Energy Savings from Small Near-Zero-Energy Houses

Integration of whole-house construction technologies in small, affordable, super-efficient houses

Introduction

This technology installation review provides an overview of the construction and monitoring of four small single-family houses that achieve dramatic reductions in energy consumption and approach the goal of "net zero energy use." (A net-zero-energy building is one that produces as much energy from solar panels as it consumes over a year.) This study discusses the construction methods, building products, appliances and equipment, and data collection methodologies used in the houses and provides data on energy savings gathered through the monitoring effort.

The houses discussed in this study were built through a collaboration among Habitat for Humanity, the Department of Energy's (DOE's) Building America Project, Oak Ridge National Laboratory (ORNL), the Tennessee Valley Authority, and the building and appliance industries. The houses were designed by ORNL and Building America teams and constructed by volunteers from the Loudon County, Tennessee, Habitat affiliate. Building trade associations and product manufacturers donated some materials and equipment and aided in installation.

During the construction of the houses, researchers from the Buildings Technology Center (BTC) at ORNL and from FSEC (a Building America team) installed extensive sensor systems that constantly measure interior and exterior conditions and the energy consumption and output of the houses. The data are used in detailed analyses. This review uses those data to document the energy performance of each of the houses and compare it with that of a Habitat house of similar size but without the advanced energy-saving features of the "net-zero-energy" houses.

The data show that, during the monitoring periods, the first of the four houses built used about 46% less energy from the grid than a reference house of the same size in the same subdivision, and the second, third, and fourth houses built used between 52 and 54% less energy than the reference house.

One of the goals of the research effort is to help the building industry develop building methods and materials that will make possible low-cost zero-energy residences by 2010. A number of builders across the United States are building near net-zero-energy houses, but they are large houses at the high end of the housing market. For the efficiency technologies to achieve wide market penetration, the first-cost premium must be reduced sufficiently that the utility bill savings will match or nearly match the amount that the energy-saving technologies add to the mortgage payment.

Technology Description

The four near-zero-energy houses studied are located in Lenoir City, Tennessee, a small town a few miles south of ORNL in East Tennessee. They are similar in size and appearance to other houses built in the East Tennessee area by Habitat for Humanity, a non-profit organization that uses supervised volunteer labor to build modest homes that can be sold at an affordable cost to qualifying families. The houses are part of a small subdivision of Habitat houses called Harmony Heights.

The four dwellings were built between the summer of 2002 and the summer of 2004. The size ranges from 1056 to 1200 ft^2. Each house contains three bedrooms and 1-1.5 baths. Three of the houses have crawl spaces; the other has a walk-out full basement that contains the bedrooms. All four are finished with vinyl siding. All were designed specifically for the mixed humid climate of East Tennessee.

Most of the construction labor on the homes was provided by volunteers working under the direction of a trained construction supervisor from the Loudon County Habitat affiliate. Subcontractors were hired for the plumbing; heating, ventilation, and air-conditioning (HVAC) systems; site work and foundations; drywall; and concrete.

Each house includes a number of energy-efficiency technologies, and no two houses have the same combination. Some of the technologies are used in all four houses; some have been tried in only one dwelling so far. All the houses use high-efficiency HVAC systems, but no two houses have the same system.

Each house has a rooftop solar photovoltaic (PV) system with a power rating of about 2 kWp that is connected to the local utility grid. The PV systems produce part of the electricity used by each house. 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 warm, sunny afternoons). The power consumed by the household and generated by the PV system is metered, and the homeowner is paid \$0.15 per kWh by the local TVA-affiliated utility for all the solar power produced. The percentage of energy used that is generated by the PV system ranges from around 20% to slightly under 30%.

Key energy-efficiency technologies employed in building all the houses include the following.

- Structural insulated panels (SIPs) made of thick sheets of foam insulation sandwiched between two sheets of oriented strand board. The panels are made in custom sizes, and rough openings for windows and doors and channels for wiring are cut into them at the factory. SIPs are highly insulating. They generally form more airtight building envelopes than conventional building materials and, because they combine insulation and sheathing in one unit, can be erected more quickly. The SIPs used in these houses generally were 8 ft high and of various lengths.

Wall/ceiling SIP

- Airtight building envelopes. SIPs are joined with splines and well sealed with caulk, tape, and foam at every edge where panels meet. While a typical frame house has a level of air leakage equivalent to a hole more than 15 ft^2, these houses have air leakage equivalent to about 13.5 in.^{2}. Each house underwent a blower door test before completion to test airtightness and identify any significant leaks that needed to be sealed. The natural air infiltration rate in the houses is less than 0.1 air change per hour (ACH) (the average for a same-size conventional new frame house built by the same Habitat affiliate ranges from 0.2 to 0.25 ACH).
- High-efficiency heating/cooling equipment. Each house has an electric heat pump with a high seasonal energy-efficiency ratio (SEER) rating—the lowest 13 SEER and

the highest 17 SEER. Two of the heat pumps used have two-stage compressors and variable-speed fans, which allow them to control humidity more efficiently during the cooling season. One house is equipped with a horizontal-trench ground-source heat pump, which uses the subsurface earth as a heat source for heating and a heat sink for the cooling system. Since the temperature 5 feet below ground is warmer in winter (~55°) and cooler in summer (~70°) than the air temperature, a ground-source heat pump is significantly more efficient than a conventional air-source heat pump.

- Heating/cooling ducts located inside the conditioned space to minimize heat transfer between ducts and the surroundings.
- Supply mechanical ventilation, which ensures that the house receives the amount of fresh air prescribed by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2 for ventilation and indoor air quality. CO_2 monitoring is used to determine when more fresh air is needed to accommodate the number of people in the house and the level of activity (e.g., CO_2 levels would rise during a large family gathering, signaling the ventilation system to admit more fresh air).
- Heat pump water heaters (HPWHs) or a highly efficient conventional electric resistance water heater. Three units have HPWHs, which use heat pump technology to produce hot water. (The HPWHs also produce cool, dry air that supplements the cooling system during cooling season.) HPWHs are about twice as efficient as conventional electric water heaters.
- Reflective metal roofs to reduce heat gain through the roof during hot weather. Once all reflective roofs were light in color, but now even dark roofs can be reflective because pigments are available that do not absorb solar radiation outside the visible spectrum. Two of the houses had dark green metal roofs and two have light-colored roofs.
- High-efficiency windows. All the windows used have a National Fenestration Rating Council U-factor of 0.34 and a solar heat gain coefficient (SHGC) of 0.33. (U-factor measures heat transfer; the SHGC measures how well the window blocks heat from the sun.) The glazing is double-pane, low-emissivity glass filled with argon gas.
- Extended roof overhangs to shade windows from direct sunlight during the summer months.
- Passive-solar principles. These include placing most of the windows on the south side of the house and using roof overhangs to block solar heat gain during the warm months.
- Energy Star® appliances.
- 60-90% florescent lighting

In addition to the energy-saving features, there was an emphasis on moisture management to avoid mold, mildew, and general moisture damage to the building and to control relative humidity levels that affect thermal comfort. The technologies employed include moisture barriers in the crawl spaces and basement, and HVAC systems that avoid introducing large quantities of humid outdoor air, pressure-neutralize distribution systems, and have programmable thermostats that also helped control summer humidity.

Table 1 lists building envelope features used in the four near-zero-energy houses and in a baseline Habitat house used for comparison. Table 2 lists mechanical features used in the test houses and the base house. (The base house itself is unusually energy-efficient—about 20% more so than a typical American house of the same size and layout.)

Table 1. Building envelope features of near-zero-energy houses and a base energy-efficient house

House	1	2	3	4	Base
Floors	1	1	1	2	1
Ft^2	1056	1060	1082	1200	1056
Occupancy	Nov 2001	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 # EPS (R-20) Structural splines	R-19 glass fiber batts, ¾-in. XPS boards installed on bottom side of 9½ in. I-joist (R-24)	R-19 glass fiber batts, ¾-in XPS 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, solid insulated and 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 ½ 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, polyisocyanurate, pentane blown (R-45), surface splines	Attic floor blown glass fiber (R-28.4)
Roofing	Light grey Hidden raised metal seam	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	Gray asphalt shingles

Table 2. Mechanical features of near-zero-energy houses and energy-efficient base house

House	1	2	3	4	Base
Solar system	48 43-W amorphous silicon PV modules, 2.06 kWp	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	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	2 ton air-to-air HP, SEER 14, variable-speed compressor, ECM indoor and outdoor fan	Unitary 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 crawlspace
Water heater	Integrated HPWH linked to unvented crawlspace	Integrated HPWH, linked to crawl-space that has motorized damper	Desuperheater for hot water, EF .94	HPWH vented to half-bath that is exhausted for ventilation	Electric EF~.89

Principles of Operation

A net-zero-energy house is one that produces enough, or more than enough, renewable energy on site to meet all the dwelling's power needs on an annual basis. Currently, the on-site energy source of choice is rooftop PV systems. A PV system, especially a small one, cannot produce enough energy to supply all the electricity a house needs constantly—on cloudy days or at night, it still must use power from the utility grid. However, in periods of intense sunlight, a small PV system may produce more energy than the house needs. The excess power can be fed into the utility grid and purchased by the local utility to balance the electricity purchased during less sunny times.

To reach the net-zero-energy goal, a house must be super energy-efficient, consuming no more power annually than a small PV system can supply. Otherwise, the PV system would have to be prohibitively large and expensive. That means cutting energy consumption by at least 70% compared with a conventionally built house of comparable size, according to Building America. Advanced energy-saving technologies thus are indispensable to making net-zero-energy houses feasible.

A net-zero-energy house is not a single technology but a suite of closely integrated technologies. An essential principle of the zero-energy design and building process is whole-house integration—careful planning to make all the components work together to achieve maximum energy savings (e.g., recovering waste heat to enhance the efficiency of a water heater). In the houses in this study, PV energy production is combined with several key building energy-efficiency principles—air-tightness, high-R-value insulation, high-efficiency appliances, reflective roofs, energy-efficient fenestration, passive solar techniques, recovery of waste heat, and humidity control—to move toward the net-zero-energy goal.


Airtight assembly of the SIP envelope is essential for energy savings.

Because zero-net-energy building is a new field, an essential part of this integration process is applying the lessons learned from building each dwelling to subsequent ones.

Maintenance, Service, and Operation

Since each net-zero-energy house will employ a different set of products, equipment, and building techniques, a set of maintenance and operating expectations cannot be provided. The equipment installed in the homes will require regular maintenance according to the manufacturers' guidelines.

Makers of the building materials (e.g., SIPs, high performance windows, solar panels) and equipment (e.g, heat pumps, HPWHs) used in zero-energy houses offer warranties and service contracts on their products. Individual construction subcontractors (e.g., plumbers, HVAC installers) generally offer limited warranties that cover specific problems arising from mistakes or poor workmanship on their part, as do general contractors. These would, of course, be different for every construction project.

A general observation based on experience from building the homes discussed in this study is that it is essential to use experienced, knowledgeable subcontractors to install advanced equipment. Installation of a ground-source heat pump, for example, should not be entrusted to an HVAC contractor whose training and experience covers only air-source heat pumps. Most of the problems documented for these houses were of the same sort that could arise during construction of any house. Incorrectly installed wiring or plumbing connections caused several problems affecting efficient operation of equipment among the three houses. This experience underlines the importance of inspecting all work and checking out all equipment for proper operation after it is installed.

Another general observation is that monitoring of performance is important to indicate operating problems and correct them in a timely manner. For example, although the solar PV systems themselves performed well, a faulty inverter on one system significantly reduced the amount of power produced until it was replaced. Regular monitoring of the PV system output indicated a performance problem; otherwise, the inverter problem might have gone undiscovered for a longer time.

A third observation is that even the most energy-efficient equipment may not save energy if it is not functioning properly. A low refrigerant charge in the heat pump in one house caused it to use far more energy than it would have with a proper charge, almost doubling the energy use of that house's HVAC until it was corrected.

In the second dwelling built, cracks were found at the intersection of the wall and ceiling SIPs, possibly caused by moisture trapped in the roof during construction that caused the panel to bow later.

In two of the houses, the metal roofs pop loudly on late summer afternoons. The assumption is that the popping is caused by contraction of the metal roof as it cools after being expanded by the heat of the sun during the day. This is an issue to consider in installing metal roofs.

A blower door was used to test the airtightness of each house during and/or after construction. Infiltration testing reveals leaks that would be overlooked otherwise and is an important part of ensuring energy efficiency by preventing incursions of cold air during heating season and unconditioned humid air during cooling season.

Measures of Efficiency

The overall measure of efficiency used to evaluate the performance of each of the near-zero-energy houses in this study is the amount of energy consumed in relation to the energy consumed in a conventionally built house of the same size. This measure is an imperfect comparison because the number and ages of the people in the different houses and their energy use patterns vary. However, it does show a clear difference between the four subject houses and the base house.

Energy consumption data were gathered for the main categories of consumption: heating, cooling, hot water, and lighting and plug loads.

Measures of efficiency are established by trade groups, building codes, and government agencies for all the building materials and equipment used in these four houses. PV systems, for example, are rated in terms of the amount of peak power they can produce and their efficiency in converting sunlight to electricity. SIPs are rated according to R-value. Windows are rated by the National Fenestration Rating Council for several factors, including heat transfer rate and solar heat gain. Heat pumps are assigned a

SEER rating for energy efficiency according to standards established by DOE and the HVAC industry. The energy efficiency of water heaters is rated by coefficient of performance. Household appliances are rated according to standards set by DOE and the various industries.

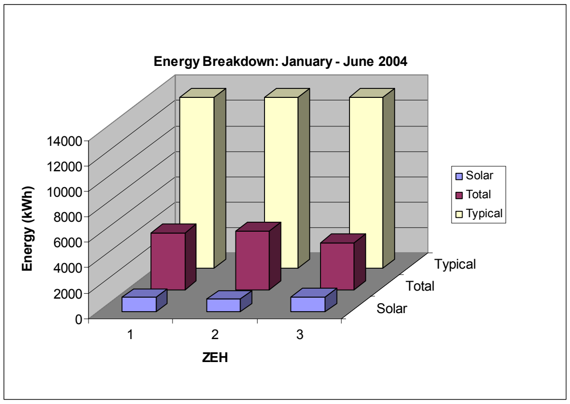
Energy Savings

Data collected on energy consumption of the four houses during their first years or months of occupation show overall energy savings compared with the base house have averaged from 40% to 60% on an annual basis.

One respected tool for evaluating the energy efficiency of a home is the Home Energy Rating System (HERS). HERS compares the energy performance of a specific house with that of a computer-simulated base house, identical in layout and size, that complies with the Model Energy Code. The base house is rated at HERS 80. Each 5% reduction in energy use compared with the reference house increases the HERS score by one point. To be certified by DOE as an Energy Star® house, a house must attain a HERS score of at least 86. All four of the Habitat houses studied surpassed that score by several points. Their HERS scores were

House 1: 90.2
House 2: 91.4
House 3: 91.5
House 4: 92.5

Thus the HERS scores showed these houses to be 20 to 26% more efficient than an Energy Star house of the same size (EnergyStar is itself a tough ranking to attain). They are 50 to 57% more efficient than a reference house of the same size that complies with the Model Energy Code. (The base house to which these houses are compared throughout this document is an HERS 84 house, 20% more efficient than the reference house.)

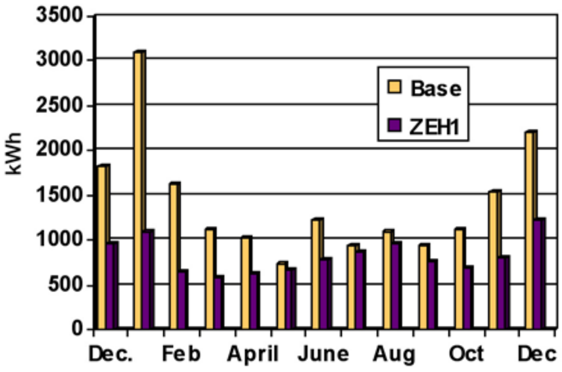


Energy use in Houses 1–3 compared with a base house, January–June 2004.

Cost-Effectiveness

The cost-effectiveness of near net-zero-energy houses will vary with energy costs, climate, the energy-consumption habits of the occupants, utility incentives for PV systems, and the cost of the particular set of technologies used in a particular dwelling. The electricity rate in Lenoir City, Tennessee, in 2004–2005 was $0.068 per kWh, well below the national average of around $0.08 per kWh. Energy cost savings would be greater in regions with higher electricity rates.

Because they were built partly as research units, the four houses studied did not benefit from economies that would be possible with production units. Production houses are expected to cost substantially less—particularly as the construction techniques used become more familiar and standardized and as the materials are produced in greater volume. Federal agencies, especially, should be able to negotiate large discounts on materials and equipment for large-scale projects involving a few standard house plans (e.g., military housing).



Comparison of utility bills for House 1 and the base house over a year.

The economic justification for net-zero-energy houses is that energy savings plus revenue from surplus electricity sold to the utility grid help offset the added price of construction. For these four houses, utility bills averaged less than $1 per day, around $25 per month, after the credit for the sale of surplus solar power back to the utility. 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. The chart shows utility costs for House 1 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, which is the same for all, and the cost of the PV systems) ranged from about $79,000 to $88,000. The cost of building the base house was about $59,300. Thus the cost of the highly energy-efficient dwelling, without the PV system added, ranged from about 33–66% more than the cost of the base house.

Table 3. Construction cost of test houses 1–4 and the base frame 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
Cost of solar	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 for house four, or from 69 to 75% more than the cost of the base house.

However, the cost of the PV systems had dropped from $22,000 in 2002, when the first house was built, to about $15,000 for a slightly larger-capacity system when the fourth house was completed in mid-2004. By late 2004, the market cost for a similar-size system was under $14,000. Over the long term the cost of PV systems is expected to continue to drop as production volume increases.

PV systems are cost-effective only if utility incentive programs, such as purchase of surplus energy from the PV systems, or mandatory renewable-generation directives, are in place. 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 further, increasing their cost-effectiveness.

Additional reductions in first cost are necessary to bring the life-cycle costs of net-zero-energy houses into line with requirements for federal housing. However, the local Habitat affiliate collaborating with this project is now attaining 100% certified >HERS 86 houses within the budget of under $60,000.

Federal Sector Potential

Military housing and other small structures are an opportunity for using net-zero-energy technologies in the federal sector. Given the large amount of military construction likely to be located in high-solar-incidence parts of the world, the high cost of establishing electric transmission and distribution infrastructure in remote areas, and the vulnerability of that infrastructure to attack, net-zero-energy military housing is a promising application. The modular panel construction can go up in a few days using a workforce with limited skills.

The life-cycle cost of building these houses must fit within the procurement requirements of the federal government. Currently, the energy savings do not offset the first cost sufficiently to offer acceptable payback periods. However, increasing demand for high-efficiency materials and equipment is expected to bring prices down gradually as production volumes increase. 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 could help to offset mortgage costs.

Other issues may work to make net-zero-energy building attractive for the federal sector, even considering high first cost:

- Environmental need for such housing could offset cost issues in some communities, for example, areas that are not meeting Clean Air standards and need to reduce emissions from power plants.
- Rising energy costs make energy-efficiency measures more cost-effective. Record petroleum prices, and forecasts of continuing high prices, put pressure on the government to make long-term investments to cut energy consumption.
- The need to conserve energy is becoming a security issue because of U.S. dependence on oil imported from volatile regions and the flow of resources to hostile nations.

Field Demonstration

Test Site

The construction and demonstration of these four near-zero-energy houses evolved from an existing partnership between DOE and Habitat. For several years, ORNL researchers and Building America had been working with Habitat to improve the energy efficiency of Habitat houses. As Habitat is one of the largest home builders in the United States, the partnership helped DOE meet goals for reducing the energy intensity of U.S. housing. It helped Habitat add value and comfort to its homes, helped Habitat homeowners save money on energy bills, gave the building industry a platform to test new energy-efficient products, and provided DOE and ORNL a field laboratory for energy-efficiency research.

When net-zero-energy houses became a possibility, the partnership with Habitat offered an ideal setting for incorporating ultra-efficient technologies into houses working families could afford. The partnership made plans to build a series of five houses, using the lessons learned from each one to move from near-zero-energy to net-zero-energy while exploring ways to reduce building costs for the super-efficient houses. The four near-zero-energy houses in this demonstration are the first four. (The fifth house, expected to be a true net-zero-energy house, was under construction in 2005.)

The four houses studied are located in a small subdivision in Lenoir City, Tennessee, which contains several other Habitat for Humanity houses. The terrain is hilly, and the building lots are mostly clear of large trees. Lenoir City Utilities Board, a distributor for TVA, is the local electrical power distributor.

Most of the labor for putting together the structure of the four houses was supplied by Habitat volunteers, who work under the supervision of a trained construction leader from the local Habitat affiliate. ORNL staff and representatives from companies donating materials and equipment helped direct the assembly of the structures, the weather-proofing, and the installation of specialized equipment. Contractors were hired for more skilled tasks such as site preparation and foundations, plumbing, installing HVAC and PV systems, hanging and finishing drywall, and pouring and finishing concrete.

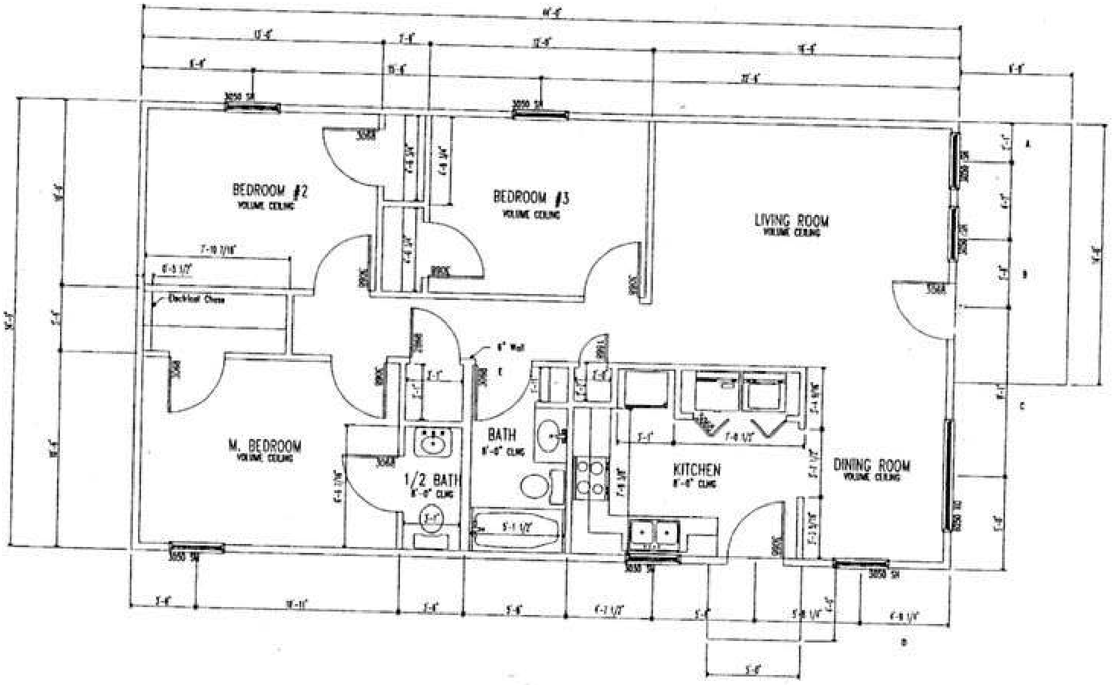
The monitoring of each house for energy consumption began after the owners had moved in. Each house was occupied by three to four people. The homeowners received no training in household energy conservation in conjunction with the purchase of the houses. Since the occupants own the houses, they are free to use energy as they wish. They set the thermostats to their preferences and decide whether to use additional energy-saving methods such as compact fluorescent light bulbs. Therefore, the demonstration reflects how these houses will perform in real life.

The Test Houses

All four houses are constructed with SIPs that are caulked, foamed and/or sealed with tape, compact thermal distribution systems with ducts inside the conditioned space, controlled mechanical ventilation, Andersen insulated windows with a 0.34 U-factor and 0.33 SHGC, extended roof overhangs, mostly south-facing windows, and Energy Star appliances. Other energy-efficiency features, such as the type of HVAC system or water heater, vary from house to house.

House 1 is a one-story dwelling containing 1056 ft^2. It has three bedrooms, a living-dining room, a kitchen, and 1.5 baths. Its 4.5 in.-thick walls, 6-in. floors, and 8-in. ceiling are all constructed of SIPs made with expanded polystyrene insulation. The ACH rate (at a pressure of 4 Pascals) is 0.08. 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

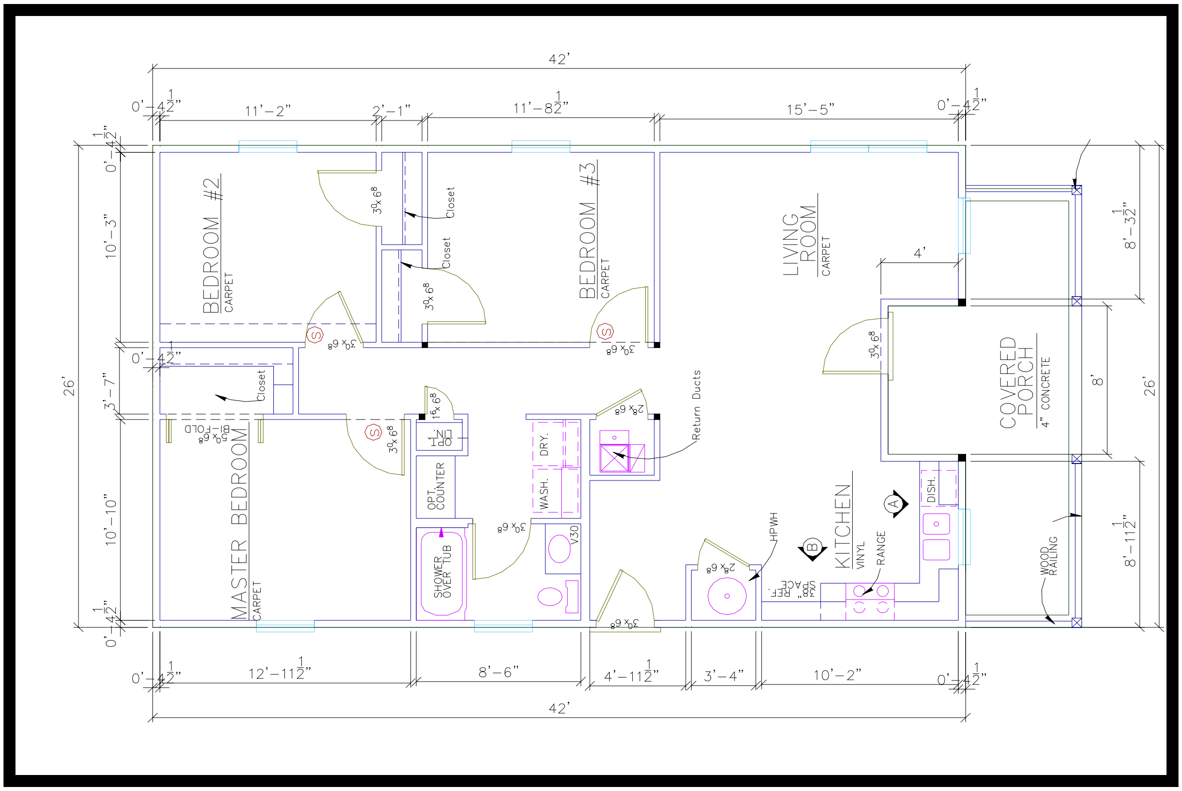
75° year-around, on average. The roof is gray reflective metal, hidden raised seam, with a 4/12 pitch. On the roof is a 2-kWp 48-panel solar PV system.



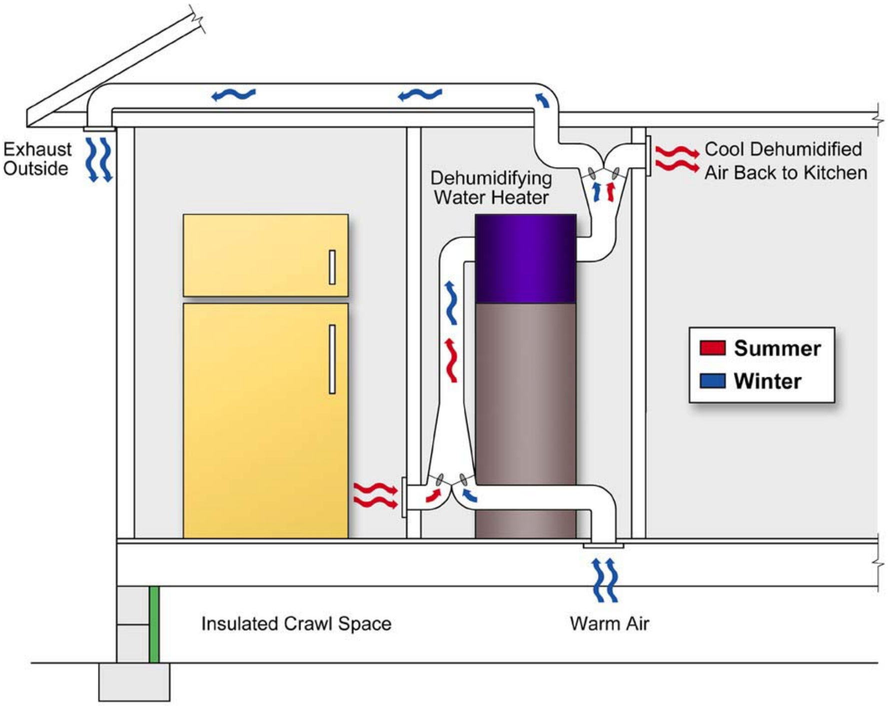
House 1 floor plan.

Hot water is supplied by an ECR International 50-gal HPWH located in a utility closet by the kitchen. During the cooling season, warm air from the refrigerator compressor is pulled into the utility closet to allow heat recovery to increase the HPWH thermal efficiency. The HPWH exhausts cool, dehumidified air, which is returned to the conditioned space during the cooling season. (During the heating season, the HPWH draws input air from the crawl space and exhausts cool air to the outside.) House 1 also has a heat recovery shower that captures the heat from warm water going down the drain and “recycles” it (the heat, not the water) to the water heater. It is equipped with energy-saving compact fluorescent light bulbs in about 75% of its light fixtures.

House 2 is one story with 1060 ft^2. Its wall and ceiling SIPs have slightly higher density and R-value than in House 1, and its ACH rate at 4 pascals is 0.07. Unlike House 1, House 2 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-around. The 50-gal. HPWH performed at a higher efficiency than the unit in House 1; the setup for the air supply to the HPWH is more compact. This house has 1.25-ft and 1-ft overhanging eaves instead of the 2-ft overhangs in the three other houses. The ceiling is 6.5-in.-thick SIPs, and the roof is green metal standing seam with a 6/12 pitch. The PV system is rated at 1.98 kWp and has 12 panels. This house initially used incandescent light bulbs; they were later replaced with compact fluorescent bulbs.



House 2 floor plan.

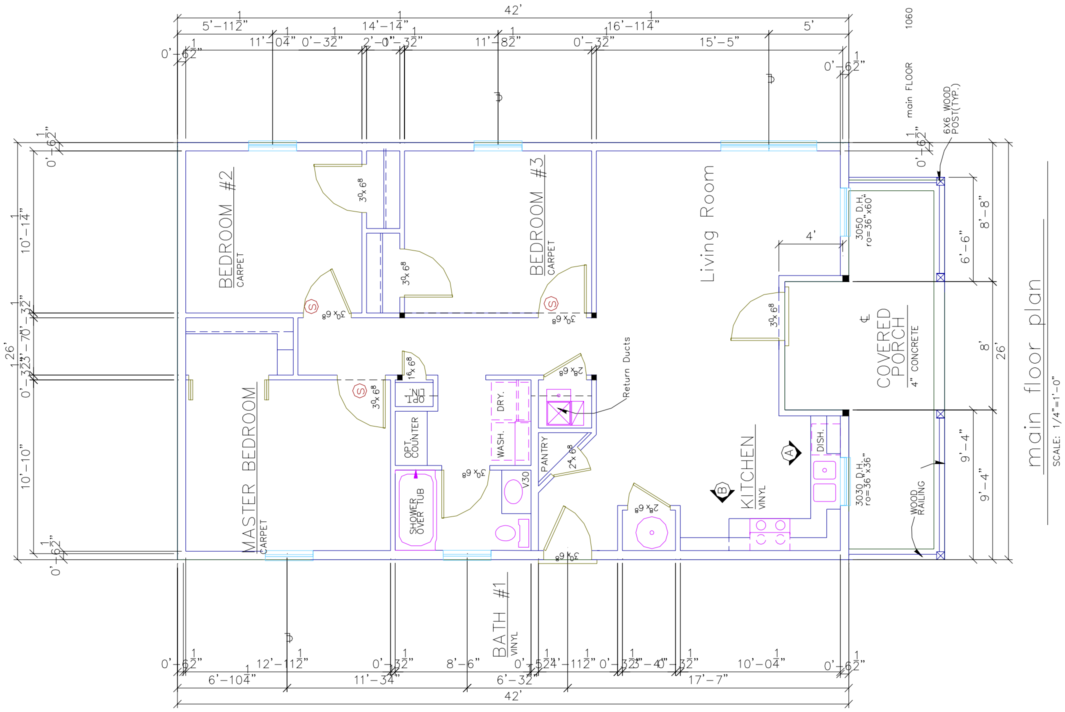


Air flow to and from the heat-pump water heater in House 2.

House 3 is one story with 1082 ft^2, of which 1042 is conditioned space. The biggest difference between it and the other three houses is that its heating/cooling system (2 ton, 16.6 SEER) is a geothermal or ground-source heat pump, which directly absorbs heat from and rejects it to the underground instead of to the air. The heat exchanger is three loops of copper pipe buried in 5-ft-deep, 200-ft-long trenches behind the house. (The system includes soaker hoses buried in the trenches in case the ground should ever become too warm to accept the rejected heat; but that is not expected to happen.)

GHP trenches behind House 3.

House 3 has 6.5-in.-thick SIP walls and 10-in.-thick SIP ceiling panels. The ACH rate is 0.03, less than half the rate of House 2. The green/ metal standing-seam roof is painted with a pigment that makes it 35% more reflective than the similar-looking roof of House 2. It has the same 6/12 pitch (26.6°) as ZEH2.

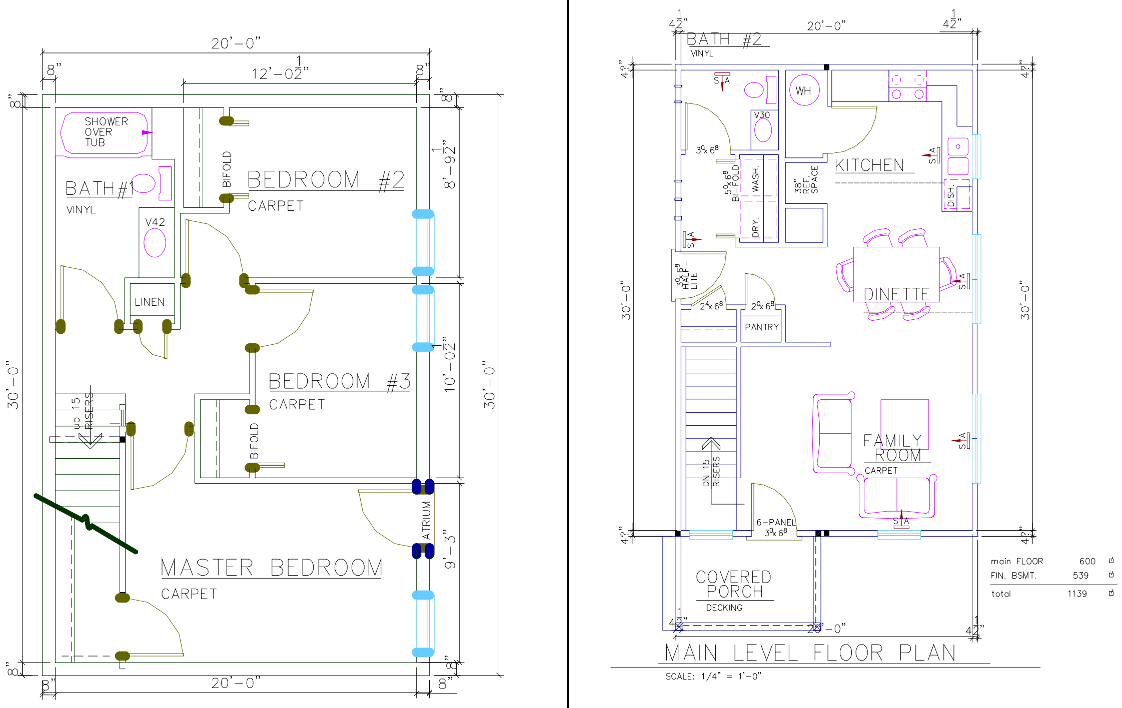


House 3 floor plan.

The PV system, like the one in House 2, is a 12-panel system rated at 1.98 kWp. The water heater is not an HPWH but a 50-gal. electric unit with an efficiency rating of 94%, the highest available in fall 2003 when the house was built. 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 House 3 kept the temperature at around 72°.

House 4, the only 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, that contains three bedrooms. The basement walls are four Tmass® 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 House 3 are made of polyisocyanurate, which has a higher R-value than the expanded polystyrene SIPs used in the other three houses. The ACH rate is 0.07. 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 Houses 1–3.

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, it draws warm air from the refrigerator compressor year-around; also unlike the others, it exhausts cool, dry air into an adjacent half-bath year-around. It is expected that the ventilation scheme for the house will avoid the cool, dry HPWH exhaust being a comfort issue during the heating season. House 4 has compact fluorescent bulbs in about 75% of its light fixtures.



House 4 floor plan. Bedrooms on first floor (left); living areas on second floor.

The Monitoring Setup

Each of the demonstration houses was equipped during construction with an array of sensors to record values such as indoor, crawl space, and ambient temperature; indoor, crawl space, and ambient relative humidity; water temperature in the water heater; heat pump operation; and indoor CO_2 level. The number of sensors installed ranges from 32 to 53. Each house contains thermocouples to measure the temperature of the HVAC equipment, duty-cycle valves to monitor equipment usage, and transducers to track the energy being used throughout the house.

At House 3, which has a geothermal heat pump, thermocouples were installed to measure the underground temperature 1, 6, 12, and 24 in. away from the buried copper heat exchanger pipeline and at 15 ft away from the pipeline. These thermocouples are buried at the same depth as the copper pipe, at a distance of 50 ft from the compressor outlet loops.

Each house is equipped with two electric utility meters, one to track the total amount of electricity the solar PV system is producing and another 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 thermal performance sensors continuously measure data that is recorded in a computer located in each house every 15 minutes. At 2:00 a.m. daily, a computer at

ORNL or the Florida Solar Energy Center calls the data acquisition system at each house and downloads the recorded data from the previous 24 hours.

The data are analyzed extensively to determine product performance and energy consumption and used in computer models. These models simulate situations such as how modifying the mix of technologies might affect the energy usage of a house or how varying inputs in a category would change overall energy performance. For example, a house could be modeled with lower or higher plug loads, or a larger PV system on a house could be simulated to determine whether the added PV production would bring the house to net-zero-energy status. Simulations such as these provide information to researchers about what technology mix might provide the most energy efficiency for the money.

Energy Savings and Costs

The calculations of energy cost in this section are based on electricity costs of $0.068/kWh. A contractual arrangement specifies that the local utility will pay the homeowner $0.15/kWh for all the solar power produced by the PV system for 10 years whether the homeowner uses it or not.

House 1. Monitoring data show that House 1, 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, which is itself more efficient than the average house. The energy cost (electricity purchased from the utility minus the amount of surplus solar power sold to the utility) amounted to about $1.01 per day at the present rate of $.068/kWh.

The rooftop solar PV system supplied 2006 kWh, about 20% of the energy used over the year. About 40% of the PV was produced at a time in which it was not needed in the house. The solar energy 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 House 1 during the monitoring year March 2003 through February 2004. As in all the houses, lighting and plug loads ("other") accounted for ~60% of the energy used.

Table 4. House 1 measured energy use, March 2003 through February 2004

Month	Space heat (kWh)	Space cool (kWh)	Hot water (kWh)	Other (kWh)	Total electric (kWh)	Solar ac generated (kWh)	Solar sold to utility (kWh)
March (2003)	127		124	325	575	167	91
April	64		146	419	629	195	100
May		94	109	460	663	188	90
June		204	87	490	781	213	88
July		314	74	494	882	209	79
Aug		359	70	536	966	219	76
Sept		187	82	491	760	195	95
Oct	34	17	117	518	686	159	77
Nov	141		138	518	797	121	45
Dec	401		187	650	1238	115	15
Jan	473		219	540	1232	120	23
Feb (2004)	344		196	466	1006	104	25
Total	**1584**	**1175**	**1549**	**5907**	**10216**	**2006**	**804**
% of total	15.5%	11.5%	15%	58%	100%	20%	
Cost ($)	$100	$74	$98	$372	$644	–$301	

The occupants of House 1 used less than 40 gal of hot water per day, about 43% less than the national average in a national survey of hot water usage conducted by ORNL. The low hot water draws are due in part to reduced distribution losses resulting from the compact plumbing system—because hot water does not have as far to travel, less of the heat is lost. Water distribution losses in a typical house are thought to be around 30%.

House 2. During the one-year period from April 1, 2004, through March 31, 2005, House 2 occupants consumed a total of 12,207 kWh. During this same 12 month measurement period 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 broken down into heating, cooling, hot water, and other.

Table 5. House 2 measured energy use, April 2004 through March 2005

Month	Space Heat (kWh)	Space Cool (kWh)	Hot Water (kWh)	Refrigerator (kWh)*	Other (kWh)	Total electric (kWh)	Solar AC generated (kWh)	Solar to the grid (kWh)
April		159	87	33	418	664	203	99
May		488	66	37	359	913	234	78
June		498	57	35	336	891	215	76
July		347	59	33	325	731	250	110
August		280	60	34	344	684	233	86
Sept.		246	56	31	299	601	217	102
October	280		70	32	346	696	159	65
Nov.	624		78	31	359	1061	145	30
Dec.	1420		109	32	403	1932	148	19
January	1392		118	33	382	1892	136	15
February	756		99	30	352	1207	142	34
March	442		102	33	391	935	223	81
Total	4914	2018	961	394	4314	12207	2305	795
Annual cost	$334	$137	$65	$27	$293	$830	-$346	
Daily cost	$0.91	$0.37	$0.18	$0.07	$0.80	$2.27	-$0.95	

* included in other

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 House 1. The higher energy cost is attributable to a low coolant charge on the heat pump. Although the heat pump was recharged on June 6, 2004 and again on February 23, 2005, average daily energy cost for the 14-SEER, two-speed compressor with a variable-speed fan motor was $1.30, compared to $0.52 per day for House 1, which had a 13 SEER, heat pump with a single-speed compressor, and $0.44 per day for House 3 with the geothermal heat pump.

Based on measurements of the heat pump supply and return temperatures, the kWh of the indoor and outdoor heat pump units, and ambient air temperatures, the HVAC system's COP for January 17 was calculated, and researchers found that the heat pump was delivering only 47% of its rated performance. Using this calculation, heating season HVAC power requirements from the beginning of the heating season until the unit was recharged in late February 2005 were adjusted, assuming a properly performing heat pump. The resulting adjusted energy use for October 2004 until the end of February 2005 is 2370 kWh or $161 per year, which equals $0.44 per day. This reduction in Heating energy for ZEH2 was 2544 kWh. The adjusted daily HVAC cost is $0.85 per day, and adjusted total whole-house daily energy cost after solar credits is $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, an improvement of 3% over the 20% of total electric demand supplied by PV in the first house.

House 3. During the one-year period from March 1, 2004 until February 28, 2005, House 3 occupants consumed a total of 11,014 kWh. During the same year the PV system generated 2241 kWh, including 29% collected during times when the energy was not needed in the house. Table 6 shows the energy usage in House 3.

Table 6. House 3 measured energy use, March 2004 through February 2005

Month	Space Heat (kWh)	Space Cool (kWh)	Hot Water (kWh)	Other (kWh)	Total electric (kWh)	Solar AC generated (kWh)	Solar to the grid (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
Annual Cost	$39	$121	$87	$502	$749	–$336	
Daily cost	$0.11	$0.33	$0.24	$1.38	$2.05	–$0.92	

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 House 1 (5907 kWh/year), House 2 (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 occupied during the day on most days. Also a significant load was due to extensive outdoor holiday decorations during November through January. To be able to more directly compare House 3 with the other houses and the Building America Benchmark, the kWh for "other" loads for House 3 is reduced. The average for "other" loads of House 1, House 2, and two Building America Benchmark houses is 5604 kWh/year, or $1.04 /day. This would reduce 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 cost for off-site energy of $0.79.

This compares to $1.01/day for House 1, as reported in ASHRAE Journal, January 2005, and $0.88/day for House 2, as reported in ASHRAE Transactions 2006, vol. 1.

The HVAC cost on House 3 with the geothermal heat pump averaged only $0.44/day, compared to $0.51 per day on House 1 with a 13 SEER, single-speed compressor. The final adjusted daily HVAC cost for House 2 came to $0.85/day.

With an adjusted "other" load for House 3 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 House 1. House 2 attained 23% of it's total energy needs from the solar PV system.

House 4. House 4 occupants consumed a total of 9843 kWh for one complete year from August 1, 2004, through July 31, 2005. During this same period 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 broken down into heating, cooling, hot water, and other.

Table 7. House 4 measured energy use, August 2004 through July 2005

	Space Heat (kWh)	Space Cool (kWh)	Hot Water (kWh)	Fridge* (kWh)	Other (kWh)	Total Electric (kWh)	Solar AC generated (kWh)	Solar to the grid (kWh)
August 2004	0	204	168	45	503	875	279	126
Sept	0	145	114	42	580	839	236	77
Oct	73	0	115	40	474	663	176	87
Nov	152	0	138	27	449	739	144	70
Dec	429	0	186	31	425	1041	146	62
Jan	438	0	190	39	441	1068	137	62
Feb	322	0	162	34	359	843	146	67
March	297	0	196	36	439	932	247	126
April	0	99	169	35	422	690	255	134
May	0	102	144	36	376	622	324	201
June	0	199	116	39	402	717	286	120
July 2005	0	267	120	46	427	814	251	87
TOTAL	1711	1016	1819	449	5297	9843	2627	1219
Annual cost	$116	$69	$124	$301	$360	$669	–$394	
Daily cost	$0.32	$0.19	$0.34	$0.08	$0.99	$1.83	-$1.08	

* Fridge included in “other” electric totals for each month

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 House 1, as reported in ASHRAE Journal, January 2005; $0.88 per day for House 2, as reported in ASHRAE Transactions 2006, vol. 1; and $0.79 per day for House 3.

The HVAC cost on the House 4 with the SEER 17 air source HP averaged $0.51/day. The HVAC cost on House 1 with a 13 SEER single speed compressor using the same $0.068 per kWh electricity came to the same $0.51/day. The final adjusted HVAC daily cost for House 2 came to $0.85/day. The HVAC cost on the House 3 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.

Summary

Four near-zero-energy houses were built to demonstrate the feasibility of making net-zero-energy housing affordable in moderately priced housing. The houses, built between 2002 and 2004, cost about $100,000, including the cost of the rooftop solar PV systems on all the houses. Their energy efficiency, documented by an elaborate monitoring system, was impressive—energy consumption 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 and the energy savings make the houses less expensive to operate, but they do not currently meet federal procurement guidelines for payback periods. Additional reductions in first cost are necessary to make the technology appropriate for federal building programs. However, prices of the materials and equipment used are expected to drop as increased demand encourages high-volume production. The cost of solar PV systems had already dropped from $22,000 to $14,000 during the two years these houses were being built.

A key to bringing down the costs of net-zero-energy houses is increased demand leading to mass production. Building researchers at ORNL are encouraging the building industry to develop net-zero-energy housing “kits” containing the materials needed to construct a small house in a particular climate zone. The kits would encourage both mass production and standardization of panels and other components.

Should the federal government adopt the net-zero-energy concept for a large number of housing units, its mass purchasing power probably would enable it to negotiate significantly lower prices for the components. If construction costs can be brought into line with federal requirements, potential federal sector applications of small net-zero-energy houses or other buildings include military housing and base structures. Much future U.S. military construction is likely to be in parts of the world with bright sunlight year-around and without widespread infrastructure for electricity transmission and distribution. For such areas, net-zero-energy construction might prove more feasible than conventional approaches. The speed with which panelized houses can be put together, by workers with limited skills, would add to their attractiveness for remote areas.