



Four near Zero Energy Habitat House Prototypes meet Building America 30% Mixed Humid Climate Joule Savings

Jeff Christian, Oak Ridge National Laboratory

September 2006

ABSTRACT

This report assists DOE's Residential Integration Program meet its 30% mixed humid climate Joule savings target by documenting all four near zero energy Habitat for Humanity prototype houses in the form of a Building America Benchmark house comparison. These houses are featured in Building America FY07 Best Practices manual.

The construction methods, building envelope technologies, appliances and equipment of four single-family houses that achieve dramatic energy reductions and approach "net zero energy" use are presented. Each of these houses is compared to the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). This comparison shows these all electric houses saved 44-47% energy compared to the Building America Benchmark. When the solar PV system generation is added to the near zero energy houses in the comparison to the Benchmark, which has no solar, the source energy savings goes up to 56-62%. The analysis shows that these prototypes could meet the 30% energy savings criteria with out the geothermal system, heat pump water heaters, and 2-2.2 kW peak solar PV systems.

Energy costs per day, based on measured data and November 2006 local residential electric rates in Lenoir City, TN of \$0.07/kWh, for these all electric houses are \$1.04 for ZEH1, \$0.91 for ZEH2, \$0.81 for ZEH3, and \$0.77 for ZEH4. These costs are based on an electric utility credit of \$0.15/kWh for all solar AC power produced by the houses. Based on measured data the percentage of total energy load supplied by the PV systems for these houses ranged from 20% to 27%.

Based on the EnergyGauge USA version 2.42 modeling (FSEC, 2006), using the Building America Benchmark comparison method, and local energy rates in November 2006 of \$0.07 /kWh, and solar buy back of \$0.15/kWh the costs per day is \$0.78 for ZEH1, \$0.72 for ZEH2, \$0.70 for ZEH3, and \$0.58 for ZEH4. These modeling prediction values are \$0.11 to \$0.19/day lower than the predictions based on measurements from the occupied houses. Based on the Building America Benchmark comparison to these prototypes energy efficiency modeling predicts these houses could meet 22-30% with the measured solar PV generated onsite.

These rather modest 1060-1200 ft² houses, built between 2002 and 2004, had construction costs of about \$100,000, including the cost of the rooftop solar PV systems. With a trained construction superintend these houses could be rapidly assembled by work crews with limited skills making them ideal for large scale rebuilding after disasters.

Introduction

Four near-zero-energy prototype houses are in Lenoir City, Tennessee a Mixed Humid Climate location with about 3600 heating degree days. The size ranges from 1060 to 1200 ft². Three of the houses have crawl spaces; the fourth has a walk-out full basement. The design, construction, and monitoring of these single-family houses lead to dramatic reductions in energy consumption and approach “net zero energy use.” (A net-zero- building is one that produces as much energy as it consumes on an annual basis.) The houses were built through collaboration with Habitat for Humanity, U.S. Department of Energy (DOE)¹, Oak Ridge National Laboratory (ORNL), the Tennessee Valley Authority (TVA), and several building component industries. The houses were designed by ORNL and Building America teams and constructed by Habitat for Humanity Loudon County Affiliate. For more detail on the test site and floor plans for all four test houses see (Christian 2006c).

During the construction of the houses sensor systems were installed that measure performance characteristics. The energy performance of each of the houses was compared with that of a “base house” — a Habitat house of similar size and built in the same development, but without advanced energy features (Christian ACEEE, 2006). The data show that during the monitoring periods the first house (ZEH1) used 46% less energy from the grid than the base house, and the second, third, and fourth houses built (ZEH2, 3, and 4) used between 52 and 54% less energy. The percentage of total energy load supplied by the photovoltaic (PV) systems for these houses ranged from 20% to 27%.

In this paper energy consumption of the test houses are also compared to the Building America Benchmark. Figure 1 shows the Energy savings of the ZEHs to the Building America Benchmark, without accounting for the solar PV, range from 44 to 47%. Figure 2 shows the same comparison but includes the PV solar and finds that the source energy savings range from 56 to 62%. These are 10 -12% higher than the measured results which are based on actual thermostat settings and different occupant “other energy uses”. The Benchmark modeling takes occupant variations out of the comparison.

Figure 1 Comparison of the Energy Consumption of the Building America Benchmark to ZEHs without accounting for the solar PV.

¹ Building America is a public-private partnership dedicated to improving the energy efficiency of housing through research and working to change housing construction practices. www.eere.energy.gov/buildings/building_america/.

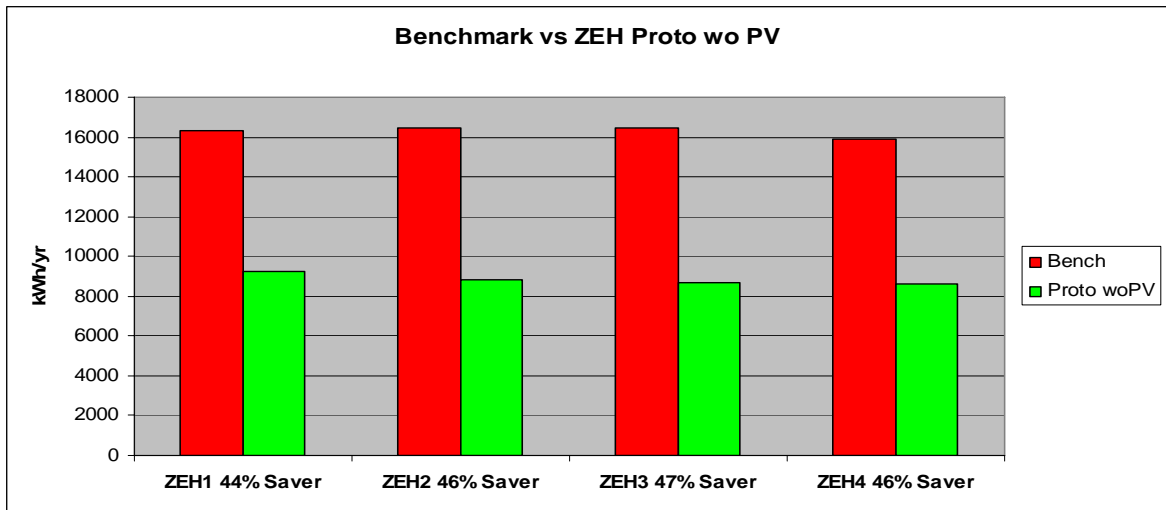
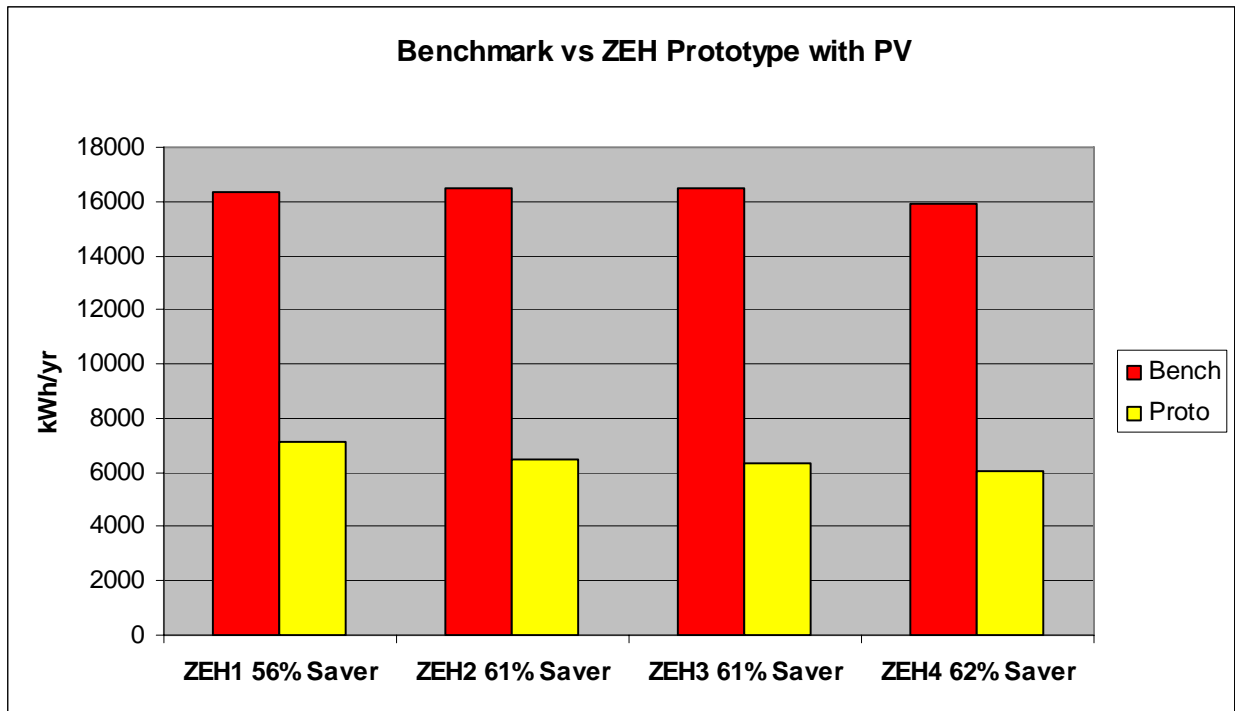


Figure 2 Comparison of the Energy Consumption of the Building America Benchmark to ZEHs with the solar PV.



Energy-Efficient Technologies

These four near-zero-energy houses were originally designed to surpass by 50% the energy efficiency achieved in the DOE Building America Benchmark (Hendron 2005). The Building America modeling process generates the analysis to support that these homes can meet affordably the 30% mixed humid joules goals. The Habitat Affiliate has adapted the air tightness

practices, locates the ducts inside the conditioned space and uses at least SEER 13 heat pumps. All four of these houses without the heat pump water heater, geothermal and solar PV technologies have documented greater than 30% energy savings as a result of the analysis presented in this paper.

The building envelope and mechanical features of the houses are listed in Tables 1 and 2. (Christian 2006c). Each house has a rooftop solar photovoltaic (PV) grid-tie system with a rating of about 2 kWp. Surplus energy flows 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.

Supply mechanical ventilation is provided in compliance with American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62.2 (ASHRAE 2004). An extensive moisture management package is provided in all four test houses.

Tables 1 and 2 list building envelope and mechanical features used in the four near-zero-energy houses and in the baseline Habitat house used for comparison.

Table 1 Building Envelope Features of Near-ZEHs and a Base Energy-Efficient House

House	ZEH1	ZEH2	ZEH3	ZEH4	Base
Floors	1	1	1	2	1
Area (ft ²)	1056	1060	1060	1200	1060
Occupancy	Nov 2002	Dec 2003	Dec 2003	July 2004	June 2000
Foundation	Unvented Crawlspace	Mechanically vented crawlspace in winter only with insulated walls, 2-in. polyisocyanurate boards (R-12)	Unvented crawl space with insulated walls, 2-in. polyisocyanurate boards (R-12)	Walkout basement with insulated precast (nominal steady-state R-16)	Vented crawlspace
First floor	6.5-in. SIPs 1# expanded polystyrene (EPS) (R-20) structural splines	R-19 glass fiber batts, ¾-in. extruded polystyrene boards installed on bottom side of 9½ in. I-joist (R-24)	R-19 glass fiber batts, ¾-in. extruded polystyrene boards installed on bottom side of 9½ in. I-joist (R-24)	Concrete slab	R-19 glass fiber batts (R-17.9)
Walls	4.5-in. SIPs 1#EPS (R-15) surface splines, house wrap, vinyl	4.5-in. SIPs 2#EPS (R-15.5) structural splines, house wrap, vinyl	6.5-in. SIPs 1#EPS (R-21), structural splines, house wrap, vinyl	2nd floor 4.5-in. SIPs polyisocyanurate pentane blown (R-27), surface splines	2×4 frame with R-11 glass fiber batts, OSB sheathing, (R-10.6)
Windows	9 windows, 0.34 U-factor, 0.33 SHGC, sill seal pans	8 windows, 0.34 U-factor, 0.33 SHGC, sill seal pans	8 windows, 0.34 U-factor, 0.33 SHGC, sill seal pans	10 windows, 0.34 U-factor, 0.33 SHGC, sill seal pans	7 windows, U-factor 0.538
Doors	2 doors, one solid insulated, one half-view	2 doors, one solid insulated, one half-view	2 doors, one solid insulated, one half-view	3 doors, one solid insulated, one full-view, one half-view	2 doors, one solid insulated, one half-view
Roof	8 in. SIPs 1#EPS (R-28), surface splines	6.5-in. SIPs 2#EPS (R-23), structural splines	10-in. SIPs 1#EPS (R-35), surface splines	8-in. SIPs, polyi, pentane blown (R-45), surface splines	Attic floor blown glass fiber (R-28.4)
Roofing	Light grey hidden raised metal seam, 0.31 reflectivity ¹	15-in. green standing 24-GA steel seam, 0.17 reflectivity	15-in. green standing 24-GA steel seam, 0.23 reflectivity	Light gray metal simulated tile, 0.032 aluminum, 0.31 reflectivity ²	Gray asphalt shingles, 0.18 reflectivity (Parker 1993)

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 strandboard; SEER = seasonal energy efficiency rating; SHGC = solar heat gain coefficient; SIP = structural insulated panel; XPS = extruded polystyrene.

1. (http://www.energystar.gov/ia/products/prod_lists/roof_prods_prod_list.pdf), 2. (http://portal.atas.com/dnn/Portals/57ad7180-c5e7-49f5-b282-c6475cdb7ee7/ATAS%20Standard%20Colors%20Reflect_Emitt.pdf)

Table 2 Mechanical Features of Near-Zero-Energy Houses and Energy-Efficient Base House

House	ZEH1	ZEH2	ZEH3	ZEH4	Base
Solar system	48 43-W amorphous silicon PV modules, 2.06 kWp, 5.3% efficient	12 165-W multi-crystal silicon PV modules, 12.68% efficient, 1.98 kWp	12 165-W multi-crystal silicon PV modules, 12.68% efficient, 1.98 kWp	20 110-polycrystalline, 2.2 kWp, 10.6% efficient	None
Heating and cooling	1.5-ton air-to-air HP, SEER 13.7, 2-speed ECM indoor fan	2-ton air-to-air HP, 2-speed compressor, SEER-14, HSPF-7.8, CFM cooling 700, variable-speed ECM indoor fan	2-ton direct exchange geothermal HP, R-417a, variable-speed ECM indoor fan, 3.7 COP@36 F	2-ton air-to-air HP, SEER 17, variable-speed compressor, variable speed ECM indoor and outdoor fan, 8.1 HSPF	Air-to-air 2-ton HP, SEER 12
Mechanical ventilation	Supply to return side of coil	Supply to return side of coil, CO ₂ sensor, bath fan exhaust	Supply to return side of coil, bath fan exhaust	Supply to return side of coil, bath fan exhaust	None
Duct location	Inside conditioned space	Inside conditioned space	Inside conditioned space	Inside conditioned space	In crawl space
Water heater	Integrated HPWH linked to unvented crawlspace	Integrated HPWH, linked to crawl-space that has motorized damper	Desuperheater for hot water, EF 0.94	HPWH vented to half-bath that is exhausted for ventilation	Electric EF~0.89

Prototype Test Houses

ZEH1s 4.5 in.-thick walls, 6-in. floors, and 8-in. ceiling are all constructed of SIPs made with expanded polystyrene insulation. The ACH @ 50 Pascals is 1.35. The HVAC unit is a 13.7 SEER 1.5-ton air-source heat pump with a 2-speed indoor circulating fan. The occupants kept the temperature at about 75° year round, on average. The Building America Benchmark modeling requirements set the thermostat at a fixed 71°F during the heating season and 75°F during the cooling season. This is one of the explanations for the better performance reported out from the modeling effort compared to the measured data. The roof is gray reflective metal, hidden raised seam, with a 4/12 pitch. On the roof is a 2-kWp 48-panel solar PV system. Hot water is supplied by a 50-gal HPWH installed to recover waste heat from the refrigerator as shown in Figure 4. For more detail see (Christian 2006c). ZEH1 also has a heat recovery shower that captures the waste heat from warm water going down the drain to preheat the cold water before it flows into the water heater. The house was equipped with 75% of its light fixtures fluorescent. The benchmark house guidance suggests using 10%. For the prototype modeling results 100% was used. ZEH1 is shown in Figure 3.

Figure 3 ZEH1



ZEH2s wall SIPs have slightly higher density and R-value than in ZEH1, and its ACH 50 is 1.15 ACH. Unlike ZEH1, ZEH2 has an insulated crawl space. The 14 SEER air-source heat

pump is a 2-ton unit with a two-stage compressor and variable-speed indoor circulating fan. The two-stage compressor was selected to provide better humidity control during the summer months. The temperature was kept at about 75° year round. The humidistat was set at 55% RH during the summer months. The actual thermostat setting because of the humidistat turning it down to least 72°F on some occasions resulted in an average measured setting closer to 73.5. This is compared to the modeling which used a fixed 75°F. In the winter the modeling used a fixed 71°F rather than the measured 75. The 50-gal. HPWH shown performed at a COP of 2 (Christian 2006a). The water heater COP in the resistance mode is 0.9. The ceiling is 6.5-in.-thick SIPs, with a slightly lower R-value than the benchmark requirements for modeling, and the roof is forest green metal standing seam with a 6/12 pitch. The PV system, shown in Figure 4, is rated at 1.98 kWp.

Figure 4 ZEH2



ZEH3 has 6.5-in.-thick SIP walls and 10-in.-thick SIP ceiling panels. The ACH 50 rated at 1.09. The biggest difference between it and the other three houses is that its heating/cooling system (2 ton, 16.6 SEER) is a direct exchange geothermal heat pump (Christian 2006c). The green metal standing-seam roof has an infrared-reflective pigmented paint that makes it 35% more reflective than the similar-looking green roof of ZEH2. Both roofs look the same color as seen in Figure 5. It has the same 6/12 pitch (26.6°) as ZEH2.

The PV system, like the one in ZEH2, is a 12-panel system rated at 1.98 kWp. The water heater is a 50-gal. electric resistance unit with an energy factor of 0.94. Water heating is augmented by a desuperheater, a heat exchanger that uses superheated exhaust from the heat

pump compressor to heat water for the hot water supply. The occupants of ZEH3 kept the house thermostat at 68-70° year round.

Figure 5 ZEH3 on the right, ZEH2 in the background



ZEH4, a two-story house, contains 1139 ft² (exterior dimensions 1200 ft²). It was built in two stories, as seen in Figure 6, because of the steepness of the lot. Instead of a crawl space, it has a walk-out basement, opening on the south side, which contains three bedrooms. The basement walls are four T-Mass[®] pre-cast panels of polyisocyanurate insulation sandwiched in concrete. The walls were precast with electrical chases and receptacle boxes installed and with rough openings provided for the windows and doors. On below-grade surfaces, 60-mil waterproofing was sprayed and covered by ¾-in. glass fiber drainage boards. Tmass walls were chosen because they provide thermal mass to store and release heat, aiding in heating and cooling; because they are airtight; and because they aid in moisture management. The top floor SIPs used in ZEH4 are insulated with polyisocyanurate. The ACH 50 rated at 1.64. The roof is light gray aluminum simulated clay barrel tiles and has a 4/12 pitch. The PV system has 20 panels and is rated at 2.2 kWp, about 10% more capacity than the PV systems on ZEH1, 2, and 3.

The heating/cooling system is a 17 SEER, 2-ton air source heat pump with a two-speed compressor and DC commutating indoor fan motor. The water heater is an HPWH. Unlike the other HPWHs in ZEH1 and 2, it draws warm air from the refrigerator compressor and condenser coil year round; also unlike the others, it exhausts cool, dry air into an adjacent half-bath year-around. The ventilation scheme for the house prevents the cool, dry HPWH exhaust from being a comfort issue during the heating season yet helps dehumidify in the summer. Every 20 minutes the fresh air inlet opens and the half-bath exhausts about 40 cfm. ZEH4 has compact fluorescent bulbs in about 75% of its light fixtures. The prototype was modeled with 100% fluorescents. The benchmark house with 10% fluorescents.

Figure 6 ZEH4



The Data Acquisition System

Each prototype houses was equipped with 32 to 53 sensors to record values such as indoor, crawl space, and ambient temperature; indoor, crawl space, and ambient relative humidity; hot water usage; heat pump operation; and indoor CO₂ level (Christian 2006c).

Each house is equipped with two electric utility meters, one to track solar PV system generation and a net meter to track whether the house is using more energy than it produces, or vice versa. The sum of these two meters equals the whole-house energy consumption. The data are analyzed to determine component performance, energy consumption and to calibrate computer models such as the Energygauge model used for the Building America Benchmark results discussed in this paper. (Christian 2006a; Christian 2006b; Christian 2006c)

Measured Energy Savings compared to model predictions

ZEH1, built in 2002, used 10,216 kWh of electricity between March 2003 and February 2004. The rooftop solar PV system supplied 2006 kWh, about 20% of the energy used over the year. About 40% of the PV power was produced at a time in which it was not needed in the house. The PV power was produced mostly on hot summer afternoons and reduced the house's peak load by a daily average of 40% between June and August. Table 3 shows the monthly measured energy usage for ZEH1 from March 2003 through February 2004. Lighting, appliance, and plug loads ("other") accounted for ~60% of the energy used. The occupants of ZEH1 used less than 40 gal of hot water per day

Table 3. ZEH1 Measured Energy Use, March 2003-February 2004

Month	Space heat (kWh)	Space cool (kWh)	Hot water (kWh)	Other (kWh)	Total electric (kWh)	Solar generated (kWh)	Solar sold to utility (kWh)
March	127	0	124	325	575	167	91
April	64	0	146	419	629	195	100
May	0	94	109	460	663	188	90
June	0	204	87	490	781	213	88
July	0	314	74	494	882	209	79

Aug	0	359	70	536	966	219	76
Sept	0	187	82	491	760	195	95
Oct	34	17	117	518	686	159	77
Nov	141	0	138	518	797	121	45
Dec	401	0	187	650	1238	115	15
Jan	473	0	219	540	1232	120	23
Feb (2004)	344	0	196	466	1007	105	25
Total	1584	1175	1549	5907	10216	2006	804
% of total	15.5%	11.5%	15%	58%	100%	20%	

Table 4 presents measured compared to modeled results. The actual weather was not input into the Energygauge model rather TMY tapes were used for this comparison so it is not a true validation exercise. There are two sets of modeling predictions the first titled “Modeled” in column 3 of Table 4, are the actual results used in the remaining of the comparisons discussed in this paper. The Building America Benchmark definitions for fixed thermostat settings, other loads and occupant schedules are used. In the second set actual measured hot water usage and thermostat settings are input into the model. These generally result in a better fit to the measured data as shown in column 5 of Table 4. The internal loads actually used in this house were about 14% higher than the BA Benchmark requirements. No attempt was made to fit the measured other loads into the calibration model. The biggest modeling differences between the measured data and the “Model Calibration” predictions, 11%, occurred for space heating. Overall this is considered a good fit.

Table 4 Modeling results for ZEH1 are compared to the measured data in Table 3.

	Measured	Modeled	Difference from Measurement	Model Calibration	Difference from Measurement
	kWh/yr	kWh/yr	%	kWh/yr	%
Space Heating	1584	1388	-12	1753	11
Space Cooling	1175	1150	-2	1178	0.3
DHW	1549	1705	10	1503	3
Other	5907	4969	-16	5091	-14
subtotal	10216	9212	-10	9525	-7
Solar generation	2006	2080	4	2080	4
Net total	8210	7132	-13	7445	-9

ZEH2 monthly and annual measured data detail can be found in Christian 2006c. Table 5 shows the annual energy usage brake down of the measured results compared to the both sets of modeling predictions, described above. This is by far the worst fit of measured vs. “Calibration Model” predictions. The heat pump experienced some refrigerant charge losses during this monitoring period and is unlikely to have performed up to specifications. This problem is believed to be the reason for the under prediction of the calibration model for both space heating and cooling.

Table 5 ZEH2 Measured Energy Use, April 2004-March 2005 compared to model predictions

	Measured	Modeled	Difference from	Calibration	Difference
--	----------	---------	-----------------	-------------	------------

			Measurement	Model	from Measurement
	kWh/yr	kWh/yr	%	kWh/yr	%
Space Heating	2551	1582	-38	1928	-24
Space Cooling	2018	1052	-52	1120	-44
DHW	961	1402	10	1122	17
Other	4314	4808	11	5292	23
subtotal	9844	8844	-10	9462	-4
Solar generation	2305	2353	2	2353	2
Net total	7539	6491	-14	7109	-6

ZEH3 occupants consumed a total of 11,014 kWh from March 1, 2004 until February 28, 2005 and the PV system generated 2241 kWh. Table 6 shows the actual energy usage in ZEH3. The “other” loads in this house of 7388 kWh were much higher than the Building America Benchmark definition house (4808 kWh/year). The actual measured data was adjusted to account for this high “other load” by reducing it to 5604 kWh. The detailed rationale for this reduction is available in Christian 2006c.

Table 6. ZEH3 Measured Energy Use, March 2004-February 2005

Month	Space heat (kWh)	Space cool (kWh)	Hot water (kWh)	Other (kWh)	Total electric (kWh)	Solar generated (kWh)	Solar sold to utility (kWh)
March	69		108	486	663	231	116
April	0	77	108	489	674	226	100
May	0	319	90	560	969	221	48
June	0	346	76	511	933	213	56
July	0	394	76	569	1039	232	48
August	0	352	76	603	1031	222	41
Sept.	0	290	79	483	852	201	55
October	57	0	99	560	716	154	49
Nov.	50	0	104	738	892	135	37
Dec.	132	0	148	1174	1454	142	28
January	176	0	144	620	940	131	40
February	85	0	171	595	851	133	41
Total	569	1778	1279	7388*	11014	2241	659

* normalized “other” usage to 5604 kWh rather than the actual 7388 kWh

With an adjusted “other” load for ZEH3 of 5604 kWh/year, this all-electric house’s fraction of solar energy collected on site amounts to 24% of the total electric demand of 9230 kWh/year, an improvement of 4% over ZEH1. ZEH2 attained 23% of its total energy needs from the solar PV system.

Table 7 shows the annual energy usage breakdown of the measured results compared to the modeling predictions. The biggest difference between the measured and “Calibration Model” prediction is for space cooling load.. The homeowner kept the thermostat below 70F for much of the cooling season. Adjustments were made to the thermostat settings in the calibration model but this is believed to have impacted the geothermal heat pump efficiency in the measured

data which was not reflected in the model. The model also over predicts the amount of energy needed to heat this house. However note that the absolute difference is very small only 121 kWh. The overall comparison of the total energy usage of ZEH3 based on measurements compared to the “Calibration Model” predictions of only 5% is considered very good.

Table 7 Modeling results for ZEH3 are compared to the measured data in Table 6.

	Measured	Modeled	Difference from Measurement	Calibration Model	Difference from Measurement
	kWh/yr	kWh/yr	%	kWh/yr	%
Space Heating	569	893	57	690	21
Space Cooling	1778	908	-48	1381	-22
DHW	1279	2094	63	1339	5
Other	5604	4808	-14	5453	-2
subtotal	9230	8703	-5	8863	-4
Solar generation	2241	2353	5	2230	-0.5
Net total	6989	6350	-9	6633	-5

ZEH4 occupants consumed a total of 9843 kWh from August 1, 2004, through July 31, 2005 and the solar system generated 2627 kWh. About 46% of the solar was collected at a time when it was not needed in the house. Table 8 shows the monthly and annual energy usage broke down. This all-electric house’s fraction of solar energy collected on site amounts to 27% of the total electric demand of 9843 kWh/year, the highest fraction of on-site generation among the four-house set.

Table 8 ZEH4 Measured Energy Use, August 2004-July 2005

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

Table 9 shows the annual energy usage brake down of the ZEH4 measured results compared to the modeling predictions. The biggest difference between the measured and

“Calibration Model” prediction is for space cooling load. This house had a humidistat that would automatically turn down the thermostat set point a maximum of 2°F if the RH condition was not met. The RH setting was 55% for most of the monitoring period and this was not modeled in the Energygauge model. This is in part the explanation for the higher Calibration Model prediction of cooling energy. However, just as reported for ZEH3 the absolute difference is quite small, only 118 kWh. The homeowner and the equipment installed in this ZEH4 performed very consistently. Very little atypical usage as evident by the other load being very similar to national average data as recommended in the Building America Benchmark house and used in the model.

Table 9 Modeling results for ZEH4 are compared to the measured data in Table 8.

	Measured	Modeled	Difference from Measurement	Calibration Model	Difference from Measurement
	kWh/yr	kWh/yr	%	kWh/yr	%
Space Heating	1711	1328	-22	1767	3
Space Cooling	1016	1072	6	1134	12
DHW	1819	1562	-23	1754	-4
Other	5297	4844	-9	5073	-4
subtotal	9843	8645	-12	9728	-1
Solar generation	2627	2627	0	2627	0
Total	7216	6018	-17	7101	-2

End-use Energy Savings

ZEH1

Table 10 shows the ZEH1 modeling results following the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). EnergyGauge 2.42 model was used to generate end-use energy estimates for the BA Benchmark, Builder Standard and the BA Prototype house. The prototype is the actual ZEH1 with the “Standard Occupants”; i.e. fixed water usages, and thermostat settings of 75 F during the cooling season and 71 F during the heating and “Other Loads”. The total site energy savings of the prototype is 56% of the benchmark. The site generation from the solar PV used is the same as the actual measured solar production for the one year of monitoring. The addition of an energy star dishwasher and cloths washer could have reduced the “Other appliance” value but was not purchased by the ZEH1 homeowner.

Table 10 ZEH1 end-use for the Benchmark, Builder Standard and Prototype.

ZEH1	Annual Site Energy		
	BA Benchmark	Builder Standard	BA Prototype
End Use	(kWh)	(kWh)	(kWh)
Space Heating	4852	4073	1388
Space Cooling	3020	2605	1150
DHW	2696	2695	1705
Lighting	996	996	429

Fridge	668	428	428
Dryer	833	833	833
Range	605	605	605
Other Appliances + Plug	2674	2674	2674
OA Ventilation			
Total Usage	16344	14909	9212
Site Generation	0	0	2080
Net Energy Use	16344	14909	7132

Figure 7 shows the ZEH1 source energy comparison of the benchmark compared to the ZEH1 prototype. The largest savings is due to space heating, followed by space cooling, domestic hot water lighting and the energy star refrigerator. No end use energy savings is assumed for the dryer, range, other appliances and plug loads.

Figure 7 ZEH1 source energy for the benchmark and prototype.

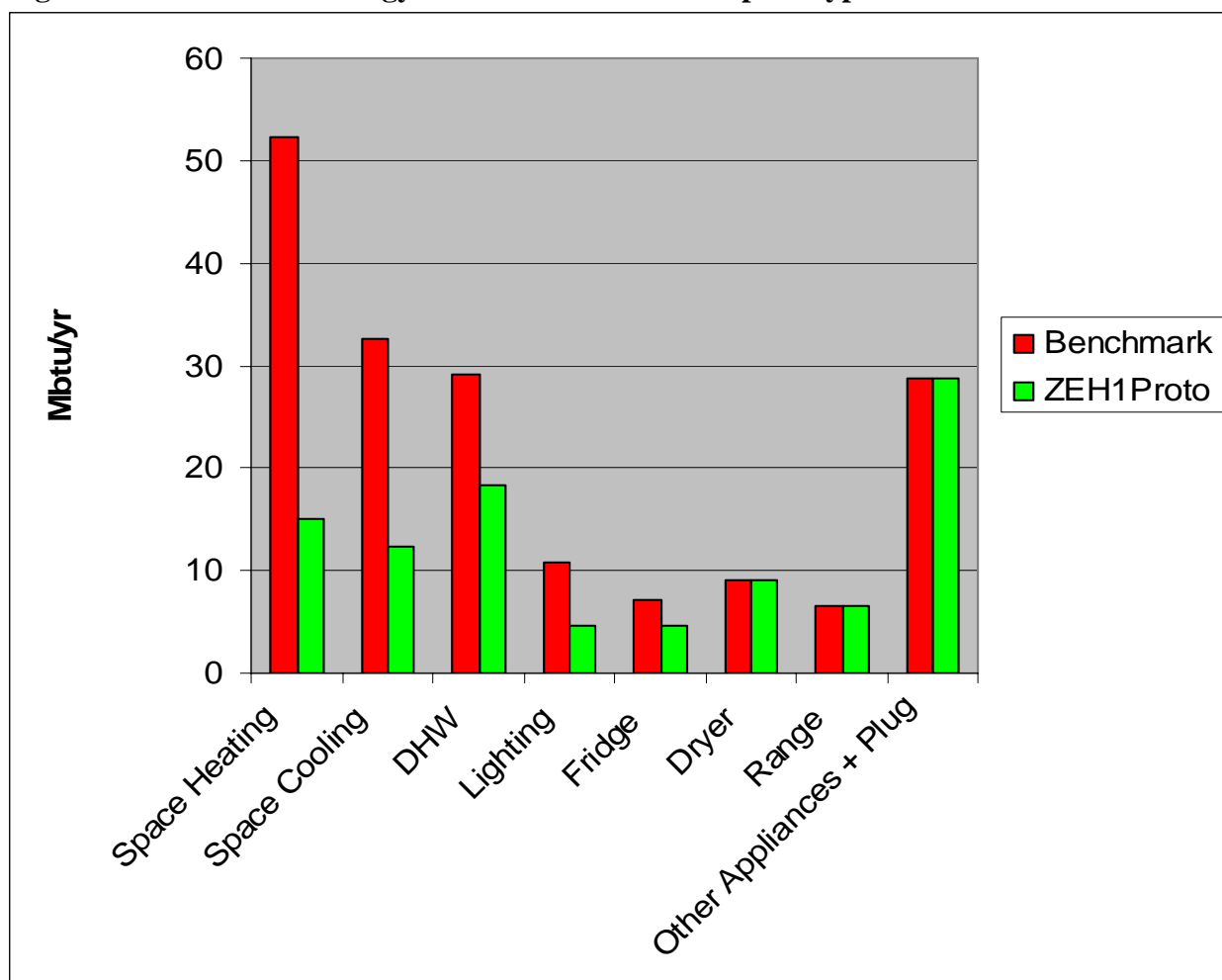


Table 11 shows the percentage of source energy savings of the prototype compared to both the Building America Benchmark base and the Builder base house. The ZEH1 saves 71% of the

heating energy used in the Benchmark, 62% cooling, 37% domestic hot water, 57% lighting and 36% refrigerator.

Table 11 ZEH1 prototype percentage of source energy savings compared to the BA benchmark base and the builders standard base.

ZEH1	Annual Source Energy			Source Energy Savings	
	BA Benchmark	Builder Standard	BA Prototype	Percent of End-Use	Percent of End-Use
End Use	(Mbtu/yr)	(Mbtu/yr)	(Mbtu/yr)	BA Base	Builder Base
Space Heating	52	44	15	71%	66%
Space Cooling	33	28	12	62%	56%
DHW	29	29	18	37%	37%
Lighting	11	11	5	57%	57%
Fridge	7	5	5	36%	0%
Dryer	9	9	9	0%	0%
Range	7	7	7	0%	0%
Other Appliances + Plug	29	29	29	0%	0%
OA Ventilation	0	0	0		
Total Usage	176	161	99	44%	38%
Site Generation	0	0	22		
Net Energy Use	176	161	77	56%	52%

ZEH2

Table 12 shows the modeling results following the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). EnergyGauge 2.42 model was used to generate end-use energy estimates for the BA Benchmark, Builder Standard and the BA Prototype house. The prototype is the actual ZEH2 with the “Standard Occupants”; i.e. fixed water usages, and thermostat settings of 75 F during the cooling season and 71 F during the heating and “Other Loads”. The total site energy savings of the prototype is 61% compared to the Building America Benchmark. The site generation from the solar PV used is the same as the actual measured solar production for the one year of monitoring, which was slightly higher during the different monitoring period for ZEH2 than that for ZEH1. The PV site generation for ZEH2 used for this comparison is 2353 compared to 2080 for ZEH1. The PV generation from the two systems was actually very similar, however to make the comparison of the model to the measured data later in this report, the approximate annual measured data is used for all the comparisons. Given the same amount of solar input for the ZEH1 and ZEH2 in reality would generate very similar solar AC generation. The prototype house is modeled with 100% fluorescents, which is more than used in ZEH1. This accounts for the smaller lighting energy used in ZEH2, 268 compared to 429 kWh. The heat pump water heater performed at a higher efficiency in ZEH2 than in ZEH1 which accounts for the lower domestic water heating energy in ZEH2, 1402 compared to 1705.

Table 12 ZEH2 end-use for the Benchmark, Builder Standard and Prototype

ZEH2	Annual Site Energy		
	BA Benchmark	Builder Standard	BA Prototype
End Use	(kWh)	(kWh)	(kWh)
Space Heating	4985	5183	1582
Space Cooling	3001	2332	1052
DHW	2697	2696	1402
Lighting	996	996	268
Fridge	668	428	428
Dryer	833	833	833
Range	605	605	605
Other Appliances + Plug	2674	2674	2674
OA Ventilation			
Total Usage	16459	15747	8844
Site Generation	0	0	2353
Net Energy Use	16459	15747	6491

Figure 8 shows the ZEH2 source energy comparison of the benchmark compared to the ZEH2 prototype. The largest savings is due to space heating, followed by space cooling, domestic hot water lighting and the energy star refrigerator. No end use energy savings is assumed for the dryer, range, other appliances and plug loads.

Figure 8 ZEH2 source energy for the benchmark compared to the modeled prototype.

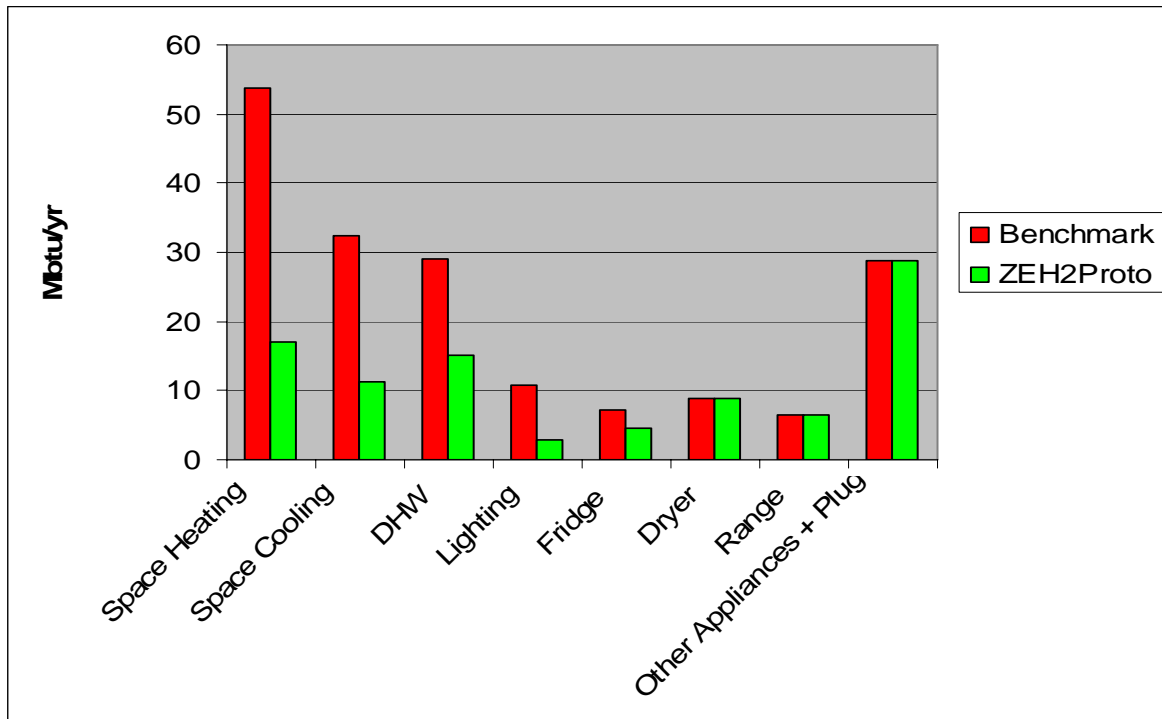


Table 13 shows the percentage of source energy savings of the prototype compared to both the Building America Benchmark base and the Builder base house. The ZEH2 saves 68% of the heating energy used in the Benchmark, 65% cooling, 48% domestic hot water, 73% lighting and 36% refrigerator. ZEH2 did not have quite as high an envelope R-value as ZEH1 but the better performing heat pump water heater off sets the slightly higher envelope energy losses

Table 13 ZEH2 prototype percentage of source energy savings compared to the BA benchmark base and the builders standard base.

ZEH2	Annual Source Energy			Source Energy Savings	
	BA Benchmark	Builder Standard	BA Prototype	Percent of End-Use	Percent of End-Use
End Use	(Mbtu/yr)	(Mbtu/yr)	(Mbtu/yr)	BA Base	Builder Base
Space Heating	54	56	17	68%	69%
Space Cooling	32	25	11	65%	55%
DHW	29	29	15	48%	48%
Lighting	11	11	3	73%	73%
Fridge	7	5	5	36%	0%
Dryer	9	9	9	0%	0%
Range	7	7	7	0%	0%
Other Appliances + Plug	29	29	29	0%	0%
OA Ventilation	0	0	0		
Total Usage	177	170	95	46%	44%
Site Generation	0	0	25		
Net Energy Use	177	170	70	61%	59%

ZEH3

Table 14 shows the modeling results following the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). This prototype has a geothermal space heating and cooling system with a desuperheater for waste heat recovery to supplement water heating. The geothermal system accounts for the much smaller space heating (893 kWh/yr) compared to (1582 kWh/yr) for ZEH2 with its air source heat pump. However, the cooling season energy use of ZEH3 (908 kWh/yr) is not that much different from ZEH2 (1052 kWh/yr). The site generation from the solar PV used is the same as that used for ZEH2; 2353 kWh/yr. The ZEH3 prototype house is modeled with 100% fluorescents and an energy star refrigerator) which is the same as used in ZEH2. Notice the energy usage for domestic hot water is higher for ZEH3 with the geothermal desuperheater (2094 kWh/yr) compared to the HPWH used in ZEH2 (1402 kWh/yr). This is believed to be caused in part due to the fact that the geothermal system simply does not have long operating periods which to build head pressure and useful waste heat. This is partly the fault of the over sizing of the geothermal system on ZEH3. Two tons were installed and the manual J calculation indicated a ton and ¼ would have been adequate. Two ton units were the smallest available at the time. The ORNL equipment researchers are developing a smaller integrated appliance to address this shortcoming.

Table 14 ZEH3 end-use for the Benchmark, Builder Standard and Prototype

ZEH3	Annual Site Energy		
	BA Benchmark	Builder Standard	BA Prototype
End Use	(kWh)	(kWh)	(kWh)
Space Heating	4985	5183	893
Space Cooling	3001	2332	908
DHW	2697	2696	2094
Lighting	996	996	268
Fridge	668	428	428
Dryer	833	833	833
Range	605	605	605
Other Appliances + Plug	2674	2674	2674
OA Ventilation			
Total Usage	16459	15747	8703
Site Generation	0	0	2353
Net Energy Use	16459	15747	6350

Figure 9 shows the ZEH3 source energy comparison of the benchmark compared to the ZEH3 prototype. The largest savings is due to space heating, followed by space cooling, lighting, domestic hot water, and the energy star refrigerator. No end use energy savings is assumed for the dryer, range, other appliances and plug loads.

Figure 9 ZEH3 source energy for the benchmark compared to the modeled prototype.

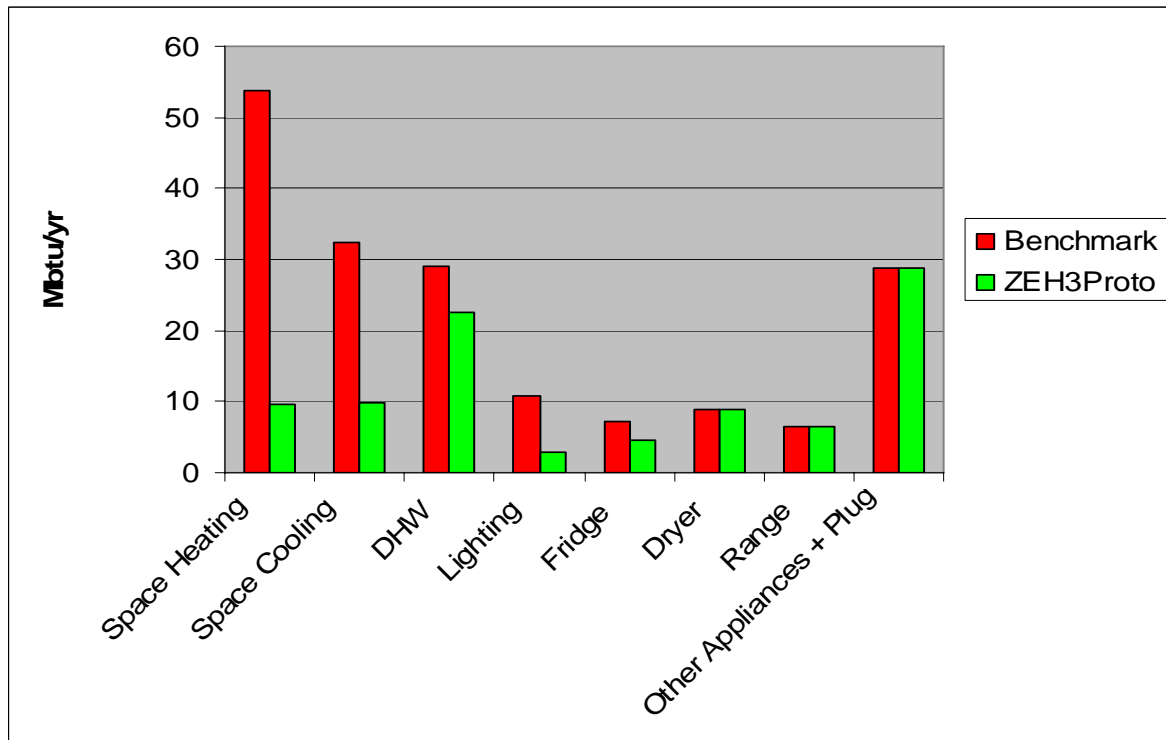


Table 15 shows the percentage of source energy savings of the prototype compared to both the Building America Benchmark base and the Builder base house. The whole house source energy savings compared to its benchmark is 61% the same as found for ZEH2. The ZEH3 saves 83% of the heating energy used in the Benchmark, 70% cooling, 22% domestic hot water, 73% lighting and 36% refrigerator. ZEH3 heating savings of 82% is the largest end use percentage savings of any end use in all four houses.

Table 15 ZEH3 prototype percentage of source energy savings compared to the BA benchmark base and the builders standard base.

ZEH3	Annual Source Energy			Source Energy Savings	
	BA Benchmark	Builder Standard	BA Prototype	Percent of End-Use	Percent of End-Use
End Use	(Mbtu/yr)	(Mbtu/yr)	(Mbtu/yr)	BA Base	Builder Base
Space Heating	54	56	10	82%	83%
Space Cooling	32	25	10	70%	61%
DHW	29	29	23	22%	22%
Lighting	11	11	3	73%	73%
Fridge	7	5	5	36%	0%
Dryer	9	9	9	0%	0%
Range	7	7	7	0%	0%
Other Appliances + Plug	29	29	29	0%	0%
OA Ventilation	0	0	0		
Total Usage	177	170	94	47%	45%
Site Generation	0	0	25		
Net Energy Use	177	170	68	61%	60%

ZEH4

Table 16 shows the modeling results following the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). This prototype has the lowest net energy use of all four prototypes, 6018kWh/yr. ZEH4 also has the highest solar fraction, 30% and the highest percentage source energy saver 62% compared to the benchmark. The whole house source energy savings percentage is slightly larger than the 61% found for ZEH2 and 3. This is partly due to the 10% larger peak solar PV capacity installed on the roof of ZEH4 compared to the other three prototypes. The PV on site generation measured during the monitoring period for ZEH4 was 2627 kWh/yr compared to 2353 for ZEH2 and ZEH3.

Table 16 ZEH4 end-use for the Benchmark, Builder Standard and Prototype.

ZEH4	Annual Site Energy		
	BA Benchmark	Builder Standard	BA Prototype
End Use	(kWh)	(kWh)	(kWh)
Space Heating	4255	3807	1328
Space Cooling	3062	2918	1072
DHW	2665	2665	1401

Lighting	1131	1131	304
Fridge	668	428	428
Dryer	833	833	833
Range	605	605	605
Other Appliances + Plug	2674	2674	2674
OA Ventilation			
Total Usage	15893	15061	8645
Site Generation	0	0	2627
Net Energy Use	15893	15061	6018

Figure 10 shows the ZEH4 source energy comparison of the benchmark compared to the ZEH4 prototype. The largest savings is due to space heating, followed by space cooling, domestic hot water, lighting, , and the energy star refrigerator. No end use energy savings is assumed for the dryer, range, other appliances and plug loads.

Figure 10 ZEH4 source energy for the benchmark compared to the modeled prototype

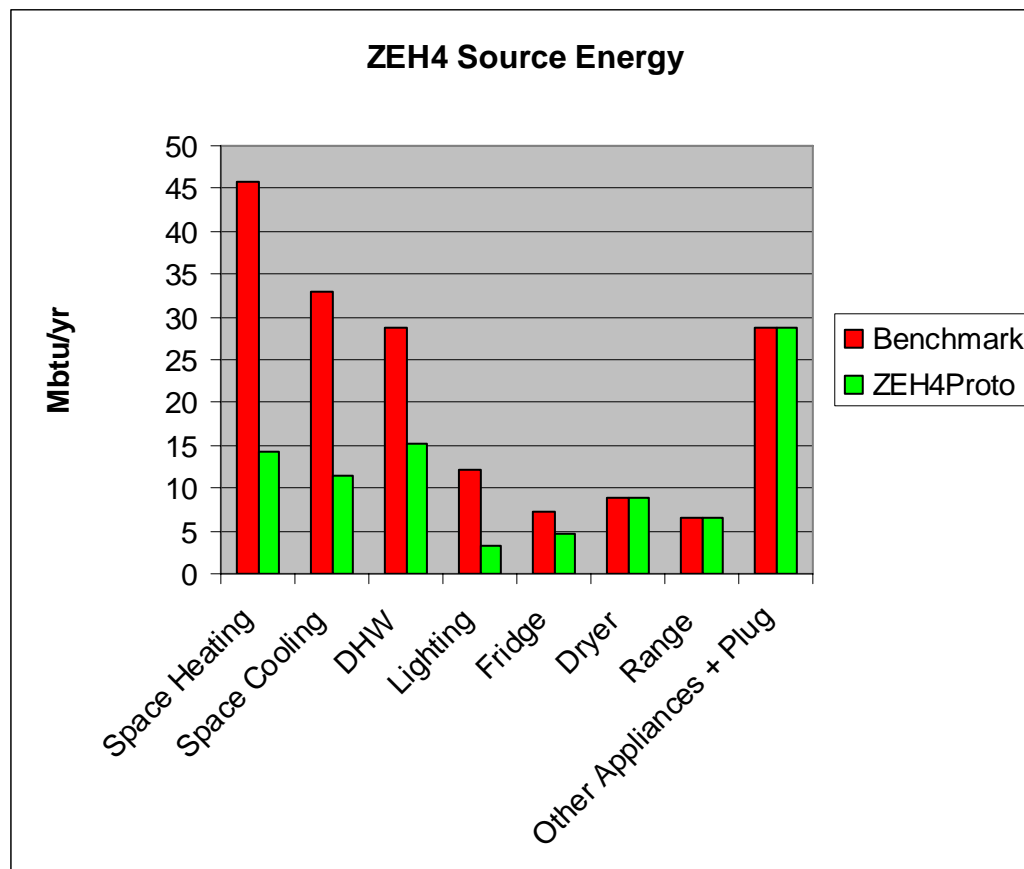


Table 17 shows the percentage of source energy savings of the prototype compared to both the Building America Benchmark base and the Builder base house. The ZEH4 saves 69% of the heating energy used in the Benchmark, 65% cooling, 47% domestic hot water, 73% lighting and 36% refrigerator. ZEH4 is the only prototype that benefited from a significant amount of internal mass resulting from the Tmass foundation system and the exterior insulated walk out

basement. Sensitivity runs with Energygauge suggest the added mass saves 147 kWh/yr, which is about 2.5% of the total annual energy usage of ZEH4. This is the only two story prototype so it did not benefit from the duct relocation into the conditioned space since the ZEH4 benchmark already had the ducts for a two story house inside the conditioned space.

Table 17 ZEH4 prototype percentage of source energy savings compared to the BA benchmark base and the builders standard base.

ZEH4	Annual Source Energy			Source Energy Savings	
	BA Benchmark	Builder Standard	BA Prototype	Percent of End-Use	Percent of End-Use
End Use	(Mbtu/yr)	(Mbtu/yr)	(Mbtu/yr)	BA Base	Builder Base
Space Heating	46	41	14	69%	65%
Space Cooling	33	31	12	65%	63%
DHW	29	29	15	47%	47%
Lighting	12	12	3	73%	73%
Fridge	7	5	5	36%	0%
Dryer	9	9	9	0%	0%
Range	7	7	7	0%	0%
Other Appliances + Plug	29	29	29	0%	0%
OA Ventilation	0	0	0		
Total Usage	171	162	93	46%	43%
Site Generation	0	0	28		
Net Energy Use	171	162	65	62%	60%

Summary of End-use Energy Savings

Space heating savings of the prototypes compared to the BA Benchmark vary from 68 to 82%. Space cooling savings varies from 62 to 70%. Domestic hot water savings from 22%, for ZEH3 which has a desuperheater installed on the geothermal system the others have a Heat Pump Water Heater, to 48%. The lighting savings varied from 57 to 73%. The higher lighting percent savings represented going from 10% fluorescent fraction to 100%.

Prototype component technology energy savings

ZEH1

Table 18 shows that ZEH1 with all the technologies included in the actual prototype house that it is a 57% source energy saver compared to the benchmark house. However, without the 2 kW of Solar PV and without the heat pump water heater the BA Benchmark modeling shows this house would still meet the goal of 30% source energy savings in Mixed Humid Climates. This does not include the conversion of all the lighting in the house to fluorescents, which adds another 8%. Converting this small house from 10% fluorescents fraction to 100%

amounts to the single largest annual dollar savings of all the technologies incorporated into the ZEH1 prototype \$92.

Using an average national electric rate which in November 2006 was \$0.10/kWh the ZEH1 saves \$932/yr. Using the local residential rate of \$0.07/kWh and the solar buyback at \$0.15/kWh this savings is slightly less; \$819.

The savings of all the building envelope improvements which include the added air tightness and positioning the ducts inside the conditioned space amount to a local energy cost savings of \$225/year. Using the national average electric rate this total climbs 30% to \$321/yr. This is equivalent to an increase in mortgage amount, using 6% interest, of \$4500.

Table 18 ZEH1 individual technology energy savings using the Building America Benchmark definition

ZEH1	Site Energy	Est. Source Energy		National Average Energy Cost*		Builder Standard (Local Costs)**			
			Savings			Energy Cost	Measure	Package	
					Savings		Savings	Value	Savings
	(kWh)	(Mbtu)	%	(\$/yr)	(%)	(\$/yr)	(%)	(\$/yr)	(\$/yr)
BA Benchmark	16344	176		\$1,634		\$1,144			
Builder Std Practice (BSP)	14909	161	9%	\$1,491	9%	\$1,044			
BSP + ducts inside	14007	151	14%	\$1,401	14%	\$980	14%	\$63	\$63
BSP + improved roof R-value	13926	150	15%	\$1,393	15%	\$975	15%	\$6	\$69
BSP + improved wall R-value	13705	148	16%	\$1,371	16%	\$959	16%	\$15	\$84
BSP + tighter envelope	12459	134	24%	\$1,246	24%	\$872	24%	\$87	\$172
BSP ++ unvented crawlspace insulation	12280	132	25%	\$1,228	25%	\$860	25%	\$13	\$184
BSP ++ Low E windows	11698	126	28%	\$1,170	28%	\$819	28%	\$41	\$225

BSP ++ SEER12.5	11412	123	30%	\$1,141	30%	\$799	30%	\$20	\$245
BSP ++ insulated trap	11382	123	30%	\$1,138	30%	\$797	30%	\$2	\$247
BSP ++ HPWH	10423	112	36%	\$1,042	36%	\$730	36%	\$67	\$314
BSP ++ Lighting	9103	98	44%	\$910	44%	\$637	44%	\$92	\$406
BSP ++ other appliances and Plug	9103	98	44%	\$910	44%	\$637	44%	\$0	\$406
Site Generation	2080								
BSP - PV	7023	76	57%	\$702	57%	\$325	72%	\$312	\$718

*national average = \$0.10/kWh

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

ZEH2

Table 19 shows that ZEH2 with all the technologies included in the actual prototype house that it is a 61% source energy saver. The table shows subpackages of technologies that contain multiple pathways to meet the DOE Building America Goal of affordable 30% energy savings. The envelope improvements in this house are all that are needed to reach 30%. The HPWH, which performed so well in this house and could add another 8% whole house energy savings is not needed but would bring the savings to 38%. With the current electric rates and limited local incentives for solar PV on this house the Building America criteria of affordability is not met, but the PV is not necessary to meet the intermediate goal for the DOE Building America Program to show houses that builders can build affordably at 30% energy savings in Mixed Humid climates in 2006.

The full technology package saves \$1000 a year using average national electric rates. Using the local rates this savings totals \$889/yr. The envelope improvement savings, which meet the 30% energy savings goal, total \$382/yr using national average rates. The largest single energy savings feature in this house is installing the ducts inside the conditioned space, amounting to \$143/year, followed by the enhanced envelope air tightness that saved \$101/yr.

Table 19 ZEH2 individual technology energy savings using the Building America Benchmark definition.

ZEH2	Site Energy	Est. Source Energy		National Average Energy Cost*		Builder Standard (Local Costs)**				
		(kWh)	(Mbtu)	Savings %	(\$/yr)	Savings (%)	Energy Cost (\$/yr)	Savings (%)	Measure Value (\$/yr)	Package Savings (\$/yr)
BA	16459	177			\$1,646		\$1,152			

Benchmark									
Builder Std Practice (BSP)	15747	170	4%	\$1,575	4%	\$1,102			
BSP + ducts inside	13701	148	17%	\$1,370	17%	\$959	17%	\$143	\$143
BSP + improved roof R-value	13763	148	16%	\$1,376	16%	\$963	16%	-\$4	\$139
BSP + improved wall R-value	13562	146	18%	\$1,356	18%	\$949	18%	\$14	\$153
BSP + tighter envelope	12114	131	26%	\$1,211	26%	\$848	26%	\$101	\$254
BSP ++ unvented crawlspace insulation	11783	127	28%	\$1,178	28%	\$825	28%	\$23	\$277
BSP ++ LowE windows	11541	124	30%	\$1,154	30%	\$808	30%	\$17	\$294
BSP ++ SEER14	11087	120	33%	\$1,109	33%	\$776	33%	\$32	\$326
BSP ++ insulated trap	11056	119	33%	\$1,106	33%	\$774	33%	\$2	\$328
BSP ++ HPWH	9793	106	41%	\$979	41%	\$686	41%	\$88	\$417
BSP ++ Lighting	8793	95	47%	\$879	47%	\$616	47%	\$70	\$487
BSP ++ other appliances and Plug	8793	95	47%	\$879	47%	\$616	47%	\$0	\$487
Site Generation	2353								
BSP - PV	6440	69	61%	\$644	61%	\$263	77%	\$353	\$840

*national average = \$0.10/kWh

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

ZEH3

Table 20 shows subpackages of technologies that contain multiple pathways to meet the DOE Building America Goal of affordable 30% energy savings. The third package titled “BSP Builder Standard Practice + ducts inside” the conditioned space rather than in the vented crawl space generates 17% whole house energy savings compared to the BA benchmark house. That comes from a 27.5% reduction in heating cost and a 15% reduction in cooling cost. The opaque envelope improvements produce another 15% savings which totals 32%. If the house was equipped with 100% fluorescents this would bring the savings level to 38%. By adding the

geothermal system and the solar PV brings this house up to a 61% source energy saver. With the current electric rates and incentives for solar PV and geothermal these two technologies on this house would not meet the Building America criteria of affordability but are not necessary to meet the intermediate goal for the DOE Building America Program to show houses that builders can build affordably at 30% energy savings in Mixed Humid climates in 2006.

Table 20 ZEH3 individual technology energy savings using the Building America Benchmark definition.

ZEH3				National Average Energy Cost*		Builder Standard (Local Costs)**			
	Site Energy	Est. Source Energy			Savings (%)	Energy Cost Savings		Measure Value	Package Savings
	(kWh)	(Mbtu)	%	(\$/yr)	(%)	(\$/yr)	(%)	(\$/yr)	(\$/yr)
BA Benchmark	16459	177		\$1,646		\$1,152			
Builder Std Practice (BSP)	15747	170	4%	\$1,575	4%	\$1,102			
BSP + ducts inside	13701	148	17%	\$1,370	17%	\$959	17%	\$143	\$143
BSP + improved roof R-value	13351	144	19%	\$1,335	19%	\$935	19%	\$25	\$168
BSP + improved wall R-value	12926	139	21%	\$1,293	21%	\$905	21%	\$30	\$197
BSP + tighter envelope	11467	124	30%	\$1,147	30%	\$803	30%	\$102	\$300
BSP ++ unvented crawlspace insulation	11148	120	32%	\$1,115	32%	\$780	32%	\$22	\$322
BSP ++ LowE windows	10901	118	34%	\$1,090	34%	\$763	34%	\$17	\$339
BSP ++ DX geothermal HP	10049	108	39%	\$1,005	39%	\$703	39%	\$60	\$399
BSP ++ GHP desuperheater	9768	105	41%	\$977	41%	\$684	41%	\$20	\$419
BSP ++ insulated trap	9737	105	41%	\$974	41%	\$682	41%	\$2	\$421
BSP ++ 94 EF HW	9422	102	43%	\$942	43%	\$660	43%	\$22	\$443

BSP ++ Lighting	8703	94	47%	\$870	47%	\$609	47%	\$50	\$493
BSP ++ other appliances and Plug	8703	94	47%	\$870	47%	\$609	47%	\$0	\$493
Site Generation	2353								
BSP - PV	6350	68	61%	\$635	61%	\$256	78%	\$353	\$846

*national average = \$0.10/kWh

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

ZEH4

Table 21 shows the ZEH4 subpackages that can be used to meet the 30% energy savings goals. By using the envelope improvements and the SEER 17 heat pump upgrade a 33% energy savings is attainable compared to the Building America benchmark house. This house does not have to employ it's heat pump water heater nor PV Solar system to meet the 30% energy savings goal in Mixed Humid climates for 2006.

The complete technology package on ZEH4 results in an annual local energy cost savings of \$902. The net daily cost for all the off-site energy to operate this house with the BA benchmark interior loads and schedules is only \$0.58/day. If the local utility had a second tier rate in which it bought back solar power from these type houses of only \$0.08/kWh more the net cost for all the energy to run this house would be zero. It turns out that the critical peak power cost to TVA, the electric utility that services these houses, is about the same \$0.23kWh. Builders could really distinguish themselves in the market by offering these houses that could be market at zero energy cost homes. Not quite zero energy but a very critical stepping stone on the path to zero.

The largest single energy efficiency saving technology is the heat pump water heater. The local energy cost savings per year is \$88. In November 2006 a very large water heater manufacture is seriously considering licensing the technology from ORNL to market a HPWH in 2007.

Table 21 ZEH4 individual technology energy savings using the Building America Benchmark definition.

ZEH4				National Average Energy Cost*		Builder Standard (Local Costs)**			
	Site Energy	Est. Source Energy				Energy Cost		Measure	Package
	(kWh)	(Mbtu)	Savings %	(\$/yr)	Savings (%)	(\$/yr)	Savings (%)	Value (\$/yr)	(\$/yr)
BA Benchmark	15893	171		\$1,589		\$1,113			
Builder Std Practice (BSP)	15061	162	5%	\$1,506	5%	\$1,054			
BSP +	14617	158	8%	\$1,462	8%	\$1,023	8%	\$31	\$31

improved roof R-value									
BSP+ improved wall R-value	14072	152	11%	\$1,407	11%	\$985	11%	\$38	\$69
BSP +tighter envelope	12952	140	19%	\$1,295	19%	\$907	19%	\$78	\$148
BSP+ extended roof overhangs	12887	139	19%	\$1,289	19%	\$902	19%	\$5	\$152
BSP ++ basement insulation and mass	12243	132	23%	\$1,224	23%	\$857	23%	\$45	\$197
BSP ++ LowE windows	11655	126	27%	\$1,166	27%	\$816	27%	\$41	\$238
BSP ++ SEER 17 Heat Pump	10,705	115	33%	\$1,071	33%	\$749	33%	\$67	\$305
BSP ++ HPWH	9442	102	41%	\$944	41%	\$661	41%	\$88	\$393
BSP ++ Lighting	8645	93	46%	\$865	46%	\$605	46%	\$56	\$449
BSP ++ other appliances and Plug	8645	93	46%	\$865	46%	\$605	46%	\$0	\$449
Site Generation	2627								
BSP ++ PV	6018	65	62%	\$602	62%	\$211	81%	\$394	\$834

*national average = \$0.10/kWh

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

A very close second largest energy saver is the airtight construction compared to the benchmark with \$78/yr. All four of these prototype houses are very tight. They end up with ACH50 of around 1. The ventilation strategy calls for at least 70 CFM for 33% of the time. The energy gage model was used to estimate the added energy needed to condition the ventilation air and run the fan. Table 22 shows the break down of this additional energy. The added cost to condition the ventilation air is \$47/yr in the ZEH4 prototype. A total of 77% of that cost occurs during the heating season. Only 15% is attributable to the added fan power.

Table 22 Energy needed to ventilate the ZEH4 prototype

	ZEH4 Prototype (kWh)	Prototype with No ventilation (kWh)	Difference (kWh)	percentage of total	Annual cost
Heating	1159	706	453	68%	\$32
Heating fan	169	98	71	11%	\$5
Total heating	1328	804	524	78%	\$37
Cooling	876	752	124	18%	\$9
Cooling fan	196	173	23	3%	\$2
Total cooling	1072	925	147	22%	\$10
Total	2400	1729	671		\$47

Table 23 presents the same energy demand for ventilation as shown for the ZEH4 prototype but in this case for the modeling assumptions used to ventilate the benchmark according to the BA Benchmark definition (Hendron 2005). This required a continuously operating fan adding 42 CFM of ventilation air to the inside conditioned space. The values in the second column show the end use energy for the ZEH4 benchmark and the third column shows the lower values when the ventilation option is shut off. The difference results in an expense of running the benchmark ventilation of \$116/yr. The heating / cooling season split is 80 /20. In reality it is unlikely that the homeowner would run an exhaust fan continuously in a house as leaky as assumed for the benchmark which has an ACH50 of 6.8.

Table 23 Energy needed to ventilate ZEH4 benchmark

Energy needed to ventilate	for the Benchmark		difference	percentage of total	cost
	Bench	No ventilation			
Heating	3706	2545	1161	70%	\$81
Heating fan	549	383	166	10%	\$12
Total heating	4255	2928	1327	80%	\$93
Cooling	2592	2301	291	18%	\$20
Cooling fan	470	427	43	3%	\$3
Total cooling	3062	2728	334	20%	\$23
Total	7317	5656	1661		\$116

Summary

Four near-zero-energy houses were built to demonstrate the feasibility of making net-zero-energy housing affordable. The houses, built between 2002 and 2004, can be used to document the 30% energy savings Building America goal for Mixed Humid Climates, even though their actual in the field performance and Building America modeling comparisons to the benchmark is much higher.

Each of these houses is compared to the Building America Research Benchmark Definition, updated December 29, 2004 (NREL, 2004). This comparison shows these all electric

houses saved 44-47% energy compared to the Building America Benchmark. When the solar PV system generation is added to the near zero energy houses in the comparison to the Benchmark, which has no solar, the source energy savings goes up to 56-62%. The analysis shows that these prototypes could meet the 30% energy savings criteria with out the geothermal system, heat pump water heaters, and 2-2.2 kW peak solar PV systems.

Energy costs per day, based on measured data and November 2006 local residential electric rates of \$0.07/kWh, for these all electric houses are \$1.04 for ZEH1, \$0.91 for ZEH2, \$0.81 for ZEH3, and \$0.77 for ZEH4. These costs are based on an electric utility credit of \$0.15/kWh for all solar AC power produced by the houses. Based on measured data the percentage of total energy load supplied by the PV systems for these houses ranged from 20% to 27%.

Based on the EnergyGauge USA version 2.42 modeling (FSEC, 2006), using the Building America Benchmark comparison method, and local energy rates in November 2006 of \$0.07 /kWh, and solar buy back of \$0.15/kWh the costs per day is \$0.78 for ZEH1, \$0.72 for ZEH2, \$0.70 for ZEH3, and \$0.58 for ZEH4. These modeling prediction values are \$0.11 to \$0.19/day lower than the predictions based on measurements from the occupied houses. Based on the Building America Benchmark comparison to these prototypes energy efficiency modeling predicts these houses could meet 22-30% with the measured solar PV generated onsite.

References

- [ASHRAE] American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 2004. "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings." *ANSI/ASHRAE 62.2-2004*. Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.
- Christian, Jeffrey E. 2005. "Ultra-Low-Energy Residences." *ASHRAE Journal*. January.
- Christian, Jeffrey E., and Jan Kosny. 1995. "Towards a National Opaque Wall Rating Label." In *Proceedings for ASHRAE/DOE Thermal Performance of the Exterior Envelope of Buildings Conference VI*, Clearwater Beach, Fla., December 4-8.
- Christian, Jeffrey E. 1996. "Thermal Performance and Wall Ratings." *ASHRAE Journal*, 38 (3). March.
- Christian, Jeffrey E., Paige Pate, Phil Childs, and Jerry Atchley. 2006a. "Small House With Construction Cost of \$100K, Total Energy Cost of \$0.88 a Day." 2006 ASHRAE Winter Meeting; Published in *ASHRAE Transactions*, 112 (1).
- Christian, Jeffrey E., Lauren Richards, Phil Childs, Jerry Atchley, and Hyeun Moon. 2006b. "Energy Efficiency, SIPS, Geothermal, and Solar PV Team Up to Near-Zero-Energy House." To Be Presented at 2006 ASHRAE Winter Meeting; Published in *ASHRAE Transactions*, 2006-2.
- Christian, Jeffrey E. 2006c. "How to Build a Zero Electric utility Cost House" ACEEE Summer Study at Asilomar, Pacific Grove, California, August 2006.

[DOE] U.S. Department of Energy. 2004. "Typical Appliance Usage." *2004 Buildings Energy Databook*, Table 7.2. Washington, D.C.: U.S. Department of Energy.

Florida Solar Energy Center, <Energygauge.com>, 2006

Hendron, Robert. 2005. "Building America Research Benchmark Definition," Updated December 29, 2004.
<http://www.eere.energy.gov/buildings/building_america/docs/benchmark_2005.doc>
Golden, Colo.: National Renewable Energy Laboratory.

Hendron, R., et al. 2004. "Building America Performance Analysis Procedures, Rev. 1." NREL/TP-550-35567. Golden, Colo.: National Renewable Energy Laboratory.

Parker, D. S., J. E. R. McIlvaine, S. F. Barkaszi, and D. J. Beal. 1993. "Laboratory Testing of Reflectance Properties of Roofing Materials," Report No. FSEC-CR-670-93. Cape Canaveral, Fla.: Florida Solar Energy Center.

[RESNET] Residential Energy Services Network. 2002.
<http://www.natresnet.org/standards/standards.pdf>.

Vineyard, E. A., et al. 2003. "Measured Performance of Conventional and High-Velocity Distribution Systems in Attic and Space Locations." *ASHRAE Transactions*, 109 (2). June.