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ZERO NET ENERGY TEST HOUSE

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INTRODUCTION

This paper describes the first phase of a residential research program to reduce the impact of new construction on the environment through research and education using a Zero Net Energy Test House as a framework. Containing four bedrooms, three and a half baths, the 1,800 square foot house, 1,000 square foot basement, is located in Omaha, Nebraska. It is being used to validate several research projects and provides a platform for applications research of a number of technological advances. Laminated photovoltaic solar panels, a wind turbine, and an occupant monitoring energy control system are some of the sustainable design innovations incorporated. Sustainable features are described that detail the application for LEED Platinum certification. Integrated into several University of Nebraska courses, the house has reached more than 200 students in the past year. Interdisciplinary teaching has involved design, construction, research, monitoring and energy analysis. Education opportunities have reached K–12 students, industry professionals, and public through tours and presentations.

KEYWORDS

residential, energy, efficiency, sustainability, LEED

Natural resource usage in the United States has become the single most important issue of our time. According to the Department of Energy (2007), the U.S. consumed 100.7 quadrillion (10^{15}) British thermal units (BTU) or 22% of the world's energy usage in 2005. This is equivalent to all of Europe at 86.3×10^{15} BTUs plus the entire continent of Africa at 14.4×10^{15} BTUs. Buildings represent 39% of U.S. primary energy use and 70% of U.S. electricity consumption (DOE, 2008). They use 12.2% of all potable water, or 15 trillion gallons per year. Buildings are also a major source of the pollution that causes urban air quality problems, and the pollutants that contribute to climate change. They account for 49% of sulfur dioxide emissions, 25% of nitrous oxide emissions, and 10% of particulate emissions, all of which damage urban air quality. In the U.S., buildings account for 39% of all CO₂ emissions—the chief pollutant blamed for climate change (EIA, 2008). Residential housing alone accounts for over 20% of the total consumption in the U.S. at 22 Quadrillion BTUs expected in 2008. Heating, ventilating, and air conditioning (HVAC) is the largest energy consumer in the home. The United States Department of Energy's Build America Program sets its goals for sustainability as reducing the average energy use for housing by 40 to 100%.

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To achieve this ambitious goal, research on residential building sustainability such as zero net energy homes is attracting much attention.

Some scattered zero net energy homes are showcased across the United States, including three in Nebraska that have been part of related research and education at the University of Nebraska-Lincoln. Contributing to this regional locus, researchers at the University of Nebraska are nearing completion of two projects, the Zero Net Energy Test House (ZNETH) the first prototype, and a second project ZNETH II, planned for completion in 2012. ZNETH is the first phase of this ten-year research program. This paper describes the sustainable features, energy analysis, and educational impact. The primary goal of the program is to reduce the impact of new residential construction on the environment at minimal additional construction cost. The ZNETH will be used as a framework for ongoing research and education in the area of sustainable design, construction, and professional practices. Goals driving the ZNETH project include:

1. To design a ZNETH house in Omaha, Nebraska that produces more energy than it consumes;
2. To build a full scale ZNETH house using selected technologies and students from a variety of disciplines;
3. To monitor the house during occupation using automated monitoring, controls, diagnostics, and soft-repair technologies;
4. To educate students, industry, and the community on sustainable options through interactions with objectives 1, 2, and 3;
5. To provide LEED project experience in order for students to be eligible for the LEED AP exam.

Located in the heart of the Midwest provides an active environment to investigate a zero-net energy prototype in extreme weather conditions with cold winters and hot, humid summers. The ZNETH project exemplifies partnerships and collaborative efforts between Architecture, Construction, Engineering, and Industry. Funding has come from a diversity of sources and serves as a catalyst for future innovative ideas and experiments.

The following section reviews relevant research utilized in the design and construction of the ZNETH. The case study section describes the design process, LEED, followed by the building envelope and systems utilized. The energy analysis portion highlights how energy simulation was utilized to model building performance and what simulation results were most useful. The conclusion section describes the educational impact and final discussion on the success and failures of the ZNETH project.

APPLICABLE RESEARCH

Design discussions for the ZNETH building envelopes and zero-energy design came from an initial review of existing projects and knowledge regarding zero-net energy and included investigating current efforts to meet the goals of the U.S. Department of Energy (DOE). DOE's goal is to create the technology and knowledge base for cost-effective zero-energy commercial buildings (ZEBs) by 2025 (Torcellini, et al., 2006). This includes the DOE Building Database accessible online including 125 zero-energy projects, and only seven are single-family residential projects. The federal report on zero-energy buildings identified R & D areas that must be pursued to learn from if buildings are to substantially reduce energy consumption and sustain

human health, habitation, and environmental resources. This report also calls for new technologies and practices to arise from the Research and Development activities, to transform how buildings are designed, engineered, constructed, operated and maintained, renovated and reused, and demolished (NSTC, 2008). Research conducted by NREL suggests that it is not yet economically feasible to go “to zero,” however, an increase in efficiency of 30–40% is sufficient to reduce energy consumption without incurring an unmanageable upfront cost (Stark, 2009). According to the National Science Board (NSB), many of the technologies needed to implement zero-energy buildings are currently available.

Several research studies on residential construction have considered the effectiveness of a variety of different building envelopes. Doebber and Ellis (2005) compared the thermal performance of a conventional 2 by 4 wood framed 2400 square foot residential structure against a 2 by 6 wood frame, an insulated concrete form (ICF), and a precast concrete panel home. They found that for cold and temperate climates the heating energy savings were directly related to the R-values. In mild climates where the solar loads were contained by the walls they found that 2 by 6 framing had no effect on cooling energy loads. They concluded that aggressive ventilation could improve the energy performance by removing the energy from the conditioned space. They found capacitance instead of R-value should be improved in mild climates. Arthur and Ribando (2004) determined the time it took a 2 by 6 wood framed wall, a heavy masonry wall, and an ICF to reach steady periodic values. They did so in one, five, and 30 days, respectively. Smith and Jones (2003) analyzed the initial cost and annual energy savings realized in an Energy Star development against four conventional developments. An Energy Star home is at least 30% more efficient than homes built to the National Model Energy Code. Over two years comparing Energy Star to conventional homes, they found electrical savings of 16 and 10 percent and gas savings of 21 and 17 percent in the Energy Star homes.

Demonstration projects, of which the DOE sponsored solar decathlon is a prime learning example, are idea examples to learn from. The solar decathlon competition is between twenty national and international participants and takes place every two years in the National Mall in Washington, D.C. A website (U.S Department of Energy, 2009) provides a brief summary of each project as well as downloadable PDFs of as-built drawing sets and specifications. Additional information is sometimes available from team websites, and used to generate data sheets, which can be effectively used as a quick reference to compare building components. The level of detail and overall completion of teams’ submissions (drawings and specifications) vary widely making an accurate comparison difficult. Another complicating factor can be the language barrier, as some of the teams submit specifications that could contain many pages in either German or Spanish.

Review of the solar decathlon projects from the 2007 competition reveal that many of the teams employed similar if not identical equipment into their designs. Several innovative designs and technologies included laminated bamboo I-beams and plastic structural components with fused joints. Interior waterfalls and rooftop ponds were used as a heat exchanger in place of geo-thermal heat exchangers. Other technologies include modified appliances, web-based home monitoring and automation systems, integrated weather monitoring equipment connecting to web-based home controls, thermal blinds w/ motors, and nanogel insulation used with thin-film material for roofing. Due perhaps to the required performance driven by competition criteria, little variation occurred in the building forms and technologies incorporated. These homes are often ad hoc combinations of multiple and expensive technologies

lacking a holistic building integration perspective. The solar decathlon projects set high standards for design and performance and provide precedents for zero-energy design (Zaretsky, 2010). However, motivating the ZNETH project was the perspective that scattered showcases are not scalable for quick and large-scale implementation and deployment due to costs and climate variations by region.

ZERO-NET ENERGY TEST HOUSE CASE STUDY

Research and educational experiences involved students from both undergraduate and graduate programs. University of Nebraska-Lincoln programs that were directly involved include Construction Engineering, Construction Management, Architecture, and Architectural Engineering. A number of other programs were peripherally involved during construction as part of course projects or service organizations. Two main themes were common throughout the process of the ZNETH project, interdisciplinary research and education for students and professionals.

Design Process

In the fall of 2007, several University of Nebraska-Lincoln courses used the ZNETH design as the central focus of their pedagogy. Two Architecture studio classes of 15 students each used it as a junior design project. Two sophomore level Architectural Engineering courses used it for an entry-level design project. Interdisciplinary charrettes were organized to simulate real world situations and provided feedback for the final design. Over 100 students were involved in the project prior to breaking ground.

Thirty students in two design studios in the 2007 fall semester at the University of Nebraska-Lincoln, College of Architecture used ZNETH as a main design project. The pedagogical exercise involved understanding the implications of zero energy residential design strategies and technologies and how these inform the design process and thinking. The semester had a residential design focus investigating single-family housing issues and how to design for zero energy.

Students were provided a basic site plan and square foot requirements for the home. They visited the site and took extensive photos and documented existing features, trees, existing garage, alley access, proximity to the university, and transportation. Following the site visit, students prepared an analysis based on LEED criteria and renewable energy design standards. In addition, they researched similar project designs such as the Department of Energy's (DOE) Solar Decathlon. The student designs were exhibited at the conclusion of the exercise with visitors from public power, engineers, architects, and faculty from the university in attendance. Following the students' activities, the design architect for the ZNETH integrated a variety of student-generated concepts and ideas into a complete residential plan.

Construction management's Sustainable Construction Systems course was conducted with thirty students who researched, designed and completed the LEED documentation for sustainable features incorporated into the project. The original permitted design was changed during the construction process as various students from the course modified and adjusted the design based on site conditions, technological integration and preferences. A few of the original design decisions were modified in order to meet LEED criteria, economic concerns, constructability and material reuse and recycling concerns. Figure 1 shows the final design for ZNETH.

FIGURE 1. Final ZNETH design.



LEED

The United States Green Building Council developed the Leadership in Energy and Environmental Design (LEED) Green Building Rating System to accelerate the adoption of green building practices. The Partnership for Advancing Housing Technologies (PATH) is a program in the U.S. Department of Housing and Urban Development (HUD, 2009) that was previously known as Partnership for Advanced Technology in Housing. This program is an online resource for homeowners, buyers, and builders. The first concept house built under this program was completed in 2008 in Omaha, Nebraska. Known as the PATH house, the project secured a LEED Silver rating and was the first home in Nebraska to be LEED certified.

Learning from the PATH house, the ZNETH used local materials where possible and was sensitive to the embodied energy used to construct the house. The countertops are quartz from Minnesota, and the floors are recycled wood from a local school. The cabinets are built from reused and recycled materials, and some gypsum wallboard was collected from salvage. The ZNETH house will attempt a LEED Platinum rating and, if successful, will be the first Platinum house in Nebraska.

LEED criteria researched by the Sustainable Construction students include solar photo voltaic panels, horizontal and vertical geothermal loops, landscaping, grey water recovery systems, rainwater collection system, and a windmill turbine, which will be discussed in more detail below. Others include healthy indoor environmental features like low VOC paint, nontoxic floor and cabinetry finishes, formaldehyde free insulation and cabinets, and no carpets. Water conservation features incorporated into the building include dual flush toilets and low-flow showerheads and faucets. Other energy reducing features include LED lights and Energy Star appliances. In addition, the building includes recycled and salvaged materials in a number of products and applications.

Landscaping was designed to minimize the environmental impact by using all native vegetation including drought tolerant plants and rain gardens. The property has no traditional sprinkler system or sod. Erosion is controlled by a retaining wall composed of plants. Two retention ponds store excess rainwater and pervious materials were used for walkways. Water stored in the retention ponds gradually migrates into the earth in a natural process reducing the demands on the storm sewer system. Two cisterns with a total capacity of 600 gallons store rainwater that can be used to water gardens and plants.

BUILDING ENVELOPE

Construction Engineering and Construction Management students, Figure 2, were involved in the construction of the building envelope as part of a course or as a service project. Graduate students were project managers, organized construction, scheduled crews, and ordered materials. Other student groups and courses used the ZNETH property for service learning exercises. The basement walls are 12" Insulated Concrete Forms (ICF) as are three walls on the first level. The fourth wall on the first level and all the walls on the second level are 2 by 6 wood framed walls.

The insulation in the wood framed walls will be open cell soy based foam on the first level and closed cell soy based foam on the second. Soy based insulation is applied using water, does not off-gas, and is moisture resistant making it more environmentally friendly than some

FIGURE 2. Students working on ZNETH.



other alternatives (EMEGA Biopolymers, 2010). Typical residential construction is wood framed 2 by 4 walls. Typical fiberglass insulation in the three and a half inch cavity provides an R-value of 11. Open cell soy based insulation in the same space provides an R-value of 12.6 or R3.6/inch. The equivalent space using closed cell would provide an R-value of 23.8 or R6.8/inch. This results in an R37.4 for the 2 by 6 walls using closed cell insulation. In addition, the closed cell provides some additional structural support that allows 24" spacing between studs reducing the amount of wood in the structure.

The ICFs selected were twelve-inch wide configuration called Fox Blocks by Airlite Plastics Company (2008). They include a six-inch concrete core with five and a quarter inches of Expanded Polystyrene. The R-value of this configuration is 21.64 with an infiltration rate of .05 to .10 air changes per hour. This compares favorably to traditional 2 by 4 framing with batt insulation at an R-value of 11. The ICF wall system will not degrade over time, and the materials are non-toxic and stable in high moisture environments. In addition, the ICFs include a sound transmission class of 45 to 50, which indicates high sound insulating properties.

The exterior walls were covered with an Exterior Insulation Finishing System (EIFS) system. EIFS is a composite building system that incorporates insulation, waterproofing, and a finish surface. The insulation layer consists of a layer of expanded polystyrene (EPS) 1 inch thick. EPS is then coated with a cementitious adhesive with an embedded fiberglass reinforcing mesh. Next, the finish coat is applied with a trowel or spray to create a stucco-like finish. The Oak Ridge National Laboratory (2008) found this system was more energy efficient and moisture resistant than wall systems with brick, stucco, or cement fiber siding.

Figure 3 is an exterior view of the completed house. The roof is a standing seam metal roof made from recycled materials and a galvalume metal chosen for its high reflectivity to reflect heat energy back into the air. The windows are double glazed, low solar gain, low-emittance windows with an average U-value of 0.25.

FIGURE 3. Exterior view of final project.



SYSTEMS INTEGRATION

Renewable Energy

The photovoltaic solar panels were the Solar Laminate PLV Series from Uni-Solar. They are 15.5 inches wide and can be laminated to the standing seam roof between the seams in the flat without penetrations. These flexible panels weigh approximately one pound per square foot. The system is designed to provide 1 Kwh of power with six-136 Watt 24 Volt panels 216 inches long and four-68 Watt 24 Volt panels 112.1 inches long. The orientation of the system was analyzed for efficiency by All Native Services and tested for efficiency using a SunEye by Solmetric. Because of the orientation of the building, the roof design and slope, the results of the investigation indicated a 96% annual solar access. The maximum electricity capable of being generated from the solar panels is 2kW. Taking the average available solar radiation for the Omaha area of 4.6 hours/day and multiplying the expected electricity by the average available solar radiation results in approximately 9.2 kWh of energy from the sun per day.

Wind in Omaha can produce wind speeds ranging from 5.1 to 5.6 m/sec. The Honeywell WT6500 Wind Turbine by WindTronics (Earthtronics, 2009) is a new gearless configuration that uses the blade tip to generate the power. Most residential wind turbines require 7–9

mile per hour winds just to overcome the gearing. The Honeywell wind turbine can produce electricity in winds as low as 2 mph. According to the manufacturer, the turbine is rated to produce 2000 kWh/year in class three winds and costs less than \$6,000. The annual produced energy was divided by 365 days to produce an estimated daily energy output of the turbine of 5.48 kWh per day.

Combining the solar panels energy potential with the wind turbine the ZNETH's daily energy potential is 14.68kWh. Over the entire year this would result in approximately 5,000kWh of energy produced, approximately three-quarters of the ZNETH annual energy needs. The house is net metered to the local utility with a wholesale exchange rate for energy returned to the grid. Currently, the home is completing its final blower door testing and is expected to require additional renewable energy in order to meet the zero-net energy goal.

Geothermal

Heating, cooling, and hot water will be provided by a geothermal heat pump. This configuration has the potential to reduce the energy demands by about 50%. Because the temperature of the earth a few feet below the surface is mostly constant, this energy source is independent of weather conditions. Four vertical wells 235 feet deep were designed to provide four tons of cooling load. Rock was encountered and the design was revised to six wells 145 feet deep. A ton is equivalent to 12,000 btu/h. Radiant heating was considered but forced air was determined the more economical because of the cooling load requirements.

Energy recovery systems will reduce additional energy requirements to heat or cool incoming outside air. There are two types of energy-recovery systems typically used, heat-recover ventilators (HRV) and energy-recovery ventilators (ERV). The main difference between these two heat-exchange systems is the ERV transfers a small amount of water vapor along with the heat energy. The ZNETH will use an energy recovery ventilation (ERV) system. An ERV captures the energy stored in the stale indoor air when exchanged with fresh outside air as required to maintain indoor air quality. For example, during the winter, energy is minimized when heating the incoming fresh air by transferring heat from the warm interior air being exhausted.

Plumbing

The grey water reuse system uses a Sloan Valve system housed within a vanity cabinet and piped to a plumbing drain line. The system collects the wastewater from lavatories and showers and filters it before sending it to a storage container. The filtered water is then pumped to the toilet tank where it is mixed with potable water. This system and other water consuming innovations reduce the demands on our water supply and reduce pollutants flowing back into our rivers. This is particularly important in Omaha where the storm and sewer systems are still combined in the older parts of the city.

Omaha, Nebraska has its own plumbing code in which PEX (Crosslink Polyethylene) plumbing is not allowed. The PEX distribution system is much like that for electricity with a manifold from which flexible supply lines distribute water to each point of use. The PATH Concept House was the first in Nebraska to be approved through a waiver to install PEX plumbing in Nebraska. The ZNETH house also acquired a waiver to use PEX plumbing. The system is easy to install and repair and has a number of advantages over conventional systems including flexibility, fewer fittings, and more burst resistance.

ENERGY ANALYSIS

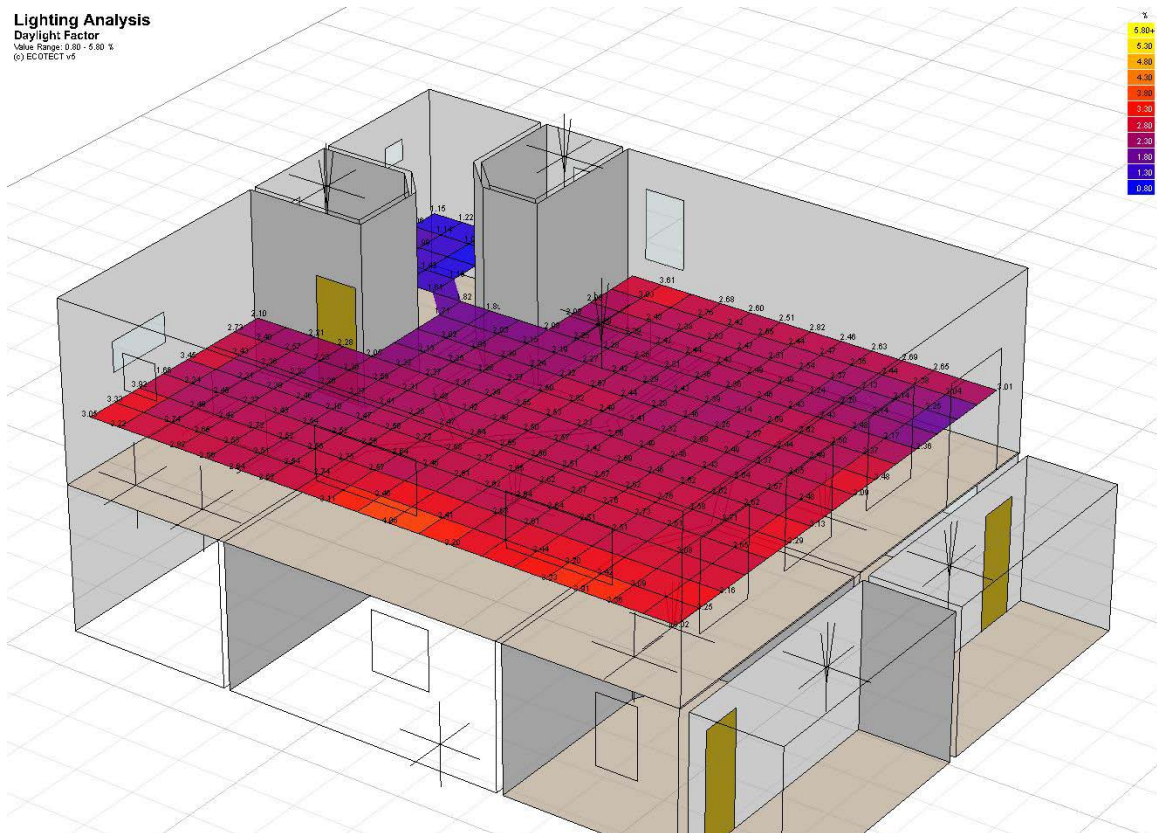
More commonly used in commercial design and construction, simulation tools are more frequently being used in residential and conceptual design phases impacting and validating energy use estimates early on. Several energy analyses were conducted on the ZNETH design with a number of iterative improvements in plans and material selection toward maximizing energy efficiency. The energy simulation for ZNETH was determined by using Ecotect™, and Trace 700™ energy modeling programs. Simulation software was used as a validation and analysis tool. Four analyses were conducted including thermal analysis, lighting analysis, shading analysis, and resource consumption analysis. The lighting analysis simulation was the most helpful and is discussed next.

Lighting Analysis

Lighting analysis computes the natural and electric lighting levels at chosen points or over an analysis grid (2D or 3D). This analysis was performed based on an average cloudy sky in mid-winter, which is the worst-case design scenario. This analysis gives a good indication to the design team of how much natural light will be present and the efficiency of the electrical light system. The simulation results are presented in five different options: daylight factor, daylight levels, electric light levels, overall light levels, and illumination vector.

The most useful simulation was a lighting analysis completed for the living room at the first floor level, Figure 4. Daylight factor is the percentage of light available from the sky, based on

FIGURE 4. Daylight factor (left) for the interior spaces.



the worst-case scenario for interior spaces. It can be seen that the room will have a percentage of daylight between 2.5%–3.5% that passes through the windows. At this point in time in the design the final lighting system of ZNETH was not selected. Therefore, the analysis of the daylight factor was helpful to determine the location and type of electric light needed.

Designing lighting systems for zero-energy homes presented a unique challenge in balancing the natural daylight requirements with mechanical systems performance. Maximizing daylight by providing too much glazing risks overheating the interior or allowing too much heat loss in the winter. The simulation tools aided design decisions by determining the minimal amount of natural light available during the day. Two main daylight strategies that resulted involved east facing windows in the stairwell for morning light and solar light tube system for daylighting the second floor.

CONCLUSION

Educational Impact

The most obvious outcome has to do with the educational impact of new residential construction on the environment through research and dissemination of new technologies. A major challenge in improving our energy efficiency is to educate engineers, architects, educators, the community, and policy makers in a manner that leads to substantive changes in the way we use our natural resources while preserving our quality of life. ZNETH has the potential to transform the way we holistically design our building systems and the way we think about the interaction between systems through simulation, validation, and implementation through a full-scale model.

Over 1100 people have visited the ZNETH project in the past year. This includes classes, field trips, workshop attendees, and professional society meetings conducted at the site. Presentations have been given for business associations, engineering groups, secondary schools, community colleges, energy seminars, counselor workshops, and professional conferences. The ZNETH project has been on TV, radio, the Internet, and in various publications. A promotional video has been shown at university athletic events including being broadcast during football games on national TV.

Educational outcomes from the public exposure, while not measurable, are certainly apparent. The University is providing the public and professionals with information on energy efficiency through the ZNETH effort. Students are learning to consider environmentally friendly designs and construction processes as a requirement of their profession. The heightened awareness of the professional societies results in a number of venues for education regarding the use of our natural resources. Additionally, sustainable features educate the public as well as regulatory agencies about longer-term outcomes to overcome the common first cost bias.

Sustainable Building

The ZNETH program has exceeded expectations in the area of education with student involvement, industry presentations, and community outreach. The project considers human activities, weather conditions, and the indoor environment in a holistic framework that provides the catalyst for an improved relationship between health and comfort and our environment. Locating a project locally provides increased access to the public year-round, during, and throughout the construction process as well as during occupancy. The ultimate goal of this ten-year program is to find the optimal mix of technologies that result in a production

ready ZNETH without appreciably increasing the initial cost. ZNETH was constructed for an approximate market value of \$350,000. Given the additional costs of the wind turbine, solar panels, geothermal system, and quality of interior finishes this was expected. ZNETH II hopes to build on the success of the first prototype with the construction a 1,000 square foot, two-bedroom and one-bath home for \$100,000.

Learning from this project, several energy efficiency enhancements for future ZNETH designs include replacing ICF walls with closed-cell insulated walls, incorporating more passive solar energy features including the length of the overhang, reducing window sizes and installing reflectors, and increasing the number of solar panels. ICFs provided an air-tight, durable building envelope; however, the remaining stud framed walls insulated with closed-cell foam were equally air-tight and had a higher R-value. The porch-overhang was longer than needed to optimize solar gain in the winter, but was designed to function as a porch and respect the neighborhood context. Additional windows were added to the design to experiment with different coatings and types asked for by the industry partner. This led to more heat gain and loss through the building envelope. The house was constructed with concealed conduit allowing additional solar panel capacity to quickly and easily be modified and changed over the lifespan of the house.

Incorporating applied research as done in the ZNETH created a framework for validating the results of fundamental energy efficiency research. A number of projects are affiliated with the house involving grey water systems, renewable energy, and behavioral research to name a few. The goal of producing more energy than consumed will be tested when the building is occupied and actual daily use patterns are established. However, the cost associated a true zero-net energy accomplishment is challenging, particularly in Nebraska given low cost of energy, resulting return on investment, and the restraints by lending institutions regarding investments in energy efficient features. Another barrier is the state of technology performance. Photovoltaic efficiency fluctuates seasonally and is based on the PV material used resulting in cost variations from panel to panel. What might be affordable to install, may not produce much notable energy. Conventional wisdom in wind turbine energy production does not suggest small scale residential systems are feasible. Urban areas produce a high amount of turbulence in prevailing winds resulting in lower wind speeds and therefore less energy production. Validating technology performance through the ZNETH application will provide useful information to the next generation of zero-net energy homes.

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