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The NREL/Habitat for Humanity Zero Energy Home:

A Cold Climate Case Study for Affordable Zero Energy Homes

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Technical Report
NREL/TP-550-43188
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NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337

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National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

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Acknowledgments

The authors would like to thank the many individuals and organizations that supported this project: homeowner Amy Whalen; The U.S. Department of Energy Building Technologies Program; Midwest Research Institute; Battelle; Energy Outreach Colorado; Xcel Energy; The Governors Office of Energy Management and Conservation (now the Colorado Governor's Energy Office); Secretary of Energy Samuel Bodman; Colorado Congressman Bob Beauprez; Lori Vaclavic, Bruce Carpenter, Andy Blackmun, Brady Nelson, Pandora Reagan, and Lynne Brown of Habitat for Humanity of Metro Denver; Paul Kreischer of Lightly Treading; Pete Beverly; Ren Anderson, Admiral Truly, Dan Arvizu, Jessie Harris, Byron Stafford, Kerry Masson, Lee Boughey, Sarah Barba, Jay Burch, and Scott Horowitz of NREL; Betsy Petit of Building Science Corporation; Barbara Miller of the National Affordable Housing Network; and Rob Dumont of the Saskatchewan Research Council.

Executive Summary

The design of this 1,280-square-foot, three-bedroom Habitat for Humanity of Metro Denver zero energy home carefully combines envelope efficiency, efficient equipment, appliances and lighting, and passive and active solar features to reach the zero energy goal. The home was designed with an early version (July 22, 2004) of the BEOpt building optimization software; DOE2 and TRNSYS were used to perform additional analysis. This engineering approach was tempered by regular discussions with Habitat construction staff and volunteers. These discussions weighed the applicability of the optimized solutions to the special needs and economics of a Habitat house—moving the design toward simple, easily maintained mechanical systems and volunteer-friendly construction techniques. A data acquisition system was installed in the completed home to monitor its performance.

This report details the design of the home, presents detailed performance data from the first year of operation, and includes summary performance data from the second year of operation.

The home appeared on Fox National News, was visited by Secretary of Energy Samuel Bodman and Congressman Bob Beauprez, and has been written up in *Home Energy Magazine*, *Energy Design Update*, countless Web pages, and several local newspaper stories. The home was also on the National Solar Tour in 2005. Habitat Metro Denver and NREL continue to receive queries about the home.

Some overall conclusions from the project are listed below:

- The NREL/Habitat ZEH exceeded its goal of zero net source energy and was a net energy producer for the first two years. The home produced 24% more energy than it consumed on a source energy basis in the first year of monitoring and 12% more energy than it consumed in the second year.
- PV system sizing for ZEHs is challenging.
  - Total home energy use for a specific house becomes highly uncertain because of occupant choices and behaviors.
  - Meeting the ZEH design goal depends on occupant behaviors.
  - The economics of excess annual PV production depends on net metering agreements.
- Zero energy does not necessarily mean a zero utility bill.
  - There are fixed monthly costs for NG and electricity service.
  - NG *costs* may not be displaced by net electricity production.
- Efficient, affordable ZEHs can be built with standard construction techniques and off-the-shelf equipment. Meeting the BA goal of cost neutral ZEH in all housing sectors will require additional research on cost-effective efficiency options.

Acronyms

BA	Building America (Program)
CFL	compact fluorescent lamp
DOE	U.S. Department of Energy
ERV	energy recovery ventilator
GCHP	ground-coupled heat pump
MEL	miscellaneous electricity load
NG	natural gas
NREL	National Renewable Energy Laboratory
PV	photovoltaic
SHGC	solar heat gain coefficient
TMY	typical meteorological year
ZEH	zero energy home

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Introduction

In October 2005, Amy Whalen and her two sons moved into their new Habitat for Humanity home near Denver, Colorado. In doing so they became partners with the U.S. Department of Energy (DOE) Building America (BA) program in a case study that aimed to understand how to create affordable zero energy homes (ZEHs) in cold climates. The home was a result of collaboration between the National Renewable Energy Laboratory (NREL) and Habitat for Humanity of Metro Denver. This report will detail the design, construction, and performance of the home.

The home appeared on Fox National News, was visited by Secretary of Energy Samuel Bodman and Congressman Bob Beauprez, and has been written up in *Home Energy Magazine*, *Energy Design Update*, countless Web pages, and several local newspaper stories. The home was also on the National Solar Tour in 2005. Habitat Metro Denver and NREL continue to receive queries about the home. This attention provides better visibility for project sponsors and equipment donors and may equate to more potential sponsors for Habitat. For the affordable home builders, this visibility is a benefit that should be considered in decisions to pursue super-efficient home projects.

A ZEH is designed to produce as much energy as it consumes over the course of a full year. The home uses the utility power grid for storage—delivering energy to the grid when the photovoltaic (PV) system produces more energy than the home uses and draws from the grid when the PV system produces less energy than the house needs. This approach eliminates the need for battery storage and reduces the cost, complexity, and maintenance of the solar electric system.

Homes account for 37% of all U.S. electricity consumption and 22% of all U.S. primary energy consumption (DOE 2007). This makes home energy reduction an important part of any plan to reduce U.S. contribution to global climate change. The goal of the DOE BA Program is to create commercially viable ZEHs by 2020. This project is a case study in reaching that goal within the affordable housing sector in cold climates. Zero energy is especially important in this sector, where increasing energy costs can take a high toll on homeowners with limited economic resources. A ZEH guarantees long-term energy cost stability for these homeowners.

Design Criteria and Process

From its inception, the NREL/Habitat ZEH project focused on finding the balance between engineering ideals and real-world practicality. The team that designed the home included two NREL building energy researchers, two Habitat staff members (the construction manager and the real estate development manager), and two Habitat energy subcommittee volunteers. The NREL engineers made suggestions based on modeling results and analysis and presented them to the design team, who then grounded the discussion with practical concerns and insights. This mix of perspectives led to a design that balanced energy performance, ease of construction, and low cost, and maintained the zero energy goal.

Project Design Criteria

A Habitat for Humanity house is an unusual opportunity: thanks to volunteers, much of the labor comes at no cost and some of the equipment is donated or purchased at reduced cost. We established the following criteria for the home design:

1. **Its goal should be zero net energy.** Zero net energy can be defined in terms of site energy (used at the building site) or source energy (sometimes called primary energy). For electricity purchased from a utility, the source energy used to produce and distribute the electricity is typically about three times as much as the delivered electricity. From a societal point of view, source energy better reflects the overall consequences of energy use. The home was designed to meet the definition of zero energy of the DOE's BA residential energy efficiency research program (see the Building America Web site at www.buildingamerica.gov). It must have predicted zero net *source* energy consumption over the course of a year using typical meteorological year (TMY2) weather data (Marion and Urban 2005) and BA Benchmark (Hendron et al. 2007) assumptions about occupant behaviors based on average U.S. behavior in terms of temperature setpoints, miscellaneous electricity loads (MELs), and hot water use.
2. **It should be replicable by Habitat for Humanity.** Construction techniques and energy efficiency technologies were vetted for their repeatability in future homes.
3. **It should take advantage of Habitat volunteer labor.** When considering construction alternatives, we took into account that Habitat's approach to building with volunteer labor presents a unique opportunity to reduce building costs. Construction techniques that were "volunteer friendly" and tended toward low material costs were favored.
4. **Tradeoffs for zero energy were done at full material cost.** Although some of the equipment in the house was donated or bought with grants at no cost to Habitat, we considered the full value of these items to find the balance between efficiency and PV production.
5. **The home should require no special operation**. This house was sold to a Habitat family. The design team wanted the home's unique attributes to be as transparent to the family as possible. From the family's perspective, it should be a normal home with no extra owner operating needs.

6. **No prototypes are used.** We designed the home with off-the-shelf proven technologies. Although optimal research systems were discussed as part of the design process, the final design aimed to use commercially available products to come as close as possible to the ideal. Because the home is expected to outlive all its mechanical systems, we wanted these systems to be easily replaceable by technicians who could be found in the local yellow pages.
7. **Keep it simple**. Many ZEHs being designed today involve complicated interconnected mechanical systems that are designed to maximize renewable energy use and distribution. We were often tempted in this direction; however, we tried to keep it simple. We believe a simpler system will have fewer problems and a greater chance at longevity.

Using Computer Simulation in the Design

The designers used a combination of computer simulations and heuristic judgment. Three simulation tools were used sequentially and iteratively during the design process:

- TRNSYS Transient System Simulation software. TRNSYS is a highly flexible simulation program (Klein et al. 1996). It was used in this project to investigate solar water heating options and as part of the BEOpt program.
- DOE2 Building Energy Model. DOE2 can be found on the Lawrence Berkeley National Laboratory Web site at www.doe2.com. It takes input on the construction of a buildings and typical weather data and runs hour-by-hour simulations of the energy performance over an entire year. Annual source energy use results from the design-phase DOE2 model are shown in Figure 1.

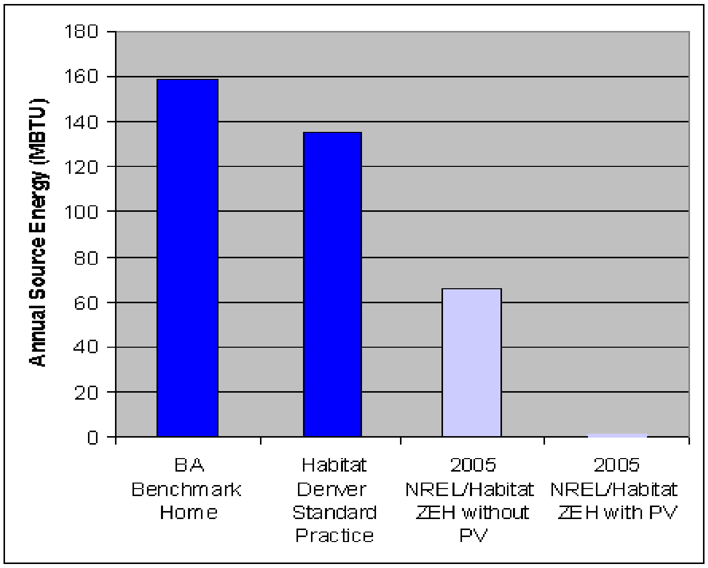

Figure 1. Comparison of annual source energy from the design-phase DOE2 model

- BEOpt Building Energy Optimization Program (Christensen, Barker, and Horowitz 2004; Christensen, Barker, and Tupper 2004). BEOpt is an advanced front-end program with a database of construction techniques, efficiency technologies, and costs that runs DOE2 and TRNSYS iteratively to find the least cost approach to reach zero energy performance. BEOpt is under development at NREL at this time. An early version (July 22, 2004) of the program was used in the NREL/Habitat ZEH project as a design tool and as a real-world test application of BEOpt.

We ran the BEOpt program early in the design process. Among other things, BEOpt indicated that for this climate and current energy and PV costs, a superinsulated envelope and a large solar water heating system were economic choices. As the design advanced, BEOpt became unavailable as it was upgraded to a new version. We turned to DOE2 for some parametric studies of window size, window type. overhang size, and double dry wall for thermal mass. We used TRNSYS simulations in parallel to study the collector size and tilt and the storage size for the solar water heating system.

Final Home Design

The completed NREL/Habitat ZEH is shown in Figure 2.

Figure 2. Completed NREL/Habitat Zero Energy Home
(Credit: Pete Beverly)

Envelope Design

The home design began with a site evaluation. Habitat Metro Denver had acquired, or was in the process of acquiring, several plots at the project's inception. We chose a site in Wheat Ridge that had fairly good solar access. A few large, well-established trees lined the south edge of the two-site plot, so we located the ZEH on the north side of the plot. A shading analysis at the site indicated that about 15% of the total solar energy available annually would be blocked by the trees.

We began to design the envelope by looking at Habitat Metro Denver's standard home plans. We sorted these plans for their applicability to the site and adaptability for a passive solar design. A standard three-bedroom, 26-ft × 46-ft design with a crawlspace was chosen. The floor plan was mirrored from its original design to accommodate the site

Motivated by BEOpt's recommendation for a superinsulated envelope, the design team considered a wide variety of approaches. Structural insulated panels and insulated concrete forms were eliminated because they tend to have high material costs and low labor costs—the opposite of what is needed to take advantage of Habitat volunteer labor. Straw bale construction was carefully considered because it has low material costs and high labor costs. However, after reviewing the literature about straw bale construction and speaking with other Habitat affiliates who have built with straw, we eliminated this option because standard techniques and details are lacking and because Habitat Metro Denver will be probably be unable to replicate it. We chose a double stud wall with fiberglass batt construction (see Figure 3) because of its low material costs, familiar volunteer-friendly construction techniques, and proven construction techniques and details, which are available from the National Affordable Housing Network. This type of

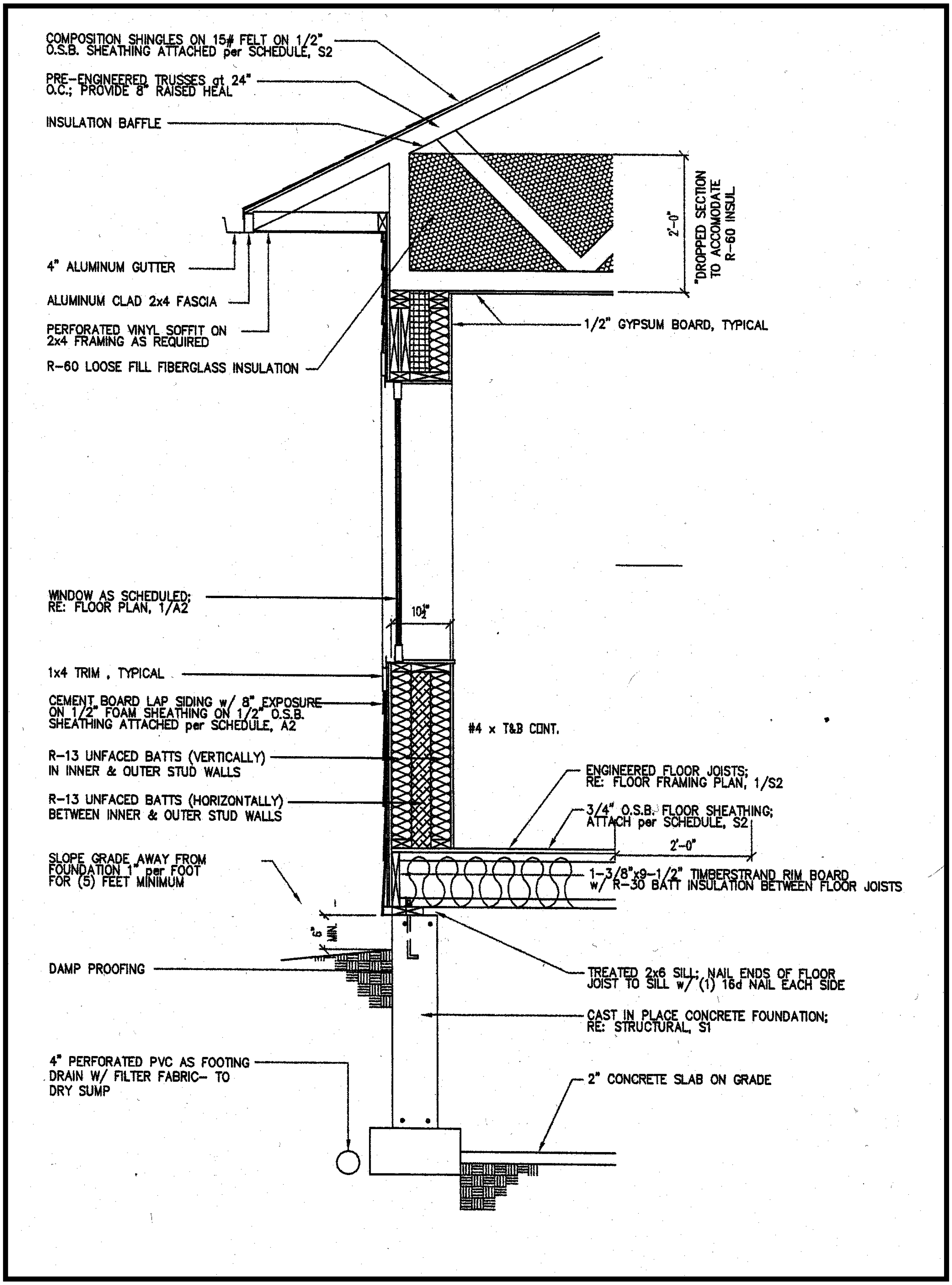

Figure 3. Wall construction of NREL/Habitat ZEH

construction has a long history in Montana and Canada where the cold climate justifies investing in highly insulated walls. When pursuing the zero energy goal, we compared efficiency option costs to the cost of energy generated by PV. Because PV energy is currently more expensive than energy from the utility grid, higher investments in efficiency are justified and double stud wall construction is justified in a much warmer climate than it has previously been widely used.

The walls consist of an outer 2 × 4 structural stud wall on 16-in. centers with R13 fiberglass batts in the cavities. Spaced 3½ in. inside this wall, a second 2 × 4 stud wall on 24-in. centers was built. Additional R13 fiberglass batts were placed horizontally in the space between the stud walls and vertically in the interior wall cavities. An outer vapor permeable house wrap and fiber cement siding and an inner poly vapor barrier and drywall complete the nominal R40 assembly. The clear wall R-value of this wall is much closer to its nominal value than a single stud wall because the thermal shorting of the studs is broken by the insulation in the space between the double stud walls. Figure 4 shows the stud wall construction.

Figure 4. Photograph showing stud wall and raised heel truss construction

Raised heel trusses were designed to accommodate 2 ft of blown-in fiberglass in the attic, which gives the top of the thermal envelope an R60 rating. Figure 4 shows the raised heels of the roof trusses. Because these levels of insulation are difficult to reach in crawlspace walls and floors, and because we intended to have all mechanical equipment and ducts inside the home, we decided to insulate the floor above the crawlspace. We chose fiberglass batts the thickness of the TJI floor joists, which provided a nominal R30 in the floors. The wastewater drainpipe slopes through the uninsulated, vented crawlspace. During normal operation this presents no problems even during a cold winter. However, if a slow drip occurs in the house during the winter, the drainpipe could freeze closed and cause a backup inside the house. The homeowners should be informed of this potential problem and encouraged to have faucet leaks fixed immediately.

The superinsulated shell dramatically reduces heating energy needs; “sun tempering” reduces these needs further (see Figure 5). We increased the glazing area on the south side of the home and reduced it on other orientations, but added no additional thermal mass. We evaluated the use of double drywall on the ceilings, where it could easily be applied without changing trim details, but DOE2 modeling suggested it would have minimal benefit. We decided not to pursue other thermal mass options such as massive floors or double drywall because they complicated construction and reduced the chances of replicating the envelope design. As a policy, Habitat Metro Denver does not equip its homes with air-conditioning, so we were sensitive to overheating potential. We used DOE2 to evaluate different southern glazing areas and types and overhangs. We compared the heating energy and simulated cooling energy (as if there were an air-conditioning system) in the ZEH and in the identical standard construction home for each window combination. We chose the design that maximized heating reduction without increasing cooling energy over the standard construction. We thus maximized heating energy displacement without increasing overheating potential. Double-glazed, low-emissivity (U-value = 0.30 Btu/h-F-ft^2) high solar heat gain coefficient (SHGC = 0.58) glass was chosen for the southern windows. Double-glazed clear windows would have provided more solar heating, but also would have increased the overheating potential. Double glazed low emissivity (U-value = 0.22 Btu/h-F-ft^2) low SHGC (0.27) were used for the east, west, and north windows. The final design heating load for the home was 15,000 Btu/h.

Figure 5. Window distribution for sun tempering in the ZEH

Ventilation System

Because we intended to build the home with very low air leakage, a mechanical ventilation system was required. To provide fresh air to the home and minimize energy losses, we chose to use a balanced energy recovery ventilation (ERV) system. The ERV exhausts air from the kitchen and bathroom and supplies fresh air to the living room and bedrooms. The warmth of the exhaust air is used to heat the incoming fresh air. This significantly reduces the heat loss from ventilation. We chose an ERV with efficient electronically commutated motors.

Space Heating System

Having a very low design heating load is a blessing and a challenge. The blessing is obvious—very little energy is required to keep this home warm. The challenge is that most commonly available heating systems are too large for this home and the low heating energy needs cannot justify a complicated or expensive system. We considered a wide variety of heating systems for the home:

- Active solar thermal with radiant floor, baseboard heaters, or fan coil in the ERV supply
- Ground-coupled heat pump
- Point-source natural gas (NG) furnace (no duct system)
- Electric resistance baseboard heating

The design team considered a solar "combisystem" that combines active solar thermal space heating and water heating. An active solar thermal system with a large collector array and a large, well-insulated water tank for thermal storage is an attractive idea for a ZEH. In fact, some ZEHs have employed this approach (Daub 2006). A properly sized system may completely eliminate the need for an electric or NG heating system. However, some challenges accompany this approach. The collectors, storage, pumps, and controls require a relatively large equipment investment. During the summer and at times during the fall, winter, and spring when the house is passively solar heated, there is no need for active heating, so the additional equipment investment for space heating delivers no energy benefit for most of the year. Also, a surplus of heat is collected in the summer when it is not needed. If the storage tank is indoors, the surplus summer heat can increase the cooling load or overheat the house. A distribution system is needed to move the heat into the home when it is needed. The pumps and fans that collect and distribute the heat can consume substantial electricity. Few integrated solar combisystems are commercially available in the United States, so most are custom designed and built and can be quite complicated. Combisystems in the BA Program homes have had operational challenges and have met only a small fraction of the heating load (Hendron et al. 2007). Combisystems are more widely used in Europe and have been studied extensively by the International Energy Agency (Weiss 2003). We decided that the high first cost, low use, complexity, and custom design of this approach were not consistent with our design criteria.

We pursued options such as radiant floors, hydronic baseboard heaters, and a coil in the ERV supply air for distributing the heat from an active solar space heating system. Radiant floor heating is a good match for active solar heating because it requires a low water temperature. However, radiant floors were considered too expensive for affordable housing and are unlikely to be replicated. The supply air of the ERV can be used to distribute heat. Hot water from the solar tank is circulated through a coil downstream of the ERV supply fan. To supply enough heat the ERV would have to be operated in its high flow mode. Even at this rate, the amount of delivered heat would be barely enough for this small house. The ERV is a balanced system, so the air changes in the home would increase when the ERV is placed in high flow mode to deliver heat. This would overventilate the home and waste some of the delivered heat with the exhausted air. A solution might be to operate the ERV in defrost mode where dampers are positioned to pass inside air in place of outside air through the ERV. However, when the home was being designed, we were not able to locate any commercially available ERVs or heat recovery ventilators that implemented this strategy for space heating. Therefore, a custom control system—which violates the design criteria—would have had to be developed. If we had pursued active solar space heating, we would likely have used hydronic baseboard heaters to distribute the heat. This delivery system cost is quite low. The disadvantage is that high delivered water temperature is necessary, which means the solar heated water would often need backup heating to meet the required delivery temperature. In the end, we decided against an active solar water heating system because of its costs and complexities.

For an all-electric ZEH, using a ground-coupled heat pump (GCHP) for heating has some attractive benefits. The GCHP can deliver three to four units of heat for each unit of electricity used. In contrast, electric resistant heat delivers one unit of heat for every unit of electricity consumed. The GCHP can also deliver cooling in the summer, but the heat pump and the ground loop are quite expensive and would require an air handler and duct system to deliver the heating. The compact size and superinsulated shell of the NREL/Habitat ZEH reduced heating needs to such a low level that the cost of the GCHP was not justified.

The use of NG for heating, cooking, and clothes drying in a ZEH is somewhat controversial. Some believe that because a ZEH exports only electricity, it must consume only electricity. However, in most of the United States, the electricity consumed comes primarily from fossil fuels. So the home consumes fossil fuels when it uses electricity and offsets that consumption when it produces excess PV electricity. This is similar for a ZEH that consumes NG. The PV system is sized to produce and excess electricity to offset the NG used. The source energy use is net zero.

The economics of these choices differs. An all-electric home that is too small and efficient to use a GCHP requires a larger PV system and is substantially more expensive. The all-electric approach has the advantage of eliminating the monthly fixed cost of having an NG hookup, which is about $9/month in the Denver, Colorado area. The NREL/Habitat ZEH design team decided to use NG to reduce the required PV array size and to take a hybrid approach to space heating.

The space heating system combines a point-source direct vent NG furnace in the living/dining area of the home and small baseboard electric resistive heaters in the three bedrooms. This approach is relatively low cost, elegantly simple, and provides zone heating because each appliance has its own independent thermostat.

Water Heating System

Although we ruled out a solar combisystem, the results of the early BEOpt runs convinced us to incorporate a high solar saving fraction water heating system into the home design. We used TRNSYS to conduct parametric studies. We found that mounting the collectors flat at the roof pitch rather than raising them to their optimal angle incurred only a small energy penalty (Christensen and Barker 2001). TMY weather data and BA Benchmark hot water use indicated that a 96-ft^2 collector area with 200 gal of water storage would result in an 88% annual solar saving fraction that includes pump energy losses. All summer hot water needs would be exceeded with this system. This means that the thermal storage will reach maximum storage temperature many times throughout the summer and the collectors will stagnate. If we used a glycol system, the frequent high stagnation temperatures may break down the glycol. The pressurized 200-gal storage tank would also be quite expensive, so we chose a drainback system.

We specified an NG tankless water heater as a backup to the solar system. Unlike tank water heaters, the tankless system uses no heating energy when the solar water tank is at or above the 115°F hot water delivery temperature. The disadvantage of using the tankless system is the added cost compared to a tank system. We considered using the tankless water heater for space heating, but ultimately decided to use separate systems to avoid the complexity of the combined system.

Photovoltaic System Sizing

Once all possible energy loads in the house were significantly reduced, the PV system was sized to meet the remaining electricity needs and offset the expected NG use. In a similar home built to BA Benchmark standards, about one-fourth of the energy in the home is consumed by lighting, appliances, and MELs. We reduced the lighting load by using CFLs throughout the home. The appliance load was reduced with ENERGY STAR® appliances. This leaves the MELs, which include everything the occupants plug in—TV, hair dryer, toaster oven, computer, aquarium, etc. Because all other loads have been dramatically reduced, the MELs in the NREL/Habitat ZEH are expected to consume 57% of all energy used annually (see Figure 6). Although the BA Program is researching ways to reduce these loads, they are currently out of the control of the home designer. Furthermore, these loads are highly unpredictable and vary substantially from household to household. Thus, the ZEH designer is faced with sizing a PV system for a home where the largest load is not known with any accuracy.

The BA Benchmark includes assumptions that we used to estimate the MELs and size the 4-kW PV system. These assumptions are based on the best available nationwide studies of energy use (Hendron 2005), so the home's PV system is sized with the assumption that it will be occupied by a "typical" American household. If the household were typical, the home would achieve zero energy. If the household were atypical, the home may not achieve zero energy or may be a net producer. (See Table 1 for a summary of the NREL/Habitat ZEH attributes.)

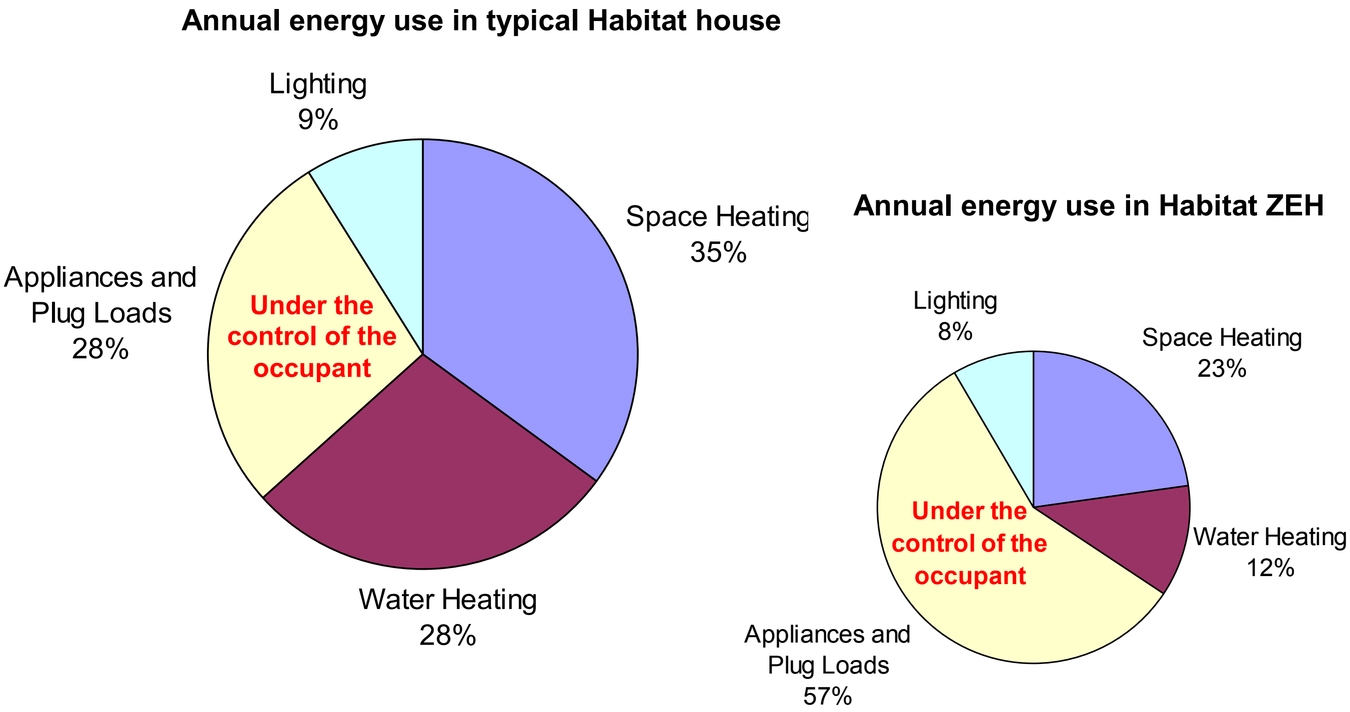

Figure 6. Graphs comparing energy use in typical Habitat house and in NREL/Habitat ZEH

Table 1. Summary of NREL/Habitat ZEH Attributes

Square footage	1,280 ft^2
Number of bedrooms	3
Number of occupants	3
Design heating load	15,000 Btu/h
Walls	Double stud wall Fiberglass batt insulation Nominal R-value = 40 h ft^2 F/Btu
Ceiling	2-ft raised heel trusses Blown-in fiberglass insulation Nominal R-value = 60 h ft^2 F/Btu
Floor	Fiberglass batt insulation Nominal R-value = 30 h ft^2 F/Btu
South windows	Low-e, high SHGC U = 0.30 Btu/h ft^2 F, SHGC = 0.58
North, west, and east windows	Low-e heat mirror U = 0.23 Btu/h ft^2 F, SHGC = 0.27
Solar tempered	96 ft^2 of south facing windows 3-ft overhangs for summer shading
Water heating	Drainback solar system 96-ft^2 collectors with 200-gal storage tank NG tankless water heater for backup
Ventilation	ERV system with electronically computated motors
Space heating	Direct vent ductless NG heater in living room Electric baseboard heaters (750 W each) in bedrooms
Lighting	CFLs throughout the house
Appliances	ENERGY STAR clothes washer and refrigerator
Solar electric	Nominal 4-kW_p DC PV system
Other features	All mechanical equipment is within conditioned space Light-colored roof shingles Increased attic ventilation

Construction Costs

Habitat Metro Denver tracks the construction costs of all the homes it builds. All site, material, and labor cost for trades such as plumbers and electricians, as well as the value of donated material, are recorded and categorized within the cost data. The value of the volunteer labor used to build the house is not included in the cost figures. Even if the volunteer hours put into the home were recorded, it would be difficult to value these hours because the experience of the volunteers varies considerably. The time Habitat staff work on the home is also not included in the cost data.

In 2005, when Habitat Metro Denver built the ZEH, it also built a home that closely matches the ZEH in square footage and number of bedrooms. This home was built to Habitat Metro Denver standard building practices and is used as a reference for comparison to the ZEH.

Table 2 shows the cost categories divided into two sets: those that may have been affected by the ZEH design and those that were not. Table 3 shows the differences between the ZEH and the standard practice home in the cost categories that may have been affected by the ZEH design. A bar chart of the costs affected by the ZEH design is shown in Figure 7.

Overall, the ZEH cost 8% more per square foot than the standard practice home. However, this number is a bit misleading because the land, water, and sewer costs for the standard practice home were substantially higher than for the ZEH. The totals for the cost categories affected by the ZEH design were 42% higher for the ZEH than for the standard practice home. The home cost is affected nearly as much by the land and site-related costs as by its design to reach the zero energy goal.

The main incremental costs and savings associated with the ZEH are highlighted in Figure 7. The actual system costs for the solar electric and water heating systems are shown along with incremental costs for framing, windows, and insulation. Incremental cost savings are seen in the mechanical category because of the simplified ductless heating system in the ZEH. Combining the costs and savings in only the six categories shown yields a total incremental cost of $28,054—about a 21% incremental cost over the total standard practice home cost.

The cost shown for the solar electric system ($17,489) is the actual, deeply discounted price paid to Altair Energy. Before the Colorado Amendment 37 rebates went into effect, the installed price for a 4-kW solar electric system was $32,000 to $40,000. At the time of this writing, with the Amendment 37 rebates, a 4-kW system may cost somewhat less than the NREL/Habitat ZEH system. Because of the timing of the NREL/Habitat ZEH system installation, it was eligible for the rebates as well. The rebates entirely paid for the installed system cost. However, the benefit of the rebates was not included in this cost analysis. When developing plans for ZEH homes, it is important to check for local rebates.

Table 2. Construction Cost Data for the ZEH and Reference House

	ZEH	Standard Practice Home	Incremental Costs
Square feet	1,284	1,222	
Number of bedrooms	3	3	
May Be Affected by ZEH Design ($)			
Excavation, foundation	10,630	10,543	87
Joists, decking, framing	9,497	6,029	3,468
Concrete flatwork	5,017	4,248	769
Windows, exterior doors	3,099	1,561	1,538
Trusses, roof, sheathing	3,496	6,137	–2,641
Shingles, gutters	1,723	1,697	26
Siding	4,423	4,696	–273
Mechanical	2,600	5,805	–3,205
Electrical	19,744	4,567	15,177
Plumbing	14,002	6,340	7,662
Insulation	2,893	1,197	1,696
Drywall	3,174	2,473	701
Painting, staining	1,498	1,548	–50
Appliances	903	1,792	–889
Subtotals	**79,525**	**56,160**	**23,365**
Not Affected by ZEH Design ($)			
Vinyl floors	1,784	1,025	759
Interior trim	537	2,177	–1,640
Carpet	1,440	1,209	231
Cabinets	1,384	1,384	0
Land	18,797	39,729	–20,932
Permits	4,529	1,565	2,964
Temporary utilities	636	1,361	–725
Landscaping	5,509	3,480	2,029
Property taxes	33	313	–280
Property development	6,101	4,978	1,123
Soils, surveys	1,219	2,005	–786
Water, sewer	24,603	13,013	11,590
Punch list	80	355	–275
Subtotals	**69,826**	**75,067**	**–5,241**
Grand totals	**149,351**	**131,227**	**18,124**
Cost per square foot	**116**	**107**	**8%**

Table 3. Construction Differences between the ZEH and the Reference House

Categories	Differences between the ZEH and Standard Practice Homes
Excavation, foundation Joists, decking, framing Concrete flatwork	ZEH foundation is larger to allow for the thicker walls and still create a floor plan identical to the standard practice house. The ZEH walls are double 2 x 4 stud walls. The standard practice home is a single 2 x 6 stud wall.
Windows, exterior doors	The windows in the ZEH are orientation specific with heat mirror windows on the north, east, and west and double-pane high SHGC low-e windows on the south. The southern window area is enlarged for solar gain. The standard practice home has double pane low SHGC, low-e windows throughout.
Trusses, roof, sheathing Shingles, gutters	The ZEH has a larger raised heel truss to allow for added insulation. The roof is also larger due to the thicker walls and to provide proper southern window overhangs.
Siding Painting, staining	The exterior of the home is somewhat larger than the standard practice home because of the thicker walls.
Mechanical	The ZEH uses inexpensive electric baseboard heaters and a point-source direct-vent natural gas heater. There is no air handler or heating duct system. The ZEH uses an energy recovery ventilation system. A small duct system for the ventilation air is contained in a drop ceiling in the hallway. The standard practice home includes a 90% efficient closed combustion furnace with sealed heating ducting in the crawlspace and continuous exhaust fan ventilation.
Electrical	The electrical for the ZEH includes the PV system.
Plumbing	The plumbing for the ZEH includes the solar water heating system. Both homes use tankless water heaters.
Insulation	The ZEH has fiberglass insulation in the ceiling, walls, and floor, (R-60,40, and 30 respectively). The standard practice home has R-38 fiberglass ceiling insulation, R-19 fiberglass insulation in the wall stud cavities with ½ inch of exterior foam sheathing, and R-19 blanket insulation on crawlspace walls.
Appliances	Both homes use EnergyStar appliances and CFL lighting. The ZEH uses a stacked washer/dryer due to space limitations in the mechanical room.

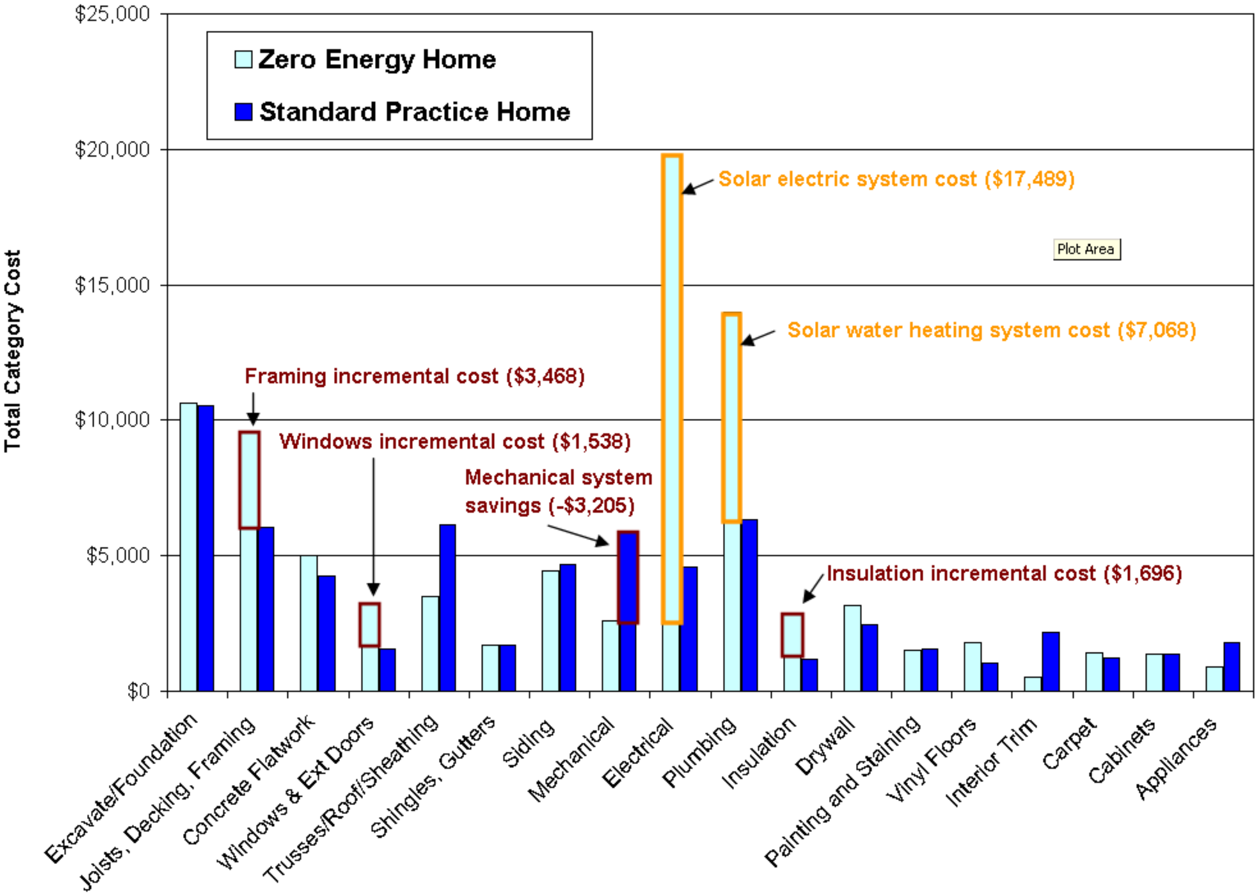

Figure 7. Construction costs for the NREL/Habitat ZEH and standard practice home

Data Acquisition System Design

A data acquisition system was installed to determine whether the home met its zero energy design goal. The system was designed to allow disaggregation of the PV energy production and some end uses. A summary of the data collected and the equipment used is given in Table 4.

Data were collected at 1-min and 1-h intervals. The 1-h data were used to conduct most analyses of the home performance. The 1-min data were used for troubleshooting and to investigate transient behavior of the solar water heating system. We created an Excel spreadsheet with array formulas to aggregate daily and monthly averages and sums and to create graphics about the performance of the home. All electricity end use measurements were in place by February 2006. However, the water flow and NG end use monitoring was not completed until April 2006. Unless otherwise stated, all annual figures in this report include the period of April 2006 through March 2007.

Table 4. Measurements and Components of the Data Acquisition System

Measurements	Component	Make	Model
Electrical Energy Measurements			
PV energy production	Pulse output Watt-hour transducers	Continental Controls	Wattnode WNA-1P-240-P
Baseboard electric heaters			
Hard-wired lights			
Kitchen range			
Ventilation system			
Solar pump			
Space and water heating controls			
All other loads			
NG Measurements			
Space heater	Diaphragm NG meters with pulse output	American Meters	AM250TC
Backup water heater			
Indoor and Water Temperatures			
Living room	Type T thermocouples	Omega	FF-T-20S-TWSH
North bedroom			
Southeast bedroom			
Cold water supply			
Solar tank			
Solar—water to collectors			
Solar—water from collectors			
Solar—water to backup heater			
Hot water supply to house			
Water Flow			
Hot water use	Water meter	Omega Engineering	FTB-6107-A-PS
Weather-Related Measurements			
Outdoor temperature and relative humidity	T&RH sensor with shield	Campbell Scientific	CS500-L and 4020
Solar radiation—horizontal	Pyranometer	Li-Cor, Inc.	LI-200SZ
Solar radiation—plane of collectors	Pyranometer	Li-Cor, Inc.	LI-200SZ
Data Logging Equipment			
	Logger	Campbell Scientific	CR-10
	Thermocouple multiplexer	Campbell Scientific	AM25T
	Switch closure multiplexer	Campbell Scientific	SDM-SW8A
Communications			
	Cell phone modem	Redwing	Airlink 100

Home Energy Rating

The home received a Colorado E-star rating of 95. Blower door results yielded a leakage rate of 460 cfm at 50 Pa (2.7 ACH 50). This corresponds to a natural ventilation rate of about 0.15 ACH, which indicates that the constuction crew did an excellent air sealing job.

First Year Home Performance

The home's net source energy performance exceeded expectations. The PV system was sized to achieve net zero annual source energy with TMY2 weather data for Boulder, Colorado (Marion and Urban 1995) and BA Benchmark assumptions for occupant effects such as temperature setpoints and miscellaneous energy use (Hendron et al. 2005). The BA Benchmark represents U.S. average occupancy choices and behaviors. The occupants of the NREL/Habitat ZEH use less energy than the BA Benchmark occupants average energy users, so the home performed beyond zero and was a net source energy producer. A summary of the overall home performance is given in Table 5.

Table 5. 12-Month Performance Summary of NREL/Habitat ZEH

	kWh (MBtu)
Site Energy Summary	
Total site electricity consumption	3,585 (12)
Total AC site PV electricity production	5,127 (17)
Net site electricity production	1,543 (5.3)
Total site NG consumption	1,665 (5.7)
Source Energy Summary*	
Total source energy consumption	13,025 (44)
Total source energy offset	16,201 (55)
Net source energy offset	3,176 (11)
Percent of source energy consumption offset via on-site renewable production	**124%**

* The site-to-source energy conversions are U.S. national averages according to the BA Analysis Procedures (Hendron et al. 2004): site-to-source multiplier for electricity = 3.16; site-to-source multiplier for NG = 1.02.

The monthly site electricity and NG consumption by end uses are shown in Figures 8 and 9. The monthly source energy consumption by end use is shown in Figure 10. These figures are consumption only—they do not include the electricity generated by the PV system. Rather than being separately monitored for the entire year, the average daily refrigerator energy use over an 84-day period was measured and applied to each day of the year.

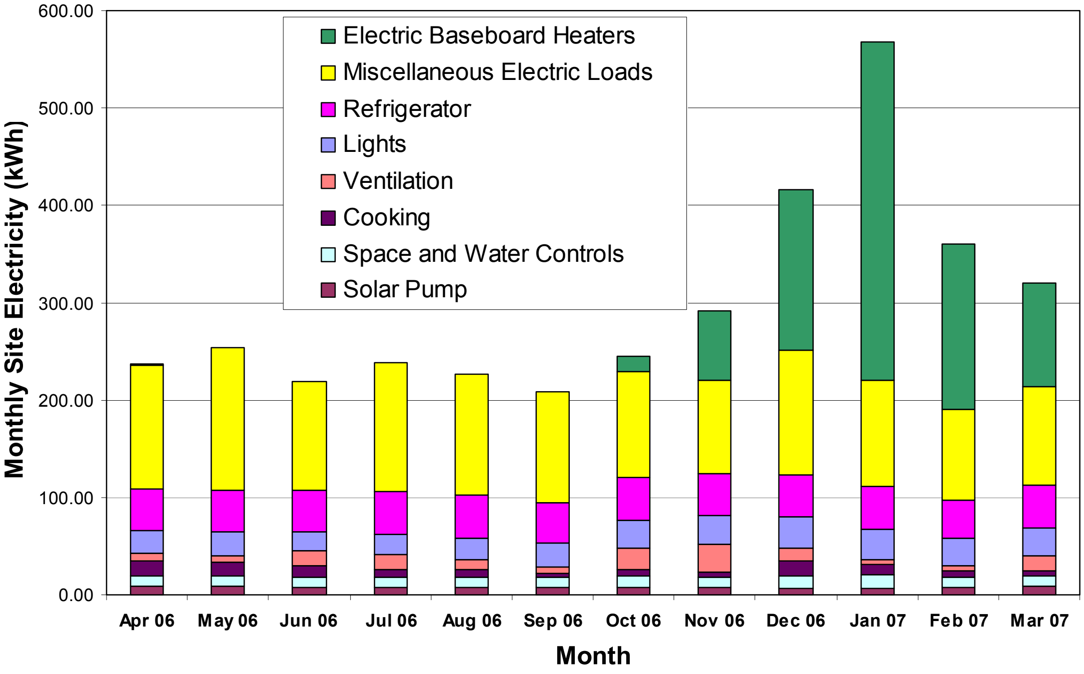

Figure 8. Monthly site electricity consumption by end use

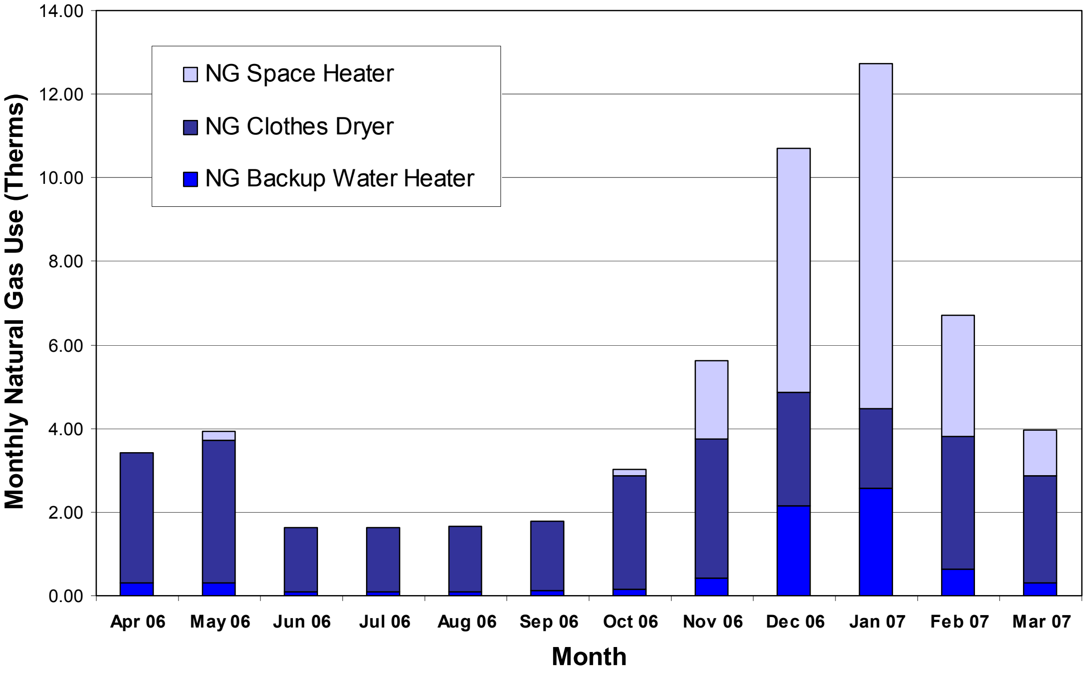

Figure 9. Monthly site NG consumption by end use

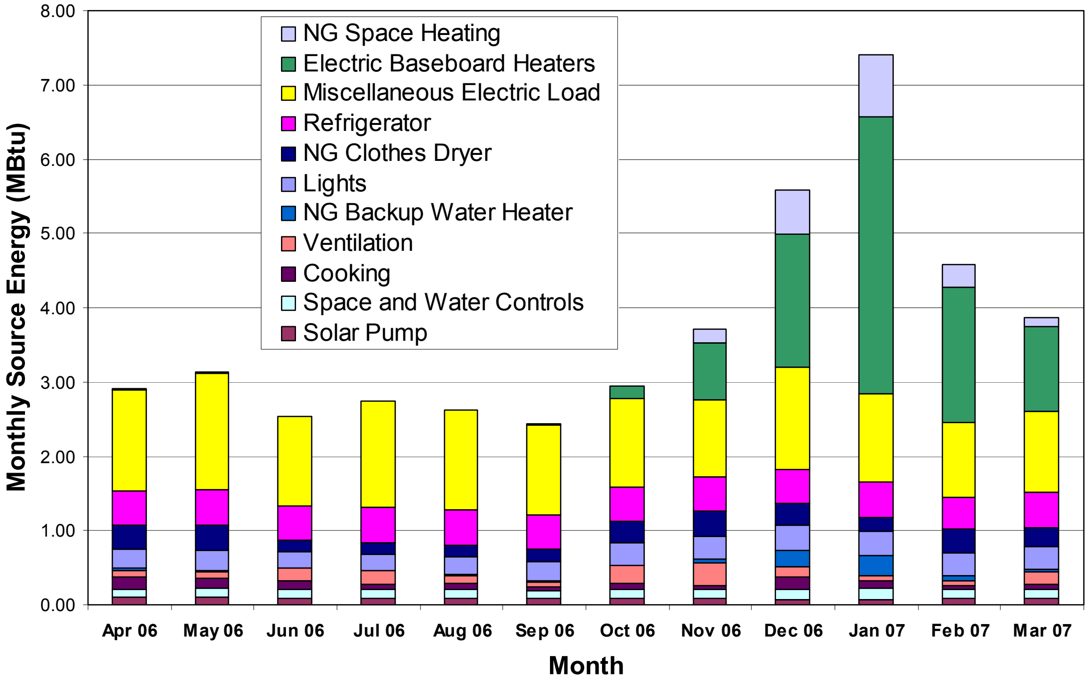

Figure 10. Monthly source energy consumption by end use

The ventilation energy use in the home was lower than expected. We found that the adjustment for the continuous ventilation rate installed in the mechanical room turned off the ventilation system when it was at the “low” setting. The ventilation system was often turned off during the monitoring year, so many of the monitoried ventilation data represent only the standby power draw. A stop on the adjustment that maintains the minimum ventilation rate at ASHRAE 62.2 recommendations would solve the problem.

As expected, space heating is largest electricity, NG, and source energy consumer during the winter months. During the design phase, we assumed the NG heater in the living room would provide the bulk of the home heating. This assumption was based on conversations with builders who had built similarly sized double stud wall homes in colder climates and used point source heating with favorable results. The NG heater was sized to meet the entire design heating load. The baseboard heaters were seen as backups to the NG heater if the distribution of the heat to the bedrooms was inadequate. However, in reality the baseboard electric heaters accounted for 60% of the total space heating site energy and 82% of the total space heating source energy. This indicates the heat distribution to the bedrooms from the NG heater was not adequate. Additional NG heaters or a heat distribution system would be needed for the house to rely more on NG for heating. Meeting all of the heating load with natural gas would have lowered the source energy use in the first year by about 12%.

Despite submetering of most large end uses, the other electricity loads was the largest single year-round end use category. The annual average power draw of the other electricity loads was about 164 W.

The annual source energy by end use is given in Table 6. Generally, the end uses within the control of the building designer include the space conditioning, water heating, ventilation, and lighting. If we sum all other loads (often referred to as appliance and plug loads), they account for 58% of the total source energy consumption. These loads result primarily from occupant choices and behaviors. They vary substantially with homeowner and time, and presents a challenge for ZEH designers. The PV system output must be sized to match all energy consumption to reach the ZEH goal, but the energy consumption is dominated by loads that are out of the designer's control, vary substantially with different homeowners, and are unknowable in advance for a specific home.

Table 6. Annual Source Energy by End Use

End Use	Annual Source Energy MBtu (kWh)	Percent of Total
Other electricity loads	15.5 (4,550)	34%
Electric baseboard heaters	9.2 (2,690)	21%
Refrigerator	5.6 (1,630)	13%
Lights	3.3 (970)	7%
NG clothes dryer	2.8 (830)	6%
NG space heating	2.0 (590)	5%
Ventilation	1.6 (460)	4%
Space and water controls	1.5 (420)	3%
Cooking	1.3 (370)	3%
Solar pump	1.0 (300)	2%
NG backup water heating	0.7 (220)	2%
Totals	**44.5 (13,030)**	**100%**

The other electric loads, refrigerator, and lights add up to 7,150 kWh source energy or about 2,260 kWh site energy per year. This equates to an annual average power draw of about 258 W. This energy eventually appears as heat in the home. Based on a monthly energy analysis, the average total site space heating energy used during the months requiring heating is about 330 W. This indicates that the heat generated by the other electric loads, refrigerator, and lights is meeting over 40% of the average heating load.

Base Other Electricity Loads

The annual average hourly profile of the other electricity loads is shown in Figure 11. The line in this figure shows the other electricity load at a given hour of the day averaged over every day of the year. The annual average power draw of the other electric loads is 164 W. About 40% of the this power draw (64 W) varies hour by hour; peaks occur in the morning before the occupants leave for school or work and in the evening when they return but before they retire for the day. The remaining 100 W is drawn continuously, day and night, whether or not the occupants are home. We used plug-in energy meters that can measure energy draws greater than 5 W to investigate these loads. The results are given in Table 7. The measured end uses account for 40 W of the baseline electricity loads. The remaining baseline other electric loads were not identified. Some hard-wired end uses that may contribute to the remaining load include ground fault interrupters, doorbell transformers, smoke alarms, and our data acquision system (estimated to be 7 to 9 W).

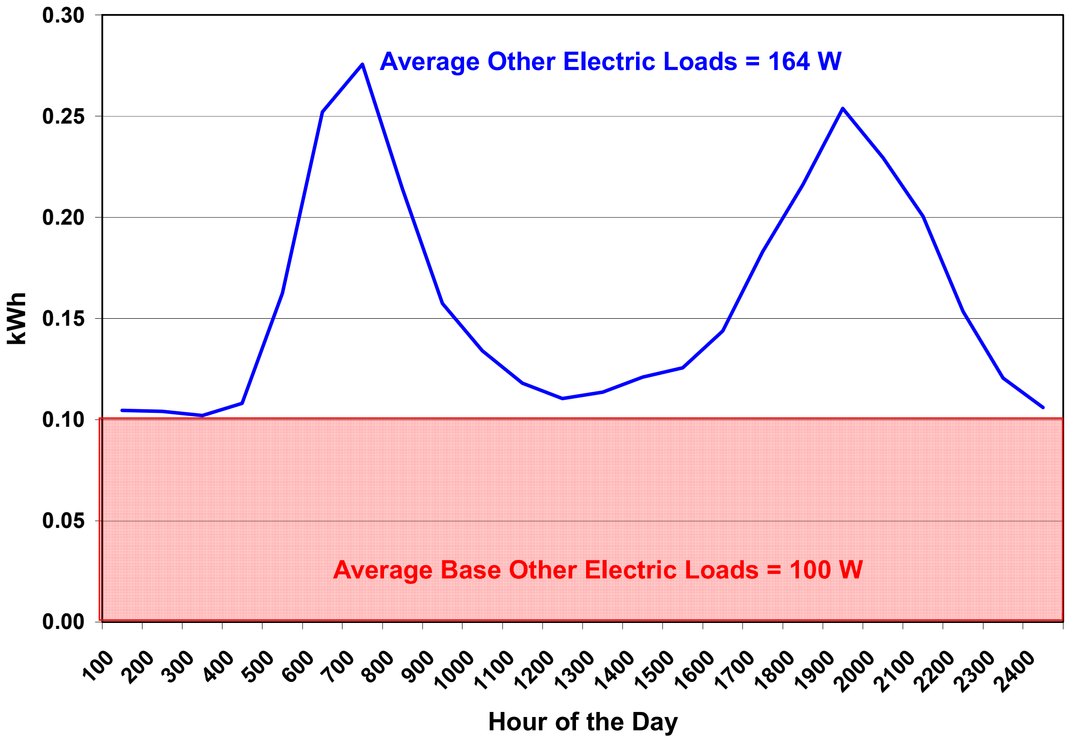

Figure 11. Annual average hourly profile of the other electric loads

Table 7. Measured Baseline Electricity Loads

End Use	**Power Consumption (W)**
Entertainment center standby*	26
Additional TV	6
Computer, monitor, printer standby	5
Digital clock (rated power draw)	3
Microwave oven standby	0 (<5)
Clothes washer standby	0 (<5)
Clothes dryer standby	0 (<5)
Totals	**40**

* Includes TV, stereo, cordless phone, DVD player, and digital clock.

Photovoltaic Electricity Production

A free PV performance calculator, called PVWatts, is available on NREL's Renewable Resource Data Center Web site (http://rredc.nrel.gov). The PVWatts simulation of the 4-kW_p DC PV system using TMY2 weather data from Boulder, Colorado predicts the system will deliver 5,756 kWh (19.6 MBtu) of AC electricity per year with no shading. The PVWatts default DC-to-AC derate factor of 0.77 was used for this prediction. A

Solar Pathfinder shading analysis indicated a 15% loss of solar radiation because of shading from mature trees on the site that reduce the expected annual PV production to 4,892 kWh (16.7 MBtu) The actual energy delivered was 5,127 kWh (17 MBtu), which exceeds the prediction by 5%. The production exceeded expectations, even though the measured total horizontal radiation was about 4% lower than that in the TMY2 data and the PV system was covered in snow and produced no electricity for 35 days during December 2006 and January 2007. This indicates that the PVWatts default derate factor may be conservative or that the Solar Pathfinder shading analysis overestimated the impact of the shading.

The daily and cumulative net electricity use is shown in Figure 12. The PV system produced more electricity than the home used nearly every day throughout the spring, summer, and fall. Despite the long period of net use with no production in January 2007, the home completed the 12-month period with a net electricity production of 1,543 kWh (5.3 MBtu).

We calculated a simple monthly average PV system efficiency by dividing the monthly total AC electricity production by the monthly total solar radiation on the plane of the collectors times the area of the collectors. The monthly average efficiency varied from a low of 2.1% in January 2007, to a high of 13.1% in November 2006. The annual average efficiency was 10.2%.

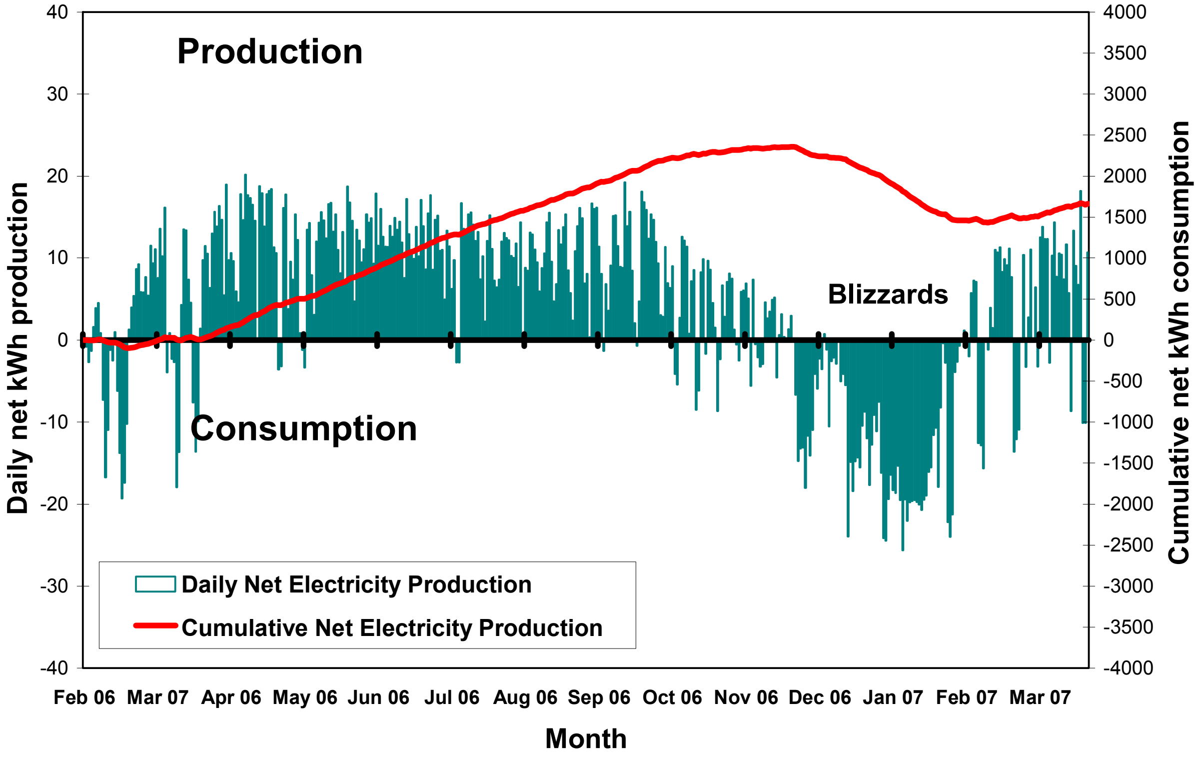

Figure 12. Daily and cumulative net site electricity use

Peak Electricity Demand

Late summer afternoon air-conditioning loads in Colorado cause peak electricity demand. ZEHs often reduce peak demand compared to standard practice homes because their higher efficiency envelopes and equipment lead to lower energy demand and because the PV system may produce energy during the peak period. In the summer of 2005, a community of near ZEHs in California was compared to nearby homes of the same vintage and found to have about half the peak demand during the local utility's peak demand period (Keesee and Hammon 2006).

Because Habitat Metro Denver does not install air-conditioning systems, these homes inherently do not contribute to the utilities' summer afternoon peak demand problem.

We investigated the alignment of PV power production and peak demand during the two highest demand days in 2006: June 15 and July 25. Xcel Energy supplied data for its total Colorado demand on these days. The total Colorado demand is plotted with the ZEH demand and PV production in Figures 13 and 14. The peak periods are shown by the ligher shaded regions on the graphs. The peak demand period for Colorado occurred between about 2:00 p.m. and 6:00 p.m. The figures show that PV production at the NREL/Habitat ZEH led to net electricity production during the peak periods in 2006. However, at this time in the afternoon, PV production declines well beyond its own peak, which is around noon. This decline is exacerbated by frequent cloudy summer afternoons in the Denver area. July 25 was partially cloudy all day and June 15 had a cloudy afternoon. If peak reduction were to become a more central goal for ZEHs, the PV systems could be oriented toward the west rather than due south. This would reduce overall energy production, but would bring the peak PV production more in line with the peak system demand.

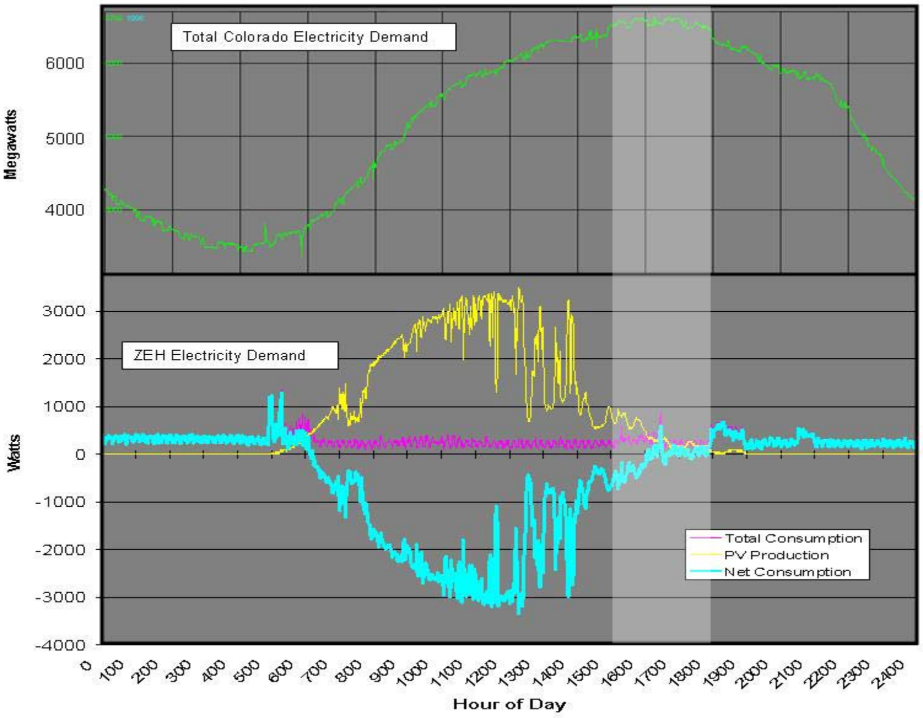

Figure 13. Peak demand on June 15, 2006

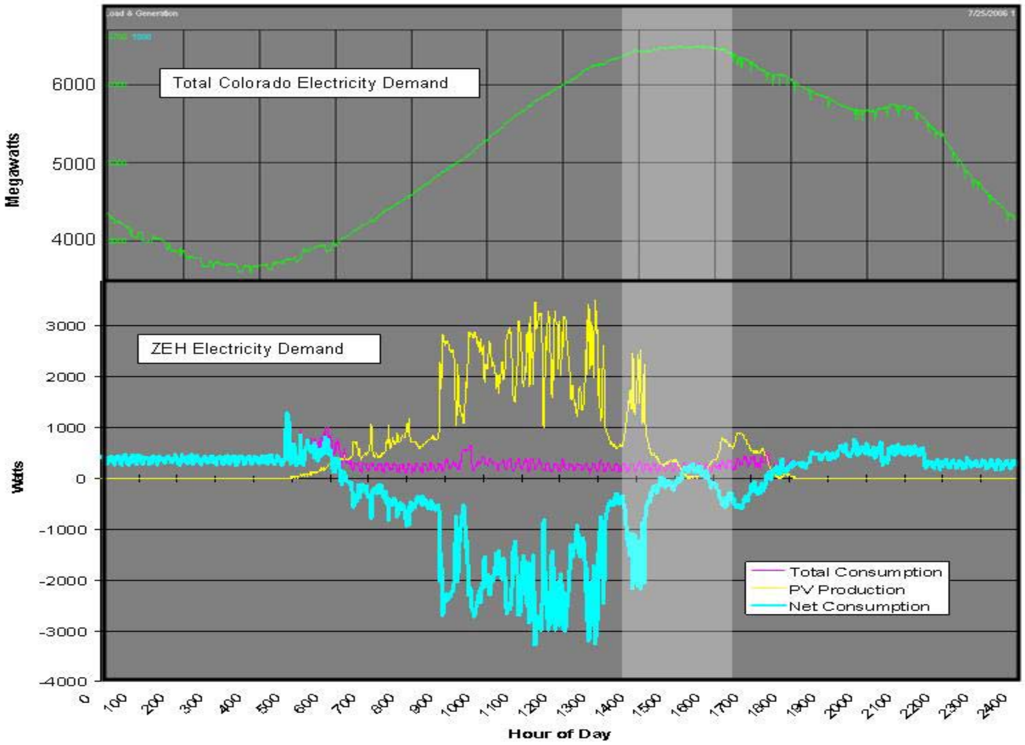

Figure 14. Peak demand on July 25, 2006

Solar Water Heating

We used TRNSYS modeling software (Klein et al. 1996) to develop design expectations for the solar water heating system. We used the model to investigate tradeoffs with tilt angle, collector size, and storage tank size. The initial BEOpt results indicated that an investment in a high savings fraction system was justified. The final design incorporated a drainback system with 96 ft^2 collector lying directly on the roof (tilt angle = 27 degrees), with 200 gal of water for thermal storage.

We tracked the energy delivered to the backup water heater by the solar system by measuring the water temperature entering the solar tank heat exchanger, the water temperature entering the backup water heater from the solar tank heat exchanger, and the water flow rate. The flow*ΔT calculation is perfomed continuously by the data logger and stored on a 1-min basis. We also logged the electricity used by the solar pump and the NG used by the tankless backup water heater. We used this information to define three solar saving fractions:

1. Thermal site solar saving fraction = $Q_s /(Q_s + Q_{ng})$
2. Total site solar saving fraction = $(Q_s - E_p)/Q_s + Q_{ng})$
3. Total source solar saving fraction = $(Q_s -(E_pM_e))/((Q_s + Q_{ng}M_g))$

Where:

Q_s = Thermal energy delivered by the solar system to the backup water heater
Q_{ng} = Energy content of the NG consumed by the backup water heater
E_p = Electrical energy used by the solar pump
M_e = 3.16 = site to source multiplier for electricity (Hendron et al. 2004)
M_g = 1.02 = site to source multiplier for NG (Hendron et al. 2004)

Table 8 lists the predicted and measured perfomance characteristics of the solar thermal system. The period of the analysis is only 10 months water flow and NG data for February and March 2006 are lacking.

Table 8. Predicted and Measured Performance of the Solar Water Heating System

	Predicted	Measured	Percent Difference
Average daily hot water use	63.4 gal	20.5 gal	–68%
Delivered energy	12.29 MBtu (3,602kWh)	2.21 MBtu (647 kWh)	–82%
Pump energy	0.638 MBtu (187 kWh)	0.321 MBtu (94 kWh)	–50%
Ratio of pump energy to delivered energy	0.052	0.145	179%
Maximum monthly thermal site solar saving fraction	1.00	0.95	–5%
Annual thermal site solar saving fraction	0.92	0.75	–18%
Annual site solar saving fraction	0.88	0.64	–27%
Annual source solar saving fraction	0.78	0.40	–49%

The delivered energy of the solar water heater was a small fraction of the predicted value. The main reason for this appears to be that the occupants used less than one-third of the predicted average daily hot water. The prediction is based on the BA Benchmark, which represents national average hot water use. Although the thermal site solar saving fraction was nearly unity during the summer months, the delivered energy was low because of small hot water demand. Thus, the pump energy becomes more significant and the total site solar saving fraction was only 0.66 compared to the prediction of 0.88. On a source energy basis, the savings fraction drops to 0.39 because of the site-to-source multiplier for the electricity used by the pump.

We calculated a simple overall system efficiency for the solar water heater by dividing the thermal energy delivered from the solar tank to the backup water heater by the total solar radiation on the plane of the collectors times the area of the collectors. The monthly average efficiency varied from 2.8% in August to 7.4% in December. The annual average efficiency was 4.8%.

The low delivered energy of the solar thermal system begs the question of whether the investment is justified. The installed cost of the solar thermal system was $7,068. The tankless backup water heater cost $1,340 plus installation (the cost of installation is not available). We used measured PV and solar water heating data to pose the following question: “What would it cost to increase the size of the PV system and use an electric tank heater?” Conventional wisdom hold that the solar water heating system is a better investment. A comparison of the two systems is shown in Table 9. For both cases, all source energy use is displaced by the solar systems.

Table 9. Comparison of Thermal and PV Solar Water Heating Systems Based on Measured Data from April 2006 through March 2007

	Thermal Solar Water Heating Sytem with Tankless Backup (EF = 0.84) and PV to Displace NG Use	Incremental PV with an Electric Tank Water Backup Heater (EF=.95)
Site energy from solar system	2.21 MBtu (647 kWh)	0
Site pump energy	0.321 MBtu (94 kWh)	0
Site energy to water heater	0.727 MBtu(213 kWh)	2.97 MBtu (870 kWh)
PV energy needed[1]	0.549 MBtu (161 kWh)	2.97 MBtu (870 kWh)
PV needed (W_p)[2]	125	672
Solar water heater installed cost	$7,068	n/a
Conventional water heater cost[3]	$1,340	$400
Incremental PV installed cost[4]	$881	$4,702
Total system cost estimate	$9,289	$5,102

[1] For solar water heater case, this includes the pump energy plus the PV energy required to displace the source energy from the water heater (= 94 kWh + 213/3.16 kWh).

[2] Annual PV production was 1.295 kWh per rated peak Watt of the PV system.

[3] Installation costs for the conventional systems are not included.

[4] In both cases we assume that the balance of system investments such as inverter, combiner box, and disconnects have already been made and the full retail installed incremental cost for PV of $7/W_p.

This analysis depends on specific system costs and the 12 months of weather, hot water use, and NREL/Habitat ZEH solar water heater system performance on which these are based. If the low hot water use of the household had been known in advance, a smaller solar water heating system could have been installed at lower cost. PV costs would be higher if an additional inverter were needed. Cost rebates, which are not considered in this analysis, vary considerably around the country. Colorado currently has a rebate of up to $4.50/$W_p$ for PV. The size of the PV in the incremental PV option could be reduced by using a heat pump water heater in place of the conventional electric tank heater. The only conclusion that can be drawn from this simple analysis is that the conventional wisdom may not be true in all cases and additional investigation into the comparison of solar water heating and PV investments may be warranted.

Utility Bills

Zero energy performance does not necessarily equate to zero utility bills. The NREL/Habitat ZEH was designed to use NG for space heating, backup water heating, and clothes drying. The Xcel Energy net metering arrangement calls for any excess energy accumulated by the end of the calendar year to be zeroed out and compensated for at the “average hourly incremental cost of electricity supply over the most recent calendar year” (Public Service Company of Colorado 2006). In a heating-dominated climate, a ZEH produces more energy than it consumes during the summer when daylight hours are long and consumes more energy than it produces during the winter when daylight hours are shorter and energy is consumed for space heating. Because the accumulated excess energy is zeroed out in the winter when PV production is low, the homeowner will likely have to pay for net electricity consumption during January and February. Because the cost of production is lower than the retail cost of the electricity, the compensation the homeowner receives for the excess energy accumulated by December 31 will be less than the cost of the net electricity used in Febuary and March. A more ideal time (for the homeowner) to zero out the accumulated net production would be near the spring equinox, when the accumulation would be closest to zero. In addition to charges for energy use, utility bills include a fixed monthly charges for electricity and NG. In the design phase of the project we used simulated energy performance to estimate a monthly average utility bill of $30 for the house under the current Xcel rate structure.

As energy use decreases, fixed charges become a larger percentage of the utility bill. For the NREL/Habitat ZEH, there was no use charge for electricity most months because it was a net producer, but the fixed charge for electricity still applied. This made it easy to determine the fixed charge for electricity. Disaggregating the NG fixed charge from the use charge on the utility bill was surprisingly difficult. Instead, we applied the fixed charge from the rate tariff and assumed the remainder was the use charge.

Some billing problems occurred with the house, probably because it was one of the first net metered houses under Colorado's renewable portfolio Amendment 37. The home began with an analog meter that ran backward as the PV produced more electricity than the house consumed. The first bill was not received until the home had been occupied for four months. When it arrived, the meter reading was interpreted as indicating a large positive number rather than a small negative number and the occupant received a $939.68 electricity charge on her first bill. Billing continued to be erratic throughout the first year. An additional hitch came when the analog meter was replaced by a digital net meter. An incorrect final analog meter reading was later corrected. Rather than having the accumulated net positive electricity zeroed out at the end of December, it was zeroed out when the analog meter was replaced on November 8, 2006. At this time the home had generated 2,517 kWh more than it had consumed since the meter was installed in October 2005. The homeower was reimbursed for this excess generation at a rate of $.04291/kWh. In January 2006 she received a check from Xcel Energy for $108.

The total annual and average monthly electricity and NG costs are given in Table 10. The average total utility bill was about $17/month.

Table 10. Total Annual and Average Monthly Utility Bills for the Monitored Period

	Fixed Charge	Use Charge	Total
Total annual electricity	$94.69	$69.58	$164.27
Reimbursement for net production		–$108.00	–$108.00
Total annual NG	$106.43	$43.03	$149.46
Total annual bill	$201.12	$4.61	$205.73
Average monthly electricity	$7.89	$5.80	$13.68
Reimbursement for net production		–$9.00	–$9.00
Average monthly NG	$8.86	$3.58	$12.46
Average monthly total utility bill	$16.75	$0.38	$17.14

Space Heating and Comfort

The hourly average temperatures in the living room, two of the three bedrooms, and outdoors are shown in Figure 15. The temperature distribution in the home appeared to be fairly uniform; the temperature difference between any two of the three rooms monitored was less than 3°F for 97% of the hours during the year. The indoor winter temperatures averaged about 68°F; however, the indoor temperature commonly oscillated by about 6° to 8°F because of solar gain on sunny winter days.

During the summer, the indoor temperatures tended to track outdoor temperatures and often exceeded standard comfort conditions. The indoor temperature remained lower than outdoor temperatures during hot sunny periods, which indicates the southern overhangs prevented overheating. On two occasions the indoor temperatures exceeded 90°F for several hours. The homeowner reported that indoor temperatures were similar to those in a Habitat Metro Denver standard practice house next door. She was coached to open the windows during the cooler evenings and close them during the hot days. However, security concerns prevented her from opening the windows at night.

In recent years the Denver area has experienced outdoor temperatures of 90° to 100°F for several periods each summer. This trend may necessitate re-evaluation of air-conditioning in affordable homes in Denver.

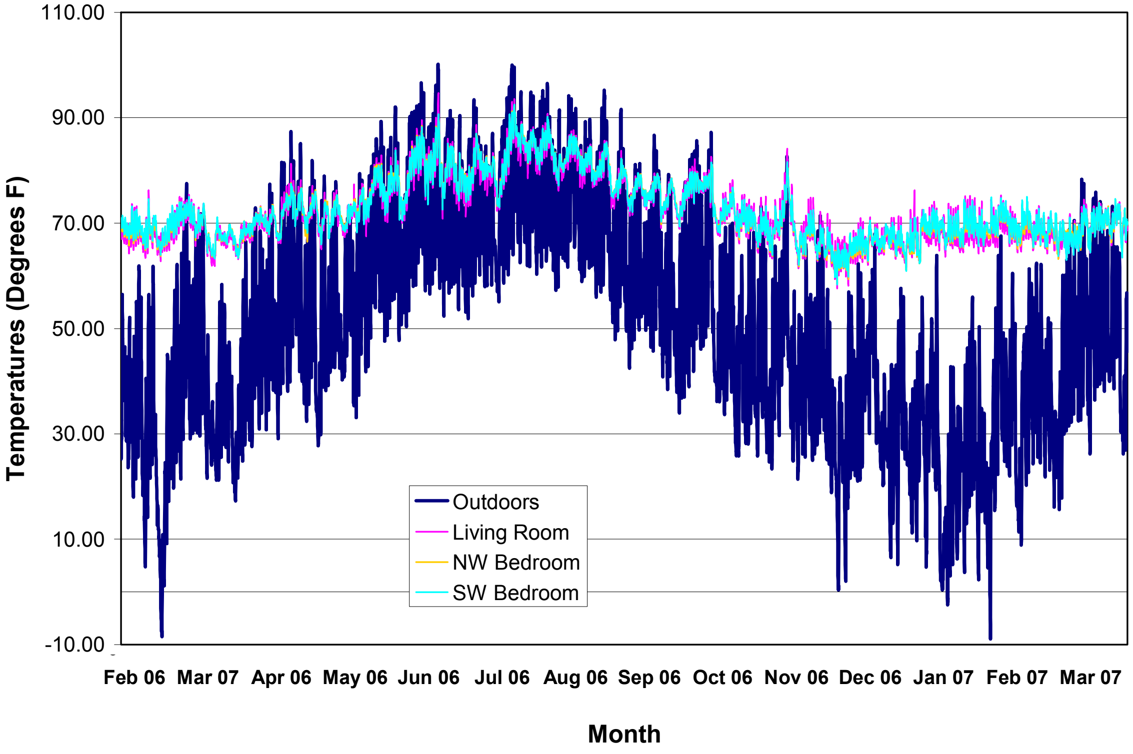

Figure 15. Hourly average indoor and outdoor temperatures

Several paths may provide efficient cooling for homes such as the NREL/Habitat ZEH. If the security concerns could be overcome (perhaps with security grills on specific windows), a whole house fan could take advantage of Denver's diurnal temperature swings and reduce the cooling load. A small, high seasonal energy efficiency ratio minisplit AC system could then be used to provide any additional cooling needed.

Modeled versus Actual Performance

DOE2 software was used to conduct the final design energy simulation of the home. This simulation is driven by TMY2 weather data, and uses assumptions for setpoints, appliance and plug loads, lighting and plug load schedules, and hot water use based on the BA Performance Analysis Proceedures. After collecting a year of monitored data, we reran the simulation, leaving the building and equipment models unchanged but driving the simulation with measured weather and occupant effects. The changes made to "tune" the model to actual weather and occupants are listed here:

- Hot water used was reduced to 20.4 gal/day (BA assumption = 65.6 gal/d).
- Appliance and plug loads were reduced to 2,079 kWh/yr (BA assumption = 3053 kWh/yr).
- Dryer energy use was reduced to 28 therms/yr (BA assumption = of 76 therms/yr).
- Cooking was changed from NG (which was originally anticipated) to electric (which was installed).
- Base lighting kilowatt-hours were adjusted down by 30% and the impact of CFLs was increased from a 60% reduction to a 75% reduction based on measured data.
- The lighting schedule was adjusted based on monitored data.
- The plug load and miscellaneous electricity use schedule was adjusted based on monitored data.
- The Hot water use schedule was adjusted based on monitored data.
- Thermostat settings were adjusted based on monitored data.
- Monthly PV was adjusted to monitored values (from 5,274 kWh/yr to 5,127 kWh/yr).
- Ventilation energy was lowered from 298 kWh/yr to 144 kWh/yr.
- Solar domestic hot water effectiveness was adjusted to 80% solar saving fraction annually.

The monthly electricity and NG consumption predicted by the original and the tuned simulations are shown with the measured data in Figures 16 and 17.

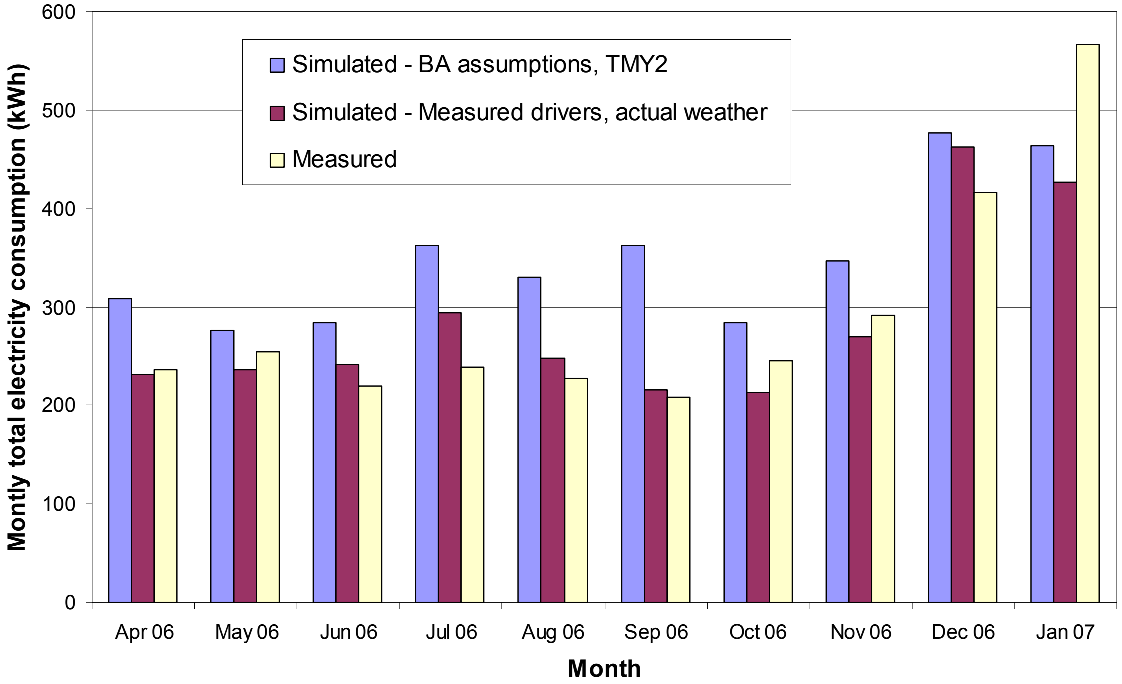

Figure 16. Simulated and measured monthly electricity consumption

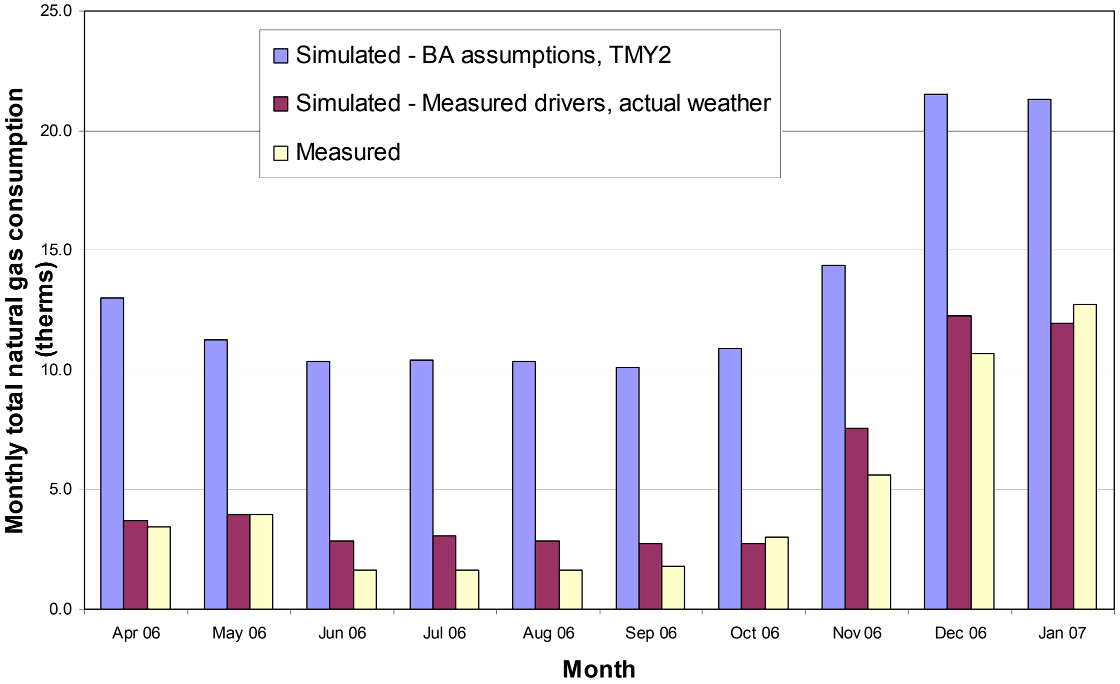

Figure 17. Simulated and measured monthly NG consumption

The simulation that used BA assumptions and TMY2 weather overestimated the annual electricity consumption by 19%. However, when the simulation used measured occupant and weather drivers, it agreed with the measured data on annual electricity consumption to within 3%.

The simulation that used BA assumptions and TMY2 weather overestimated the annual NG consumption by more than 200%. The simulation overestimated all NG end uses: clothes drying, backup water heating, and space heating. In the tuned simulation, the clothes drying NG and the hot water uses were set to the measured value. The measured annual average solar saving fraction was used to simulate backup water heater NG consumption. Measured room temperatures were used to generate more representative thermostat settings. With these changes, the difference between simulated and measured NG consumption decreases to 17 therms. Because the NG consumption of the home is light, this still represents a 32% difference between tuned simulation and measurement. The simulation still overpredicts the space heating NG consumption during the coldest months. This difference is probably due to imperfect modeling of the NG heater and remaining differences between simulated and actual daily temperature setpoints.

When NG and electricity are combined, the tuned simulation is within 8% of the measured annual energy consumption.

Second Year Performance Summary

This section contains a summary of the second year performance compared to the first year detailed in the previous section.

The overall performance of the home in the second year followed similar patterns to the first year performance. The home exceeded the zero energy goal again in the second year, though by a narrower margin. The two-year performance summary is given in Table 11. The daily and cumulative net electricity performance pattern for the second year also closely followed the pattern established in year 1. The daily and cumulative net electricity performance for both years is shown in Figure 18.

Table 11. 24-Month Performance Summary of NREL/Habitat ZEH

	April 2006 to February 2007	April 2007 to February 2008	Percent Change
	kWh (MBtu)	kWh (MBtu)	
Site Energy Summary			
Total site electricity consumption	3,585 (12)	4,224 (14)	18%
Total AC site PV electricity production	5,127 (17)	5,388 (18)	5%
Net site electricity production	1,543 (5.3)	1,164 (4.0)	–25%
Total site NG consumption	1,665 (5.7)	1,811 (6.2)	9%
Source Energy Summary			
Total source energy consumption	13,025 (44)	15,195 (52)	17%
Total source energy offset	16,201 (55)	17,025 (58)	5%
Net source energy offset	3,176 (11)	1,830 (6)	–42%
Percent of source energy consumption offset via on-site renewable production	**124%**	**112%**	

* The site-to-source energy conversions are U.S. national averages according to the BA Analysis Procedures (Hendron et al. 2004): site-to-source multiplier for electricity = 3.16; site-to-source multiplier for NG = 1.02.

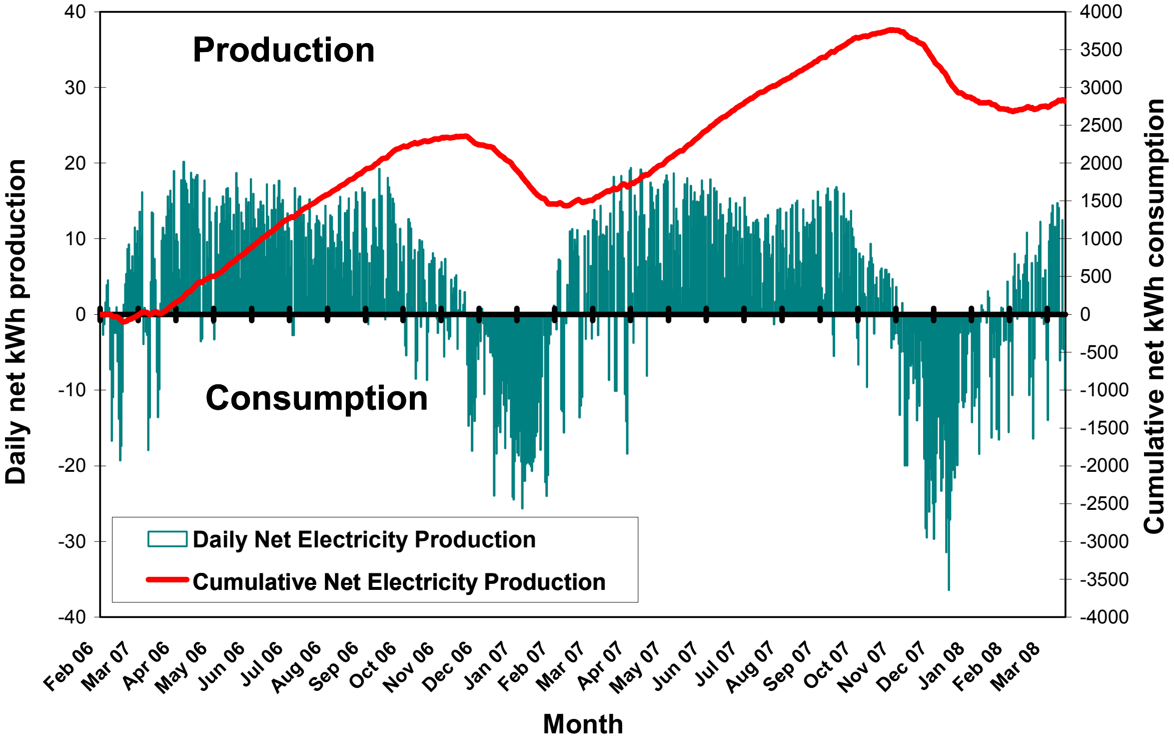

Figure 18. Simulated and measured monthly NG consumption

Discussion and Conclusions

The NREL/Habitat ZEH is a success story on many levels. It has enabled a small, single-parent family to buy an affordable home that is efficient and comfortable. It has enabled NREL and Habitat Metro Denver to work together to explore ideas about how to make energy efficiency and renewable energy work in this context. And because of the overwhelming public response, it has proven to be a wonderful public relations and educational tool.

Installation problems were encountered with the ERV system. In addition to the control problem described previously, some of the ducts were incorrectly connected during the installation. As ERV systems become more common, some ERV commissioning is recommended if the installation contractor is not familiar with these sytems.

The built-in thermostats included with the baseboard heaters proved to be imprecise at best. In 2007 we installed wall-mounted line-voltage thermostats for each heater.

The economics of a ZEH is a function of the specific net metering tariffs for its location. Some of these tariff structures are more favorable than others. For example, the Tennesee Valley Authority buys 100% of the PV-generated electricity from home PV systems at $0.15/kWh. The cost of electricity varies with the area. In Oak Ridge, Tennessee, the electricity use charge is $0.07543/kWh, so homeowners are paid nearly twice their electricity rate for their PV production. Table 12 shows what the energy costs for the house would be if the Oak Ridge electricity and NG rate structures were available in Denver. Rather than having to pay the utility bills, the homeowner would have received an average of $24/month from the utility. In locations with incentive programs that are less favorable than Tennessee's, a ZEH can be seen as a hedging strategy against uncertainty in energy prices. Owners of affordable homes are generally less able to absorb energy price shocks and would benefit from the low and stable home energy costs of ZEHs.

The PV sizing for this project was based on BA Benchmark appliance and plug load use designed to represent mid-1990s national averages. With this strategy, one could expect the home's chances of achieving zero energy performance to be 50/50—half of the occupants will be above average energy consumers and half will be below average. The NREL/Habitat ZEH appliance and plug load energy use was 32% less than the Benchmark level and still accounts for 58% of all energy used in the home. This is one of the main reasons the home exceeded the net zero energy goal and was a net energy producer. Yet the occupants' lifestyle is not one of deprivation for the sake of energy savings. Another sizing strategy that could be adopted would be to size the PV system for a below average user and provide educational material to the occupant that outlines the energy budget to achieve zero energy. An inexpensive whole-house energy meter can be installed for feedback.

Table 12. Cost of Energy at the Oak Ridge, Tennessee Rate Structure

	Value	Units	Oak Ridge Cost/Unit	Total Cost
PV reimbursement	5127	kWh	–$0.15	–$769.05
Electricity fixed charge	12	months	$7.46	$89.52
Electricity use charge	3595	kWh	$0.07543	$270.42
NG fixed charge	12	months	$3.50	$42.00
NG use charge	57	therms	$1.4030	$79.97
Total annual cost				–$287.14
Total average monthly cost				–$23.93

It was a design decision to use NG in the NREL/Habitat ZEH and displace the NG use with excess PV electricity generation to achieve net zero source energy. The PV system required for this approach is smaller than for an all-electric house with resistive water and space heating, and reduces overall home cost to achieve net zero source energy with the same societal benefits. However, because the occupants are below average energy users, the net *site* energy use was nearly zero. This means the occupants could use electric resistance heat to meet the loads currently served by NG and still come very close to the zero energy goal without additional PV panels. Eliminating the NG would further simplify the mechanical equipment and reduce the already small utility bill by eliminating the fixed charges for natural gas. Making the home all-electric and using the PV sizing strategy may be a reasonable approach for cold climate affordable ZEHs.

The person-to-person variability of appliance and plug load energy use makes sizing the PV system for zero energy challenging. One advantage of net metered PV is a 100% utilization factor. If the occupant does not need the energy being provided by the PV, it is sent to the grid for others to use. (Economic compensation for this energy varies considerably.) In contrast, if the homeowner uses less hot water than expected, the solar thermal system stagnates at its maximum temperature and cannot take advantage of additional solar resource. In effect, the energy that could have been collected is lost. Because water use is highly variable, it presents a sizing challenge that is similar to the PV system. If the water use is lower than expected, the savings drop off substantially and the economic value of the system is reduced. For a ZEH that must supply all its energy from renewable resources, the economic value of solar thermal and PV needs to be carefully weighed, and the uncertainty of the occupant effects needs to be taken into account. This area warrants further investigation.

Some final conclusions from the project are listed below.

- The NREL/Habitat ZEH exceeded its goal of zero net source energy and was a net energy producer for the first two years.
- PV system sizing for ZEHs is challenging.
    - Total home energy use for a specific house becomes highly uncertain because of occupant choices and behaviors.
    - Meeting the ZEH design goal depends on occupant behaviors.

    - The economics of excess annual PV production depends on net metering agreements.
- Zero energy does not necessarily mean a zero utility bill.
    - There are fixed monthly costs for NG and electricity service.
    - NG *costs* may not be displaced by net electricity production.
- Efficient, affordable ZEHs can be built with standard construction techniques and off-the-shelf equipment. Meeting the BA goal of cost neutral ZEH in all housing sectors will require additional research on cost-effective efficiency options.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2008

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
The NREL/Habitat for Humanity Zero Energy Home: A Cold Climate Case Study for Affordable Zero Energy Homes

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
P. Norton, C. Christensen, E. Hancock, G. Barker, and P. Reeves

5d. PROJECT NUMBER
NREL/TP-550-43188

5e. TASK NUMBER
BET88001

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-550-43188

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

The design of this 1,280-square-foot, three-bedroom Habitat for Humanity of Metro Denver zero energy home carefully combines envelope efficiency, efficient equipment, appliances and lighting, and passive and active solar features to reach the zero energy goal. The home was designed with an early version (July 22, 2004) of the BEOpt building optimization software; DOE2 and TRNSYS were used to perform additional analysis. This engineering approach was tempered by regular discussions with Habitat construction staff and volunteers. These discussions weighed the applicability of the optimized solutions to the special needs and economics of a Habitat house—moving the design toward simple, easily maintained mechanical systems and volunteer-friendly construction techniques. A data acquisition system was installed in the completed home to monitor its performance.

15. SUBJECT TERMS
zero energy home; habitat for humanity; building optimization; doe2; trnsys; beopt

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		

19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18