ABSTRACT
This paper compares and contrasts two contemporary homes that strive to achieve net-zero energy in the state of Minnesota, including the Tofte Cabin in Tofte, Minnesota by Sarah Nettleton Architects et al and the Science House by Barbour & LaDoucer Architects et al for the Minnesota Science Museum in St. Paul, Minnesota. Each house is considered in terms of five issues: project and energy goals; reducing loads; meeting loads; energy and fuel sources; and monitoring. These homes demonstrate that there are significant opportunities for energy savings from solar design in Minnesota. Lessons are discussed related to design strategies and priorities; process and methods; installation, operations, and maintenance; monitoring and commissioning; costs; and the role of design excellence.

1. INTRODUCTION
During the past several years the concept of the zero energy home (ZEH) has inspired the residential construction industry and design professions. Examples of zero energy housing can be found throughout the U.S., including projects supported by the U.S. Department of Energy’s Zero Energy Homes research initiative and the Building America/Building Science Consortium Partnership. As the DOE notes, the goal of a ZEH is to balance energy consumption and production on an annual basis: “A Zero Energy home combines renewable energy technologies with advanced energy-efficient construction...Because the home produces about as much energy as it consumes during a year, it is considered to achieve ‘net zero’ energy consumption.” This ambitious energy goal requires an integrated multi-strategy approach, which generally includes at least five critical strategies:

1. Set project and energy goals: determine performance standards, benchmarks, and programming strategies for energy conservation and efficiency.
2. Minimize loads: use strategies such as passive solar heating, natural ventilation, and daylighting; efficient use of space; and high-performance envelope and glazing, shading, and systems.
4. Use appropriate energy and fuel sources: consider passive and/or active solar, geothermal, and/or wind.
5. Monitor the project: optimize and evaluate the building and systems performance through time.

Two contemporary projects have recently been constructed in Minnesota that strived to achieve the net-zero energy goals. The first project is the Tofte Cabin, located on Lake Superior in Tofte, Minnesota and completed in 2000 by Sarah Nettleton Architects et al. The second project, completed in 2003, is the Science House, located at the Science Museum of Minnesota in St. Paul, Minnesota by Barbour LaDoucer Architects et al. The most important aspect of these projects is that they were completed in a cold climate and in a community with limited experience in solar and renewable energy. Neither project demonstrates new innovations in design or technology, but...
they do prove that the challenges of integrating conservation, simple design strategies, and off-the-shelf technologies can help move toward net-zero energy housing in Minnesota. While there are many intriguing design issues concerning sustainability for both projects, the focus of this discussion will be on the design, energy, and technological strategies and processes used to further the goal of net-zero energy housing in Minnesota.

2. TOFTE CABIN

2.1 Set Project and Energy Goals

The Tofte Cabin, by Sarah Nettleton Architects et al, is the first contemporary home in Minnesota with the goals of net-zero energy and zero emissions. These goals are addressed by integrating architectural design and renewable systems and technologies. The program for the cabin had ambitious sustainability goals including the restoration of the landscape; rigorous standards for material efficiency, reuse, and health; and the integration of passive solar design with photovoltaic and wind energy. Completed in 2000, the project provides valuable information on the challenges of integrating solar design and renewable energy systems in Minnesota.

2.2 Minimize Consumption: Architectural Design

Multiple strategies are used at the Tofte Cabin to reduce energy consumption. Programming was considered as an opportunity to address how ecological impacts and energy loads could be reduced from the onset. The cabin is designed to support a modest lifestyle and space needs. The footprint (945 square feet) was kept small to respect the site and minimize energy consumption. Architectural strategies such as thoughtful attention to site, solar orientation, daylighting, and finishes successfully create an aesthetic appropriate to the north woods while also meeting solar needs. Located on an extraordinary site on Lake Superior, the cabin has excellent solar and wind access. The section and plan of the 1947 cabin was extensively remodeled to optimize daylighting, passive solar gains, and natural ventilation.

Large southern windows and a clerestory provide dramatic views of the lake as well as abundant light, heat, and air. The section effectively integrates pragmatic concerns for thermal and lighting comfort while also revealing the beauty of the site. Daylight celebrates the exposed structure, wood ceiling and finishes, and interior spaces. Thermal mass is provided in the floor of the cabin and integrated with a hydronic heating system. Conservation is also addressed through the design and detailing of the envelope, which is well insulated and carefully detailed to minimize infiltration. Extruded insulation was factory cut to fit the curve of the roof, eliminate waste, and provide a U-value of 0.026. The walls are insulated with blown in cellulose, which yields a U-value of 0.048. The crawl space is insulated to a U-value of 0.05. The window U-value is 0.27 with a solar heat gain coefficient (SGHC) of 0.27. Insulation levels are comparable to a code base of U-value 0.034 for the roof, 0.052 for the walls, 0.10 for the foundation, and 0.37 for the windows. As winner of two AIA environmental design awards, Sarah Nettleton Architects successful addressed energy considerations while integrating aesthetics, human experience, and design excellence at the Tofte cabin.

Fig. 1: Exterior views of Tofte Cabin (© Petro Petrovich)

Fig. 2: Diagram of energy systems and plan view (SNA)

Fig. 3: Interior views of Tofte Cabin (© Petro Petrovich)
2.3 Meet Energy Loads  High Performance Systems

The cabin is occupied on average one week per month. The number of occupants includes the owner and periodic guests. During the heating season, the temperature is set at 68 degrees when occupied and 45 degrees when unoccupied (to protect the materials from freezing and thawing). The cabin incorporates high performance mechanical systems. A ground source heat pump supplements passive heating. The unit has a heating Coefficient of Performance (COP) of 2.5 compared to a code base of 2.0. The system also provides domestic hot water to replace the original propane tank heater. Propane now serves as a back-up system. (With 90% of the energy met by renewable systems, the annual propane consumption is modest.) A heat recovery ventilator (HRV) captures waste heat from exhausted air and warms the supply ventilation. The high performance appliances include a washer/dryer and refrigerator.

The Weidt Group utilized DOE-2.1E to perform a post construction energy analysis of the cabin. For purpose of comparison, a code base model of the project was also constructed. The model assumed occupation of the cabin by two people. The heating set point was 55 degrees unoccupied and 65 degrees during occupation. The model estimated total building loads at 11,000kWh/yr; which is 43% less then an equivalent ASHRAE 90.1 1999 building, or 49.95 KBtu/sf/yr verses 88.13 KBtu/sf/yr. Figure 4 illustrates the estimated end-use energy for the base model and cabin. When comparing the code base to the cabin, the most significant load reduction is found in space heating. The cabin reduced space heating by 80% from code. An additional 20% reduction in the actual cabin comes from domestic hot water heating.

2.4 Use Appropriate Fuel Sources

The Tofte cabin utilizes a dual source approach to renewable energy generation, including wind and photovoltaic (PV) systems. The combined peak kW rating for the wind and PV is 11.2 kW. The wind generator is a reused mid-century Jacobs Longcase wind turbine. The model has a 14–foot diameter rotor, with a rated output of 2,400 to 3,600 watts at a wind speed of 14 mph. It is estimated to produce 7,000kWh of electricity annually. It is located on a 90-foot tall wind church north of the cabin. To maximize solar exposure, the 415 square foot PV array is located on the garage, which is in a small clearing above the cabin. The PV panels face south on a 35-degree incline. Invertors for both systems and a limited battery back up are located in the garage. The cabin is grid tied; it draws electricity from the grid in the winter, and feeds excess production to the grid in the summer.

2.5 Monitor the Project

Monitoring is necessary to accurately determine whether the net-zero energy goal has been achieved. While monitoring has been conducted periodically since the cabin was completed, it was in the fall of 2005 that an annual monitoring protocol was established. The Tofte Cabin is currently being monitored to assess the performance of the systems and building as constructed. Whether the project meets the zero energy goal has yet to be determined. Despite the lack of conclusive data from monitoring, the Tofte Cabin still provides valuable lessons. The data, if and when it is made available for publication, will provide designers with an even deeper understanding of the design and technological challenges of zero energy housing in Minnesota.

3. SCIENCE HOUSE

3.1 Set Project and Energy Goals

The Science House is a renewable energy demonstration project for the Science Museum of Minnesota in St. Paul. This project was developed under the supervision of the Science Museum with Barbour & LaDoucer Architects, Innovative Power Systems, L.S. Black Constructors, and the Weidt Group, with support from the National Renewable Energy Lab (NREL) and building manufacturers. The project goal was to create a zero-emissions building with net-zero annual energy consumption. This goal was achieved through the integration of passive solar design, a thin film PV standing seam roof, geothermal heat pump, and high performance equipment and appliances. Completed in 2003, the house has been monitored for the past two
years, which provides insight into the effectiveness of passive solar and PV in Minnesota.

Fig. 5: South view of the Science House (K. Ferfaro)

3.2 Minimize Consumption: Architectural Design

The house was programmed to minimize energy consumption by using a small footprint (1,400 s.f.); strategies for daylighting, passive heating, and natural ventilation; efficient equipment and systems; and paying attention to occupancy patterns. The museum is still tuning the building and considering how it is best occupied and conditioned on a diurnal and annual basis. The massing and section of the Science House are classic passive solar diagrams. Direct gain passive solar strategies include extensive south glazing, thermal mass in the concrete floor, and proposed external shading for solar control (not yet constructed). Windows are limited to the south and north for solar gains, control, and cross-ventilation. The energy analysis found significant contributions from the passive solar, which reduced equipment loads and size. While it is not the most efficient solar technology, the museum chose to demonstrate how PV could be used to power the geothermal heat pump for heating and cooling (versus active solar thermal systems). The thin film PV standing seam roof successfully meets the power demand for not only the geothermal heat pump, but also the electric lights, equipment, and appliances (see following discussion). The construction and detailing also play important roles in reducing energy consumption. Patrick Hamilton, Director of Environmental Science and Earth-system Sciences at the Museum, describes the building as a “thermos bottle”. The envelope is constructed with 2x6 framing, energy efficient windows, and Icynene spray-in foam insulation to minimize infiltration and provide high thermal performance. These strategies result in a U-value of 0.023 for the roof, and 0.035 for the walls. The window U-value is .32 with a solar heat gain coefficient (SGHC) of 0.25. Insulation values are comparable to a code base U-value of 0.045 for the roof, 0.091 for the walls, and 0.62 for the windows. While the demonstration emphasis is on the PV system; the house successfully combines programming, architectural strategies, construction technology, and solar and high performance systems to reduce energy consumption.

Fig. 6: Section of Science House (Science Museum)

Fig. 7: Interior view of the Science House (K. Ferfaro)

3.3 Meet Energy Loads: High Performance Systems

Since the Science House is used as a demonstration project it has an occupancy and load profile that is unique. The house is occupied seven days a week by staff and visitors during the months of May to September (from 9:30 a.m. – 9:00 p.m. Monday to Saturday and from 11:00 a.m. – 5:00 p.m. on Sunday). From October to May the house is officially closed, but staff and visitors occasionally use the building. During the heating season, the temperature is set at 68 degrees 24 hours a day (which is warmer than most residences during winter nights when thermostats are typically set to lower temperatures). The temperature is set
at 72 degrees during the cooling period. The appliance, hot water, and plug loads are less than typical residential energy consumption since there is no laundry or stove. The building incorporates high performance systems to meet energy loads. Supplementing passive heating and cooling is a four-ton ground source heat pump. The unit has an Energy Efficiency Ratio (EER) of 12.7 and a heating Coefficient of Performance (COP) of 3.1. An energy recovery ventilator (ERV) operates when the bathroom exhaust is turned on, or when the CO2 levels exceed 1000ppm. Additional energy saving strategies include occupancy and daylighting sensors to reduce lighting related energy consumption.7

3.4 Use Appropriate Fuel Sources

A grid tied PV roof supplies renewable energy for the Science House. During schematic design the estimated PV electric generation capacity for the given roof area was determined to be between 9,000-11,000 kWh annually. This assumption set the design energy target for the project at 10,000 kWh/year, equivalent to 30 KBTus/sf/yr.8 The Weidt Group performed energy analysis utilizing DOE-2.1E on the schematic design developed by Barbour & LaDoucer Architects. The code base model of the project predicted consumption at 92 KBTus/sf annually equal to 25,720 kWh. Additional energy modeling and design revisions guided the refinement of the building envelope and systems. The result was a 60% reduction in estimated energy use over code, which met the energy target.

Fig. 8: Science House code and design base energy estimate

3.5 Monitor the Project

The Science Museum of Minnesota received funding from the NREL to monitor the project. Beginning in January 2004, the Weidt group collected data on energy consumption by end use including heating, cooling, lighting, fans, pumps, lights, and equipment; and energy generation from the PV. Monitoring in 2004 and 2005 revealed that annual on-site energy production exceeded energy consumption. For the period from December 2004 thru November 2005 total energy use was 6,451 kWh. The energy produced by the PV was 9,172 kWh, which provided a net surplus of 2,721 kWh.

Fig. 9: Science House energy summary Dec 04 – Nov 05

4. CONCLUSIONS

While Minnesota architects, designers, and researchers have made significant advances in sustainable design strategies for energy conservation and construction, little attention has been given to solar design and technologies. The following discussion summarizes lessons from these projects that can help advance solar architecture in Minnesota.

4.1 Achieving Zero Energy

Although the net-zero energy goal has yet to be determined in both projects, these two houses demonstrate that it is possible to move toward net-zero energy in a cold-climate. Both projects illustrate that designers’ need first to drive down energy consumption through good design and conservation, including the design of the building massing and envelope, and then by selection of efficient equipment and appliances. Off-the-shelf technologies can be coupled with passive systems to meet annual energy needs. The steep learning curves on installation, operations, and maintenance and the cost of systems and monitoring are still the greatest challenges for implementation.

4.2 Process and Methods

The project teams for both houses emphasize the importance of early collaboration with designers, engineers, and contractors. The programming proved particularly important in defining and reducing the initial loads and determining how the users would occupy the building through time. In the case of the Science House, guidelines were provided to the designers from the energy consultants to inform the massing, orientation, window area and location, and roof form.

4.3 Monitoring and Commissioning

Although data is pending on the Tofte Cabin, both teams underscored the importance of commissioning and monitoring. Commissioning allowed tuning of building systems and an opportunity to troubleshoot problems and
issues. On-going monitoring not only allows the tracking of energy use and production, but also reveals systems failures, seasonal energy use trends, and daily and yearly occupancy patterns. This information can then be used to maintain and even enhance building performance over time. For example, early data from the Science House showed greater then expected electrical use. The energy use was traced to the electric resistant heaters, which are meant to serve as a back-up for the ground source heat pumps, but had been serving as a primary source due to a pump malfunction. Additional data from the Science House has revealed other operational problems such as drops in power output that have revealed hardware problems (e.g. an inverter twice went into ground fault in the summer of 2004). Shifts in activity and equipment use during the change of seasons and occupancy patterns are also evident in the data. The projects illustrate the value of monitoring, yet the challenge is to determine how this type of research can be funded in projects without NREL support, expertise, and resources.

4.4 Costs

A complete cost analysis has not been done for either the Tofte cabin or the Science House. Cost data for the Tofte cabin project was not available for publication. Total cost for the Science House was $981,247, including all consulting, construction, and monitoring fees. One quarter of the cost is attributed to the pier foundation, which was required due to poor soil conditions on the site. The installed cost for the PV roof and associated equipment was $62,000. Useful information would be gained from a complete analysis of component, assembly, and system costs along with energy savings and electricity generation. This analysis could subsequently support technology transfer to the market place. While specific cost information is not available for both projects, the budgets exceed those for affordable or mid-range housing. Obtaining funding for energy consulting, system installation, and maintenance is a challenge. Incentives are needed to promote and support the growth of solar and renewable energy in Minnesota.

4.5 Installation, Operations, and Maintenance

A challenge in Minnesota is that the solar construction industry is still emerging. There are a limited number of knowledgeable and experienced individuals and companies working in solar design and technology. Partnerships with local and regional renewable energy educators, organizations, consultants, and industry are needed to develop a comprehensive educational and training program to help move forward the state-of-the-art in solar architecture in Minnesota.

4.6 The Role of Design Excellence

Solar and renewable energy can dramatically inform and inspire architectural design in terms of the building form, massing, section, and detailing. Yet, designing with all the appropriate strategies and technologies does not necessarily assure that there will be design excellence. To move beyond the solar architecture of the 1970s, the design professions and building industries need to consider a comprehensive integration of solar and renewable energy to address design performance and design quality. At its best, today’s solar architecture meets the highest standards for performance while also enhancing architectural aesthetics and human experience and delight.

The Tofte Cabin and the Science House provide precedents that solar and renewable energy in architecture are possible in a cold climate with limited experience and expertise in renewable technologies. For Minnesota’s design professionals and the construction industry, the most important lesson remains that we can move toward zero energy housing with off-the-shelf technologies and straightforward design strategies. The projects help to dispel the persistent myth that solar is not feasible in Minnesota. The more projects that move toward net-zero energy, the greater the opportunity to build the infrastructure necessary to transition to a renewable architecture. While there are areas of the country where solar and renewable energy are well established, there are still regions where these strategies and technologies are unfamiliar. Minnesota needs regulatory change, incentives, and a greater level of experience to realize the transition to renewable energy. These two precedents help move the design profession and construction industries toward a new possibility and level of understanding of solar and renewable architecture in Minnesota.

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6. ENDNOTES

(3) See the Tofte Cabin website at Sarah Nettleton Architects, www.sarahnetletonarchitects.com
(5) The Weidt Group, Jason Steinbeck, “Getting to Zero”
(6) The Weidt Group, “Science Museum of Minnesota”
(7) The Weidt Group, Jason Steinbeck, “Getting to Zero”
(8) Ibid.