How to Build a Zero Electric Utility Cost House

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ABSTRACT

The construction methods, building products, appliances and equipment of four single-family houses that achieve dramatic energy reductions and approach "net zero energy" use are presented. A 30-50 sensor data acquisition system constantly measures performance characteristics of each house. This data is used to develop guidelines for building a zero energy cost house. The energy performance of the test houses are compared with a "base house" — same size and location, but without advanced features of "net-zero-energy" houses. The data show the houses used about 50% less energy from the grid than the base house.

Energy costs per day for these all electric houses were $1.01 for ZEH1, $0.88 for ZEH2, $0.79 for ZEH3, and $0.75 for ZEH4. These costs are based on an electric rate of $0.068/kWh and utility credit of $0.15/kWh for all solar AC power produced by the houses. The percentage of total energy load supplied by the PV systems for these houses ranged from 20% to 27%.

The 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, have construction costs of about $100,000, including the cost of the rooftop solar PV systems. These houses can be assembled by workers with limited skills making them ideal for rebuilding on a large scale after man made or natural disasters.

Introduction

The design, construction, and monitoring of four small single-family houses lead to dramatic reductions in energy consumption and approach "net zero energy use." (A net-zero-energy building is one that produces as much energy from on-site renewable energy as it consumes on an annual basis.)

These 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 building component industries. The houses were designed by ORNL and Building America teams and constructed by Habitat volunteers.

During the construction of the houses the sensor systems are installed that measure performance characteristics. The energy performance of each of the houses is compared with that of a "base house" — a Habitat house of similar size and built in the same development, but without advanced energy features.

Energy consumption of the base house and the test houses are summarized in Figure 1. 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.

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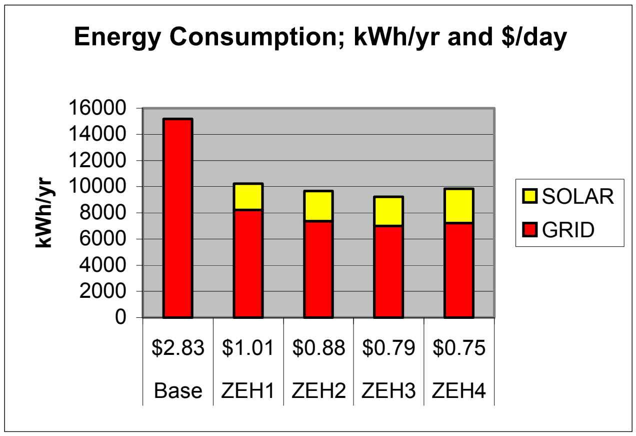
[1] Building America is a public–private partnership dedicated to improving the energy efficiency of housing through research and working to changen housing construction practices. www.eere.energy.gov/buildings/building_america/.

Energy costs per day for these houses were $1.01 for ZEH1, $0.88 for ZEH2, $0.79 for ZEH3, and $0.75 for ZEH4. These costs are based on the actual current residential electric rate in 2004-2005 of $0.068/kWh and TVA's solar credit of $0.15/kWh for all AC power produced. In 2004 the national average residential electric rate was $0.09 kWh. If the solar collection and solar buy back rate remains the same this represents a national average daily total energy cost of $1.35/day. The percentage of total energy load supplied by the photovoltaic (PV) systems for these houses ranged from 20% to 27%. ZEH5 was constructed as an unoccupied test facility to focus on research breakthroughs to reach 70% energy savings and 100% solar collection.

Figure 1. Comparison of the Energy Consumption of the Base and ZEHs



Technology Description

The four near-zero-energy houses are in Lenoir City, Tennessee. The size ranges from 1060 to 1200 ft^2. Three of the houses have crawl spaces; the other has a walk-out full basement. All four are finished with vinyl siding.

Design Process

These five near-zero-energy houses were designed to surpass by 50% the energy efficiency achieved in the DOE Building America Benchmark (Hendron 2005). The design process started in the laboratory. For example, hundreds of hot box tests and evaluations were examined to select a wall system with minimum thermal shorts (Christian & Kosny 1995) and inherent air-tightness potential (Christian & Kosny 1996). The results from multi-year tests of HVAC systems in test houses of similar size in identical climatic conditions led the design teams to locate the HVAC distribution systems inside the insulating envelope (Vineyard et al. 2003). Before specific building components were selected, design optimizations were done using whole-house building computer simulation software.

The design team selected only technologies that were believed to have the potential to be applicable for affordable housing by 2010, based on assumptions that technology development, market growth and economies of scale, and utility, state, and federal incentives would all lead to lower costs in the near future. The design goal initially was to see how close to zero energy these technologies could carry the whole house performance.

Energy-Efficiency Technologies

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. A 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.

Supply mechanical ventilation is provided in compliance with American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62.2 (ASHRAE 2004). The HPWHs in these houses are more than twice as efficient as conventional electric water heaters (Christian 2006). 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 a baseline Habitat house used for comparison. The base house is measured by Home Energy Rating System (HERS) rating of 84, which indicates about 20% better performance than a typical 2004-05 American house (RESNET 2002) of the same size and layout.

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)

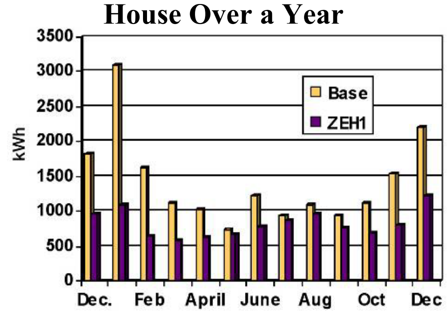
Notes for tables 1 and 2: ECM = electronically commuted motor; EF = energy factor; EPS = expanded polystyrene; HP = heat pump; HPWH = heat pump water heater; HSPF = heating seasonal performance factor; OSB = oriented strandboard; SEER = seasonal energy efficiency rating; SHGC = solar heat gain coefficient;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

Cost-Effectiveness

Figure 2. Comparison of Utility Bills for House 1 and the Base House Over a Year



The cost-effectiveness of near net-zero-energy houses will vary with energy costs, climate, the energy-consumption habits of the occupants, utility, state, and federal incentives for PV systems, and the cost of the technologies used in a particular dwelling. The electricity rate in 2004–2005 was $0.068 per kWh, below the national average of around $0.086 per kWh. Energy cost savings would be greater in regions with higher electricity and solar credit rates.

The economic justification for net-zero-energy houses is that energy savings plus revenue from renewable energy sold to the utility grid help offset the added price of construction. For these four houses, utility bills averaged less than $1 per day after credit for the sale of solar. The fourth house built had an average daily cost for electricity of 75 cents per day. A conventionally built house of similar size in the same community would be expected to average $4 to $5 per day for electricity. Figure 2 shows utility costs for ZEH1 and the base house over a period of a year.

Table 3 shows the building costs for all four houses and for a base house of similar size in the same locale. The costs of volunteer labor and donated materials are factored in. The costs of building the four study houses (not including the cost of land and infrastructure and the PV systems) ranged from about $79,000 to $88,000. The cost of building the base house was about $59,300.

Table 3. Construction Cost of Test Houses 1–4 and the Base House ($)

	Base	1	2	3	4
House	59,295	78,914	83,953	87,889	85,189
Land and infrastructure	14,500	14,500	14,500	14,500	14,500
PV system	0	22,388	16,000	16,000	14,935
Total cost	73,795	115,802	115,953	122,329	114,624

With the cost of the PV systems included, the construction cost ranged from about \$100,000 to about \$104,000. Over the long term the cost of PV systems is expected to continue to drop as production volume increases. Photovoltaic systems can be cost-effective if utility and government incentive programs are in place , such as purchase of solar energy from the PV systems, or mandatory renewable-generation directives.[2] If TVA raises the rate it pays for energy from the PV systems from 15 cents to, say, 20 cents per kWh, that would lower net energy costs for these houses by about \$0.25 per day.

Additional research is needed to bring the life-cycle costs of net-zero-energy houses into line with requirements for affordable housing. However, the local Habitat affiliate collaborating with this project is now attaining 100% certified HERS ratings of over 86 for houses they build for around \$60,000.

Affordable Housing Sector Potential

The cost-effectiveness of net-zero-energy housing would be enhanced in remote areas because of the high cost of establishing electric transmission and distribution infrastructure there and its vulnerability to disruption. The modular panel construction can go up in a few days using a workforce with limited skills. These houses would be excellent candidates for rebuilding after military conflicts and natural disasters.

The life-cycle cost and federal affordability standards in 2006 in general cannot be met without utility and government incentives, which are on the increase. However, increasing demand for high-efficiency materials and equipment is expected to bring prices down gradually as production volumes increase. Continued energy cost escalation such as the 20% increase for natural gas per year from 2002-2006 could close this gap in a very short timeframe. Mass purchasing of the building components for a large number of housing units might be a means of attaining acceptable life-cycle costs. The federal government has the buying power to push cost-reduction measures such as large-volume production of SIP zero-energy houses in standard sizes.

Utility support for energy-efficient housing is growing because of the cost of building new power generation, the need to reduce peak loads, and the need to reduce power plant emissions. Increased reimbursement levels for the PV power produced, which they can sell at a premium green power rate, could significantly offset mortgage cost differentials. Encouraging all-electric zero peak communities offer the opportunity to capture off-peak winter heating revenues without the cost of providing larger winter peak capacity.

Other issues may work to make net-zero-energy building more attractive:

- Environmental need for such housing could offset cost issues in some communities, for example, areas that are not meeting Clean Air standards.
- Rising energy costs make energy-efficiency measures more cost-effective.
- Energy efficiency decreases U.S. dependence on foreign oil and enhances national security.

[2] Information about incentives to promote renewable energy is available through the Database of State Incentives for Renewable Energy (DSIRE) at http://www.dsireusa.org.

Field Demonstration

Test Site

The construction and demonstration of these four near-zero-energy houses evolved from an existing partnership between DOE and Loudon County, Tennessee, affiliate of Habitat for Humanity. When net-zero-energy houses became a the major goal of the DOE Building Technology Office, the partnership with Habitat Loudon County offered an ideal setting for incorporating ultra-efficient technologies into houses that working families could afford. For more detail on the test site and floor plans for all four test houses see (Christian 2006c).

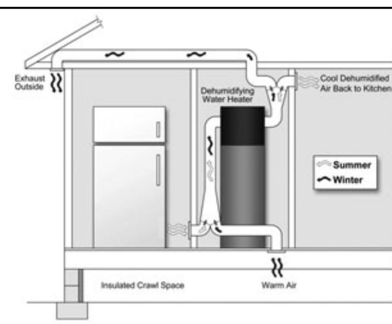
The Test Houses

Figure 3. ZEH1

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 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.

Figure 4. Air Flow To and From the Heat-Pump Water Heater in ZEH2



ZEH2s wall and ceiling 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 50-gal. HPWH shown in Figure 4 performed at a higher efficiency (2 compared to 1.7) than the unit in ZEH1; the setup for the air supply to the HPWH is more compact (Christian 2006a). The ceiling is 6.5-in.-thick SIPs, and the roof is forest green metal standing seam with a 6/12 pitch. The PV system is rated at 1.98 kWp and has higher efficiency modules than used in ZEH1, resulting in only 12 modules, compared to 48 in ZEH1.

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. It has the same 6/12 pitch (26.6°) as ZEH2.

Figure 5. ZEH3

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 efficiency rating of 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 temperature at around 72° year round.

ZEH4, a two-story house, contains 1139 ft^2. It was built in two stories 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 SIPs used in ZEH4 are insulated with polyisocyanurate. The ACH 50 rated at 1.64. The roof is light gray aluminum simulated 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.

Figure 6. ZEH4

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 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 Data Acquisition System

Each of the demonstration 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 CO_2 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 validate computer models. (Christian 2006a; Christian 2006b; Christian 2006c)

Energy Savings and Costs

ZEH1, built in 2002, used 10,216 kWh of electricity between March 2003 and February 2004. That is about 40% less than the base Habitat house. The energy cost (electricity purchased from the utility minus the amount of surplus solar power sold to the utility) amounted to $1.01 per day. 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 4 shows the monthly measured energy usage for ZEH1 from March 2003 through February 2004. As in all the houses, 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, about 43% less than the national average of 64 gal estimated from a national survey of hot water usage (U.S. DOE 2004). The low hot water draws are due in part to reduced distribution losses resulting from the compact plumbing system.

Table 4. 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%	
Annual cost	$100[a]	$74[b]	$98	$372	$644	-$301	
Daily cost	$0.51[a]	$0.44[b]	$0.27	$1.02	$1.76	-0.82	

[a] Heating days only [b] Cooling days only

ZEH2 occupants consumed a total of 12,207 kWh from April 1, 2004, through March 31, 2005 and the PV system generated 2305 kWh. About 34% of the solar energy was collected at a time when it was not needed in the house. Table 5 shows the energy usage brake down.

Table 5. ZEH2 Measured Energy Use, April 2004-March 2005

Month	**Space heat (kWh)**	**Space cool (kWh)**	**Hot water (kWh)**	**Other (kWh)**	**Total electric (kWh)**	**Solar generated (kWh)**	**Solar sold to utility (kWh)**
April	0	159	87	418	664	203	99
May	0	488	66	359	913	234	78
June	0	498	57	336	891	215	76
July	0	347	59	325	731	250	110
August	0	280	60	344	684	233	86
Sept.	0	246	56	299	601	217	102
October	280	0	70	346	696	159	65
Nov.	624	0	78	359	1061	145	30
Dec.	1420	0	109	403	1932	148	19
January	1392	0	118	382	1892	136	15
February	756	0	99	352	1207	142	34
March	442	0	102	391	935	223	81
Total	**4914**	**2018**	**961**	**4314**	**12207**	**2305**	**795**
% of total	40%	17%	8%	35%	100%		
Annual cost	$334[a]	$137[b]	$65	$293	$830	-$346	
Daily cost	$1.83[a]	$0.75[b]	$0.18	$0.80	$2.27	-$0.95	
Adjusted daily cost	$0.95[c]				$1.83[c]		

[a] Heating days only [b] Cooling days only
[c]Based on correctly charged heat pump using 2544 kWh rather than actual 4914 kWh used by incorrectly charged heat pump

The measured net daily cost of off-site energy to run this all-electric house was $1.32, compared to the daily energy cost of $1.01 for ZEH1. The higher energy cost is attributable to a low coolant charge on the heat pump. The performance penalty estimate for the low charge lead to the adjusted daily cost shown in Table 5 (Christian 2006a), assuming a properly performing heat pump. The resulting adjusted energy use for October 2004 until the end of February 2005 is 2370 kWh or $0.44 per day. This reduction in heating energy for ZEH2 was 2544 kWh. The resulting adjusted daily HVAC cost is $0.85 per day, which yields a total whole-house daily energy cost after solar credits of $0.88. Assuming a properly functioning heat pump, the solar energy collected on site amounts to 23% of the house's total electric demand of 9837 kWh/year, 3% higher than found in ZEH1.

ZEH3 occupants consumed a total of 11,014 kW from March 1, 2004 until February 28, 2005 and the PV system generated 2241 kWh, including 29% collected during times when the energy was not needed in the house. Table 6 shows the actual energy usage in ZEH3.

The net daily cost for off-site energy to run this all-electric house was $1.13. The "other" loads in this house of 7388 kWh were much higher than ZEH1 (5907 kWh/year), ZEH2 (4314 kWh/year), and the suggested internal loads from the Building America Benchmark house (6512 kWh/year). In part this is explained by the house being mostly occupied during the day 7 days a week. Also a significant load was due to unusually extensive outdoor holiday decorations during November through January. To be able to more directly compare ZEH3 with the other houses and the Building America Benchmark, the kWh for "other" loads for ZEH3 is reduced (Christian 2006b). The average for "other" loads of ZEH1, ZEH2, and two Building America Benchmark houses is 5604 kWh/year, or $1.04 /day. This would reduce the "other" load by 1784 kWh, which would represent a cost reduction to the homeowner for off-site energy shown in Table 6 of

$0.34/day, resulting in an average daily net-cost for off-site energy of $0.79. This compares to $1.01/day for ZEH1 (Christian 2005), and $0.88/day for ZEH2 (Christian 2006a).

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**
% of total	5%	16%	12%	67%	100%		
Annual Cost	$39[a]	$121[b]	$87	$502	$749	–$336	
Daily cost	$0.22[a]	$0.66[b]	$0.24	$1.38	$2.05	–$0.92	
Adjusted daily cost				$1.04[c]	$1.71[c]		

[a] Heating days only [b] Cooling days only
[c] Based on normalized "other" usage of 5604 kWh rather than the actual 7388 kWh

The HVAC cost on ZEH3 with the geothermal heat pump averaged only $0.44/day, compared to $0.51 per day on ZEH1 with a 13.7 SEER, single-speed compressor. The final adjusted daily HVAC cost for ZEH2 came to $0.85/day.

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.

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 7 shows the energy usage broke down.

The net daily cost for off-site energy to run this all electric house was $0.75. This compares to $1.01 per day for ZEH1 (Christian 2005), $0.88 per day for ZEH2 (Christian 2006a), and $0.79 per day for ZEH3 (Christian 2006b). The HVAC cost for ZEH4 with the SEER 17 air source HP averaged $0.51/day. The HVAC cost on ZEH1 with a 13.7 SEER single speed compressor came to the same $0.51/day. The final adjusted HVAC daily cost for ZEH2 came to $0.85/day. The HVAC cost on the ZEH3 with the geothermal HP averaged only$0.44/day. 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 7. ZEH4 Measured Energy Use, August 2004-July 2005

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

[a] Heating days only [b] Cooling days only

How To Reach Zero Electric Utility Bill

The ZEH4 total annual energy cost shown in Table 7 of $669 and a solar green power credit of $394 leaves a net utility bill of $275/year or $0.75/day. One way to make up that cost is to convince the electric utility that the peak load savings, availability of green power that can be sold at a premium price, environmental benefits, marketing opportunity to capture more residential heating energy revenue without requiring added peak capacity, and good old public relations with their customer base add up to another $0.105/kWh of benefits. Thus the homeowner now would receive $669 (2627 X $0.255/kWh) in solar credits and for the year a net utility bill of $0.00.

Another way to reach zero energy bill is to replace the 17 SEER air source heat pump used in ZEH4 with the geothermal system measured performance in ZEH3 shown in Table 6. ZEH3 used only 569 kWh to heat for the entire year. That is 1142 kWh less measured in ZEH4. This reduces the total annual load to 8695 kWh and the cost to $591, less the solar credit of $394 or $197 ($0.54.day). Now you only need to appeal for another $0.075/kWh for your solar credits or a total credit rate $0.225/kWh to reach a zero utility bill.

A third approach is to go with geothermal and very aggressive selection and management of efficient lighting, appliances and all the electrical uses plugged into the ZEH. Let's say you actually cut the "other" load in half of what was measured by a family of 3 living in ZEH4. This is a savings of 2649 kWh. Your new total annual load is 6047 kWh or $17.20 (nickel-a-day). You might break out a case of your favorite micro brew and say "good enough;" or just buy a case of bud and reach zero.

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, had construction costs around $100K, including the cost of the PV systems. Their energy efficiency, documented by a monitoring system, in the first house built was 40% less than in an energy-efficient base house and 62% less than in a conventional frame house of the same size.

The technology is performing well. Promising improvements in energy efficiency and increasing policies to encourage incentives of energy efficient key components of zero-energy houses is likely to accelerate the progress toward a vibrant ZEH market. Construction of ZEH5 was completed in 2005 and research work in this test facility is focused on attaining 70% whole-house energy savings. The house has a very promising lower cost geothermal system and grey-water waste heat recovery. The speed with which panelized houses can be put together by workers with limited skills would enhance their value for building housing on a large scale after man-made and natural disasters.

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