

A Cold-Climate Case Study for Affordable Zero Energy Homes

Preprint

P. Norton and C. Christensen

*To be presented at Solar 2006 Conference
Denver, Colorado
July 9–13, 2006*

Conference Paper
NREL/CP-550-39678
July 2006

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



A COLD-CLIMATE CASE STUDY FOR AFFORDABLE ZERO ENERGY HOMES

Paul Norton
Craig Christensen
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
Paul_Norton@NREL.gov
Craig_Christensen@NREL.gov

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 1/2” 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.

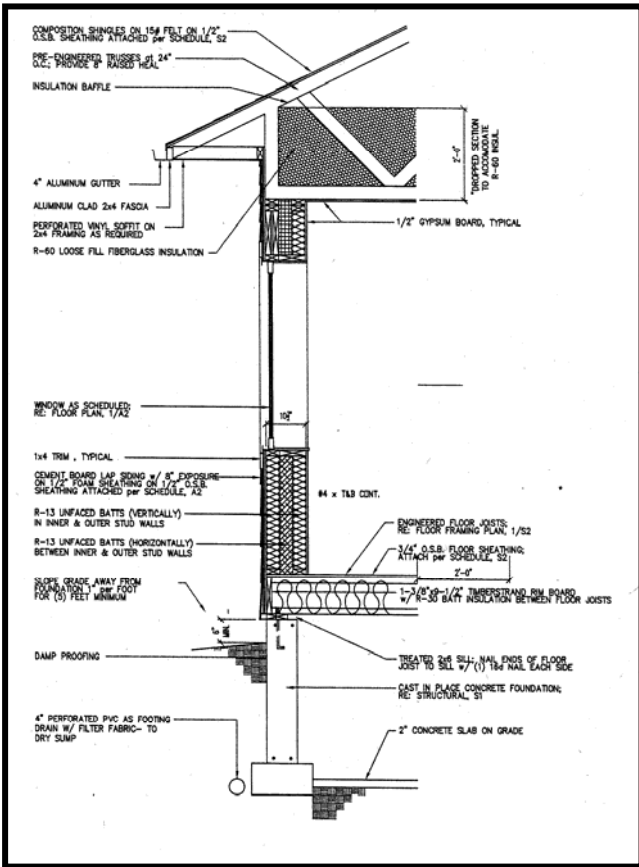


Fig. 2: Details of the double stud wall design

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

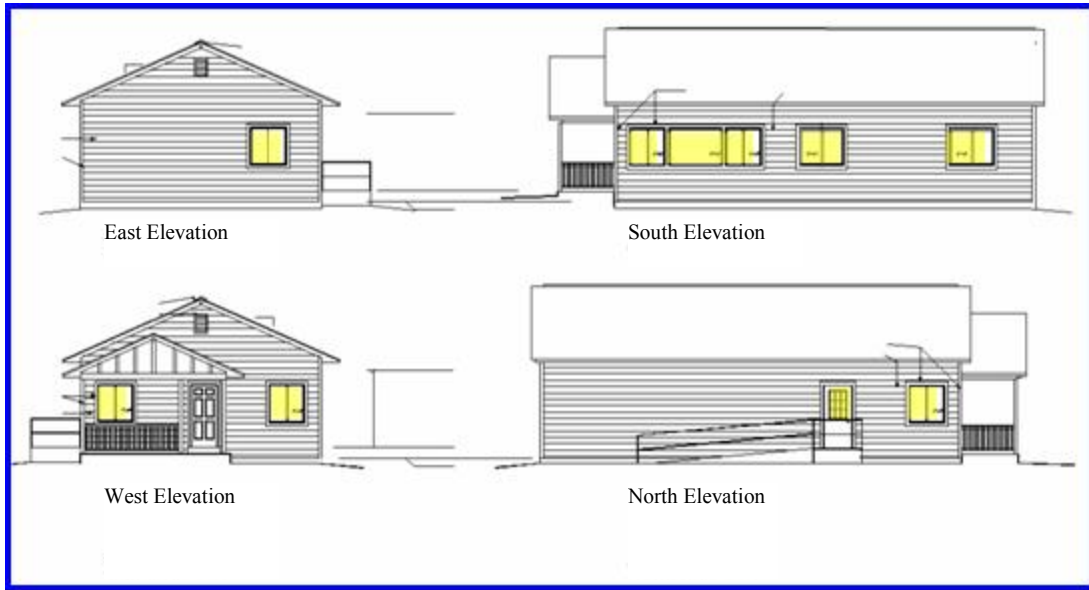


Fig. 5: Windows have been moved to the south wall to provide solar heating.

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 ($U\text{-value} = 0.30 \text{ BTU/hr-F-ft}^2$), high solar heat gain coefficient ($\text{SHGC}=0.58$) 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 ($U\text{-value} = 0.22 \text{ BTU/hr-F-ft}^2$) 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

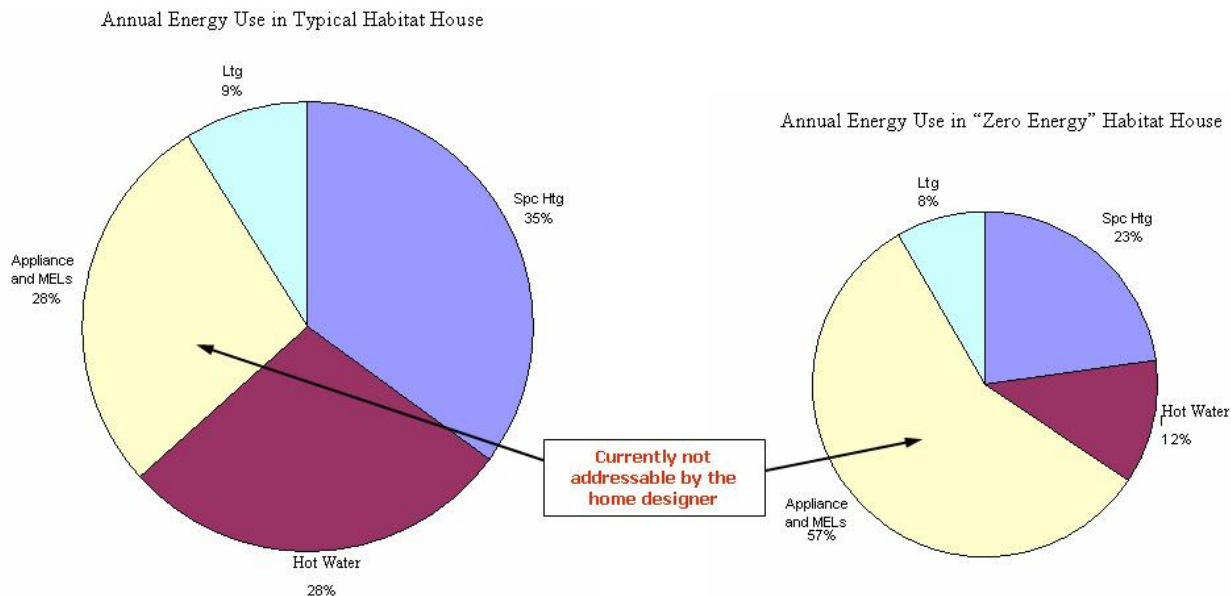


Fig. 6: Energy end uses for a typical design and the zero energy home.

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

The authors would like to thank the many individuals and organizations that supported this project including: homeowner Amy Whalen; The U.S. Department of Energy’s Building Technologies Program; Midwest Research Institute; Battelle; Energy Outreach Colorado; Xcel Energy; The Governors Office of Energy Management and Conservation; Secretary of Energy Samuel Bodman; Congressman Bob Beauprez; Lori Vaclavic, Bruce

Carpenter, Andy Blackmun, Brady Nelson, Pandora Reagan, and Lynne Brown of Habitat of Metro Denver; Paul Kreischer of Lightly Treading; Pete Beverly; Paul Reeves of the Partnership for Resource Conservation; Ed Hancock and Greg Barker of Mountain Energy Partnership; 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.

6. REFERENCES

- (1) For more information on the Building Energy Program of the Department of Energy see <http://www.buildingamerica.gov>
- (2) Marion, W. and Urban, K. User's Manual for TMY2s Typical Meteorological Years, Derived from the 1961-1990 National Solar Radiation Data Base, National Renewable Energy Laboratory, 1995
- (3) Hendron, B., et. al., Building America Benchmark Definition, Updated December 29, 2004, National Renewable Energy Laboratory, NREL/TP-550-37529, 2005
- (4) Klein, S., et al., TRNSYS: A Transient System Simulation Program – Reference Manual, Solar Energy Laboratory, University of Wisconsin, 1996
- (5) DOE2.2 Building Simulation Software, developed by Lawrence Berkeley National Laboratory, Berkeley, CA 94720, available at <http://www.osti.gov/estsc/> or <http://www.doe2.com>
- (6) Christensen, C.; Barker, G.; Horowitz, S. A Sequential Search Technique for Identifying Optimal Building Designs on the Path to Zero Net Energy, Proceedings of the Solar 2004 Conference Including Proceedings of 33rd ASES Annual Conference and Proceedings of 29th National Passive Solar Conference, American Solar Energy Society, NREL/CP-550-36099, 2004
- (7) Christensen, C.; Barker, G.; Tupper, K., Optimal Building Designs on the Path to Zero Net Energy, Proceedings of the Solar 2004 Conference Including Proceedings of 33rd ASES Annual Conference and Proceedings of 29th National Passive Solar Conference, American Solar Energy Society, NREL/CP-550-36100, 2004
- (8) Christensen, C.; Barker, G., Effects of Tilt and Azimuth on Annual Incident Solar Radiation for United States Locations, Proceedings of Solar Forum 2001: Solar Energy: The Power to Choose, 2001

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) July 2006		2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE A Cold-Climate Case Study for Affordable Zero Energy Homes: Preprint			5a. CONTRACT NUMBER DE-AC36-99-GO10337		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) P. Norton and C. Christensen			5d. PROJECT NUMBER NREL/CP-550-39678		
			5e. TASK NUMBER BET6.8004		
			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/CP-550-39678	
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) 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.					
15. SUBJECT TERMS Building America; U.S. Department of Energy; zero energy homes; affordable houses; Habitat for Humanity; BEOpt					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)