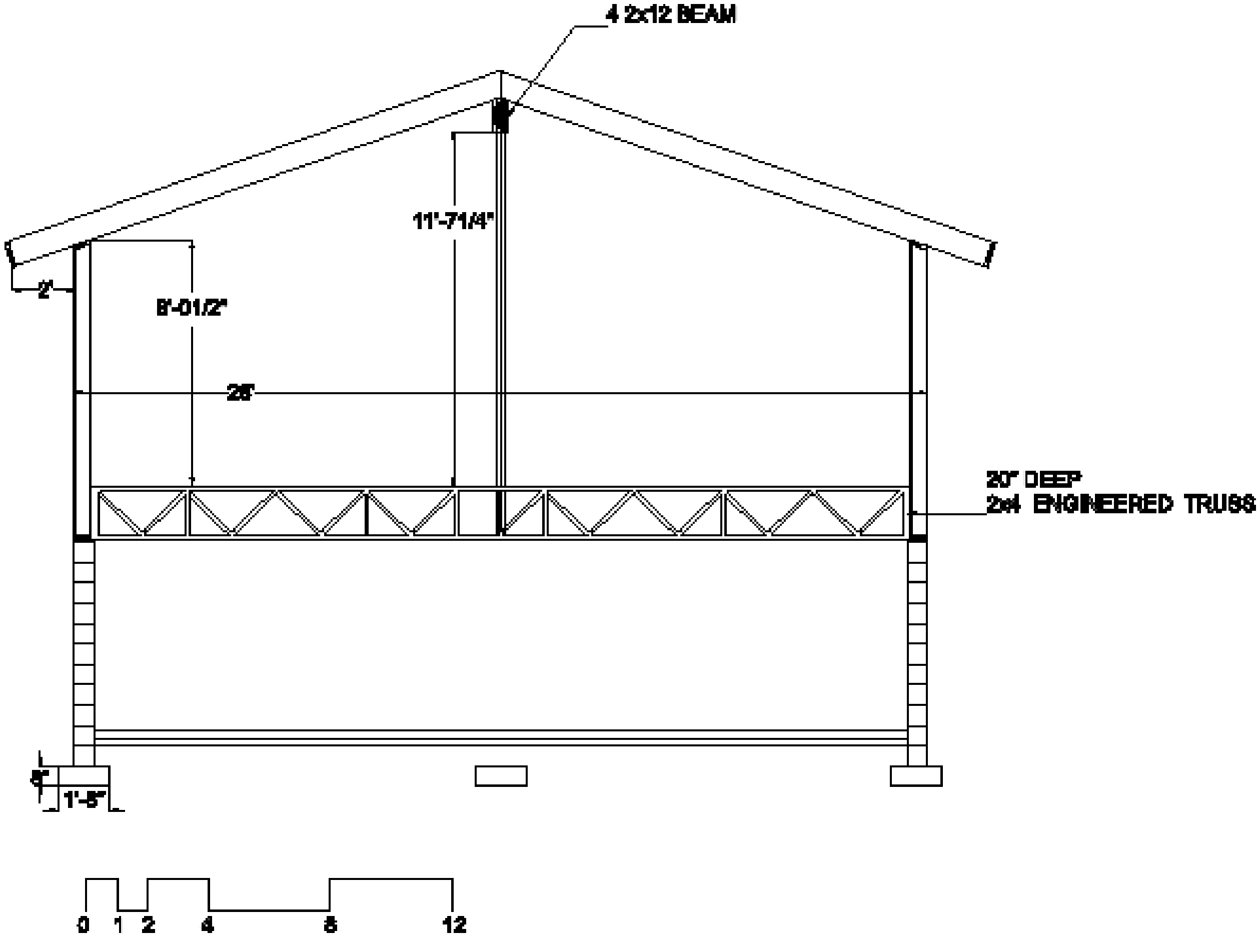

Figure 13. Basic building cross section.

2.5 SIP Cut Drawings

Figures 14-19 are from the SIP manufacturer, Premier Building Systems. These drawings start with the digital CAD files sent to the SIP manufacture from the builder. It is extremely important for the location and size of the window and door rough openings to be correctly captured on these panel-cut drawings. Structural load points and wire chases should all be clearly marked. The thickness of the wall and ceiling panels and the type of splined panel connection are also critical. The floor and foundation interface details need to be clearly illustrated on both the builder's original drawings and on the SIP manufacturer's cut drawings.

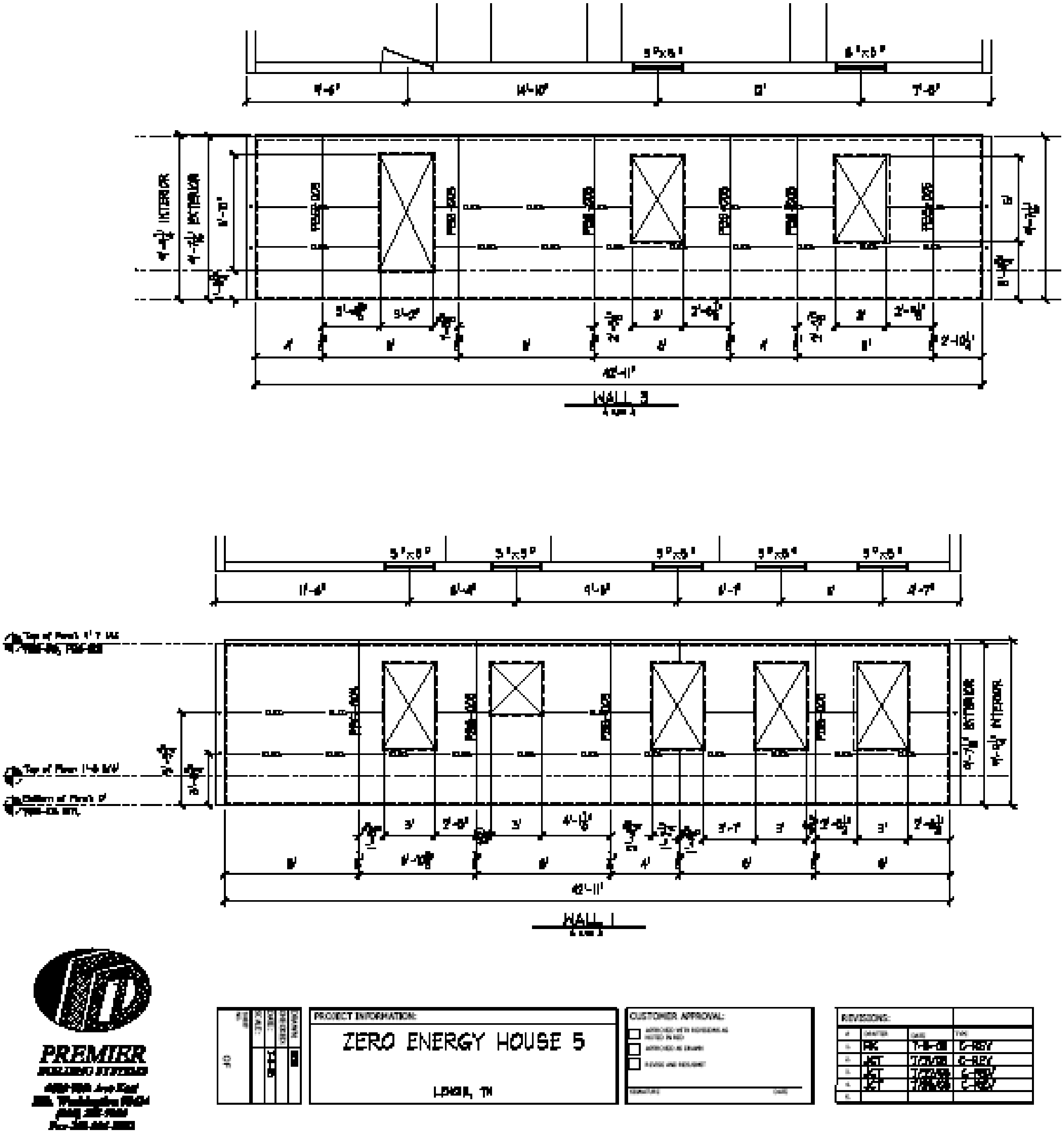

Figure 14. Panel layout of the north (labeled wall 3) and south (labeled wall 1) walls.

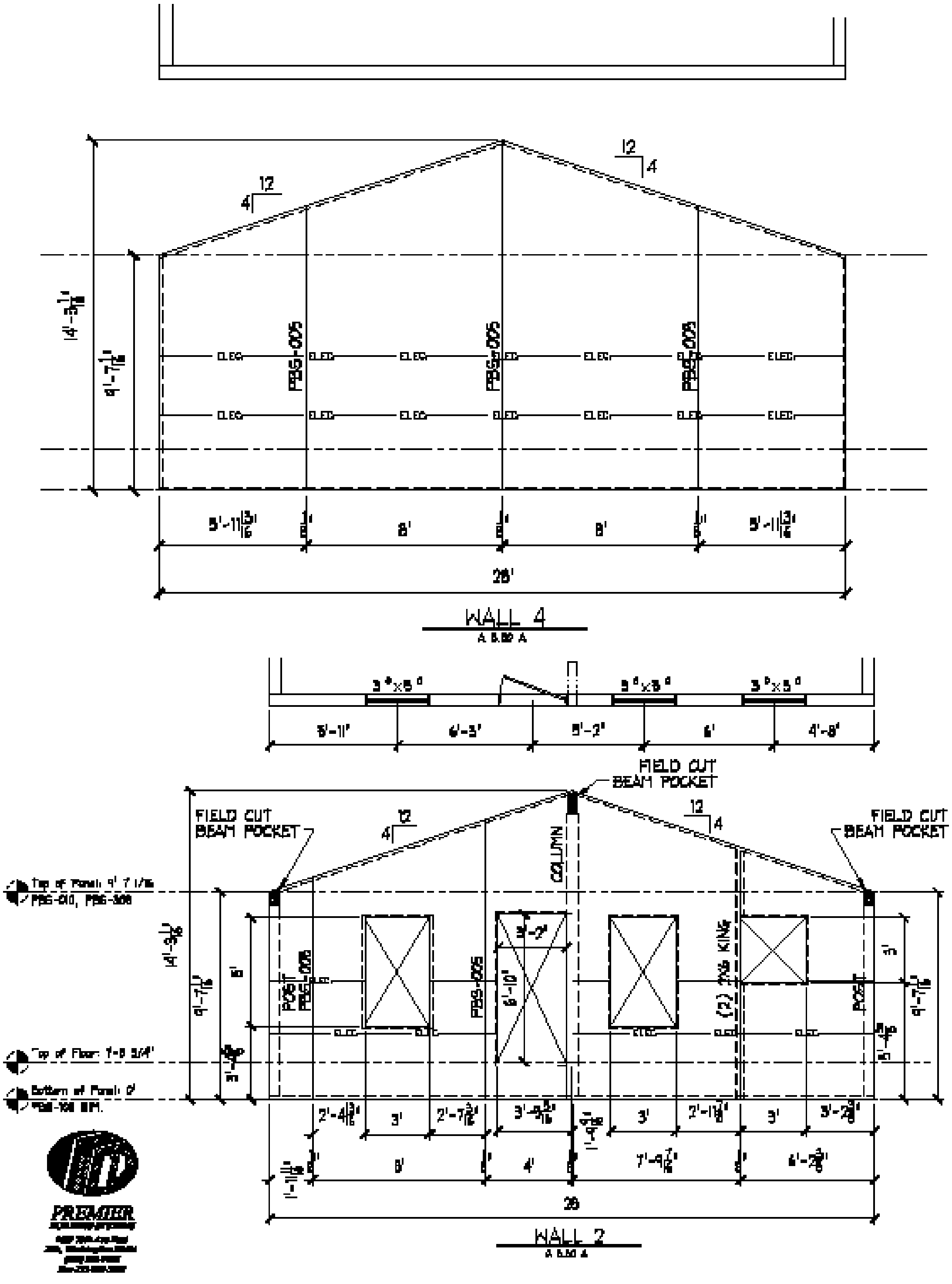

Figure 15. Layout of walls 2 (east) and 4 (west). The west wall was modified on the site to contain a column to support the full-length ridge beam similar to that shown in the east wall.

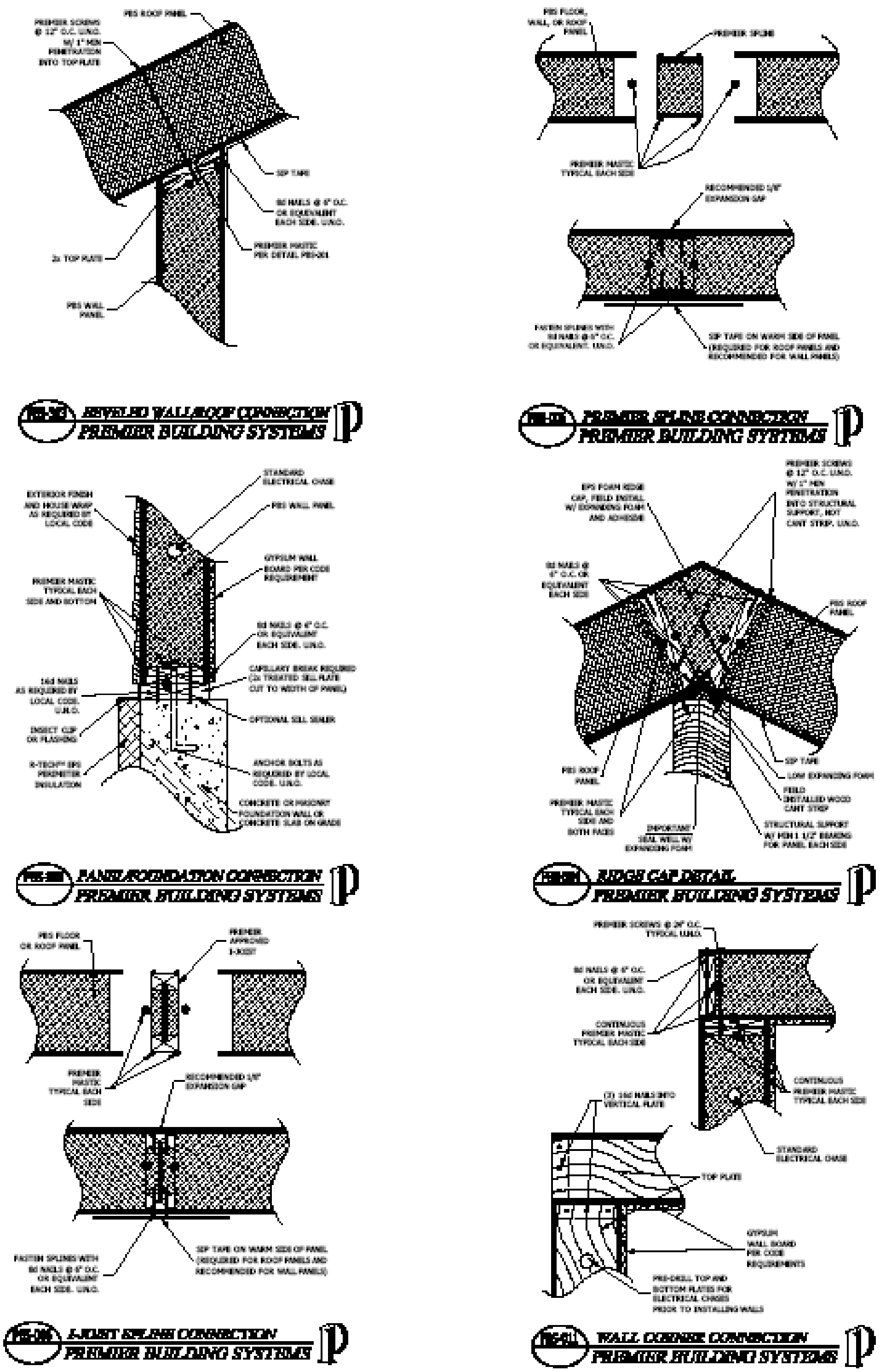

Figure 16. Connection details. (The panel foundation detail shown in this figure was not used; see the foundation detail in Figure 27).

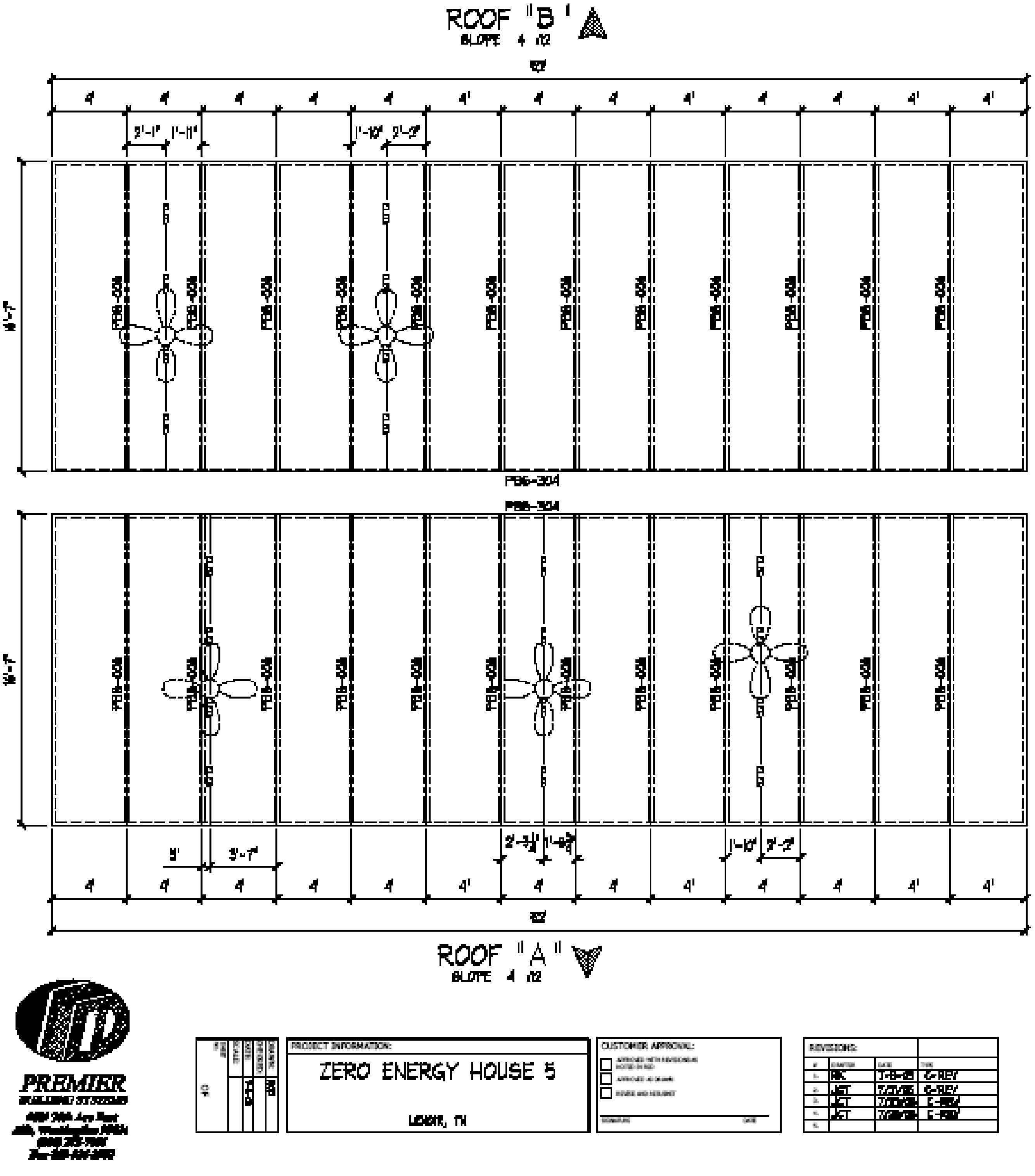

Figure 17. Roof panel layout. These panels carry over the front porch.

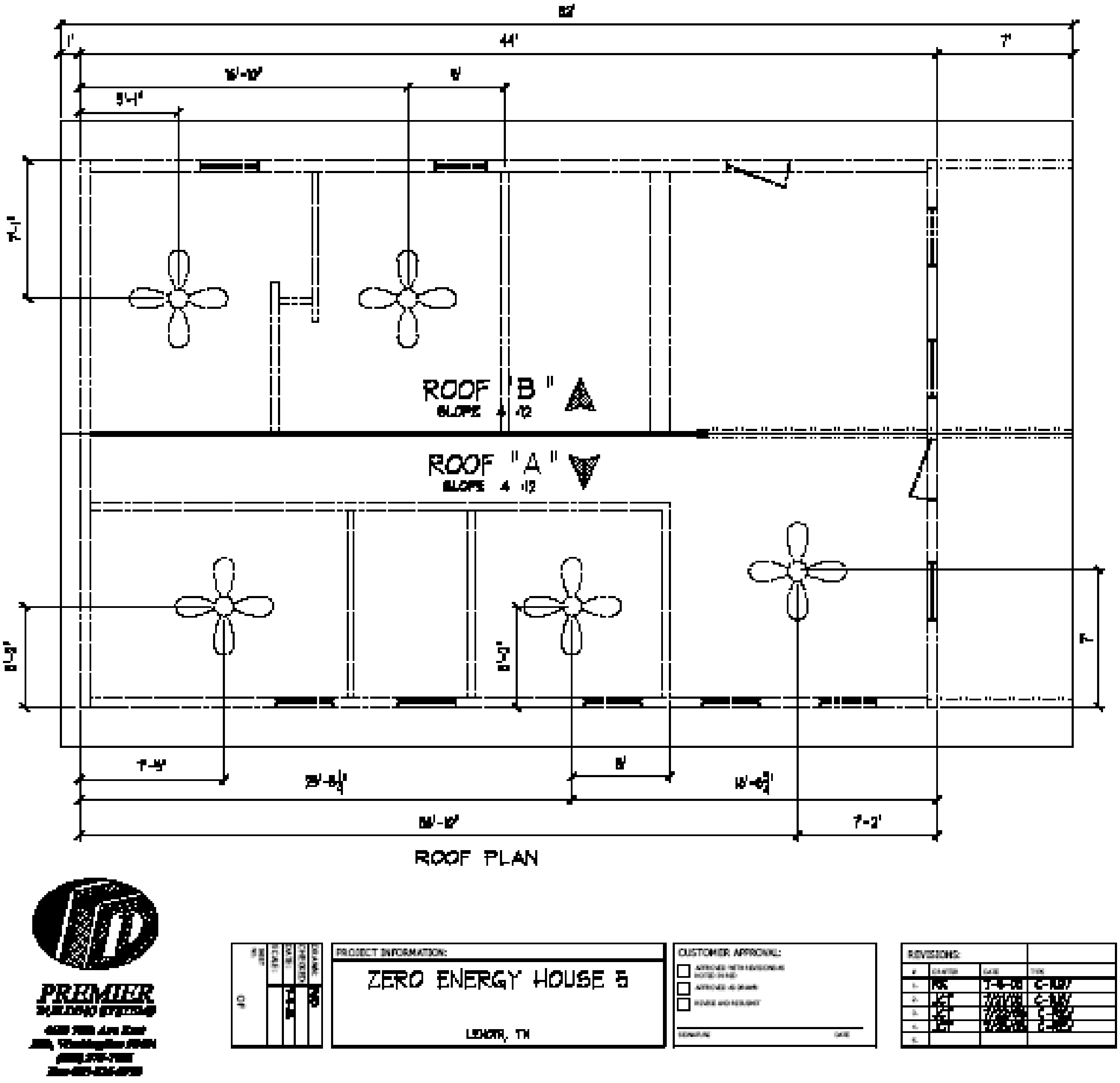

Figure 18. Ceiling fan location and interior wall placement. The positioning of the ceiling fans is important in order to provide structural wood to fasten securely to the ceiling panels. Routing the wire chases to switches and power must also be detailed on these drawings.

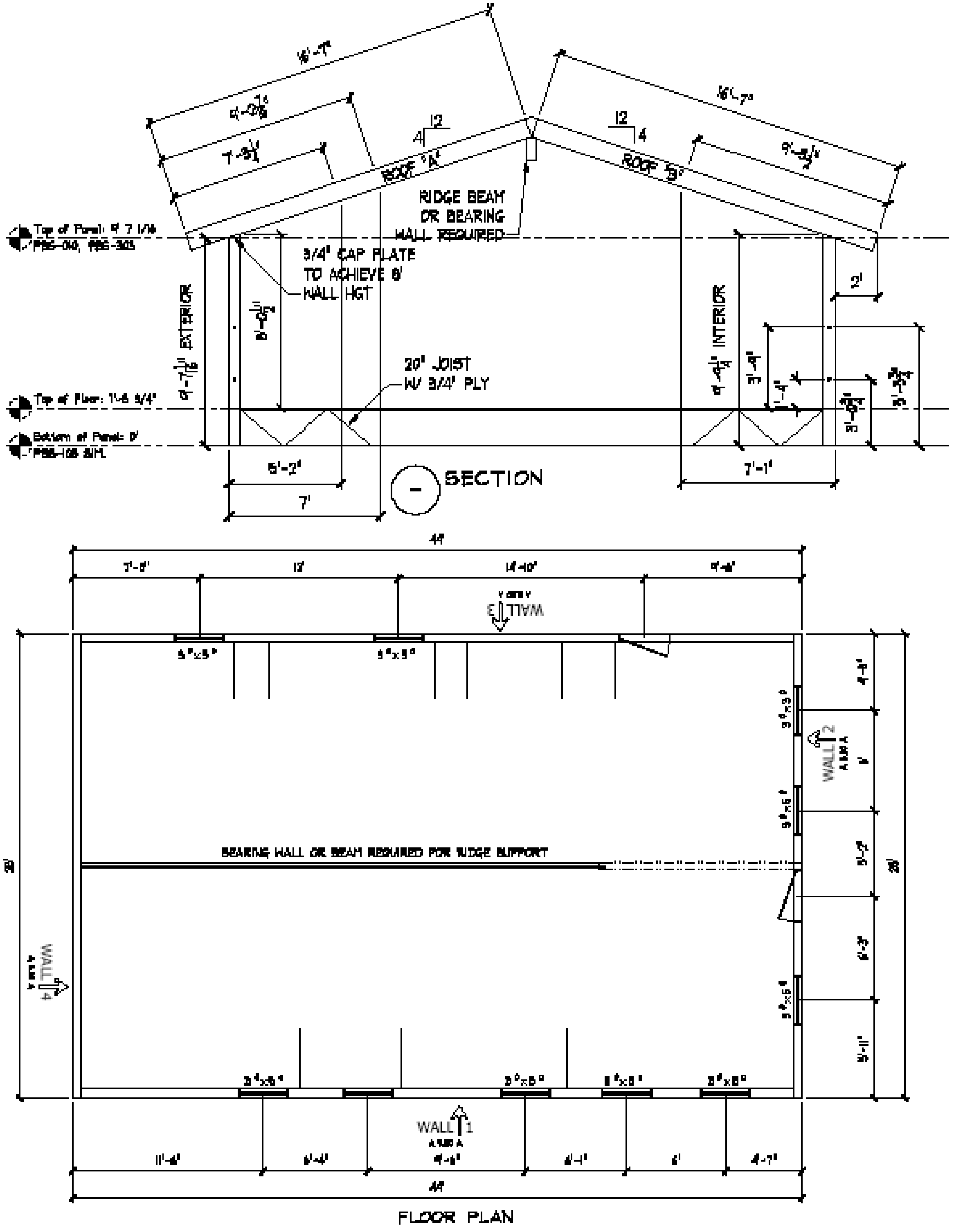

Figure 19. Basic section and structure requirements. The extended overhangs are SIPS, which provides substantial labor savings compared to site-assembled roof extensions. The drawing shows a partial ridge beam and bearing wall. The house was constructed with a continuous ridge beam with two intermittent

structural support points that carried all the way down to a spread footer located below the walkout lower level floor.

3. Site Characterization and House Orientation

Selecting a site that allows an orientation to the south in the mixed-humid climate will make it easier to reach 40% energy savings. This may mean picking lots or sites with views from the house to highlight those that are predominately to the south. Allow for vegetative screens on the west side to minimize the impact of the hot sunny summer afternoons on the cooling load attributed to the building walls. Select the plantings carefully so that their mature height does not block solar access to the roof collectors. Southern sloped lots are best for capturing maximum daylight year around, winter time passive heating, and ease of shading to minimize unwanted solar heat gain in the summer. Southern sloped lots that allow walkout lower levels not only capture more daylight and passive heating but also provide lower-cost space and thermal mass, if insulated and ventilated correctly, that contributes to annual energy savings and lower peak space heating and cooling loads.

In planned sustainable communities that ultimately want at least half of the house roof space preserved for PV panels and solar hot water collectors and do not want the modules to make a major visual statement from the street or the back yard decks, lots may be laid out with the longer dimension perpendicular to the street. This also allows for high density “streetscaping” in traditional neighborhood developments (planned urban developments) that continue to gain popularity in 2008. The narrow lot dimension reduces the street paving and utility infrastructure and allows land somewhere else in the development to be preserved. The garage placement could easily be located in the back of the house with an alley entrance. The ZEH5 plan provided in this report fits this growing need.

High performance house development, with street and lot layout that is conducive to 40% energy saving houses as initially built should always allow for the longer term capacity to add solar PV and solar water heating. The general solution is to develop conservation communities with the housing in higher density patterns. The smaller lots are more conducive to the ZEH5 shotgun-style house plan detailed in this report. Planned urban developments or conservation developments are allowed in many building zoning ordinances. Thus keeping the same number or more lots and optimizing for the maximum number of solar access lots gets the development off in the right direction for reaching zero peak energy and ultimately zero annual energy. Preserving land gives the whole development the flexibility to include natural noise barriers, maximize solar access, and increase lot value. A general rule of thumb in East Tennessee is that every foot of road, with storm water, sewer, and potable water, adds $325-$400 to development cost (Henry, 2007). This does not count excavation, which can vary depending on the amount of rock. Infrastructure cost savings can be put into more thoughtful layout of small, deep, long, narrow lots with minimum road and utility distribution expense and maximum solar roof access.

ZEH5 was modeled using Energy Gauge (FSEC 2006) and then rotated in each cardinal direction, north, south, east, and west. The heating and cooling energies for a south orientated ZEH5 are shown in Table 4. Table 10 shows the impact on heating and cooling energy if the house is orientated in other directions.

Table 10. Increase in calculated heating and cooling loads for ZEH5 when modeled house is oriented to east, west, or north

	% higher than true south orientation
East	4.7%
West	4%
North	2.5%

4. Envelope Specifications

Table 1 highlights the envelope technologies used in these test houses. The total daily energy costs for these houses ranged from $0.69 to $1.04 per day, compared to $3.36 per day for a benchmark house (ASHRAE 2005, ASHRAE 2006A, ASHRAE 2006B, ACEEE 2006, FEMP 2006).

4.1 Foundation and Crawl Space (Walkout lower level)

Figure 20 shows an exterior insulated foundation similar to that used in ZEH5. ZEH5 actually used a standard 10-in., 2-hollow-core block wall with the floor truss resting on top of the wall rather than the 12-in. and suspended floor trusses as shown. However, the rest of the detail is consistent.

The waterproofing, insulation, and above-grade finish system is from Tremco (www.guaranteedDryBasements.com). The waterproofing is a water-based polymer/asphalt spray-applied membrane as shown in Figure 21. It is applied wet, 60 mil thick, directly to the outside of the below-grade masonry wall after the mortar is dry and all loose aggregate and sharp protrusions have been removed. The water vapor permeance of the waterproofing is reported by Tremco to be 0.08 perm for a 40-mil dry coating using the ASTM E-96 dry-cup method.

Fiberglass drainage board, 2 3/8 in. thick with a density of 6 lb/ft^3, is placed over the waterproofing as it cures, as shown in Figure 22. The walkout lower level wall that is exposed above grade was covered with 9 lb/ft^3 fiberglass board. The higher density was necessary to provide a firmer substrate on which to apply the elastomeric-emulsion-based coating above grade. This insulated board is mechanically fastened to the wall and has mesh reinforcing on the outside surface. The lower-density below-grade board's R-value was measured at ORNL according to ASTM C518 to be 10.0 hft^2 ^{o}F/Btu. The higher-density above-grade board was measured at 10.2 hft^2 ^{o}F/Btu.

The exposed fiberglass above grade is covered with Tremco's "Horizon Foundation Finishing System." Mesh strips are fastened over seams as well as the mechanical fastener indentations. A "fill" material is used to cover these locations to make the insulation a uniform surface for spray-applied elastomeric coating. The preparation around inset windows shown in Figure 23, to place the window inside the drainage plane and still avoid thermal shorts, can be rather labor intensive but is a much better solution to minimizing moisture ingress. Whenever possible the fasteners should be located slightly below grade when only small above-grade wall heights are needed between grade level and the top plate. For larger areas the mechanical fastener indentations will need to be filled and leveled to avoid telegraphing through to the final surface.

The final step is the spray-applied paint. Figure 24 shows this coating being sprayed onto the elastomeric coating. If the paint is applied during high humidity periods, which are common in the hot humid climate and mixed humid climate, avoid touching the surface for at least 24 hours. According to the manufacturer, the 40-mil coating has a water vapor permeance of 6 perms as measured using ASTM E-96.

The foundation system is complete once the footer drains are run to daylight. Figure 25 shows footer drains on both the inside and outside of the first course of walkout lower level block wall. These perforated drains were connected to a 4-in. plastic pipe with no holes pointing downward and run to daylight on the southwest corner of the house. The foundation system in ZEH5 has had no leaks of any kind up to the time of this writing.

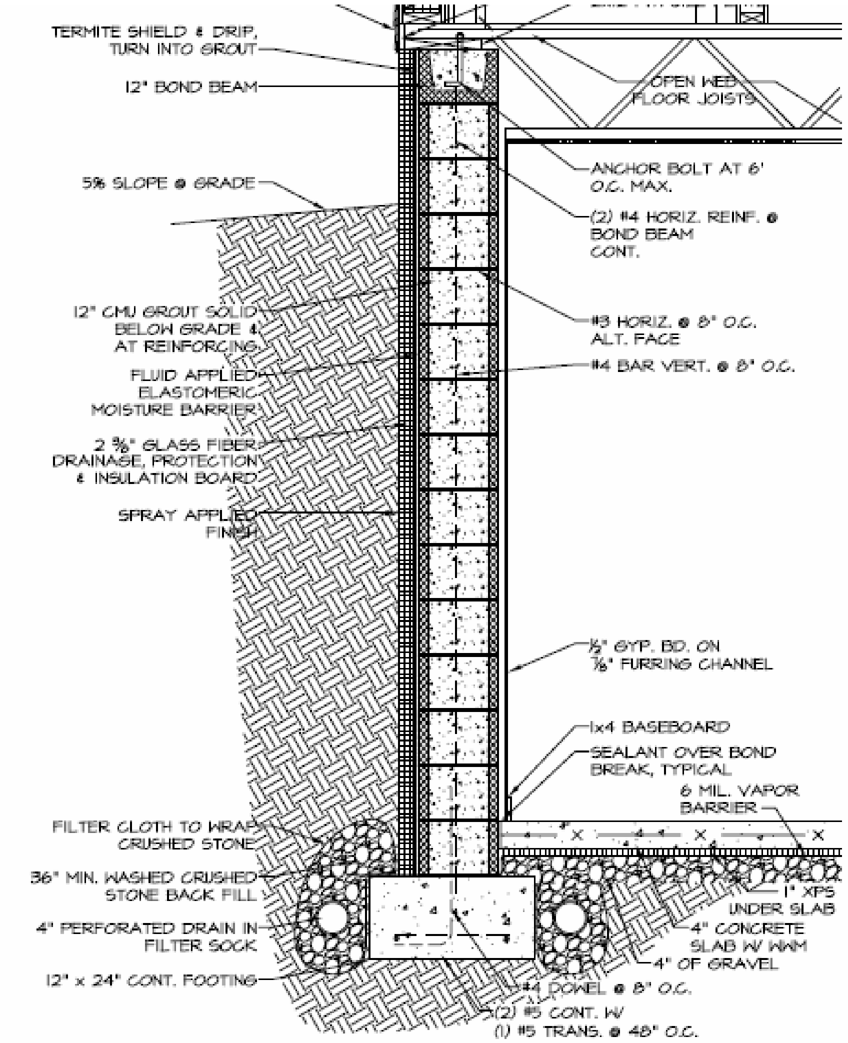

Figure 20. ZEH5 foundation detail, Eason Architects, 2007.

Figure 21. Waterproofing. Note to be OSHA compliant the over cut of the house needs to be sloped 45^o for depths greater than 5 ft deep.

Figure 22. Installation of 4 x 8-ft fiberglass boards sized to cover the waterproofing.

Figure 23. Detailing around inset windows to avoid thermal shorts and minimize water penetrations is very important.

Figure 24. The above-grade portion of the foundation wall receiving final spray covering.

Figure 25. Footer drains run to daylight on both sides of the wall below the walkout lower level floor.

4.2 Walls — Structurally Insulated Panels (SIPs)

We chose SIPs because of the whole wall hot box thermal performance and test room air-tightness tests performed at the ORNL Buildings Technology Center Laboratory test facilities. A SIP wall had the highest whole-wall R-value of 18 systems reported in (Christian 1996). The whole-wall R-value we reported for a conventional 6-in. SIP was 21.6 hft^2/Btu. SIP houses when designed correctly have few thermal shorts, and our first-hand experience with the five test houses demonstrated that they are easy to consistently make airtight. Blower door tests before and after drywall installation in all these houses showed that the final anticipated airtightness was the same as that measured before drywall. This makes it simple to seal the most likely sources of overlooked leaks, which tend to be through the base plate of interior walls where most of the utilities come from the crawl space and unconditioned attics into the conditioned space. We suggest specifying the peel-and-stick tape manufactured by Ashland Chemical (http://www.ashchem.com/ascc/) at panel-to-panel seams. The ridge and wall roof interface as well as all roof and wall seams at the corners and straight panel-to-panel connections are carefully taped as shown in Figure 26.

Figure 26. Peel-and-stick panel tape provides added assurance that panel seams will remain airtight.

SIP manufacturers that provided precut kits for these five near-ZEHs are found at the following web sites:

- Pacemaker Plastics, http://www.pacemakerbuildingsystems.com/ (ZEH1)
- FisherSIPS, http://www.fischersips.com/ (ZEH2)
- Insulspan, http://www.insulspan.com/ (ZEH3)
- Winter Panel, http://www.winterpanel.com/ (ZEH4)
- Premier Building Systems, http://www.premier-industries.com/ (ZEH5)

When working with SIPs the ten most important considerations according to Todd Helton (Habitat for Humanity Loudon County Affiliate Construction Supervisor and Certified Union Carpenter Trainer on ZEH2, ZEH3, ZEH4, and ZEH5) are the following.

1. Trained personnel

Either train yourself or have trained personnel involved in the project at as early a stage as possible. The affordable ZEH project at ORNL has spawned three educational programs:

a. The United Brotherhood of Carpenters of North America has prepared certified training for Union Carpenters. Todd Helton helped develop this training and offers this course at the local Union Hall 50 located next to ORNL in East TN.

b. Cleveland State Community College in Cleveland, TN, now has a two-year program inspired by this research. The program is lead by Allan M. Gentry, Cleveland State Community College Technology Department. The school has approved curriculum for a one-year Zero-Energy-Housing certificate that focuses on 6 courses (17 credit hours). This curriculum is offered with flexible scheduling options to accommodate working adults. Distance and on-line learning options are coming in the future.

c. Four- and five-year college programs are also becoming available that formally teach the building science behind the design and construction of zero-energy buildings with an experiential community outreach project consisting of the design, construction, and monitoring of an affordable ZEH. A good example is the University of Tennessee, Department of Architecture, where a Zero-Energy Building Series is now a formal module within the Environmental Management Controls Course (Arch 342). This module includes zero-energy house design, envelope systems including heat, air, and moisture management, whole-building energy performance simulation tools, HVAC sizing, and energy monitoring and analysis. The students review the five ZEH case studies and then design their own near-zero-energy house. This course was modified for Engineering Students at the University of Wisconsin Spring term 2007. The designs presented in a one hour, open to the community, lecture and one 3-hour workshop were the starting point for a 3-credit engineering elective course. The community seminar gathered a number of practicing architects, builders, engineers, building supply vendors and interested ZEH buyers to serve as a resource base in which the students could draw upon as they worked through their main class project. The project was a set of detailed design drawings and specifications for an affordable house as close to zero energy use as practical for the local UW student Habitat for Humanity affiliate chapter to construct.

2. Protect the panels

Avoid damaged panels — they take more time to install. Coordinate with SIP manufacturer to load and ship panels to minimize handling of panels on site. Panel protection begins with on-site staging by well planned unloading, and stacking high, dry, and flat. It is generally the contractor's responsibility to unload the truck when the SIPs arrive unless predelivery arrangements have been requested. Be prepared to stage the panels in a logical manner, with first up at the top of the pile closest to the foundation.

3. The right equipment

This list includes a boom truck and proper rigging for lifting the ridge beam and SIP ceiling panels. An all-terrain forklift will also come in handy. For the occasional panel adjustment, foam hot wires and panel (beam) cutter should be on site. Beam cutting attachments are available to fit worm-drive circular and electric chain saws. If the foundation layout is not square you may have to cut one or more of the panels. Foam scoops are usually supplied as part of your SIPS package. The BARBEQUE starter type foam scoops have a radius in the corners of about ½ in. and do not square the corners so you have to make another pass down each side with the iron turned 90 degrees to square the corners. On all five of the test houses the SIP manufacturer provided the caulk; one provided a power caulker. ZEH5 has 930 ft of panel seams. The wall/floor and wall/roof each require 4 beads of caulk totaling 1792 linear feet of caulk. The wall/wall and roof/roof seams each take 6 beads of caulk totaling 3492 feet of caulk. The ridge detail requires 8 beads of caulk totaling 416 feet. This totals 5092 ft of caulk. That is going from goal line to goal line on a football field 17 times. Get a power caulker.

4. Foundation accuracy

There is less tolerance in SIP construction than in stick construction for lack of plumb, level, and square. The top of the foundation needs to have provisions for a termite shield and capillary break. This can be an aluminum flashing traversing the top of the foundation from inside to outside the wall surfaces. It is also important that the outside skin of the SIP be fully supported to avoid creep and loss of structural integrity. Double-check to make sure you have the right dimensions for the footer, foundation wall, and floor on the design drawings, and follow up with measured confirmation of plumb, level, and square of the footer, foundation wall, and floor during construction. The foundation for ZEH5 was not as square as desired. The end result was that a 4-in. SIP wall section needed to be fabricated on site and added to the North wall.

Figure 27 shows the foundation/floor/SIP wall detail used on ZEH5. Some floor truss lengths can be slightly shortened on site. This feature is recommended to allow unanticipated adjustements to make sure a good seal can be made at the floor/wall interface. The outside facing of the SIP must have continuous structural support the full length of the bottom edge. It would be best to leave a small gap between the SIP wall and the end of the floor trusses (install backer-rod and caulk seal) than to hang the SIP face over the edge of the top plate. The concrete subcontractor needs to understand that a SIP foundation must be closer to square, plumb, and level than the typical residential construction industry accepted standard.

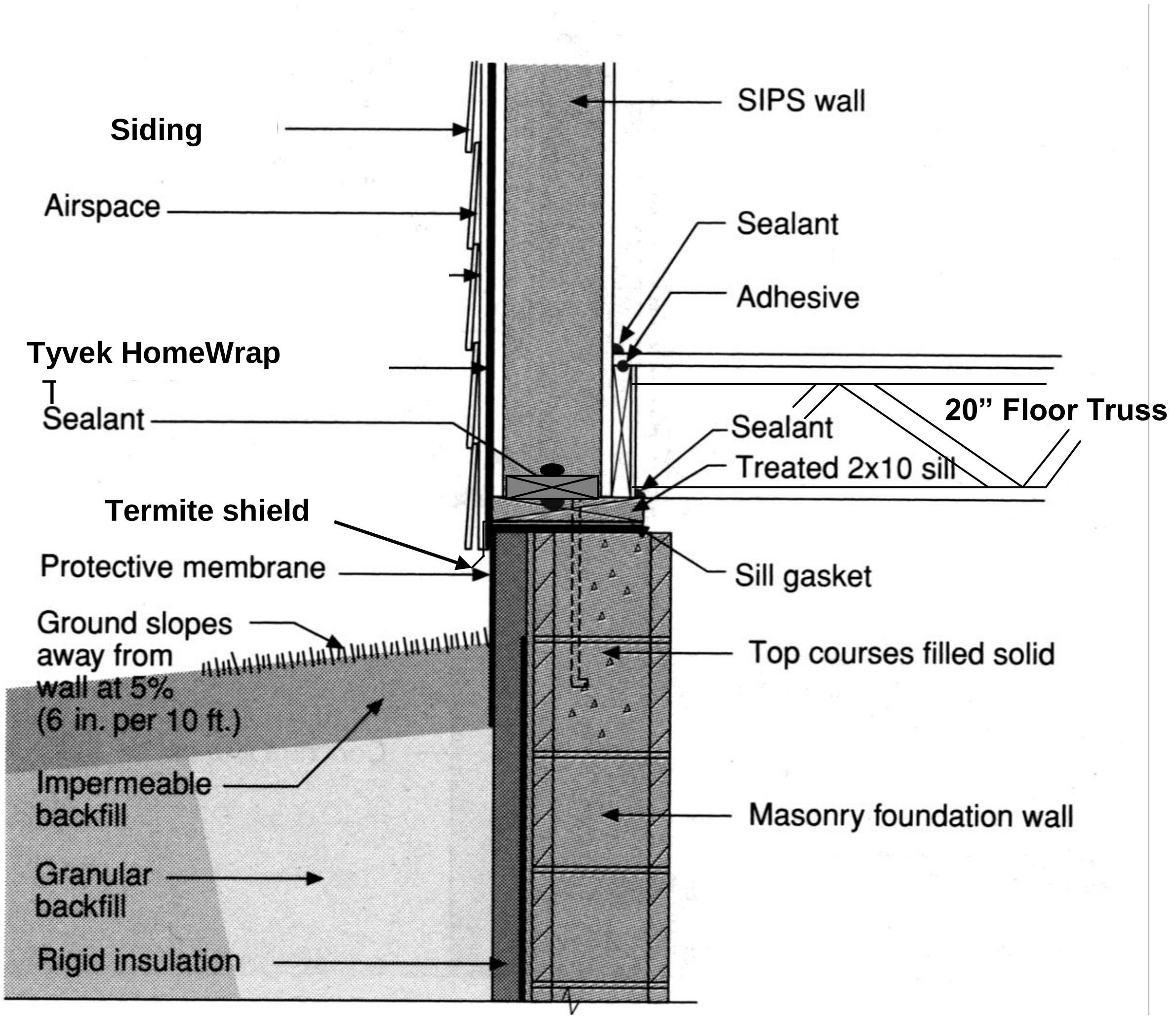

Figure 27. ZEH5 Foundation/floor/SIP wall detail.

5. Drain plane

> “*Water damage is the worst thing that could happen.*”
> — Todd Helton, Union Carpenter

The above grade wall drainage plane in the ZEH’s is attained by wrapping the house with DuPont Tyvek (www.tyvek.com) and making sure the window/SIP interface is correct. This includes providing pans that drain only to the outside under each window and door as shown in Figure 28. The drainage plane must be continued at the base of the first floor by providing flashing that directs any wind driven rain water away from the wall at the wall/foundation junction.

With a SIP roof it is also recommended that a roof drainage plane be provided. Figure 29 shows the drainage plane between the #30 felt paper and the raised metal seam roof. This gap not only provides moisture control, it also provides a cavity in which natural convection will help keep the hot summer heat from penetrating into the conditioned space and will contribute to the cooling of the underside of the solar modules. The panel clip fastened to the SIP holds the metal roof about 1/4 to 3/8 inch off the #30 felt, providing a continuous drainage area.

Figure 28. Panned window opening.

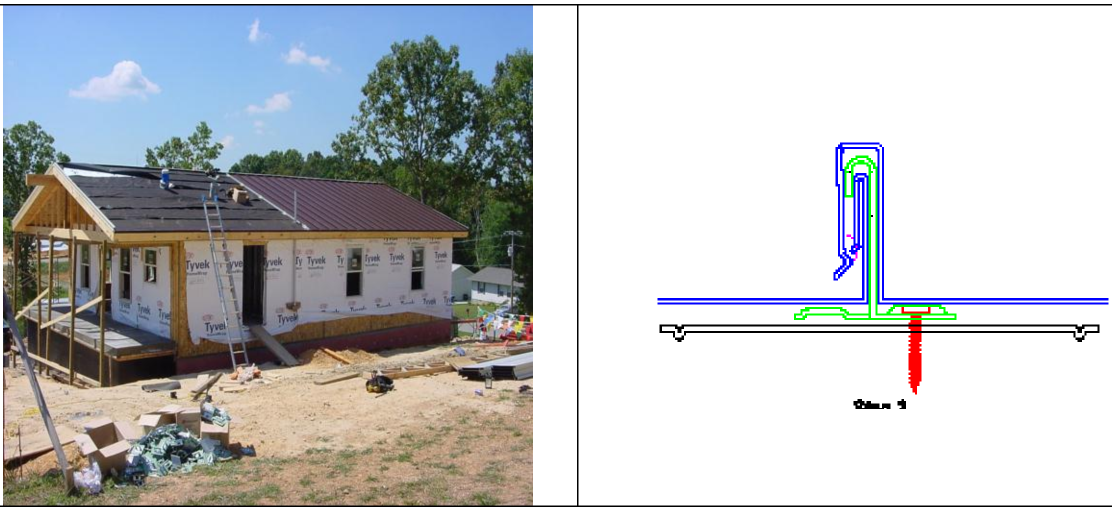

Figure 29. Roof drainage plane under the raised metal roof.
(See http://www.englertinc.com/roofing-panels.aspx?Page=7).

6. Know connection details — minimizing air leakage is a primary goal.

Electrical wiring placement should be designed to stay as much as possible within interior walls. Electric chases are cut in the SIP foam prior to shipping, and when the panels are installed you must provide 1–1/2-in.-diameter access holes in plating, structural splines, and the precast foundation to align with electrical wire chases in the panels. The wall-foundation detail selected in Figure 27 was in part done to make it easier for the electrical subcontractor to run wires from the walkout lower level up into the exterior walls. From the walkout lower level the electrician can easily measure the location of each vertical wire chase. All electrical wires are pulled after cutting out the outlet box locations and prior to setting electric boxes. The boxes are threaded onto the wires and set in the SIP. Apply low expanding foam sealant around the box and in the chase once all the wires are pulled to block this potential air leakage path.

When you position ceiling fans and other heavy lighting fixtures be sure the locations are clearly dimensioned on the drawings sent to the SIP manufacturer so they can provide added structural support and electric chases in the SIP ceiling panels. This was done for all the ceiling fans in ZEH5 as shown in Figure 17 and 18 panel drawings. With a little planning the desired location of these fixtures can be aligned with the panel splines and additional solid wood inserted in the panels in the factory. Along the ridge beam is also a good location to include a wire chase.

The ridge detail is important to assure air-tightness throughout the life of the structure. Manufacturers have different favorite details. The five-test ZEH’s each have a different ridge detail. Established SIP manufacturers have been aware of the importance of ridge detailing for a long time. ZEH5 was taped with the peel-and-stick tape applied to the inside surface of all seams. If at the time the panels were installed heavy rain occurred, or the quality of the panel seam caulking and sealing is in anyway suspect, tape it!

Another common leakage point we find is where the exterior door dead bolts have been drilled into the door frames. Careful application of low expansion foam filling the space between the door frame and the rough opening will seal this up.

If your blower door test, run before installation of the drywall on the wall and SIP ceiling, indicates air leakage, tape it! The series of electrical chases and the panel seams create a three-dimensional matrix of potential passages for air to leak into and out of the SIP envelope. Experience with blower door studies prior to installation of the drywall on SIP wall and ceiling systems suggests that you should never detect any air leakage at any panel seams. We always find some leakage at electrical outlets. At 50 Pascal suction, you very quickly can get a feel for what is “typical” and what is “excessive” by simply running your hand over every outlet. Those that are high can easily be sealed at the outlet box. At this point in the construction the wires have been pulled and it is relatively easy to seal the outside of the electrical box while mounted in the SIP.

ZEH5 was blower door tested numerous times and was found to have a natural air change of 0.08. The only taping prior to conducting the test was the six inch fresh air supply. However, when the motorized damper was closed we found no detectable difference in the whole-house air tightness measurements. The mechanical ventilation motorized damper is installed to open when not energized so be sure to shut the HVAC system off and tape the fresh air inlet during the blower door test.

7. Check panel drawing accuracy

Roof panel span tables are available from the SIP manufacturer. Be sure to check that the roof panels are not exceeding the maximum allowable spans between load points provided in the span tables. The span tables for the SIP roof in ZEH5 can be found at < http://www.premier-industries.com/pbs/Page.aspx?hid=320>. The spline detail is shown in Figure 16, PBS-005 I-Joist Spline Connection. The thickness of the roof panel was 8 ½ in. Table 4 on the Premier Building

Systems web site for determining roof transverse loads shows that for a 14 foot span from ridge to eave and this delivers a design load of 70 lb/ft^2 for an L/240 deflection. In general the entire exterior wall needs to be supported all the way to the foundation. The ridge beam generally has several intermittent load points that also must transfer the design load all the way to the ground. Understanding where these load points are located is important to maintain not only the needed structural support within the conditioned space but also to maintain chase ways for HVAC, plumbing, and electrical distribution.

Avoid designs that call for ganged or mulled windows because they are heavy, awkward to handle, and harder to install. They also require more solid wood headers in the SIP panels in place of insulating foam, which has a much higher R-value. The floor plan for ZEH5, Figure 4, shows all windows are separated by at least 2 ft.

8. Attaching solar modules to SIPs

The recommended roofing to cover a SIP roof structure and attach solar collectors is raised metal seam, as shown in Figure 30 (www.atas.com/dutchseam , http://www.englertinc.com/roofing-panels.aspx?Page=7) with reflectance of at least 0.3 in the mixed-humid climate. This is attainable by metal roofs in almost any color. The ZEH5 has an Englert S2000 Series with a brown color and a reflectance of 0.31. This high reflectance for what appears to be a dark roof is due to the use of infrared-reflective pigments in the coating that selectively reflect most of the heat from the sun that comes in the infrared portion of the electromagnetic spectrum. The ZEH5 metal roof panels were sized and shaped on site. Some effort was required to design the exact location of the raised seams so as not to interfere with the roof penetrations for the solar water heater pipes that needed to fall directly over an interior wall chase leading to the solar water tank in the walkout lower level utility room.

Figure 30. Infrared selective coating was used on the brown raised metal roof to cover ZEH5.

The standing seams on the roof allow for attachment of the solar water heater collectors and photovoltaic modules without any roof penetrations. This is advantageous because fewer roof membrane penetrations mean less water leak risk. By using S-5 clipping mechanism (www.unirac.com/s5.htm) shown in Figure 31, the solar modules can be installed on the roof with no penetrations.

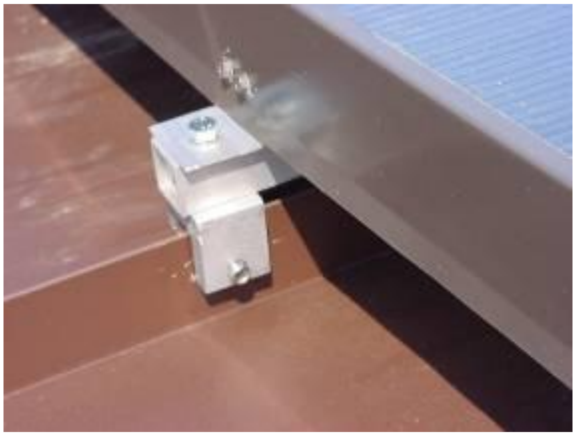

Figure 31. S-5 mini clip holding a solar module on ZEH5 to the raised metal seam.

9. SIP roof installation

The quickest way to get a simple SIP house closed up in a day is to stick with a single ridge beam and have it available on site to lift in place just as soon as the walls are up, plumbed, leveled and squared. With a crane on site, a rigging plan should be developed, i.e. everybody on site wears a hard hat, everybody learns the standard signals for mobile cranes, particularly "stop" (Headley 2005).

Lifting the ridge beam in place with a boom truck is the best method. Use a riggers sling made up of double choker hitches. Have the roof panels and crews in place so that once the crane arrives and the beam is placed, the roof panel placement can commence immediately, so that rigging time and costs are minimized.

Set up a two-person crew on the ground rigging and sealing up the edges of the roof panels, and a second two-person crew installing the panels. The I-joist splines in the ZEH5 roof panels were factory installed on one edge of each panel.

Figure 32 shows the SIP roof panels being installed on ZEH5. A string run, from gable to gable, lines up the ridge, just like setting conventional trusses. Stop blocking installed on the bottom side of the panel a distance equal to the overhang and the thickness of the wall provides a rough stop to get the panel dropped close to the string. One good idea is to not fasten down the leading edge of the ceiling panels until the next panel is in place. This enables the panels to fit together smoothly without a lot of heavy pounding on the panel edges. Aligning the panels and tightening each joint goes quickly and safely with the right work plan and good teamwork. If the roof pitch is steeper than the roof crew is comfortable walking on, install walk boards on the top side of the panels for safety. Alternate roof panel installation with one on each side of the ridge to keep the roof forces balanced during construction.

Figure 32. The SIP roof panel installation.

10. Planning

Lastly and most importantly, have a good plan that matches the resources you have available. This cannot be completely articulated without many site-specific variables, but having a good plan and taking the time to meet with all the subcontractors and key personnel will make a better whole building. Know the location of structural point loads. Continuously check accuracy of shop drawings and that the installation matches the intent of the plans. Make sure that the window and door rough openings are correct and that the HVAC chases are specified and maintained as construction proceeds. Make sure the electrical plan is complete and reflected in the panel cut drawings sent to you for your approval prior to panel fabrication. Keep all plumbing out of exterior walls and keep the electrical in exterior walls to the bare minimum. Run all vertical chases into floor spaces by routing from exterior to interior walls and then up or down. An excellent book to read before you put up your first SIP house is by Michael Morley. (Morley, 2000).

4.3 Windows

For the mixed-humid climate, with all-electric houses and energy costs around $0.094/kWh, it is recommended that the National Fenestration Rating Council R-value be at least 0.34. The solar heat gain coefficient should be no higher than 0.33. The visible transmittance for the windows used on the five test houses was 0.51. The warranty on the test house windows is not prorated and covers glass for 20 years and non-glass parts for 10 years. The specific vinyl-clad wood windows specified for the test houses were Andersen 200 Series tilt-wash, double-hung, low-E, model numbers 244DH3030 and 244DH3050 (www.andersenwindows.com). The ten-window package for ZEH5 is estimated to cost about $2900 from a local window distributor in 2005. If you are going to install interior window trim, specify jamb extensions. This will speed the window installation on site. The rough openings required for the two window sizes used are exactly 3 ft x 3 ft and 3 ft x 5 ft. Before the house wrap is installed be sure to inspect all window and door rough openings in the SIP panels. They are commonly made with a router and are rounded. These may need to be squared off, before installing the house wrap, for tight fitting windows and doors

The windows are installed after the house wrap which was DuPont's Tyvek HomeWrap (www.tyvek.com). The windows are installed as outlined below:

1. The rough opening, which is covered by the house-wrap, is cut out and except for the top, folded into the window buck after checking that rough opening will permit plumb, level, and square window installation. The top flap is folded up and out of the way until the window is installed.
2. Panned with DuPont FlexWrap (see Figure 28).
3. Continuous bead of caulk applied to the house wrap on the outside wall around the rough opening on sides and across the top, not the bottom.
4. Flanged window is installed.
5. Window is centered in opening and shimmed. Pay close attention to the middle part of the window frame. When you are doing drywall returns shim to maintain a uniform reveal.
6. Window leveled and secured through the flange.
7. Jamb flashings on both sides installed so as to cover the entire window flange. Test houses used DuPont StraightFlash (www.tyvek.com) for jambs and headers.
8. Header flashing installed covering the entire mounting flange and extended beyond outside edges of both jamb flashings.
9. Fold the taped up house wrap above the window back over the taped flange above the window and tape.
10. Insulate interior between window and wall framing on all four sides. Use low-pressure expansion foam or backer rod and caulk.

4.4 SIP Roof and Ceiling

For the mixed-humid climate affordable ZEH, a SIP with thickness of at least 10 5/16 in. and 0.95 lb/ft^2 expanded polystyrene core foam and 7/16-in. OSB facers are recommended for the roof. It is suggested that a ridge beam be used in the design of the SIP roof because it is easier to air seal the ridge. An extended overhang on the eaves of 2 ft helps control the solar gain in the summer.

The roof and wall panels should be certified by the manufacturer in accordance to:

1. Structural codes, ASTM E72 for transverse load, axial compressive load, racking shear and header loading, ASTM E695 Impact testing, ASTM E1803 cold creep
2. Fire testing with approved finishes (minimum 15-minute thermal barrier such as ½-in. drywall or 1x wood paneling) shall have passed ASTM E-119 – 1-hour fire resistant wall assembly, UBC 263 – corner room test.

Prior to ordering the SIPs, design loads must be provided, roof transverse loads (live, dead, calculation of the wind load, and total), wind loads (basic wind speed, design wind loads for walls and roof uplift), and Seismic design category. Be sure to include the weight of the solar collectors for the PV and solar water heater in the dead load calculation. Consider including in the dead load calculation tripling the weight of the solar collectors to allow the house to attain true zero energy in the future. If seismic hold downs are required special preplanning is necessary.

The ZEH5 ridge beam was sized to be supported by the posts embedded in the gable wall and two intermediate locations carrying the load down to a spread-footer.

The roof transverse load must be less than the allowable load as provided by the SIP manufacturer that used ASTM E72. ASTM E72, section 11 is a span test that uniformly loads the panel to the point of failure. In the case for ZEH5 with a 14 ft span horizontally from the eave to the ridge. The pounds per square foot measured at failure is recorded, and divided by a safety factor of 3 determined the allowable load. Before the roof fails it will deflect. So when the span tables are generated they are presented as a function of the allowable deflection of the panel. The deflection is measured by taking the horizontal length of the roof span and dividing by a deflection factor of L/240. This means that in ZEH5 the roof when fully loaded will not deflect more than 14/240 or about 11/16 in. The ZEH5 roof used 4 foot wide panels the full length from ridge to the end of the eave, engineered I-joist splines as shown in Figures 16 and 17.

Roof with a ridge beam should be assembled by placing the roof panels in opposition, one on each side of the ridge, working down from gable to gable.

The roof should be covered as quickly as possible with #30 asphalt-impregnated roofing paper (ASTM 4869 Type II). Before covering with roofing paper seal the panel joints with asphalt cement to help prevent the OSB skins from absorbing moisture and swelling with extra strips of underlayment laid over the patch to keep the tar under control. If the SIP roof does get wet be sure it has time to dry before covering. The preferred roofing system is raised metal seam with a space left between the metal roof and the building paper to serve as a drainage plane.

5. Space Conditioning Equipment

5.1 Sizing

A ZEH in mixed-humid climates is well suited for heat pumps, either high efficiency split air source or geothermal. A DC commutating fan motor should be used to meet the ASHRAE Standard 62.2 ventilation air requirements using low fan power.

The suggestions provided here are based on data from the test houses which are described in this report. Table 2 highlights the equipment used in these test houses.

Heating and cooling design loads were calculated using Manual J (eighth edition) for the whole (2632-ft^2) house, which includes conditioning the walkout lower level (Rutkowski 2004). The breakdowns for the heating and cooling design loads are shown in Table 11. The HVAC was sized for the entire house both up stairs and down, even though the first year of measurement only heated and cooled the top floor with 1240 ft^2. These loads were cross checked with the Energy Gauge model for this house and were found consistent with the more detailed modeling imbedded in the DOE 2 model which is the engine used in EnergyGauge version 2.6.06-09/-4/2007 (FSEC 2006).

Table 11. Heating and cooling design load breakdowns for ZEH5, calculated using Manual J

	Heating	Cooling
	Heat loss (Btu/h)	Sensible gain (Btu/h)
Vertical glass	3641	3404
Doors	1761	898
Above-grade wall	4946	0
Below-grade wall	1995	1429
Ceiling	2952	0
Floor	119	246
Infiltration	4124	7573
Duct	0	0
Ventilation	2177	640
Blower heat	0	685
Latent heat	0	3701
Totals	21716	18575

5.2 Geothermal Heat Pumps

ZEH5 used a 2-ton WaterFurnace E-Series unit (model # W024TR111/NBDSSA), with an ECM Blower and R-410A refrigerant (www.waterfurnace.com). The unit was sized to match the Manual J, eighth edition load for the entire house of 2632 ft^2. The design heating load was 21,716 Btu/hr, and the design sensible cooling load was 18,575 Btu/h. The estimated COP at peak was assumed to be 3.66 and the EER, 16. This heat pump did come equipped to help heat domestic hot water with an on-board, factory-installed desuperheater and pump. However, the measurements in ZEH3 suggest that unless considerable space cooling is needed at the same time as hot water is used, little water heating energy would be saved in typical applications.

The ground loop was experimental at the time. The horizontal loop was placed completely within the trenches dug around the house for other purposes during construction. The HDP (high density polyethylene) pipes are filled with an environmentally friendly antifreeze/water solution that acts as a heat exchanger. In the winter, the fluid in the pipes extracts heat from the earth and carries it into the house. In the summer, the system reverses and takes heat from the house and deposits it to the ground. Figure 33 shows where 1500 ft of ¾-in. pipe is installed, in a six-pipe 244-ft trench made up by:

- 109 ft of walkout lower level foundation over cut,
- 63 ft of water trench dug 3 ft deeper to keep the heat exchanger pipe away from the water line so as to avoid freezing of potable water pipes in the winter and heating of incoming cold water in the summer,
- 50 ft of sewer line trench running from the street to the outlet on the south side of the foundation, and
- 22 ft of footer drain trench run out to daylight on the southwest corner of the foundation.

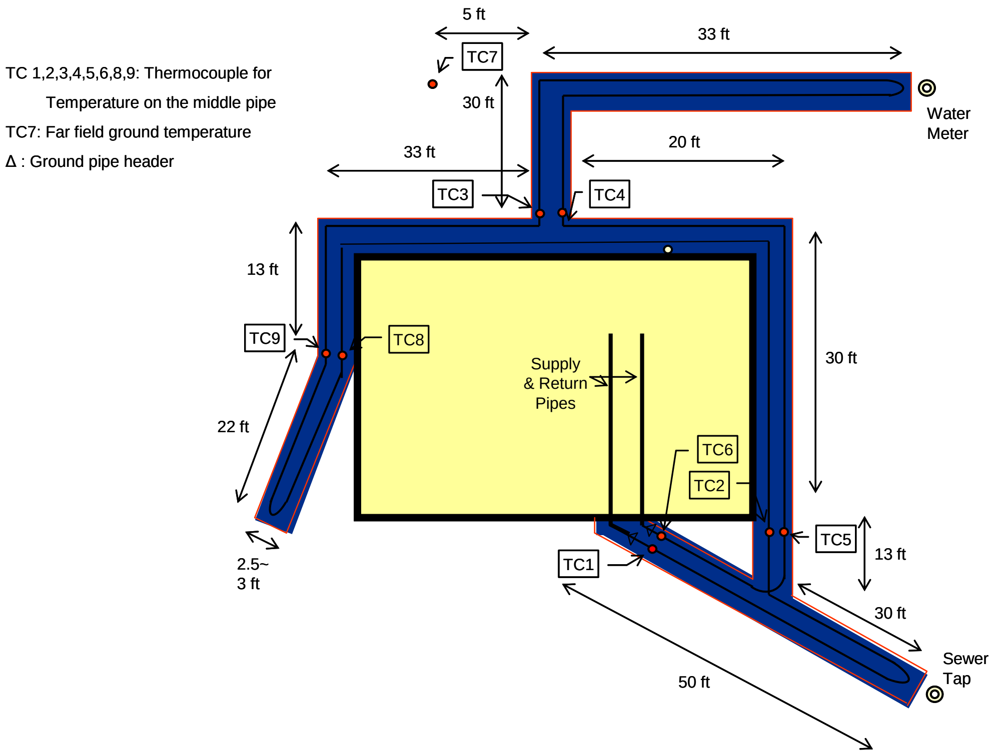

Figure 33. Locations and lengths along trenches where ground heat exchanger pipe was installed for ZEH5.

Three loops of about 500 ft each were run out and back in the full 250 ft of available trench. The length of the loop was determined by WaterFurnace using an in house program and some engineering judgment. This is an identified need to develop an accurate coil design tool that also takes into account the impact of the heat gain and loss from the below grade walkout lower level walls and the close proximity to the sewer run-out. The three loops are headered up to a single 1.5-in. inlet and outlet HDP pipe on the south side and run into the equipment room in a trench under the walkout lower level slab. The inlet and outlet pipe is connected to the circulating pump in the bottom-floor ZEHcor wall near the vertical WaterFurnace unit. No additional excavation required. Two PVC conduits must be provided in the foundation drawings and confirmed placement prior to pouring the footers and/or installation of the foundation wall in line with the geothermal loop header and the placement of the ZEHcor wall, geothermal unit and circulating pump location.

The ¾-in.-diameter pipe was selected in part because it was much easier to install the turn-arounds at the end of each ditch to complete the loop without having to cut and install elbows. The header is buried about 4 foot deep and 8 ft from the south side of the house. The location needs to be well documented and kept in the user manual for the house. Accidental damage while landscaping or making other exterior additions like decks and sun rooms are a common cause of horizontal loop damage. The fact that more than half of the loop is located under other buried service pipes enhances the long-term durability of the ground loop. The common trenching of utilities is frequently used in commercial buildings and does require careful communication and integration during construction between the general contractor and the trades. The construction supervisor must make sure the excavation subcontractor understands that the width and depth of the common utility trenches need to be slightly deeper and potentially a bit wider. This is handled in high performance house construction by major trade statements of work and checklists for job ready and job completion quality assurance programs. Also proper staging in the correct order must be clearly communicated. For example, the water trench needs to be dug, followed by the six-pipe geothermal coil installation, pressure checking the loop for leaks, partial backfilling to proper depth for the water line placement (space at least 3 feet from the nearest geothermal loop and far enough below grade to meet code for freeze protection), and finally complete backfilling to grade.

The standard practice for installation of horizontal ground heat exchangers is to keep the pipe at least 10 ft away from the building foundation footer to avoid freezing the ground and potentially causing foundation structural problems. Since the foundation system is insulated on the outside wall surface with 2 3/8-in., 6 lb/ft^3 fiberglass drainage board, and both external and internal footer drains run to daylight, the soil moisture content should stay near saturation levels, and only minimum soil freezing and no foundation structure freezing is likely to occur in the mixed humid climate. Even if the ground near the footer and surrounding the geothermal pipe should freeze, the insulation board would serve as a slip plane and compression cushion between the expansion and potential uplift of frozen soil. The insulation on the outside of the structural foundation wall keeps the temperature near inside conditions. Even with no added heat in 2006, the walk out lower level was always above 60°F. Added protection is provided by the WaterFurnace unit itself, which has a lockout whenever the water circulation loop temperature drops below 15°F. Heat load at that point is met by the electric resistance backup heaters.

The sewer runout is also separated from the six-pipe system, to minimize the risk of freeze waste water. However, it was felt that in winter warm waste water heat would be partially recovered and in the late summer the waste water flow would actually help cool the soil and carry away reject heat

Figure 34. Geothermal heat exchanger pipe being installed in the trench dug for sewer lines.

from the house. Figure 34 shows the three-loop, six-pipe ground heat exchanger being installed in the sewer trench to the street.

This experimental house has a second grey water waste heat recovery system which can discharge waste water at temperatures as low as 40°F. In the summer this cool water would help provide an even better soil heat sink, potentially reducing the required length of the ground heat exchanger pipe. At this time grey water in house storage is not part of the proposed package for a 40% energy saving house.

During the winter of 2005–2006, the space heating load of the first floor (1232 ft^2) was easily met by the geothermal heat pump, with no supplementary heat and with no reduction in soil temperature next to the ground coils, as measured against a reference in a far-field thermocouple buried at the same average depth (about 5 ft) as the six-pipe loop. The cost to install the loop, test for leaks, purge, charge, and commission the unit was $2000. It took 16 person-hours to install the loop and 8 person-hours to commission the unit. The rule of thumb at the time the installation was performed, in August 2005, was that loops are installed and units commissioned for $1000/ton. The pipe cost is estimated at $250/ton, installation labor at $750/ton. The heat pump is a packaged water-to-air unit that is factory charged with refrigerant, avoiding the problems and higher costs associated with field-charged split systems. The underground high-density polyethylene piping is usually guaranteed for 50 years. ASHRAE Equipment Handbook lists the median service life of a water source heat pump as 4 years longer than that of an air source heat pump.

The geothermal system should be installed by a certified installer. The International Ground Source Heat Pump Association (IGSHPA) is a non-profit, member driven organization that offers both design and installation training http://www.igshpa.okstate.edu/. Thermal fusion fittings were used to connect all pipe sections. Thermal fusion connections are either socket- or butt-fused together to form a joint stronger than the original pipe. A fusing iron that heats up to ~550ºF is used to melt the pipe to each fitting. Before backfilling, the loop should be pressure tested with water or air to be sure there are no leaks. Generally this is at 60 psi for a minimum of 20 minutes. A good web site for general geothermal heat pump information is http://www.ghpc.org/about/how.htm.

5.3 Ducts

The central location of the blower equipment with respect to the floor plan allows short and simple duct runs. In the one-story model of ZEH5, the supply ducts are in conditioned space. The single return and the indoor fan unit are actually considered to be in the crawlspace. For the two-story ZEH5 model, all of the ducts and HVAC equipment are in the conditioned space. The recommended location of the ducts in a single-floor house with a fully insulated cathedral ceiling like ZEH5 is in the conditioned space above the dropped ceiling. The area available for locating the ducts and indoor fan unit above the dropped ceiling in ZEH5 is shown by the shaded area in Figure 35. The ducts are show in this conditioned chase in Figure 36.

The ducts were sized using Manual D (ACCA 2006). The measured air flow in cubic feet per minute (CFM) for each room is shown in Figure 37. The needed CFM for each room comes from the Manual J eighth edition room-by-room load calculation. The main supply trunk should be hard-piped, sealed with mastic, and insulated on the floor, and lifted into place. Insulated ducts mitigate condensation risk. Short flex duct runs are used to connect the main supply trunk with high wall supply registers in every room except the laundry and the bathrooms.

Transfer grills are used in each of the bedrooms with high registers inside the room and low in the hallway. When an internal wall chase is not available, jump ducts should be used to minimize pressurizing the bedrooms and depressurizing other areas of the house when the circulating fan is running and bedroom doors closed. Keeping minimum pressure differences from room to room and from inside to outside helps control unintentional air flow and minimizes unwanted air and moisture exchange through the building envelope. A single central return is positioned on the floor in the central hallway nearest the front door. A low-resistance return path between every room and the return is maintained by transfer grills and jump ducts. In general low return systems are used in all five test houses.

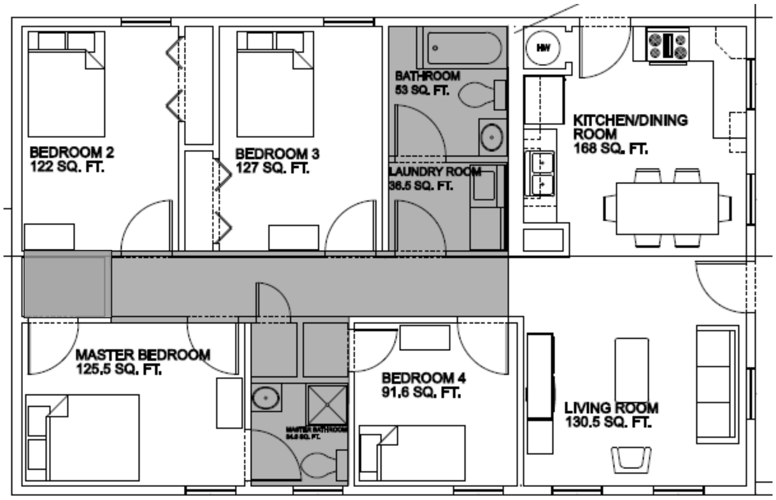

Figure 35. The shaded area marks where the ceiling is dropped to accommodate the HVAC system.

High sidewall supply outlets discharge air parallel to the ceiling toward the outside walls. Figure 37 shows the measured air flows delivering thermal comfort to this space for the one-year measurement period. The correctly sized outlets discharge pattern extends to the opposite wall, and high-velocity air will not drop into the occupied zone. Sidewall outlets perform best during the cooling mode, so they are more suitable for homes that are located in warm climates. The high cathedral ceilings provide an ideal mixing zone for secondary air exchanges between the supply air momentum and the room air. This enables the jet of supply discharge air to entrain a large amount of room air as it develops into a secondary air pattern.

Figure 36. Supply ducts located in the conditioned chase formed by the ceiling SIPS and dropped ceiling.

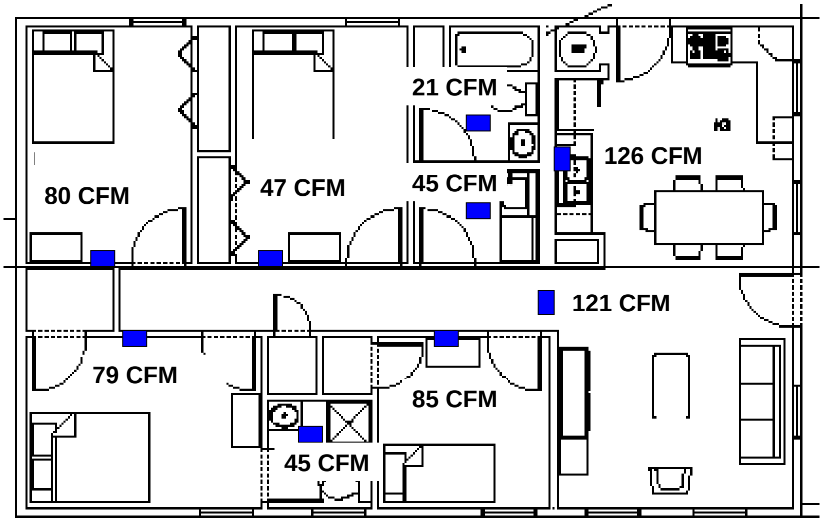

Figure 37. Measured air supply CFM delivered to each room in ZEH5 and location of each high sidewall register (solid blue rectangles).

5.4 Ventilation Air Treatment

ZEH5 has a 6-in. fresh air supply duct running from the north side of the house, through the ZEHcor wall, to the return side of the blower. A manual damper and a motorized damper control the amount of ventilation air. The Air Cycler (www.Aircycler.com) is used to monitor the heat pump compressor. For at least 10 minutes every half hour the motorized damper is opened and when the compressor is not needed to condition the space, the AirCycler turns on the HVAC central ECM fan at low speed and brings in a prescribed amount of fresh air. The design was to meet the current version of ASHRAE 62.2, which in the case of the ZEH5 is 50 CFM for the four-bedroom residence. The AirCycler is wired to also signal a relay which energizes the bathroom exhaust fan to help balance the house air pressure and assure adequate ventilation air for indoor air quality and moisture control.

Figure 38 shows that the HVAC system provided good thermal comfort in ZEH5 from January to December 2006, as measured by the hourly average interior temperatures and relative humidity. The sensors were located 2 ft above the thermostat in the central hallway.

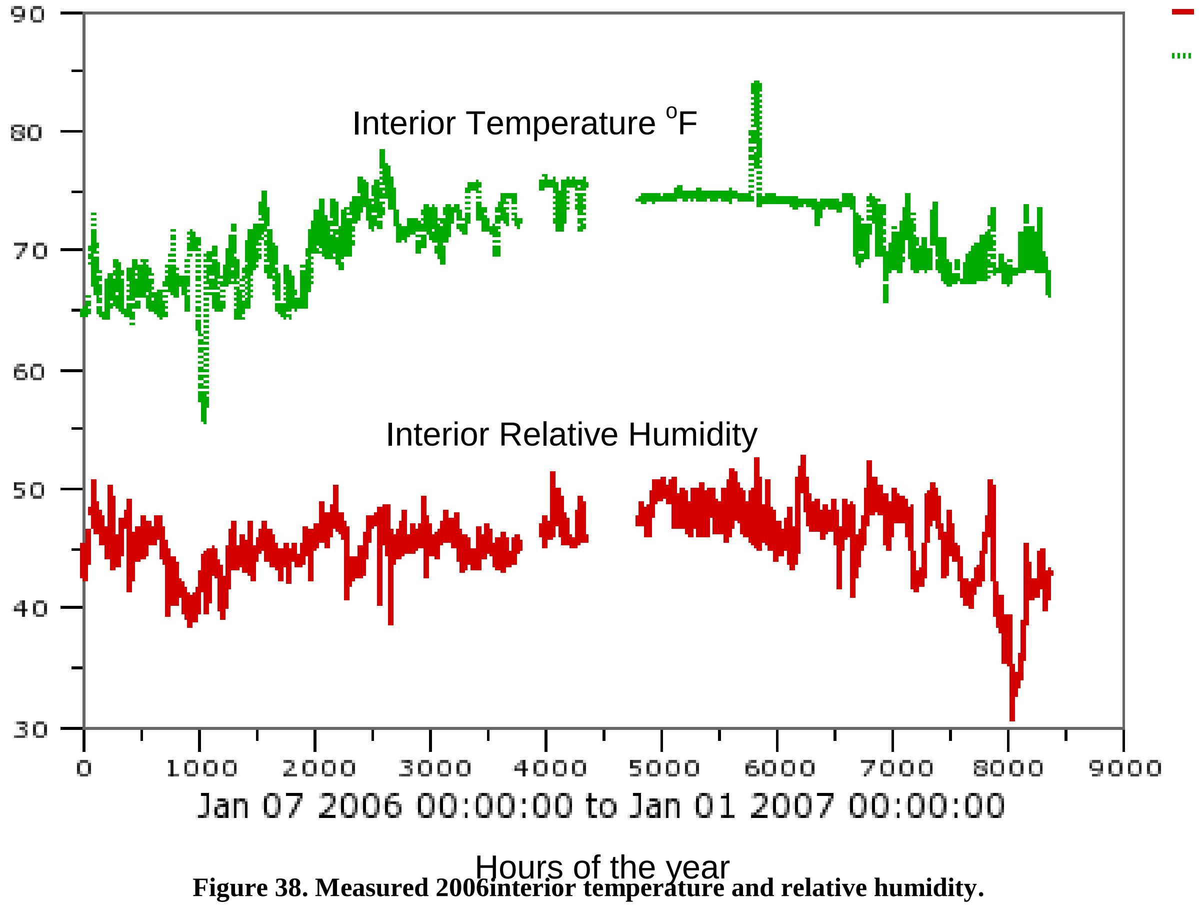

Figure 38. Measured 2006interior temperature and relative humidity.

The Manual J calculations for conditioning the top floor of ZEH5 confirm that a 1.5-ton unit would have been adequate in the cooling season. The air-tight, well-insulated lower level adds 1400 ft^2 to the top level of 1232 ft^2, and the 2-ton unit is a much better match for the 2632 ft^2 ZEH5, as found during the 2007 measurement period when both floors were continuously conditioned.

6. Electrical

6.1 Wiring

If possible, consider minimizing electric wire chases in exterior walls. Chair railing and base molding can be slightly built out to form wire chases. Making these out of wood can help accessorize the interior décor. In both SIP and stick construction the electric outlets are always a major residual leak risk after dedicated envelope air tightening. In ZEH5 the space available above the ridge beam was used as a wiring chase to reach the ceiling fixtures. After the wiring is complete this space is completely foamed. See Figures 39, 40, and 41.

Figure 39. Space above the ridge beam is used for a wiring chase.

Figure 40. Wires being pulled into the space above the ridge beam.

Figure 41. A wedge of foam is provided by the SIP manufacturer to fill the space at the ridge.

After hearing grumbling from the electrical crew on the fourth SIP ZEH we selected a detail for ZEH5 that allowed the electricians to run wires more easily from the walkout lower level into the above grade exterior walls. Vertical wiring chases were cut into the panels every 4 ft starting 2 ft in from each vertical seam. Figure 42 shows how the panel does not sit on top of the floor, but rather at the same level as the 20-in. floor trusses, giving plenty of access for wire fishing.

6.2 Ceiling Fans

The location of ceiling fans and heavy ceiling light fixtures should be clearly marked on drawings sent to the SIP manufactures. The added pullout strength needed for ceiling fans, as well as the location of all embedded wiring chases, can easily be accommodated at the factory. Look for Energy Star ratings on all ceiling fans purchased for your ZEH.

6.3 Lighting

The goal is to install all florescent lighting and LEDs as they become available and affordable. Some ceiling fans more easily accommodate a compact fluorescent bulb than others. Consider using either globe or sconce lighting packages. Under- and above-cabinet fluorescents in the kitchen work very well. Wall sconces work well with compact fluorescents, as shown in Figure 43. In ZEH5 fluorescent bulbs were used through out the house even around the bathroom mirrors. These bulbs are now reasonably priced and LED bulbs with even better lumens/watt than fluorescents are expected to be available as early as 2009 at the time of this writing. A good source for helping you selected your lighting package is the Energy Star Advanced Lighting Package specification: www.energystar.gov/index.cfm?c=fixtures.alp_consumers .

Figure 42. Mounting the wall panels on the side of the floor trusses leaves easy access to run electric wires from the walkout lower level into the vertical wiring chases in the

6.4 PV Systems

Data from the PV system on ZEH4 was used as the onsite solar energy generation for ZEH5 in this report. The roof slope, solar access, and orientation of ZEH4 and ZEH5 are identical.

TVA's Green Power Generation Partners program pays homeowners $0.15/kWh for all the AC solar power generated in a grid-tied arrangement. A schematic of how TVA requires the PV system to be tied to the grid is shown in Figure 44. All interconnected equipment must be UL-listed to the appropriate UL Standards for terrestrial power systems. The system must have a lockable disconnect device accessible outside the house and a standard watt-hour meter to measure the AC output of the generation system located at the same level as the billing meter and within one foot of the billing meter. The systems must be installed in full compliance with all requirements of the latest edition of the National Electrical Code (NEC) (ANSI/NFPA-70). The PV system designed for ZEH5 is described below.

Figure 43. Sconces with compact fluorescents.

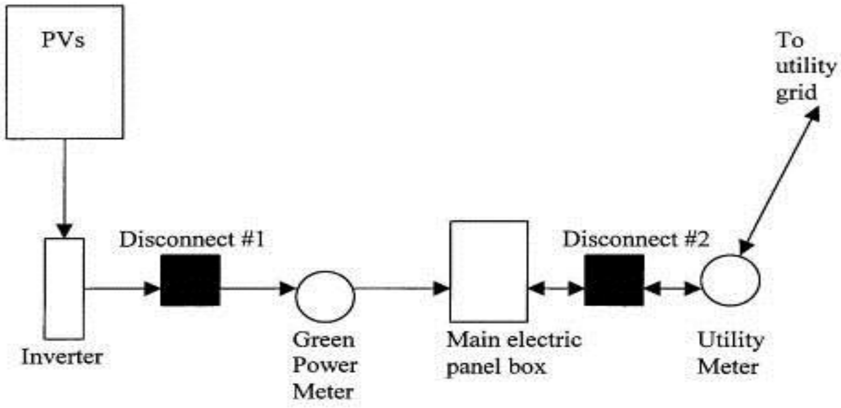

Figure 44. Arrangement TVA requires for tying solar systems to the grid.

6.4.1 PV System Designed for ZEH5

Twenty PV modules were installed on ZEH4 by Big Frog Mountain (www.bigfrogmountain.com/) on aluminum rails bolted to 7-in.-high standoffs. (Figure 31 shows the suggested method of attaching the PV modules to the raised metal seam roof with no penetrations.) The modules are shown in Figure 45 as installed on ZEH2. In May 2004 the distributor cost for these 20 solar panels was $9580. The next most expensive item was the Sunny Boy 2500U SBC w/LCD Inverter at $2905. The electrical and mounting hardware totaled $3308. Labor for system design and installation, which took two workers a day, was $2000. Shipping of this equipment to the site in Lenoir City added another $700. This totals $18,500. In the long term the costs of the modules and the inverter are expected to come down. In December 2007, the world supply and demand situation determines the cost of solar modules to be 11% higher than in May 2004, as shown in Figure 46 (http://solarbuzz.com). This would put the estimated installed cost in December 2007 at about $20,500.

The photovoltaics would be configured somewhat differently if installed today, using 12 180-W polycrystalline modules (Evergreen Solar ES-180s) to make up a 2.2-kWp system. These modules are designed for a maximum allowable pressure of 80 lb/ft^2, which corresponds to a wind speed of more than 125 mph. These modules come with the same power output warranty as the Sharp modules on ZEH2 shown in Figure 45. The 12 modules would take up about 200-250 ft^2 of roof area.

The manufacturer suggests a clearance of at least 4 in. under the module to permit air circulation and cooler operating temperatures. Elevated temperature not only lowers operating voltage; it also shortens service life. The modules are 37.5 in. x 61.8 in. and about 1.5-in. thick. Each module weights 40.1 lb. This amounts to an added dead load to the roof of 721 lbs. The south-facing roof area of ZEH5 is 865 ft^2. The added roof dead load attributable to the solar modules amounts to less than 1 lb/ft^2.

Figure 45. Solar modules sit nicely on the roof of ZEH2. The dark green roof makes for a very pleasing appearance with the dark bluish-green polycrystalline module.

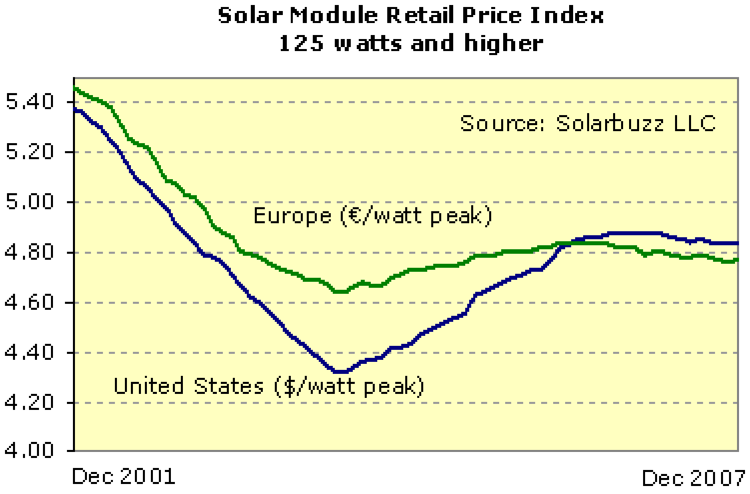

Figure 46. Solar module cost in the United States and Europe, December 2001 to December 2007.

Figure 47. PV modules are clamped to aluminum rails and carefully grounded.

Figure 48. Sunny Boy (red box at left) installed in TVA-approved Green Power Generation hookup.

6.4.2 Inverter

ZEH4 uses a Sunny Boy SWR 2500U inverter, which has on-board islanding protection and meets UL 1741. The unit is 17 x 12 x 8.5 in. and weighs 70 lb. Inverter location should be at eye level, as shown in Figure 48, on the north side under the extended roof overhang. The unit should not be in direct sun and exposure to rain minimized. There is no fan to dissipate heat; instead a heat sink is mounted on the top and it can reach 175°F, so good natural air circulation around the inverter must be maintained. The unit at times will have an audible hum and should not be located close to living spaces in the house. With the high dollar value per ft^2, you may want to give some consideration to mounting the inverter to minimize the risk of theft.

7. Water Heating

ZEH5 was designed with a solar water heater. The collectors are shown in Figure 49. ZEH1, 2, and 4 all used heat pump water heaters, with very positive overall results. In fact, in these particular houses we considered the heat pump water heater to be the preferred option. However, the performance of the selected solar water heater exceeded expectations. Figure 50 shows that for the month of June, if daily hot water demand was less than 50 gallons, the average daily energy consumption for water heating was only 0.328 kWh. We estimated that for the entire year for a household demanding 47 gal per day, the solar water heater would use 0.053 kWh/gal. The best performing heat pump water heater was in ZEH2. There we measured an average daily hot water usage of 36 gallons and total annual energy use of 961 kWh. Using the Energy Gauge model we

Figure 49. SolarRoofs, SkyLine System 5 solar water heater, with 38 ft^2 of solar collector area installed on the roof of ZEH5.

predicted that the total amount of electric back-up energy needed by the solar water heater in ZEH5 for a daily demand of 36 gal would be 470 kWh.

The ZEH5 solar water heater is a SolarRoofs, SkyLine System 5. This water heater was developed partially under a Technology Transfer Program managed by ORNL and funded by the DOE Office of Industrial Technology. One of the appealing features of this system is its ease of installation. The solar collectors are very light and can be placed into position quickly. A very good set of instructions and complete kit of parts was included that accommodated the over all ZEH design concept of minimizing first costs by making the assembly of the entire house very easy and "kit-friendly." (The current installation instructions can be found at http://solarroofs.com/purchase/documents/060503Sys5InstallManual.pdf. We used the August 2005 version of these instructions.)

The 2005 material cost including the 80-gal tank was $2400. The installation took one day — two person-days by two Habitat for Humanity volunteers with modest plumbing experience. It is estimated that the total installed cost value would have been $3200.

This solar system meets the Solar Rating and Certification Corporation standard. Two 20-ft^2 solar panels were mounted on the raised metal seam roof of ZEH 5 as shown in Figure 49. Figure 7 shows that we did make two penetrations for the two pipes leading to and from the water tank. The H5 mini clips, shown in Figure 31, were used for both the solar collectors and the small 20-W PV module for powering the 12V DC circulation pump. The controls are entirely solar-dependent. When the PV collector voltage reaches a minimum threshold, the pump is powered and circulation is initiated. A flow meter installed in the loop measured a maximum circulation of 0.41 GPM. The 80-gal heat exchanger storage tank is a Rheem/Rudd/Richmond Model Number 81V080HE180.

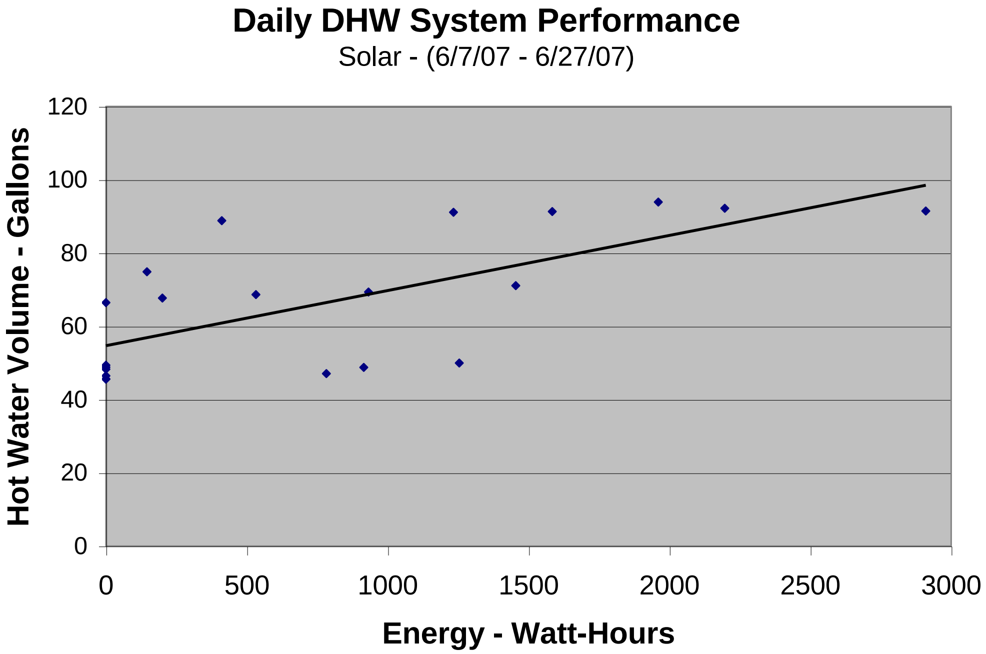

Figure 50. In June, solar water heater brings back-up energy needs to zero.

8. Appliances

You should purchase Energy Star® appliances — fridge, clothes washer, ceiling fans, and dishwasher. Refrigerators and clothes washer manufacturers have made significant energy savings improvements in the last decade. Including more efficient appliances in the mortgage of the new home means that the slightly higher first costs are spread over the life of the mortgage and offset by lower energy costs. Consider also having built-in Energy Star® entertainment center and home office equipment. Be sure to select LCD screens rather than Plasma. The Energy Star ratings are updated periodically, and options are often available that go beyond Energy Star standards.

ZEH5 has a Whirlpool 18-ft^3 Energy Star® refrigerator that was donated by the Whirlpool Corporation. In August 2007 a small Kill-A-Watt meter measured an average daily refrigerator energy consumption of 0.97 kWh/day. The kitchen temperature during that period was 73ºF, though the house functioned as an office rather than a home kitchen. The average daily energy demand for the same type of refrigerator in ZEH4, when it was occupied by three persons during 2006, was 1.3 kWh/day, and its full-year energy demand was 475 kWh. The higher energy use in ZEH4 is clearly attributable to its heavier usage, with many more door openings and groceries stored and removed. The monthly average daily energy demand for the fridge for each month in 2006 in ZEH4, and for August 2007 in ZEH5, is shown in Figure 51.

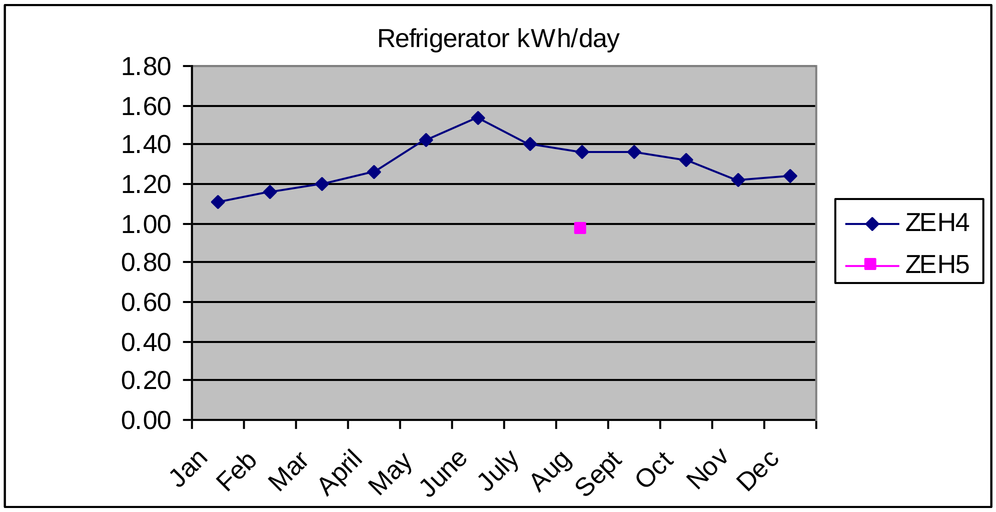

Figure 51. Daily energy demand for an 18-ft^3 Energy Star refrigerator, for all months in 2006 in ZEH4, which was occupied by three persons, and in August 2007 only in ZEH5, which was used only as an office.

9. Summary

This is a Building America 40% energy saving home. This report summarizes the comparison to a benchmark house and shows that, without the solar PV is, predicted to save 47% and with the PV 62%. This 4 bedroom 2 bath 1232 ft^2 house has a HERS index of 39, which qualifies for federal energy efficiency and solar incentives.

Based on a validated computer simulation of ZEH5 with typical occupancy patterns and energy services for four occupants, this all electric house is predicted to require 9323 kWh, 7.5/kWh-$ft^2$of conditioned floor area. The solar fraction for this home located in Lenoir City, TN is predicted to be as high as 41%.

The actual construction cost accounting for market cost of all the donated equipment and labor as well as the cost for a 2.2 kWpeak solar PV system in 2005 totals to $143,300. The panelized construction, premanufactured utility wall (ZEHcor), foundation geothermal system, falling cost for PV, addition of walkout lower level suggest the construction cost per ft^2 for a ZEH5 two-story will be cost competitive. The 2006 construction cost estimate for a finished out ZEH5 with 2632 ft^2 is $222,000 or $85/$ft^2$.

The intention of this report is to help builders and homeowners to make the decision to build a zero energy ready home. Detailed drawings, specifications and lessons learned in the construction and analysis of more than 100 sensors monitoring thermal performance for a one year period are presented. This information should be specifically useful to those considering SIP, foundation geothermal, and solar photovoltaic systems.

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