ZERO-ENERGY MANUFACTURED HOME

The Zero-Energy Manufactured Home (ZEMH) program demonstrates, evaluates, and promotes innovative energy-saving technologies for use in HUD-code housing.

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This Zero-Energy Manufactured Home is the most energy-efficient HUD-code home in the United States.

All across the country, partnerships among government groups, nonprofits, and private industry are finding ways to make energy-efficient single-family and multifamily homes more affordable for everyone. Habitat for Humanity in Colorado worked with the National Renewable Energy Laboratory (NREL) to create a home that exceeded the goal of producing as much energy as it consumed over the course of a year (see "The Little House That Could," *HE* Nov/Dec '06, p. 24). Another notable project, the Zero-Energy Manufactured Home (ZEMH) program, demonstrates and promotes innovative energy-saving technologies to the HUD code manufactured-housing industry and the home-buying public, while evaluating those technologies' energy performance. Manufactured homes are an affordable option for new-home buyers with limited incomes; 10%–20% of new homes sold are manufactured homes.

The ZEMH project is administered by the Washington State University (WSU) Energy program, funded by the Bonneville Power Administration (BPA), and coordinated with DOE's Building America Industrialized Housing Partnership (BAIHP). The authors, Michael Lubliner from WSU and Adam Hadley from BPA, teamed up to lead the project.

To further the goals of the ZEMH program, we took a 1,600 ft² manufactured home built in 2002 and added a variety of innovative energy-saving technologies. The home was showcased at the Spokane Fair in September 2002 to demonstrate the new technology. Then, to evaluate the performance of the new technologies, we conducted a detailed study of the home and compared its performance to that of another 1,600 ft² manufactured home, built by the same manufacturer at the same time, using identical floor plans. The comparison home was built to Energy Star home standards, as part of the Northwest Energy Efficient Manufactured Home (NEEM) program. The Energy Star home represents the best in home performance available to manufactured home buyers today, while the ZEMH home tests the technology that will move the manufactured home industry another step closer to the goal of creating affordable homes that create as much energy as they need each year.

Both the ZEMH and the Energy Star homes are all-electric homes with packaged air source heat pumps, using crawlspace air as the heat source. The homes are located in Lapwai, Idaho, near Lewiston. The number of occupants in each home differs, as do their lifestyles. The occupants of the ZEMH home are a middle-aged couple, one of whom stays at home most of the day while the other works. The occupant of the Energy Star home is single and younger, and is home only in the evening and on some weekends. This made it more difficult for us to compare the energy use of the two homes, but it still allowed us to draw some interesting conclusions about the influence of lifestyle on energy use.

Table 1. Comparison of ZEMH and Energy Star Home Energy Saving Technologies

Measure	ZEMH	Energy Star
Walls—2x6 ft, 16 in on center	R21 Foam-spray	R21 Batt
Floor—2x8 ft, 16 in on center	R33 (R22 Foam + R11 batt)	R33 Blown cellulose
Vented crawl space wall	R14 foil faced foam	None
Roof—4/12 pitch metal	R49 Foam, 16 in on center; Solar ready —includes mounts, flashings and chase	R33 Blown cellulose 24 in on center
Metal Roof	Mounts, flashings, and PV electric chase; 40 lb roof load	Standard 30 lb roof load
Windows—12% of floor area glazing, vinyl, argon, low-e, Energy Star	Dual blinds, heavy drapes, awnings	Single blinds, light drapes
Doors	U=0.2 metal, foam with thermal break	U=0.2 metal, foam with thermal break
HVAC	2 ton unitary air-source pump 12 SEER, 7.8 HSPF	2 ton unitary air-source heat pump 12 SEER, 7.8 HSPF
Zone heat	150 W Radiant panel in kitchen	None
Ducts—R8 crossover	Flex crossover system; Mastic with screws, more efficient duct design	Sheetmetal elbows Standard foil tape
Lighting	100% Energy Star T8 and CFL fixtures	T12 and incandescent fixtures
Appliances	Energy Star laundry, refrigerator, dishwasher	Standard laundry, refrigerator, dishwasher
Whole house ventilation	Heat recovery ventilator w/HEPA (turned off in 8/04)	low-sone Energy Star exhaust fan (operated continuously)
Spot ventilation	Energy Star bath fans, std. kitchen fan	low-sone bath fans, std. kitchen fan
Ceiling fans	Energy Star with dimmable CFL	Standard with incandescent bulbs
Domestic hot water	Solar hot water system; 80 gallon solar storage tank (pre-plumbed); 40 gallon high efficiency electric backup (EF=.93)	EF=.88
Air Sealing	Wrap with tape flashing Marriage line gasket (new product)	Wrap without tape flashing; Standard practice marriage line sealing
Total design heat loss @ 6°F - 97.5%,	20,779 Btu/hr/°F (6,090 W)	24,372 Btu/hr/°F (7,143 W)

ZEMH and Energy Star Home Measures

The innovative energy-saving technologies employed in the ZEMH home are as follows:

1. Icynene open cell spray-foam insulation is used in the floor, walls, and ceiling.
2. A Venmar HEPA 3000 heat recovery ventilator (HRV) with a high-efficiency particle arrestor (HEPA) filtration system provides continuous whole-house ventilation and filtration.
3. A 4.2 kW peak-rated PV system with a 4 kW inverter and 12 kWh battery array provides electricity to the home. (Before the net metering agreement with the utility was worked out, the PV system charged batteries for the kitchen subpanel load. As it turns out, the battery efficiencies caused the PV system, and so the ZEMH home, to be less efficient than it would have been without batteries.)
4. An active closed loop solar water heating system using a PV-controlled pump and 64 ft^2 of collector provides 80 gallons of solar storage. A 40-gallon electric resistance hot water system is used for backup.
5. The house features a solar ready design, to facilitate on-site installation of the PV net metering system and the solar water-heating system.
6. Sun-tempering features include adjustable awnings, high thermal resistance window coverings, and dual window blinds.
7. Appliances include an Energy Star refrigerator, dishwasher, clothes washer, and ceiling fan.
8. Light fixtures are Energy Star compliant.
9. A crawlspace assisted air source heat pump (CAHP) with foundation wall insulation provides heat for the home. (For more on the CAHP, see "Crawlspace Air Source Heat Pump (CAHP) Technology.")
10. The house features an improved forced-air HVAC thermal-distribution system, including mastic and mechanical fastening of ductwork connections; spray foam floor insulation that air seals and thermally isolates ductwork from the unconditioned vented crawlspace; and a tighter, more durable, and supported crossover duct system.

A summary comparison of the ZEMH and the Energy Star home energy-saving technologies is presented in Table 1.

Field Testing

We conducted fan depressurization field tests on both homes to determine envelope leakage in accordance with ASTM E779. Fan pressurization tests were conducted to determine duct leakage in accordance with ASHRAE Standard 152. We used an industry-accepted, commercially available flow-measuring device to determine flow rate at the return grille of the heat pump. Bath fan flow rates were measured using a commercially available flow box, calibrated so that flow rates were determined from

Crawlspace Air Source Heat Pump (CAHP) Technology

The CAHP uses typical indoor blowers, indoor coils, compressor, bi-flow thermal expansion valve (TXV), strip heating, and controls. But unlike the outside coil of a split-system heat pump, the outside coil of the CAHP is located in the back of the indoor unit. The CAHP utilizes a centrifugal blower with forward-curved blades attached directly to the motor shaft of a 1/3 hp permanent split capacitor (PSC) motor. This blower draws roughly 800–1,000 CFM of outside air through a vented crawlspace over the coil, and exhausts it above the roof (that is, in a single pass). The indoor coil is located in the front of the unit. A typical indoor 1/3 hp blower fan motor draws air from a central return grille over the indoor coil and distributes it to a trunk ductwork in the belly space below the floor and above the floor insulation and the bottom board (see Figure A). It is common in multiple-section homes to connect trunk ductwork using a 10–12-inch-diameter crossover insulated flex duct system, located in the crawlspace. The indoor and outdoor coils are isolated from each other within the heat pump (see Figure A).

ZEMH project staff conducted flip-flop tests to compare the two winters of typical heat pump performance (flip) with two multiweek periods of electric-resistance heating only (flop), for the CAHP units in the Energy Star and ZEMH homes. Average daily space-heating energy use in kWh was plotted against average daily indoor-to-outdoor temperature differences greater than 20°F. The flip-flop ratio is useful information for Pacific Northwest utility heat pump rebate programs, since it compares the performance of electric furnaces to that of heat pumps, while accounting for such performance factors as duct leakage, conductive loss, equipment cycling, defrost and strip heat, thermal regain, and so on.

It should be noted that high duct losses are known to cause greater efficiency problems for heat pumps than for forced-air furnaces. The measured duct leakage rates in the ZEMH and Energy Star homes were 37 CFM_{25} and 150 CFM_{25}, respectively, using ASHRAE Standard 152.

Using the regression fits, the flip-flop ratios appear to be 2.2–3.9 in the ZEMH case and 1.8–3.3 in the Energy Star home case, at outdoor temperatures of 20°F-50°F in both cases. The flip-flop tests and estimates of in situ heating coefficient of performance (COP) suggest 200%–260% improved performance over an electric furnace in the 30°F–50°F outdoor temperature range. (For more on CAHP performance, including the influence of crawlspace temperature, contact the author at lublinerm@energy.wsu.edu.)

Heat Pump Air-Flow Schematic

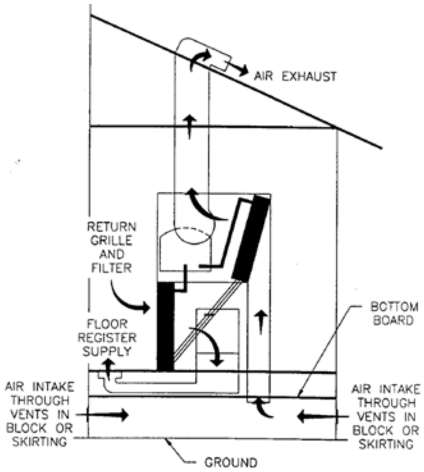


Figure A. A crawlspace assisted air source heat pump (CAHP) with foundation wall insulation provides heat for the homes.

a differential pressure measurement across an orifice.

In order to track the energy performance of each home, David Beal and Steve Bakaszi of the Florida Solar Energy Center, a BAIHP partner, installed monitoring equipment in both the Energy Star home and the ZEMH. The monitoring equipment collected the following energy use data from each home:

- total electricity use from grid;
- electricity use of resistance elements in heat pump;
- electricity use of heat pump compressor and fan motors; and
- electricity use of water-heating equipment, including gallons used.

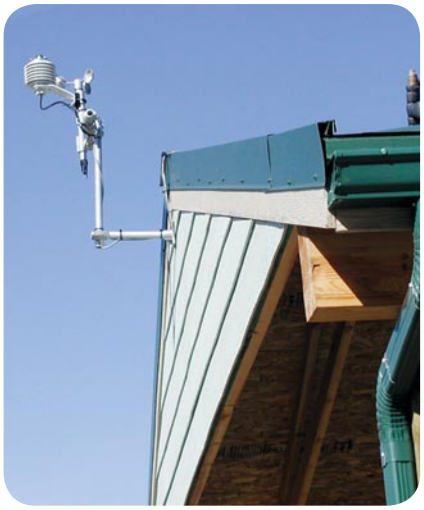
In addition, PV energy production data were collected for the ZEMH.

Sensor data were collected every 15 minutes by data loggers and were transmitted daily to the host computer. Plug-type energy loggers were installed to submeter the energy use of the refrigerator, freezer, and clothes washer in each home, and the radiant heat panel and HRV in the ZEMH.

Envelope and HVAC System Measurements

Our field measurements of the envelope and HVAC systems of the two homes produced the following results. (See Table 2 for a more detailed data summary.)

Envelope leakage. The ZEMH envelope leakage rate was only 2 ACH_{50}. This figure is 44% lower than the leakage rate for the Energy Star home, and is lower than that for any previously tested energy-efficient NEEM manufactured home. (Typical envelope leakage for HUD-code homes is 6–12 ACH_{50}; 4–5 ACH_{50} is typical for NEEM homes.) We attribute this reduced leakage largely to



(left) A plug-in line logger monitors the energy use of an older model freezer. *(middle)* Lubliner and Hadley conduct a solar site survey on the front porch of the ZEMH. *(right)* Weather station and other data is transmitted daily to the Florida Solar Energy Center WebGet research database.

the air sealing properties of the foam insulation system used in the walls, floors, and ceiling.

Duct leakage. ZEMH total duct leakage was 31% lower than total duct leakage for the Energy Star home; leakage to the outside was 75% lower than that for the Energy Star home. The ducts in the ZEMH are located in the belly space within the thermal envelope; they are also effectively within the pressure envelope of the home, as they are surrounded by foam insulation (except at the top of the trunk and branch ducts). The ducts in the Energy Star home are likewise located in the belly space. However, they are insulated with fiberglass instead of foam, so they are outside the pressure envelope. This helps to explain why leakage to the outside is significantly lower than total duct leakage in the ZEMH.

HVAC flow rates. The HVAC flow rates of the heat pumps were approximately 1,000 CFM for both homes, about equal to the design flows.

HVAC supply plenum pressure. The supply air pressure with the HVAC system operating was almost twice as high in the ZEMH as it was in the Energy Star home, though it was still within the range of acceptable practice. We believe that this was partly because the ZEMH duct design called for tighter ducts and fewer supply registers than were used in the Energy Star home.

Table 2. Comparison of ZEMH and Energy Star Home Field Testing

Test	ZEMH	Energy Star home
Envelope leakage	2.0 ACH @ 50Pa	3.6 ACH @ 50Pa
Total duct leakage	145 CFM @ 25Pa (68 L/s @ 25PA) 15% of HVAC flow	211 CFM @ 25Pa (100 L/s @ 25PA) 20% of HVAC flow
Duct leakage to outside	37 CFM @ 25Pa (17 L/s @ 25PA) 4% of HVAC flow	150 CFM @ 25Pa (71 L/s @ 25PA) 15% of HVAC flow
HVAC return flow rates	970 CFM (458 L/s)	1,008 CFM (472 L/s)
HVAC supply pressure[1]	30 Pa	16 Pa
Whole house ventilation	70 CFM (33L/s)[2]	78 CFM (37L/s)
Bath fan flow rates	110-116 CFM[3] (52-55 L/s)	31-33 CFM[4] (15-15 L/s)

[1] Measured at closest supply register
[2] Measured on low-speed with clean pre-filter and 3 month old HEPA filter
[3] Rated 90 CFM at 0.25" static pressure per HVI directory
[4] Rated 50 CFM at 0.10" static pressure per HVI directory

Whole-house ventilation. The HRV flow rate in the ZEMH was measured at roughly 70 CFM on low speed with a clean prefilter and a three-month-old HEPA filter. The flow rate for the Panasonic, high efficiency whole-house fan in the Energy Star home was measured at 78 CFM. Both flow rates exceeded the required minimum of 56 CFM, based on the HUD requirement of 0.035 CFM per square foot. (Filter replacements will cost about $100 each year.)

Spot ventilation flow rates. The flow rate for the ZEMH bathroom fan was measured at approximately 115 CFM and the bath fan flow rate for the Energy Star home was measured at approximately 32 CFM. The ZEMH Panasonic bathroom exhaust fan, like the Panasonic whole-house fan in the Energy Star home, is quiet, low-wattage, and designed for continuous use; the fan has a condenser fan motor with permanently lubricated bearings and a larger capacity than the cheap "fart fans" exhaust fans in the Energy Star home. The larger capacity explains the higher flow rate for the bathroom in the ZEMH. A minimum of 50 CFM is typically required (but often is not achieved) for spot exhaust fans in HUD code manufactured homes.

Energy Use

Total

The total energy use in the ZEMH was higher in the summer than total energy use in the Energy Star home; the two measurements were comparable during the rest of the year. As mentioned above, the Energy Star home occupant is a young man who was not often home while we were measuring home performance. On the other hand, the ZEMH occupants were home and used the air conditioning quite often in the summer, which explains the higher energy use in the ZEMH home in the summer. The fact that the two homes used about the same amount of energy overall for the rest of the year, given the lifestyle differences of the occupants, points out the superior energy efficiency of the ZEMH.

Daily average total energy use (with PV and solar domestic hot water) over the 2004–2005 monitoring period in the ZEMH was 29.4 kWh per day. Daily average total energy use included the heat pump strip heat used during flip flop testing. The owners of the ZEMH also had an old, inefficient freezer located in the carport, which consumed an average of 3.2 kWh per day. The rest of the energy use in the ZEMH averaged 2.1 kWh per day more than that in the Energy Star home. Had the occupant of the Energy Star home lived in the ZEMH, total energy use might have been reduced to 24.1 kWh per day, given the differences in lifestyle. (Figure 1 compares total monthly energy use in the two homes, broken down by hot water, heat pump, strip heat, and other loads.)

Hot Water Use

The Energy Star home used an average of 9,700 gallons of hot water per year, or approximately 27 gallons per day, versus 15,700 gallons per year, or approximately 43 gallons per day, for the ZEMH (see Figure 2). To account for these differences, energy use was normalized by hot water used. The benefits of the solar hot water system in the ZEMH vary from month to month. In summer months, almost all the hot water in the ZEMH is provided by solar. The ZEMH used roughly 47% less energy to heat water than the Energy Star home did after normalizing by the total gallons used during the monitoring period.

Other Loads

We calculated all the other loads by subtracting the space-heating, space-cooling, and water-heating loads from total energy use. The other loads for the Energy Star home averaged 4,420 kWh per year, versus 7,950 kWh per year for the ZEMH during the two-year monitoring period.

Icynene floor, ceiling, and wall spray-foam insulation resulted in the tightest HUD-code envelope and ducts ever tested.

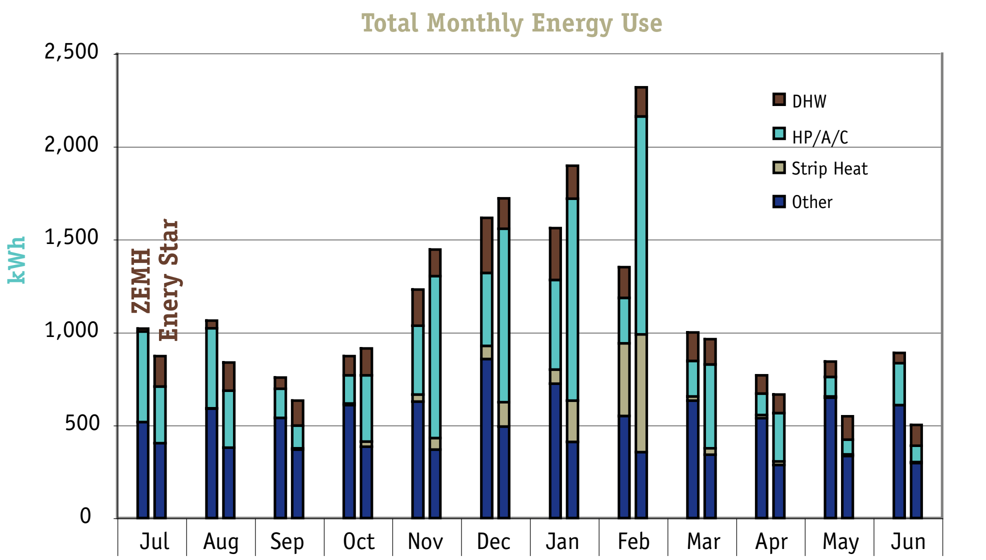


Figure 1. Daily average total energy use (with PV and solar domestic hot water) over the 2004–2005 monitoring period in the ZEMH was 29.4 kWh per day. Had the occupant of the Energy Star home lived in the ZEMH, total energy use might have been reduced to 24.1 kWh per day, given the differences in lifestyle.

Radiant-panel heater and HRV loads contributed roughly 63 kWh per month for the ZEMH. The HRV in the ZEMH, which ran on low speed all the time, used a lot more fan energy (110 kWh per month) than the ventilation system in the Energy Star home (16 kWh per month). However, the increased fan energy in the ZEMH was due to the HEPA filter, which contributed to better indoor air quality.

The rest of the difference was attributable to occupant behavior. For example, the ZEMH Energy Star washing machine used over twice as much electricity as the top-loading standard unit in the Energy Star home, because the occupants of the ZEMH used their

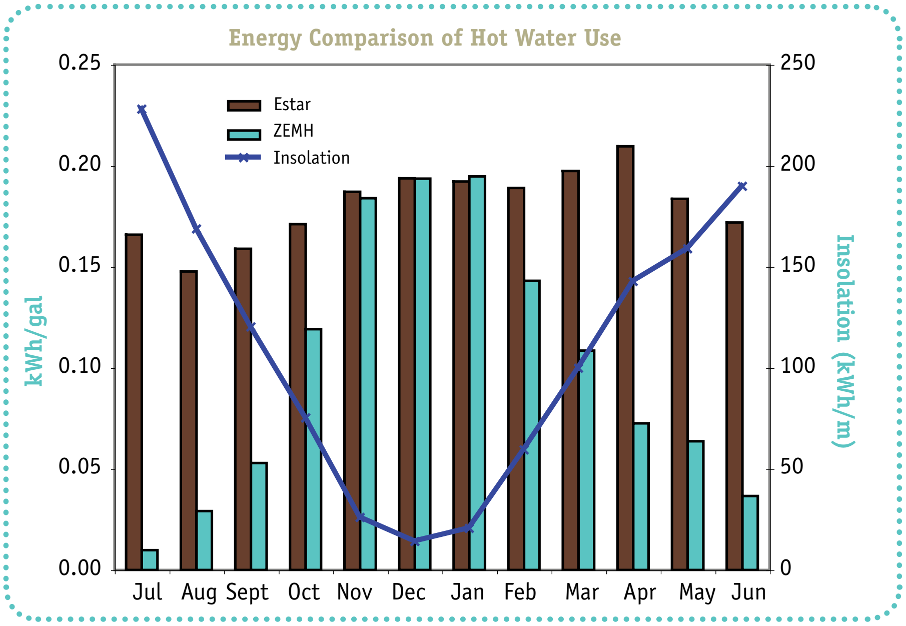


Figure 2. The ZEMH used roughly 47% less energy to heat water than the Energy Star home did after normalizing by the total gallons used during the 2004–2005 monitoring period.

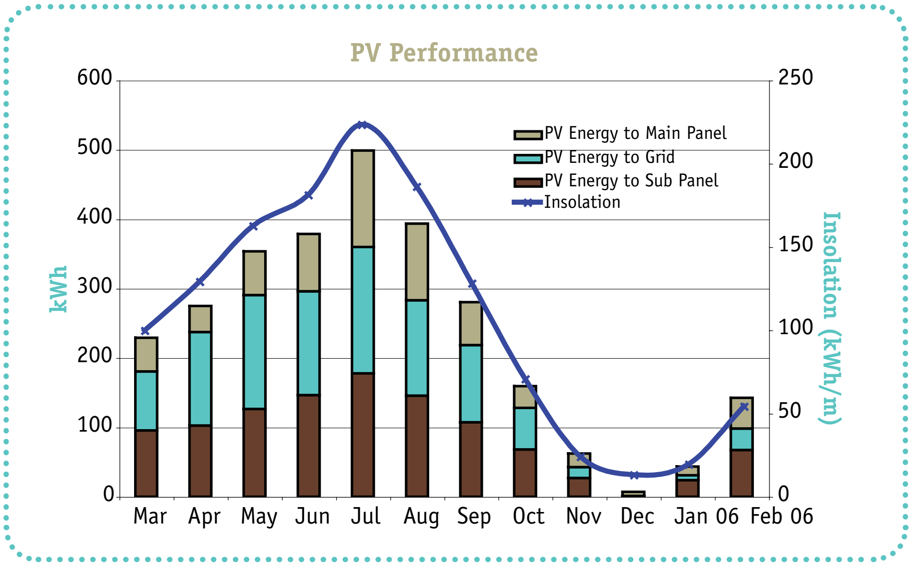


Figure 3. PV system performance varied with solar insolation levels in 2005 and 2006, with very little production in winter and as much as 500 kWh in June, 200 kWh of which went to the grid.

washing machine more than twice as often. And the ZEMH had a 20-year-old manual-defrost freezer, located in an unconditioned space under the carport, as explained above. This freezer probably accounted for an average of 3.2 kWh per day.

PV Performance

As a result of utility net metering and data logger problems, only one full year of useful ZEMH PV data were collected (see Figure 3). Total PV system production was 2,820 kWh per year. PV system performance varied with solar insolation levels, with very little production in winter and as much as 500 kWh in June, 200 kWh of which went to the grid.

Innovation Meets Affordability

We feel that the ZEMH project successfully demonstrated the implementation of highly innovative technologies in the manufactured-housing sector.

ZEMH daily average net energy use over the 2004–2005 monitoring period was 29.4 kWh per day. This figure takes into account the benefits derived from the use of PV and solar domestic hot water. The PV system with net metering provides an average of 7.7 kWh per day—or roughly one-quarter of total ZEMH energy use. The solar water heating system in the ZEMH provides most, if not all, of the hot water needed during the summer months, and accounts for roughly half of overall water-heating energy use. The ZEMH uses roughly 9% less energy per year than the Energy Star home, even though submetering showed that the occupants of the ZEMH used considerably more energy to operate their appliances, as explained above.

Measured envelope and duct leakage was much lower in the ZEMH than in the Energy Star home (or indeed, in any other NEEM home tested in the field). The envelope and ducts were substantially tighter in the ZEMH than in typical HUD-code homes. A systems engineering approach, utilizing foam insulation along with tight, correctly sized ducts, reduced overall envelope and duct air leakage. This, coupled with the use of the HRV, allowed us to apply another systems engineering principle: Build it tight, ventilate right.

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For more information about the Building America Industrialized Housing Partnership, go to www.baihp.org.