
Manufactured Home Performance Case Study: A Preliminary Comparison of Zero Energy and Energy Star

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ABSTRACT

The Zero Energy Manufactured Home (ZEMH) Project employs innovative energy-saving technologies. A comparison (base) home was built to the Pacific Northwest's Energy Star Program requirements. Tests were conducted and remote monitoring equipment installed to track the energy performance of each home. This paper presents the field testing results, preliminary monitoring results, and a description of the technologies used in the home. The impacts of occupant behavior on energy use are also discussed.

INTRODUCTION

The Zero Energy Manufactured Home Project demonstrates and promotes innovative energy-saving technologies to the HUD code manufactured housing industry and homebuying public, while evaluating those technologies' energy performance.

The project, funded by the Bonneville Power Administration and coordinated by the U.S. Department of Energy's (DOE) Building America Industrialized Housing Program (BAIHP), examines two 1600 ft² (147 m²) manufactured homes, built by the same manufacturer, using an identical floor plan.

The Zero Energy Manufactured Home (ZEMH) has been built with highly efficient and cutting edge technologies such as a photovoltaic system, sun-tempering, solar water heating, spray-in foam insulation, heat recovery ventilation, and Energy Star appliances and lighting. The ZEMH was built with energy efficiency and renewable energy as a high priority in an effort to evaluate proposed future energy efficiency targets for DOE's Building Technologies Program.

The comparison (base) home is built to Energy Star Program requirements as part of the Northwest Energy Efficient Manufactured Home (NEEM) program (NEEM 2004).

Over 120,000 NEEM homes have been built in the Pacific Northwest over the past 10 years. The base home represents

the nation's most energy-efficient commercially available manufactured home; the ZEMH is not commercially available at this time.

Both homes were built by in the summer of 2002. They are all-electric homes with unitary heat pumps, using the crawlspace as the air source.

The homes are occupied by staff at the Nez Perce tribal fish hatchery facility in Lapwai, Idaho. The ZEMH is occupied by a middle-aged couple, one of whom remains in the home most of the day while the other works. The base home's occupant is single and younger, home during evenings and some weekends.

Throughout the project, researchers worked closely with the Nez Perce Tribe, manufacturer, and retailer. The project's goals are twofold:

- To test and demonstrate innovative technologies in the manufactured housing market.
- To evaluate the energy performance of these technologies.

It is important to note that the project did not seek to achieve zero annualized energy use in the ZEMH but rather the lowest annualized energy use within the project budget, climate, and technology constraints.

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The project’s goals focus on in-depth comparative analysis, conducted over a number of years. The scope of this paper is more limited, representing a preliminary comparative analysis, and includes:

- A comparison of the technologies used in the ZEMH and base home.
- The results of envelope, duct, and HVAC field testing.
- Preliminary monitoring results, with (limited) analysis.
- A preliminary analysis of the impacts of occupant behavior on energy use.

Additional papers will follow as data collection and analysis continue (see “Future Research” below).

EXPERIMENTAL DESIGN

The following data were collected for both the ZEMH and base home:

- Total energy use, space heat, hot water, and energy use, and “other” energy usage. PV production data were also collected for the ZEMH.
- Indoor temperature and humidity. Note that while relative humidity was measured, the results are not reported here because they are not pertinent to the focus of this paper.
- HVAC system flow rates.
- Duct and envelope tightness.

Occupant surveys were also conducted to identify the impact of occupant behavior on energy use.

ZEMH and Base Home Measures

A comparison of ZEMH and base energy measures/technologies is presented in Table 1. For both homes, the primary

Table 1. Comparison of ZEMH and BASE Home Energy-Saving Technologies

MEASURE	ZEMH	BASE
Walls – 2x6 ft, 16 in. on center	R-21 foam-spray	R-21 batt
Floor – 2x8 ft, 16 in. on center	R-33 (R-22 foam + R-11 batt)	R-33 blown cellulose
Vented crawlspace wall	R-14 foil-faced foam	None
Roof – 4/12 pitch metal	R-49 foam 16 in. on center Solar ready – includes mounts, flashings, and chase,	R-33 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, lowE, EStar	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 heat 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* – R-8 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	80-gallon solar pre-heat tank (pre-plumbed), 40-gallon standard tank Solar hot water system EF = 0.93	EF = 0.88
Air sealing	Wrap with tape flashing Marriage line gasket (new product)	Wrap without tape flashing Standard practice marriage line sealing

* ZEMH crossover flex-flow system, BASE crossover used sheet metal elbows.

air and vapor barrier in the walls and ceiling is the painted, taped, and textured drywall. Penetrations in the ZEMH were sealed as part of the insulated foam system; in the base home, penetrations were sealed by caulk. The primary air and vapor area in the floors of both homes is the floor decking.

The ZEMH innovative design elements evaluated in this paper are:

1. A spray-in foam insulation system in the floor, walls, and ceiling.
1. A heat recovery ventilator with HEPA filtration system, providing continuous whole house ventilation and filtration.
2. A 4.2 kW (43.2 MJ) peak rated photovoltaic (PV) system with a 4 kW inverter and 12 kWh battery array. Since net metering was not implemented until March of 2004, only one month of post-net metering data is presented in this report.
3. A PV-controlled, active antifreeze solar water system, with 80 gallon (303 L) storage and 64 ft² (5.9 m²) of collector area.
4. A “solar ready” design, to facilitate on-site installation of a large photovoltaic net-metering system and solar water heating system.
5. Energy Star appliances.
6. A more efficient thermal distribution system.

In addition to these measures, the ZEMH incorporated numerous additional innovative design elements that are not evaluated in this paper but will be evaluated through future modeling. These include:

1. Sun tempering, including operable awnings, high thermal resistance window coverings, and dual window blinds.
2. Energy Star lighting.
3. Crawlspace wall insulation (to identify whether it will improve the performance of the heat pump, which uses the crawlspace as a buffered air source).
4. Individual components of the thermal distribution system, including:
 - ACCA *Manual D* sized supply air registers (ACCA 1995).
 - Mastic and mechanical fastening of ductwork connections.
 - Spray foam insulation in the floor that air sealed and thermally isolated the ductwork from the unconditioned vented crawlspace.
 - Tighter, more durable and supported crossover duct system.

The total design calculated heat loss for each home is as follows:

	ZEMH	Base
Envelope only	14,658 btuh/ °F (4292 W)	15,594 btuh /°F (4566 W)
Envelope, infiltration and ventilation	20,779 btuh/°F (6090 W)	24,372 btuh /°F (7143 W)

In the ZEMH, infiltration and ventilation represent 29% of the total heat loss. In the base home, these factors contribute to 36% of total heat loss.

Building Science Field Testing

Fan depressurization field tests were employed to determine the envelope leakage in accordance with ASHRAE Standard 119-1988 (ASHRAE 1988). Fan pressurization tests were employed to determine duct leakage in accordance with ASHRAE Standard 152 (ASHRAE 2002). An industry accepted, commercially available flow-measuring device was used 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 are determined from a differential pressure measurement across an orifice.

Data Acquisition Systems

In order to track the energy performance of each home, monitoring equipment was installed in both the base home and the ZEMH. The monitoring equipment collects the following energy use data from each home:

- Total electric use from grid
- Resistance elements in heat pump
- Heat pump compressor and fan motors
- Water-heating equipment, including gallons used
- PV energy production (ZEMH)

Dryer end use was not monitored in this project.

Sensor data are collected every 15 minutes by data loggers and transmitted daily to the host computer. Summary data reports are available at <<http://infomonitors.com/zmh/>>.

Plug-type energy loggers were installed in mid-March 2003 to submeter the energy use of the refrigerator, freezer, and clothes washer in each home, as well as the radiant heat panel and HRV in the ZEMH. Data from these loggers were collected (by occupant readings) in mid-December 2003.

A detailed listing of the monitoring data collected and the equipment used is provided in Table 2.

The occupant survey provided inputs for thermostat setpoint and anecdotal information about HVAC system operation.

RESULTS

Field Testing

Table 3 provides the field measurements of the envelope and HVAC systems; preliminary interpretation of the results follows.

Table 2. Monitoring Data Collected and Equipment Used

Data Collected	Location	Equipment
Relative humidity ^{*,†}	Indoor, attic, crawl, HRV to house, HP outside coil downstream	Vaisala Humiter 50Y
Temperature [*]	Indoor, attic, crawl, HRV to house, HP outside exiting coil, DHW in-out	Thermocouple
Electricity use [*]	HP comp/fans, HP strip, DHW, total kWh (grid), inverter-house, inverter-Grid	OSI 200, OSI 50, IMS pulse output per watt-hour
Hot water flow [*]	Water heater	Pulse output per 1/100 gallon (0.04 L)
Weather station [*]	Wind speed Solar insolation Outdoor temperature Outdoor humidity	MET1 LiCor – Model # Thermocouple – Copper Constantan Vaisala Humiter 50Y
Cumulative electricity use (March-December 2003) [‡]	Refrigerator Freezer Washer Heat recovery ventilator (ZEMH only) Radiant electric zone heater (ZEMH only)	Pacific Science kWh meter Line Logger™

* Campbell datalogger, 15-minute interval.

† Though relative humidity data were collected, note that the results are not reported here as they are not pertinent to the energy use comparison that is the focus of this paper.

‡ Occupant reported from linelogger, 9-month period.

Table 3. Comparison of ZEMH and Base Home Field Testing

Test	ZEMH	Base Home
Envelope leakage	2.0 ACH at 50 Pa	3.6 ACH at 50 Pa
Total duct leakage	145 CFM at 25 Pa (68 L/s at 25 PA) 15% of HVAC flow	211 CFM at 25 Pa (100 L/s at 25 PA) 20% of HVAC flow
Duct leakage to outside	37 CFM at 25 Pa (17 L/s at 25 PA) 4% of HVAC flow	150 CFM at 25 Pa (71 L/s at 25 PA) 15% of HVAC flow
HVAC return flow rates	970 CFM (458 L/s)	1008 CFM (472 L/s)
HVAC supply pressure [*]	30 Pa	16 Pa
Whole house ventilation	90 CFM (42 L/s) [†]	78 CFM (37 L/s)
Bath fan flow rates	110-116 CFM [‡] (52-55 L/s)	31-33 CFM ^{**} (15-15 L/s)

* Measured at closest supply register.

† Calculated.

‡ Rated 90 CFM at 0.25 in. static pressure per HVI directory.

** Rated 50 CFM at 0.10 in. static pressure per HVI directory.

Envelope Leakage. The ZEMH envelope leakage rate was 80% tighter than the base home and is lower than any previously tested energy-efficient NEEM manufactured home. This reduced leakage is believed to be largely the result of the air sealing properties of the foam insulation system used in the walls, floors, and ceiling. Typical HUD code homes have been found to have leakage rates in excess of 6.0 ach at 50 PA (Persily 2000).

Duct Leakage. The ZEMH total duct leakage was 46% lower than the base home; leakage to the outside was 405% lower than the base home.

The ducts in the ZEMH are located in the “belly space” within the conditioned space; they are also effectively within the pressure envelope of the home, as they are surrounded by foam insulation (except the top of the trunk and branch ducts). The base home ducts are similarly located in the conditioned space (belly) but, insulated with fiberglass instead of foam, are outside the pressure envelope. This helps to explain why the leakage to outside values are significantly lower than the total duct leakage in the ZEMH.

HVAC Flow Rates. The HVAC flow rates of the heat pumps were at around 1000 cfm (472 L/s) for both homes, (given the 8% accuracy for the flow measurement device).

HVAC Supply Plenum Pressure. The supply air pressure with the HVAC system operating was almost twice as high in the ZEMH as in the base home. This is believed to be a result (in part) of the ZEMH's tighter ducts and duct design that reduced the number of supply registers.

Whole House Ventilation. The HRV flow rates were not measured but estimated to be roughly 90 cfm, (42 L/s) based on the duct design. The measured flow rate for the base home whole-house fan was 78 cfm (37 L/s). Both home flow rates were more than the minimum 0.035 cfm/ft² (0.18 L/s m²) required for this size HUD-code manufactured home (HUD 1994).

Spot Ventilation Flow Rates. The ZEMH bathroom exhaust fan was a model with a condenser fan motor, permanently lubricated bearings, and a larger capacity than the exhaust fans in the base home, which explains the higher flow rate. A minimum of 50 cfm (24 L/s) is typically required but often not achieved for spot exhaust fans in HUD-code manufactured homes (Lubliner et al. 1997).

Total Energy Use

Figure 1 compares total monthly energy use, broken down by hot water, heat pump, strip heat, and other loads. Total energy use in the ZEMH is higher in the summer and comparable in other months.

For the half-year period prior to net metering (July-December 2003) and without adjusting for occupant behavior, the ZEMH used 6351 kWh, (22,864 MJ) compared to 6240 kWh (22,464 MJ) for the base home—2% more total energy.

With the limited contribution from the PV system, the ZEMH's net energy use was 5855 kWh (21,078 MJ), 6% less than the base home.

A revised annual comparison of total energy use will be made in April 2005 to include a full year of data with PV net metering. Attempts are also being made to make occupant behavior more consistent between the two homes, (particularly the operation of the HVAC system). These changes will be reflected in future reports.

Heat Pump Energy Use

Figure 2 shows heat pump energy use during heating and cooling, resulting from HP operation, fans, and backup strip heat, along with the indoor and outdoor temperatures. The ZEMH used less energy in the heating months and more total energy in summer months.

Figure 3 shows the strip heat use in both homes, indicating that the base home's strip heat use was significantly higher during the most severe heating months. Strip heat occurs when the heat pump cannot maintain the heating thermostat setpoint or during the defrost cycle. In both homes, the defrost cycle was factory set to occur every 60 minutes of compressor run time. The ZEMH occupants maintained a constant thermostat setpoint, whereas the occupant of the base home turned the heat pump off when the house was unoccupied. This practice can result in greater strip heat use when the heat pump is reactivated.

In Figure 4a, daily space heating energy use is plotted versus average daily outdoor temperature (ASHRAE winter design temperatures are also indicated). The no-load temperatures for both homes are about the same, 54-55°F (12-13°C.) In Figure 4b, daily space heating energy use is plotted versus

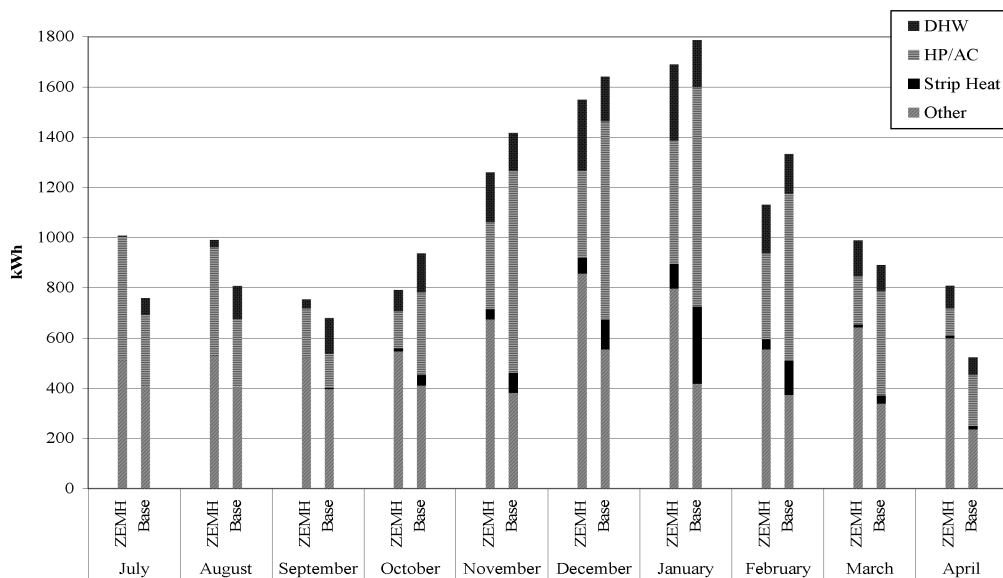


Figure 1 Total monthly energy use.

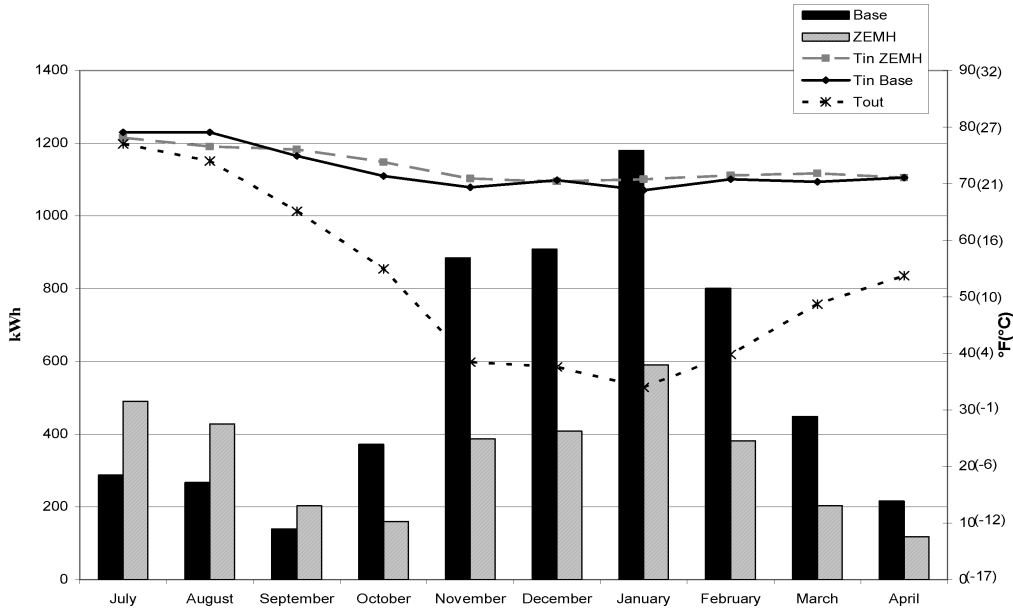


Figure 2 Heat pump energy use during heating and cooling.

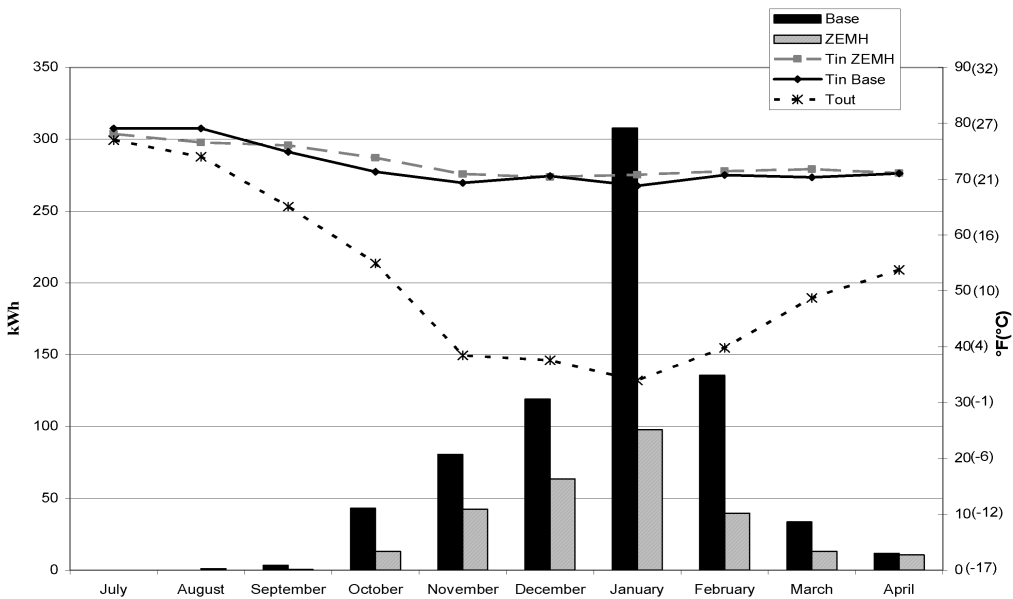
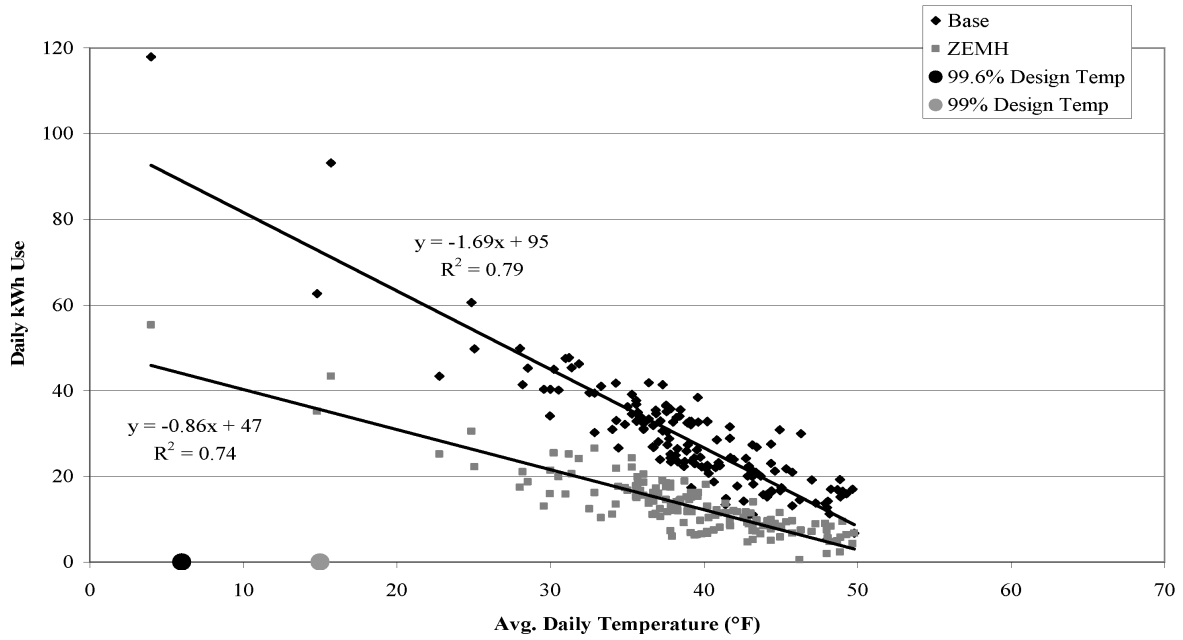


Figure 3 Strip heat use in both homes.

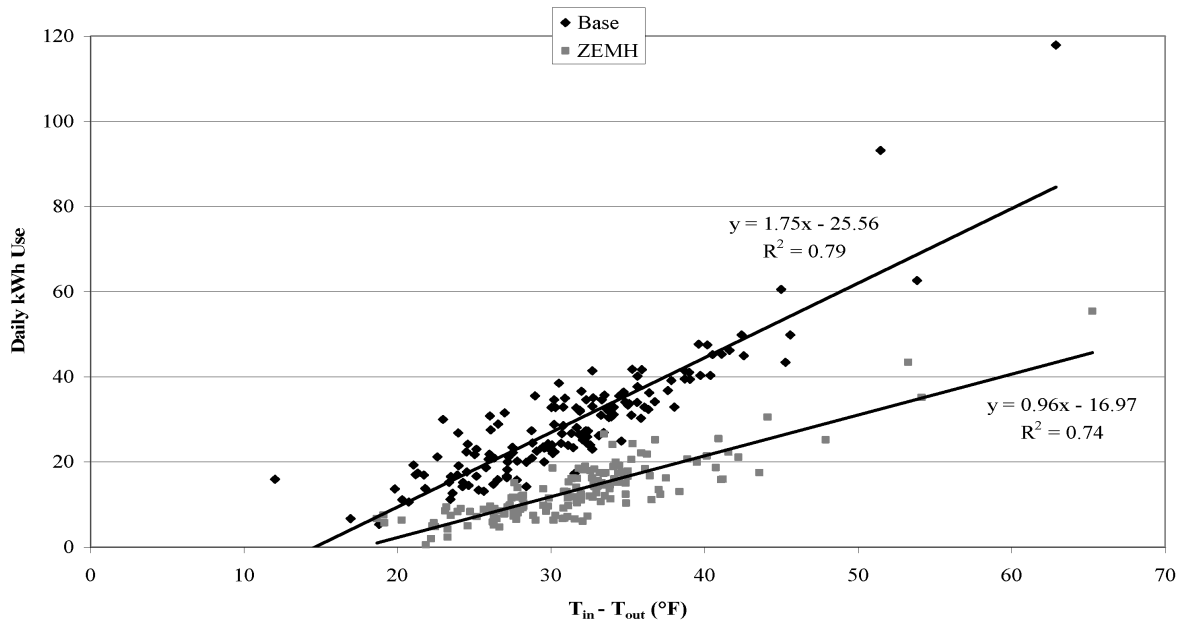
indoor-outdoor temperature difference. Regressions were conducted only for outdoor temperatures below 50°F (10°C). Figure 4b indicates an average daily space heat energy use of 1.75 kWh/°F for the base home versus 0.96 kWh/°F for the ZEMH. The curve for the ZEMH has a more gradual slope than the base home, indicating that the ZEMH required 45% less space heating energy.

Hot Water Use

Figure 5 compares energy used for hot water. Over a six-month period (July to December), the base home used 4883 gallons (18,503 L), or 27 gallons per day (102 L/day), versus 7136 gallons (27012 L), or 39 gallons per day, (148 L/day) for the ZEMH. To account for the different water usage between homes, the energy use is normalized by total water used.



(a)



(b)

Figure 4 Daily space energy heating use plotted versus (a) average daily outdoor temperature and (b) indoor-outdoor temperature difference.

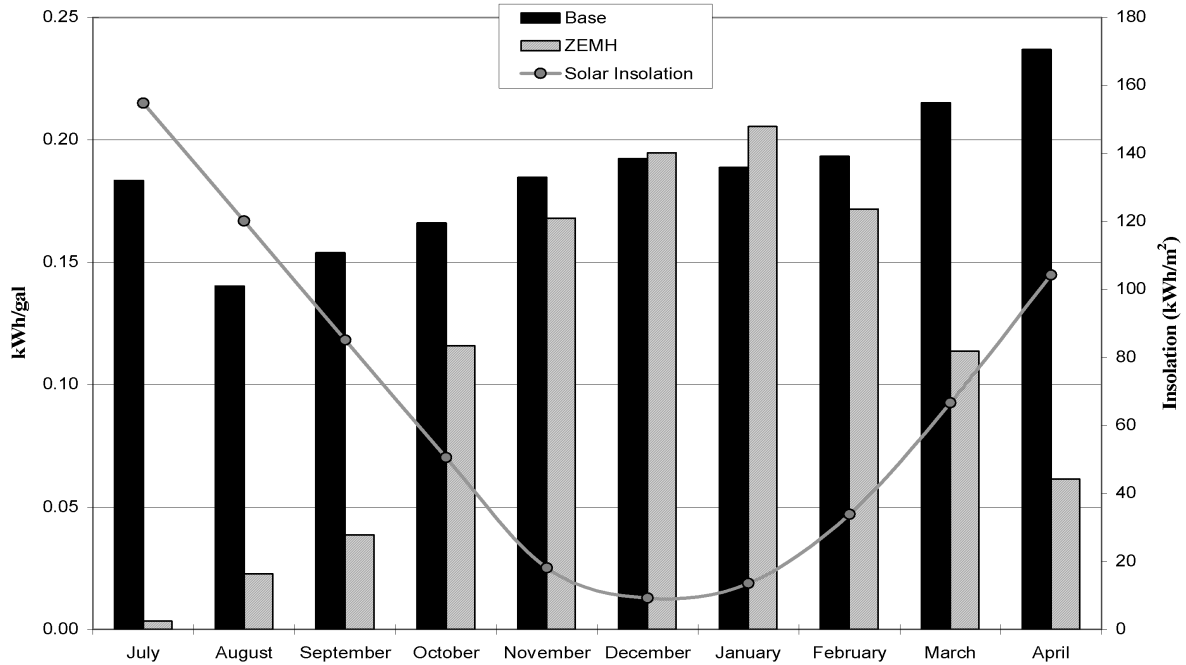


Figure 5 Energy comparison of hot water use.

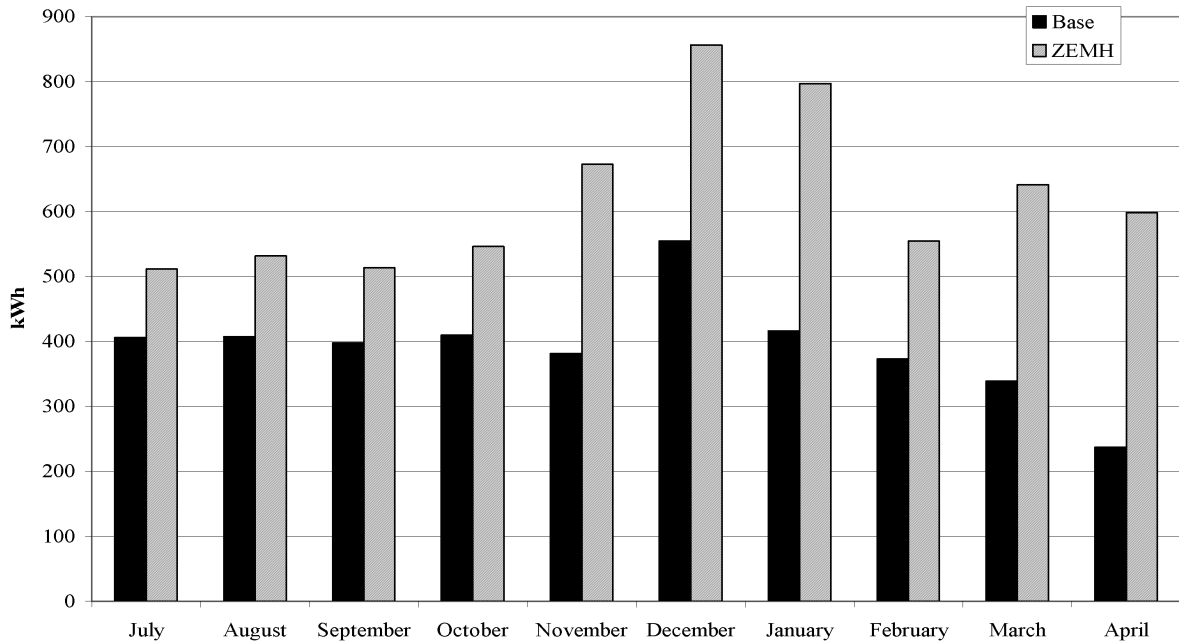


Figure 6 Comparison of all other loads.

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 additional Y axis indicates the available solar energy for each month and shows increased use of grid power for water heat during the lower insolation months. The ZEMH used roughly 45% less

energy than the base home after normalizing by the total gallons used during the half-year monitoring period.

Other Loads

Figure 6 compares all other loads, which are calculated by subtracting the space heating and cooling and water heating

Table 4. End-Load Usage 3/03-12/03

Load	ZEMH		Base Home	
Refrigerator	19 ft ³ (0.5 m ³)	314 kWh (1130 MJ) monitored 440 kWh/yr (1548 MJ/yr) Energy Guide™	15 ft ³ (0.4 m ³)	331 kWh (1192 MJ) monitored 442 kWh/yr (1591 MJ/yr) Energy Guide™
Freezer	30 ft ³ (0.8 m ³)	835 kWh (3006 MJ)	14 ft ³ (0.4 m ³)	297 kWh (1067 MJ)
Clothes washer	Energy Star™, Horizontal axis	69 kWh (248 MJ)	Standard, vertical axis	25 kWh (90 MJ)
Whole house ventilation system	Air to air heat exchanger	585 kWh* (2106 MJ) 316 kWh† (1138 MJ)	Whole house exhaust fan	143 kWh‡ (515 MJ)
Radiant Heater	Zone heat for kitchen	140 kWh (504 MJ)	N/A	N/A
Total “other” end loads		1943 kWh** (6995 MJ) 1358 kWh†† (4889 MJ)		796 kWh** (2866 MJ)

* Calculated, assuming constant ventilation system operation at 90 W.

† Measured, HRV switched off at end of summer.

‡ Calculated, assuming constant ventilation system operated at 22 W.

** Assuming constant ventilation operation.

†† Measured end-load without ventilation.

loads from the total energy use. The base home’s other loads were 2556 kWh (9201 MJ) versus 3623 kWh (13,042 MJ) for the ZEMH during the July to December monitoring period.

Table 4 presents cumulative end-load data for nine months (March through December). These end loads include the refrigerator, freezer, and washer in both homes. Radiant panel heater and HRV loads were also collected in the ZEMH. For these loads, the ZEMH monthly energy use was roughly 63 kWh (227 MJ) per month more than the base home.

Refrigerator. The ZEMH and base home’s refrigerators had comparable Energy Guide™ ratings, even though the ZEMH unit is slightly larger (both refrigerators are top freezer models). The ZEMH’s refrigerator, a 19 ft³ (.54 m³) Energy Star model, used more energy than the base home’s refrigerator, a 15 ft³ (.42 m³) non-Energy Star model.

Washer. The ZEMH Energy Star washing machine used more than twice the electricity of the base home’s top-loading standard unit, but this amounts to less than 5 kWh (18 MJ) per month and is likely due to differences in occupant use. It should be noted that the Energy Star washer reduces energy use associated with hot water and drying, which is not accounted for in these comparisons.

Whole House Ventilation. The ZEMH heat recovery ventilator (HRV) was more readily controlled by the occupants; if operated continuously (see “Impacts of Occupant Behavior” below), it would use roughly 65 kWh (234 MJ) per month. The base home’s ventilation system was wired at the breaker to run continuously; it used roughly 16 kWh (58 MJ) per month.

Freezer. The freezer in the ZEMH is a manual defrost model from the 1980s, located in an unconditioned space under the carport. The base home has a new upright freezer, with manual defrost, located in the utility room. The ZEMH freezer consumed roughly 60 kWh (216 MJ) more than the base home freezer.

PV Performance

Until an agreement between the tribe and utility addressing liability issues was in place (late March 2004), net metering was not operational. Figure 7 shows the PV performance pre- and post-net metering.

Prior to net metering, the photovoltaic system provided limited renewable energy output. PV energy was provided to the plug loads in the kitchen (refrigerator and lights). Additional renewable energy was used to “top-off” the battery storage. The battery did not provide energy to the home, since the inverter was programmed to only provide energy from the batteries during a power outage. As a result, the system produced averages of 4 kWh (14 MJ) per day during the summer, 1.5 kWh (5.4 MJ) per day in the autumn, and 0.6 kWh (2.1 MJ) per day in winter.

Since the implementation of net metering, PV energy is provided to the grid when more energy is produced than required for the kitchen plug loads. In April 2004, the PV system provided an average of 9.2 kWh (33 MJ) per day, 38% of the total ZEMH energy use.

IMPACTS OF OCCUPANT BEHAVIOR

Ideally, the homes would have been modeled using a benchmark set of occupant energy usage and operating conditions and would be unoccupied for up to a year in order to establish a baseline comparison unaffected by occupant behavior. The project timelines and resource limits would not allow this comparison. A review of the data is consistent with the results of the occupant survey.

The occupant survey revealed that the ZEMH occupants left their thermostat at a constant setting throughout the year and rarely opened windows during the cooling season. They also used their bedroom ceiling fan at night to provide comfort cooling. These factors, combined with their decision to use a

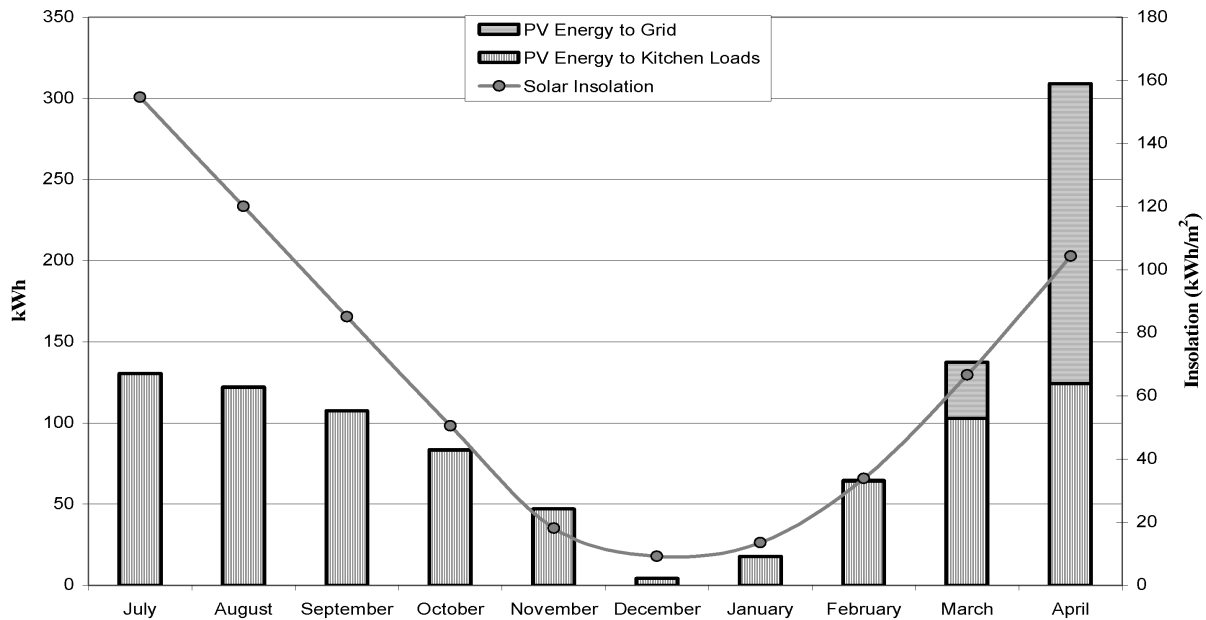


Figure 7 PV performance pre- and post-net metering.

large, inefficient freezer (located outside the conditioned space), contributed to the higher energy use in the ZEMH home during the summer of 2003.

The base home's occupant (who was not at home during the day) did not operate his air-conditioning system as often, relying more on operable windows and ceiling fans to provide diurnal cooling. Conversely, the base home occupant set back the heat pump in the winter, contributing to high strip heat use. This finding is consistent with past research, which indicates significant increases in supplemental heating due to nighttime setback of heat pumps (ASHRAE 2004; Bouchelle et al. 2000; Bullock 1978; Ellison 1977).

In late summer of 2003, the occupants in the ZEMH stopped running the HRV and did not re-start it, whereas the whole house exhaust fan in the base case home runs continuously.

The inconsistent use of the thermostats has the additional effect of casting some doubt on the comparison of heating and cooling energy use. The occupants of both homes have been asked to operate their HVAC systems in a similar fashion, to facilitate an improved HVAC system comparison (see "Future Research" below).

GENERAL CONCLUSIONS

The Zero Energy Manufactured Home Project successfully demonstrates the implementation of highly innovative technologies in the manufactured housing sector, which represents a significant portion (approximately 20%) of the new single-family home market in the U.S. At this point in the project, a determining of energy savings for the homes as a whole or for individual components is premature, but it will be the focus of future research (see below).

1. Measured net energy use of the ZEMH was 6% lower than for the base home. Note energy use is not normalized for occupant behavior; nor do they take into account that the ZEMH's PV system was only fully operational for one month.
2. The ZEMH required 45% less space heating energy. The authors speculate that the lower space heating use for the ZEMH is due primarily to improved building envelope measures and the lack of consistent HRV operation. Additional modeling and empirical analysis will be conducted to evaluate these speculations (see "Future Research" below).
3. The measured envelope and duct leakage in the ZEMH was much lower than in the base home (indeed, lower than any other NEEM home tested in the field) and substantially tighter 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 for another systems-engineering principle to be employed—"build it tight, ventilate right."
4. The solar water heating system in the ZEMH provides most, if not all, of the energy needed during the summer months and roughly 45% of the overall water-heating energy use. This energy saving is not apparent until adjustments are made to water usage between home occupants.
5. The PV system with net metering provides a significant contribution to the total utility energy use. Post net-metering PV energy was roughly 9.2 kWh (33 MJ) per day in April 2004, or 38% of the total ZEMH energy use.
6. The project highlights the importance of occupant choices and behavior on the performance of energy-efficient housing. Based on the preliminary monitoring data and occupant

surveys, the behavior patterns of the ZEMH occupants are not themselves “energy efficient.” These patterns create the appearance of a less efficient home. On the other hand, the behavior of the ZEMH occupants may shorten the payback for the innovative technologies of the ZEMH. Although this paper does not include a cost-effectiveness analysis, it is worth noting a paradox: more efficient occupant behavior means a better performing home (approaching net zero energy) but a less cost-effective one.

FUTURE RESEARCH

At least a full year of data (including net metering and improved occupant behavior) is required before overall system performance and individual technologies can be fully assessed. In addition, a significant number of research investigations are needed to accomplish the overall goals of the project’s experimental design. These investigations include:

- Co-heat tests to determine envelope heat loss rate and thermal distribution system performance.
- Comparisons of monitored performance with predictions based on hourly simulations.
- Estimates of internal gains from ZEMH technologies, including passive solar features, Energy Star lighting, and appliance technologies.
- Evaluation of the impact of perimeter crawlspace insulation on the operation of the ZEMH’s heat pump, using flip-flop tests to determine heat pump COP.
- Evaluation of HRV energy use, operating efficiency, and IAQ benefits.
- Continued evaluation of occupant behavior, with attempts at modification (especially HRV operation and thermostat setpoint).
- Evaluation of the occupants’ acceptance of the ZEMH’s innovative technologies.
- Analyze cost-effectiveness of innovative technologies to consumer and utility. Note the researchers anticipate that many of these technologies will not (in the short term) prove cost-effective, at least in terms of simple payback. The researchers will also analyze additional benefits from the use of these technologies.
- Identify benefits of solar-ready and sun-tempered designs in HUD-code homes.
- Evaluate the integration of ZEMH technologies into the manufacturing process.
- Evaluate building code and liability issues associated with net-metering.

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