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A Cold-Climate Case Study for Affordable Zero Energy Homes

Preprint

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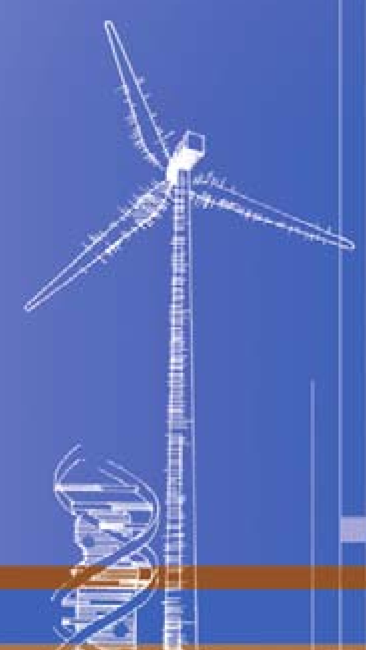

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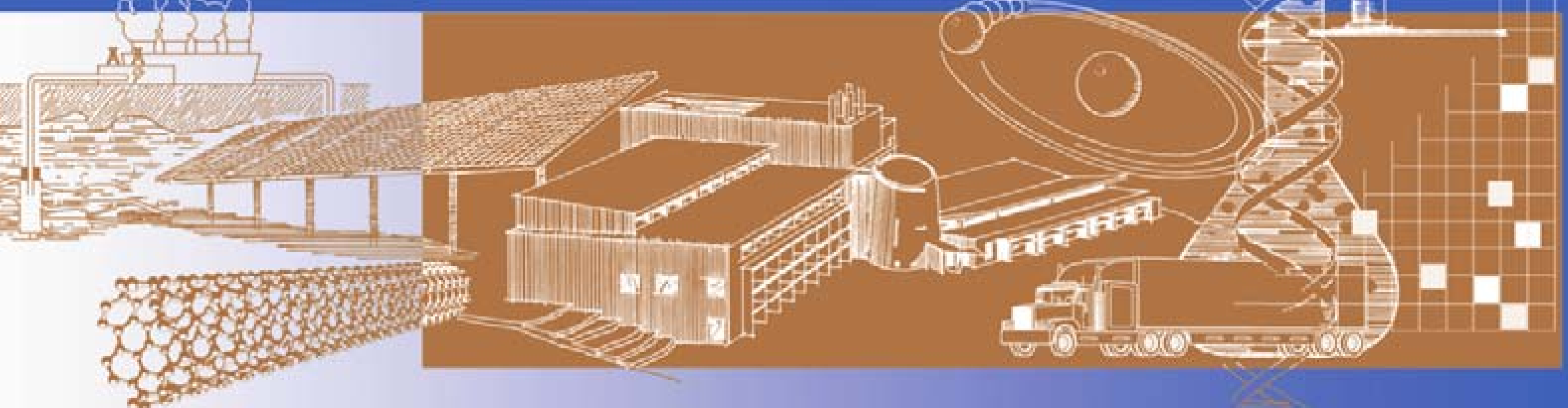

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A COLD-CLIMATE CASE STUDY FOR AFFORDABLE ZERO ENERGY HOMES

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ABSTRACT

This project, supported by the U.S. Department of Energy's Building America Program, is a case study in reaching zero energy within the affordable housing sector in cold climates. The design of the 1200 square foot, 3-bedroom 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 using an early version of the BEOpt building optimization software with additional analysis using DOE2. 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 towards simple, easily maintained mechanical systems and volunteer-friendly construction techniques.

1. INTRODUCTION

In October 2005, Amy Whalen and her two young boys moved into their new Habitat for Humanity home near Denver, Colorado. In doing so they became partners with the U.S. Department of Energy in a case study aimed at understanding how to create affordable zero energy homes 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 paper will detail the construction of the home including passive and active solar features, superinsulated walls, ceiling, and floor, and efficient equipment.

A zero energy home 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 is producing more energy than is being used in the home and drawing from the grid when the PV system is producing less energy than needed in the home. This approach eliminates the need for battery storage in the home thereby reducing 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 (EIA 2005). This makes home energy reduction an important part of any plan to reduce U.S. contribution to global climate change. The goal of the U.S. Department of Energy's Building America program is to create commercially viable zero energy homes 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 cost can take a high toll on homeowners with limited economic resources. A zero energy home guarantees long term energy cost stability for the homeowner.

2. 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 balances energy performance, ease of construction and low cost while maintaining the zero energy goal.

2.1 Project Design Criteria

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

1. 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 US Department of Energy's Building America (BA) residential energy efficiency research program (1). It must have predicted zero net *source* energy consumption over the course of a year using typical meteorological year (TMY2 (2)) weather data and BA Benchmark (3) assumptions on occupant behavior based on average US behavior in terms of temperature setpoints, miscellaneous electric loads, and hot water use.
2. It should be replicable by Habitat for Humanity. Construction techniques and energy efficiency technologies were vetted for their probability to be repeated 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 cost. Construction techniques that were "volunteer friendly" and tended towards low material cost 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. No special operation of the building needed. After construction this house was sold to a Habitat family. It was important to the design team to have the home's energy efficient attributes as invisible 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! We designed the homes with off-the-shelf proven technologies available in the marketplace today. 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 of the mechanical systems in the home, we wanted these systems to be easily replaceable by technicians the owners could find in the local yellow pages.
7. Keep it simple! Many of the recently designed zero energy homes include complicated interconnected mechanical systems designed to maximize renewable energy use and distribution. We too were often tempted in this direction. We tempered this temptation by a continual striving to keep it simple. We believe a simpler system will have fewer problems and a greater chance at longevity.

2.2 The Use of Computer Simulation in the Design

The home design process used a combination of computer simulations and heuristic judgment. Three simulation tools were used both sequentially and iteratively during the design process: TRNSYS Transient System Simulation software (4), DOE2 Building Energy Model (5), and BEOpt Building Energy Optimization Program (6,7).

Fig. 1: The NREL/Habitat Zero Energy Home

3. FINAL HOME DESIGN

The envelope design began by looking at Habitat of 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 3-bedroom 26' by 46' design with a crawlspace was chosen. The floorplan was mirrored from its original design to accommodate the site.

Motivated by the BEOpt simulation recommendation for a superinsulated envelope, the design team considered a wide variety of approaches including structural insulated panels, insulated concrete forms, straw bale, and double stud wall. Structural insulated panels (SIPs) and Insulated Concrete Forms (ICFs) 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 cost and high labor. However after reviewing the literature on straw bale construction and speaking with other Habitat affiliates who have built with straw we eliminated this option because of the lack of standard techniques and details and the low probability of replication by Habitat Metro Denver. We chose a double stud wall with fiberglass batt construction because it has low material costs, uses familiar volunteer-friendly construction techniques, and proven construction techniques and details are available from the National Affordable Housing Network (NAHN: http://NAHN.com).

The walls consist of an outer 2x4 structural stud wall on 16" centers with R13 fiberglass batts in the cavities. Spaced 3 ½" inside this wall a second 2x4 studwall on 24" centers was built. Additional R13 fiberglass batts were placed horizontally in the space between the studwalls and vertically in the interior wall cavities. An outer vapor permeable housewrap and fibercement siding and an inner poly vapor barrier and drywall complete the nominal R40 assembly. The actual whole-wall R-value of this wall will be 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.

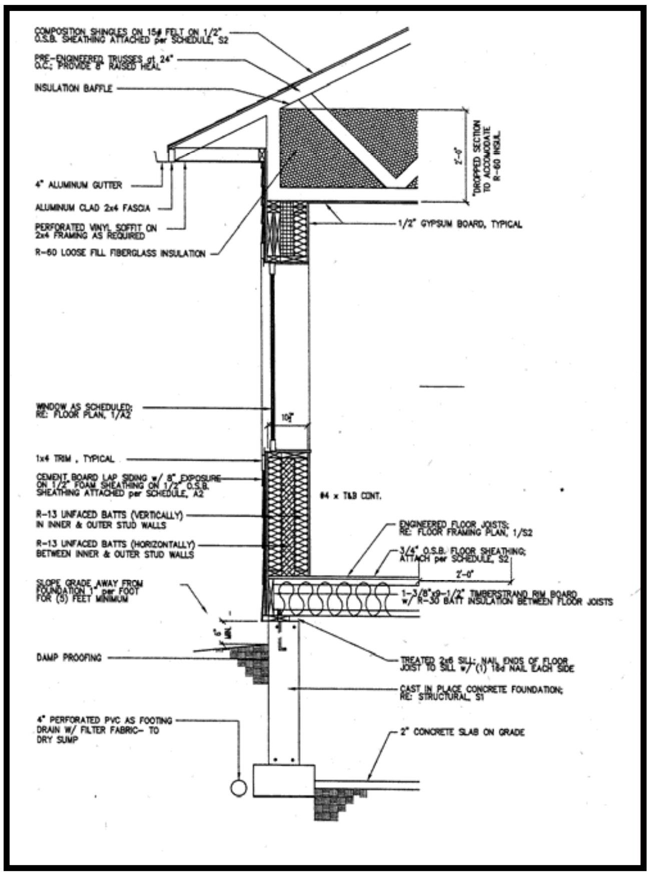

Fig. 2: Details of the double stud wall design

Raised heel trusses were designed to accommodate 2 feet of blown-in fiberglass in the attic giving the top of the thermal envelope an R-60 rating. The floors are insulated to a nominal R-30.

The superinsulated shell dramatically reduces heating energy needs; "sun tempering" was used to reduce these needs further. We designed the home with increased glazing area on the long south side and reduced glazing area on other orientations. As a policy, Habitat Metro Denver does not equip their homes with air conditioning, so we were sensitive to overheating potential. Using DOE2 we evaluated different southern glazing areas and types and overhangs. We compared the simulated heating energy and simulated cooling energy (as if there were an air conditioning system) in the ZEH and the identical standard

Fig. 3: Double stud wall framing

Fig. 4: Raised heel trusses

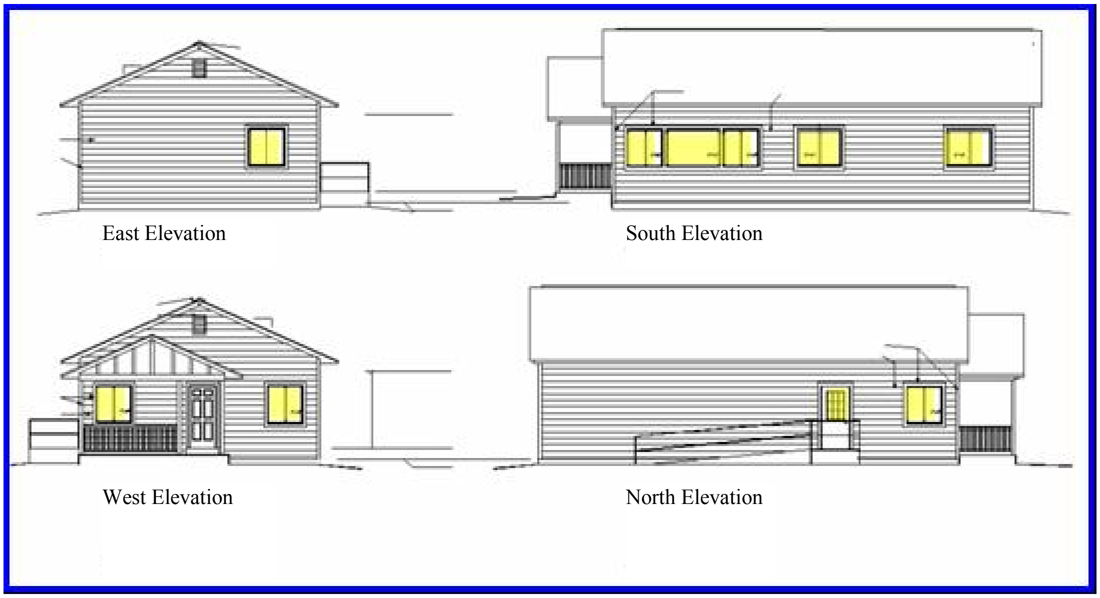

Fig. 5: Windows have been moved to the south wall to provide solar heating.

construction home for each window combination. We chose the design that maximized heating reduction without increasing cooling energy over the standard construction. Double glazed, low emissivity (U-value = 0.30 BTU/hr-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 and would have lacked the thermal comfort and ultraviolet screening benefits. Double glazed low emissivity (U-value = 0.22 BTU/hr-F-ft^2) low SHGC (0.27) were used for the east, west, and north windows.

3.1 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 while minimizing 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 the bedrooms. The warmth of the exhaust air is used to heat the incoming fresh air. This significantly reduces the heat loss due to ventilation. We chose an ERV with efficient electronically commutated motors.

3.2 Space Heating

Having a very low design heating load is a blessing and a challenge. The blessing is obvious – it takes very little energy to keep this home warm! The challenge is that most commonly available heating systems are oversized 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 including:

- Active solar thermal with radiant floor, baseboard heaters, or fan air coil in the ERV supply
- Ground-coupled heat pump
- Point-source natural gas 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. However, this approach requires a relatively large equipment investment. During the summer and during periods when the house is passively solar heated during the fall, winter and spring there is no need for active heating. Therefore the additional equipment investment for space heating is delivering no energy benefit for most of the year. Few integrated solar combisystems are commercially available in the U.S. so most of these systems are custom designed and built and can be quite complicated. We decided that the high first cost, low utilization, complexity and custom design of this approach was not consistent with our design criteria.

For an all electric ZEH, using a ground coupled heat pump (GCHP) for heating has 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. In addition the GCHP can deliver cooling in the summer. However, the ground loop for the GCHP and the heat pump itself are quite expensive and would require an air handler and duct system or a hydronic system to distribute the heating. The compact size and superinsulated shell of the Habitat ZEH reduced heating needs to so low a level that the cost of the GCHP was not justified.

The use of natural gas for heating, cooking, and clothes drying within a ZEH is somewhat controversial. There are those who believe that since a ZEH exports only electricity, it must consume only electricity. However, in most of the U.S., the electricity consumed comes primarily from fossil fuels. So the home is consuming fossil fuels when it is using electricity and offsetting that consumption when it is producing excess photovoltaic electricity. This is similar for a ZEH that consumes natural gas. The photovoltaic system is sized to produce an excess of electricity to offset the natural gas used. The source energy use is net zero.

The economics of the use of natural gas or all-electric differ. For an all-electric home too small and efficient to use a GCHP, the all-electric approach 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 a natural gas hookup which is about $9.00/month in the Denver, CO area. However, the Habitat ZEH design team decided to use natural gas in the home, reducing the required PV array size by 1.1 kW and to take a hybrid approach to space heating.

The space heating system combines a point-source direct vent natural gas 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.

3.3 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 solar water heating system into the home design. TRNSYS was used to do parametric studies to design the system. We found that mounting the collectors at the roof pitch rather than raising them to their optimal angle incurred only a small annual energy penalty (8). We found that a 96 sq. ft. collector area with 200 gallons of water storage would result in an 88% annual solar savings fraction using TMY2 weather data and BA Benchmark hot water use. This solar savings fraction includes pump energy use.

We specified a natural gas 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 degree F hot water delivery temperature, although it may use electricity in standby. 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 also, but ultimately decided to use separate systems to avoid the complexity of the combined system.

3.4 Photovoltaic System Sizing

Once all possible energy loads in the house were significantly reduced, the photovoltaic system was sized to meet the remaining electricity needs and offset the expected

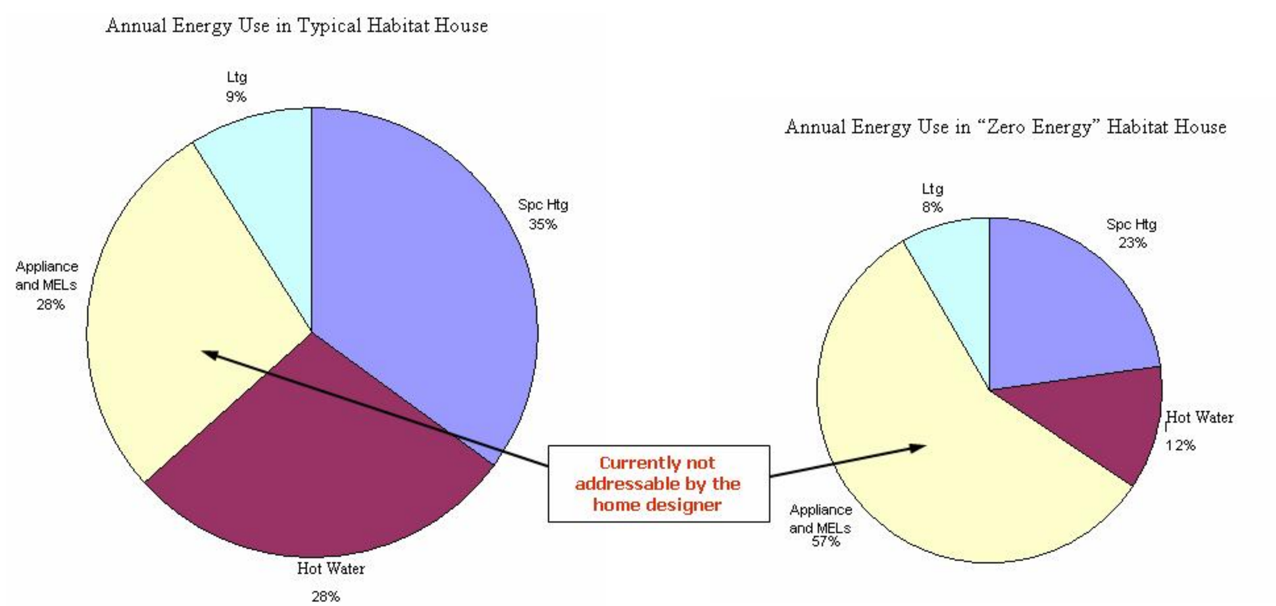

Fig. 6: Energy end uses for a typical design and the zero energy home.

natural gas use. In a similar home built to BA Benchmark standards, about one quarter of the energy in the home is consumed by lighting, appliances, and miscellaneous electric loads (“LAME” loads). We reduced the lighting load by using compact fluorescent lights throughout the home. We reduced the appliance load through the use of energy star appliances. This leaves the miscellaneous electric loads (MELs) that include everything plugged in by the occupants…. TV, hair dryer, toaster oven, computer, aquarium, etc. Because all other loads have been dramatically reduced, the MELs in the Habitat ZEH are expected to consume 57% of all energy used annually (see Fig. 6). Although the BA Program is pursuing research into 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. So the ZEH designer is faced with sizing a PV system for a home where the largest load is really not known with any accuracy.

The BA Benchmark includes assumptions that we used to estimate the MELs and size the 4kW PV system. These assumptions are based on the best available nationwide studies of energy use. So the home’s PV system is sized with the assumption that it will be occupied by a “typical” American household. If the actual household and weather are typical, the home will achieve zero energy. If the household or weather is atypical, the home may not achieve zero energy or may be a net producer.

4. FOR MORE INFORMATION ON THE PROJECT

We installed a data acquisition system in the home in January 2006 and will monitor the performance of the home for at least one year. Periodic email updates on the project are available from NREL. If you would like to receive these updates, send your email address to Paul_Norton@NREL.gov. A conference paper on the home’s performance will be available early in 2008 and a full technical report on the project will be available in mid-2008. These reports will be posted on the BA website at http://BuildingAmerica.gov.

5. ACKNOWLEDGMENTS

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