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RESEARCH ARTICLES

NET ZERO ENERGY HOMES: An Evaluation of Two Homes in the Northeastern United States

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ABSTRACT

This paper will discuss two Net Zero Energy homes in the United States. The aim is to discuss the differences and similarities in the construction type, energy use, active and renewable systems of the two homes. While each of the homes is designed to achieve net zero site energy use, the design and systems are very different. Furthermore, the measure that is used to qualify a home as net zero energy does not account for the full scope of work on each home. It is suggested that a new set of metrics be developed to allow for a more robust understanding of net zero energy buildings, one that integrates passive design strategies, occupant health and comfort, and durability. The objective is to facilitate a broader understanding of efficient and sustainable residential design. This understanding is critical to bringing Net Zero Energy Buildings to the public.

KEYWORDS

net zero energy, construction, systems, homes, northeast, sustainable

INTRODUCTION

The design and construction of Net Zero Energy buildings are a key factor in mitigating the impact of buildings on the environment. Emerging technology and advanced building techniques already enable the design and construction of Net Zero Energy buildings, but critical questions about what it is and how it can be achieved are warranted. What does Net Zero Energy mean? How does one build to net zero? Are these buildings sustainable (healthy, durable, resource efficient)?

Residential and commercial buildings in the United States use 70% of all electricity produced and account for 79% of all electricity expenditures (Coburn, 2008). Annual CO_2 emissions linked to electricity consumption in U.S. buildings (658 million metric tons of carbon for residential and commercial combined) constitute about 39% of the country's annual total CO_2 emissions, almost equaling the combined yearly total CO_2 emissions of Japan, France, and the United Kingdom (US DOE, 2008). In the last quarter century, global temperatures and CO_2 emissions have increased dramatically, increasing both the risk and reality of catastrophic environmental disasters and homeland security issues (Rocky Mountain Institute, 2002). Analysts estimate that global carbon emissions will more than double by 2050 if drastic changes are not made in the way we build, drive, and live.

There is a growing national awareness of the need for energy independence and this awareness is increasingly reflected in the way we design and build. Professional organizations, government programs, engineers, building contractors, architects, and homeowners are beginning to work towards implementing energy efficient building practices. The U.S. Department of Energy, the Energy Independence and Security Act of 2007, and the American Institute of Architects call for all new buildings to consume zero net energy by 2030. Technological advances in efficient HVAC equipment, better insulation, smarter design, and occupant awareness of energy efficiency and renewable energy are now bringing Net Zero Energy Buildings to the mainstream. Net Zero Energy Buildings, or NZEBs, are buildings that produce as much energy as they

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consume on an annual basis. An NZEB is capable of producing, at minimum, an annual output of renewable energy that is equal to the total amount of its annual consumed/purchased energy from energy utilities (Fortmeyer, 2006).

This paper highlights current trends in NZEB design and construction by comparing and contrasting two zero energy homes in the northeastern United States. These two projects illustrate different building strategies to achieve zero energy, in terms of design, construction, and mechanical systems. There is a range of possibilities for a successful NZEB, and this paper documents and compares specific performance parameters that qualify a home as net zero energy. The objective is to illustrate different strategies for achieving zero energy use and to showcase alternative building techniques with a focus on energy conservation. It is also aimed towards motivating the home building industry to support energy and resource conservation, healthy indoor environments, and a lasting building stock.

BACKGROUND AND MOTIVATION

In a heating degree dependent climate like that of the northeastern United States, reducing a building's annual heating load is vital to energy efficient design. The prevailing design strategies include a heavily insulated and tight building envelope, high-efficiency windows, controlled ventilation, and passive solar considerations (Norton *et al.,* 2005). NZEBs improve upon these shell upgrades and further minimize heating, cooling, and electrical consumption loads by using high-efficiency equipment and lighting. Renewable energy production systems, such as photovoltaic panels (PV) or small scale wind turbines, are used to generate electric power, and biomass, solar thermal, or geo-thermal systems are used to satisfy a greatly reduced heating design load (Baechler *et al.,* 2007).

NZEBs can mean freedom from rising future energy prices, a reduced yearly cost of living, and higher resale values as demand increases for high-efficiency homes. Owners benefit from tax breaks and incentives that are becoming increasingly available. Potential barriers may be higher initial costs of construction and renovation, difficulty applying for tax breaks and refunds, the lack of builder experience, and the reality that building occupants need to become more involved in daily maintenance and operation of the buildings in which they live and work (Soratana & Marriott, 2010).

This paper focuses on homes that are designated zero site energy, which is strictly based on annual energy consumption. In this type of NZEB, the amount of energy provided by on-site renewable energy sources is equal to the amount of energy used in the building. This definition is the one generally used to describe NZEBs in the United States (Torcellini *et al.*, 2006). A crucial limitation of this definition is that it does not mean that the home is sustainable. In this context, "sustainable" is defined as sized, shaped, and sited to reduce energy intensity, healthy with respect to indoor air quality, and durable—i.e. that it was constructed to last the typical lifetime of a residential dwelling (100–200 years). In practice, however, a zero energy home may be constructed from rare imported woods, have a substantial building footprint, finished with high VOC material, and suffer from poor construction techniques that lead to premature degradation.

Designing an NZEB that is sustainable necessitates a delicate balance between energy generation/consumption and social/environmental impact. In other words, in addition to incorporating advanced construction practices, on-site and off-site energy generation, innovative HVAC technologies, *sustainable* NZEBs (*S*ZEB) must go beyond current definitions of net zero energy. However, existing standards, measures, and protocols for designing and evaluating low-energy buildings (LEED, or other green building formulations) fall short of ensuring true environmental sustainability (Vieira & Horvath, 2007). A review of current research on NZEBs reveals that the focus is largely on energy efficiency and energy conservation from the perspective of system operations, prioritizing the design of HVAC systems to reduce operating energy loads (see for example, Chela et al., 2009; Parker, 2009; Holmes & Hacker, 2007). Thus, in the pursuit of net zero energy, other impacts of buildings are often ignored altogether.

METHOD AND STUDY AREA

Shape, size, orientation, climate, materials, construction techniques, equipment, occupancy behavior, and energy production systems are all part of the range of decisions that must be considered for an *S*ZEB. Building size is one of the most significant contributing factors to the resource efficiency and the environmental impact of a home (Wilson & Boehland, 2005). In conjunction with building size, decisions that capitalize on orientation, geometry, massing, and layout can effectively minimize building energy use (Lechner, 2008). Optimization strategies to reduce building energy demands by considering these measures exist and have been widely used by the building community (Xia et al., 2008). Additionally, the building envelope must be explicitly detailed—in terms of its construction, materials, insulation, and air and moisture barriers—to ensure reduced energy use, durability, and well as improved comfort for the building's users. Here, the environmental impact associated with the long-term viability of the home needs to be considered. The primary culprit in building degradation is moisture. Unanticipated moisture intrusion and condensation within building envelopes is the leading cause of compromised durability and the presence of molds and fungi (Rose, 2005). Poor barrier performance and less than best-practice construction have resulted in significant energy losses in buildings. Other parameters like the lack of maintenance and local weather conditions also influence building deterioration (Balaras *et al.,* 2005). Additionally, there are health risks associated with the use of specific kinds of paints and lacquers, building materials and furnishings, as well as glues and adhesives. These emit Volatile Organic Compounds (VOCs) that contribute to indoor air pollution. The US Environmental Protection Agency has reported that there can be a serious threat from the cumulative effects of these sources (EPA, 2009). It is only after these factors (relating to building geometry and envelope) have been addressed can the building's operational costs be lowered—by selecting efficient systems, appliances, and lighting. For each one of these areas of consideration, there are a variety of approaches, much of which depends on the aesthetics, budget, and expertise of the design team and its ability to work closely together to optimize the functioning of the whole building as a system.

Analytical Procedure

In this paper, three primary areas are considered to extend the definition of net zero energy towards *S*ZEB. The three areas are categorized with respect to (a) architectural organization, (b) building envelope, and (c) electromechanical systems.

a. Architectural organization refers to the interior space layout, size, orientation, massing, roof forms, and location of the home. Numerous studies have proven the importance of evaluating the effects of these parameters on building energy performance (Lin, 1981; Augenbroe, 2001; Aksoy & Inalli, 2006). These features are qualitatively evaluated based on narrative documents submitted by the two owners and occupant interviews for further clarification.
b. Building envelope refers to the exterior system—in terms of materials, construction, and the thermal and moisture barriers. A comparison of each building's construction systems is presented. This involves assessing the type and extent of envelope insulation, air leakage, provisions for moisture control, and humidity levels at each home. This data is based on energy audit reports provided by the owners.
c. Electromechanical systems refers to the heating, cooling, hot water, and ventilation systems that were installed in each home. Overall energy performance is quantified based on the annual energy budgets of the heating, cooling, hot water, lights and appliance loads. Energy budgets as well as the output of the energy generation systems are reported in annual MMBTU (million British Thermal Units) or KWhr (kilowatt-hours) and based on utility energy data. In addition to providing at least twelve months of utility bills, the owners completed an energy use spreadsheet in which they recorded the distribution of the total load per system type—i.e. how much energy was required for hot water, lighting and appliances, and heating/cooling.

Study Area

The two homes that were selected to compare and contrast different strategies for achieving net zero site energy use are both located in the northeastern part of the United States. Both the homes have been continuously occupied and documented (close to) net zero energy use for at least one year. One of the goals of this paper is to highlight ways to achieve

FIGURE 1. Photograph of H-1 house (photo credit Rich Hollabaugh).

FIGURE 2. Plan of H-1 house (credit Robert Dimock).

zero energy, in order to provide architects, owners, and building contractors with the information necessary to design and construct zero energy buildings. The two homes selected for the analysis present two very different ways of achieving net zero energy use. The hope is to show that there are a range of different strategies in terms of construction practices, renewable technologies, sustainable materials, innovative mechanical, electrical, and plumbing systems, and lifestyle choices that impact zero energy homes.

The first case study, the H-1 (figure 1) home in Lebanon New Jersey, is a 2-story 4,200 square feet (390 square meter) post and beam colonial farmhouse on an 11-acre lot (4.5 hectares). It has an open floor plan (figure 2), 4 bedrooms, 2.5 baths, living room, dining room, kitchen, laundry room, and a full walkout basement that is unfinished but conditioned. The home maximizes passive solar gain, uses photovoltaic panels to provide for 90% of the electrical load, supplies 100% of the domestic hot water load with a solar hot water system, and is equipped with energy efficient appliances.

The second case study, the P-1 (figure 3) home in Charlotte Vermont, is 2,800 square foot (260 square meters) all-electric home, in which all systems are powered by the wind. The home's geometry and spatial layout (figure 4) help to maximize energy efficiency through a variety of techniques. The house faces true south to obtain optimal sunlight on a daily basis, uses energy efficient lighting and appliances, is heated using a geothermal heat pump, and was constructed using advanced construction techniques to minimize heat loss through conduction and air infiltration. It is also Vermont's first LEED Platinum rated house—the highest rating attainable from U.S. Green Building Council.

RESULTS AND DISCUSSION

Architectural Organization

In this section, building orientation, layout, framing, type, and materials are examined. A summary of these elements is provided in the table below (figure 5). The first three elements are planned in the early stages of design and must be considered if incorporating working daylight, passive solar heating, or passive cooling in a home is desired.

FIGURE 3. Photograph of P-1 house (photo credit Jim Westphalen).

FIGURE 4. Plan of P-1 house (credit David Pill).

FIGURE 5. Organizational elements featured in H-1 and P-1.

ELEMENTS	H-1 House	P-1 House
Building Orientation	True south passive solar heating, daylighting	True south daylighting
Layout	Open plan	Open plan
Conditioned Area	4200 sf (390 sm)	2800 sf (260 sm)
Framing	2 × 4 @ 16″ O.C. (38 x 80 mm @ 406 mm O.C.)	2 × 6 @ 24″ O.C. (38 x 140 mm @ 610 mm O.C.)
Type	Single-family detached	Single-family detached
Materials	Douglas fir Southern Pine	FSC Certified wood Local crafted concrete countertops Local sustainable harvested maple flooring & hardwoods Cellulose & denim insulation Reclaimed fir columns No VOC paints & finishes

The H-1 house has an open floor plan, which allows sunlight from the windows to reach most areas of the house. This reduces the need for artificial lighting during daylight hours. The house also utilizes a direct gain passive solar heating system that allows the temperatures to remain constant throughout the day. In general, maintaining consistent temperatures with passive direct gain solar heating is difficult, because there are no controls to ensure the space does not overheat or lose heat. However, with the use of a thermal mass element, a temperature lag can be instituted. The thermal mass element absorbs the heat from the sun during the day—like a heat storage battery—and at night, radiates the heat back into the space. The H-1 house uses a 12″ (305 mm) concrete slab for heat storage and an active mechanical system to modulate temperature swings more effectively. During the day an air handler pulls warm air down from the vaulted ceiling to air ducts embedded in the concrete floor slab, then up to floor vents in each room. Due to the thermal mass of concrete, the temperature of the house remains consistently at 70°F (21°C) with little need for back-up heat, even at night.

The H-1 house is built with conventional materials and insulation, with one exception—the basement. The walls are traditional post-and-beam construction using Douglas fir but the basement walls are made from second growth southern yellow pine pressure-treated wood. In general, it is unusual to construct foundation walls out of wood, rather than concrete. But not only are wood walls cheaper to build, they have less embodied energy than concrete. Because the basement of the H-1 house is conditioned, the usable area of the home is significantly larger than most zero energy homes. Minimizing square area is one important way to reduce the energy load of a home.

The P-1 house is almost 30% smaller than the H-1 house, which accounts for significantly less materials and resources, both in construction and operation. Furthermore, the house is built on a lot that was previously developed for agricultural use and 99% of it is constructed on the existing footprint of a farmhouse that has since been demolished. The remaining land is being restored for agricultural use. The P-1 house faces true south to obtain optimal sunlight on a daily basis. A simple massing technique is employed along with second floor overhangs and a light colored exterior to prevent overheating during the summer. The passive solar system is mainly intended to provide natural daylight during the day rather than as a heat source (as in the H-1 house). As a result, there is no need for artificial lighting on most sunny days.

The P-1 house is an unconventional home built with a contractor's normal framing crew. The exterior walls are 2 × 6 (38 × 140 mm) framing with studs at 24 inches (610 mm) centers to minimize the amount of wood. Greater stud spacing provides 5.5

inches (140 mm) cavity for insulation rather than a 3.5 inch (89 mm) cavity (for more typical 2 × 4 framing (38 × 89 mm)). It has 10% less lumber and 30% fewer pieces. The unconditioned basement is insulated with locally manufactured, natural cellulose insulation. The basement ceiling is further insulated with recycled denim (jeans). Other local materials such as concrete countertops and sustainably harvested wood further reduce embodied energy. In addition, all wood framing is certified by the Forest Stewardship Council, all paints and finishes are low/no VOC, and a metal roof is highly durable.

Building Envelope

An energy efficient home must be tightly insulated and carefully constructed to prevent air infiltration and heat transfer through the building envelope. In particular, resistance to air flow is necessary prevent convective losses and retard the flow of moisture-laden air from entering the building assembly, which causes decay and mold (Rose, 2005). Moisture control is particularly important in the northeastern climate and has a significant effect on building durability and occupant health. Moisture is typically controlled with high density foam acting as both insulation and air barrier system (Lstiburke & Carmondy, 1994). In the basement, moisture is most effectively controlled through free-draining building materials and a waterproof membrane. Free-draining materials such as crushed stone permits the flow of groundwater downwards and when properly installed, prevents water from collecting at the foundation walls and slab. Controlling groundwater entry involves installing waterproofing barriers or membranes.

The H-1 home's thermal envelope consists of R-35 °F-ft^2-hr/BTU (6 °C-m^2/W) insulation on all 6 sides. It utilizes an exterior air retarder comprised of two layers of 2″ (50 mm) foil-faced rigid urethane insulation staggered, taped, and caulked to minimize air infiltration and prevent thermal bridging. All through-wall penetrations through the insulation envelope were eliminated except where needed. Double pane insulated windows (R-3 °F-ft^2-hr/BTU; 0.5 °C-m^2/W) and insulated steel doors are used for their energy efficiency. The basement floor and walls are completely insulated from the ground to ensure a dry and comfortable area. There is a minimum of 12″ (305 mm) of crushed stone under the slab insulation and 2 to 3inches (50 to 76 mm) of crushed stone around the basement walls. Between the insulation and stone is a tough polyurethane membrane that keeps moisture from penetrating into the insulation.

The P-1 home's thermal envelope is constructed with closed cell urethane foam insulation, sprayed into the stud cavities. Thermal bridging is mitigated by installing polyisocyanurate (rigid foam board) on the exterior. The entire wall assembly has an R-value of 40 °F-ft^2-hr/BTU (7 °C-m^2/W). All two stud corners are filled with foam and these are topped with a layer of taped sheathing. On top of all this is a layer of house wrap, which creates a highly efficient air barrier. The places where joints and studs met are all sealed and caulking is used on every joint to guarantee building tightness. The ceiling is insulated similarly and has an R-value of 56 °F-ft^2-hr/BTU (10 °C-m^2/W). Thermally efficient triple pane, low-e, argon gas filled fiberglass windows with orientation specific glazing are used for additional energy efficiency. The P-1 house does not have an aggressive insulation strategy for its basement because the priority is simply to keep the basement dry but not conditioned.

Both homes use rigid foam insulation to help prevent moisture leakage. Due to the tight building envelope, moisture does not escape readily. As a result the relative humidity can be maintained at 40–45% year-round. In conventional houses the relative humidity drops to about 25% during the winter heating season. The side effects of lower humidity are reduced comfort and the energy (heat of vaporization) it takes to evaporate moisture that has been absorbed by the interior wall boards and wood framing. The typical house absorbs hundreds of gallons of water during the summer months and then during the heating system, evaporates about half of it at considerable energy expense (970 BTU/lb or 2254 KJ/kg of water) during the winter. Because humidity is stable, both houses save energy and maintain comfortable humidity levels throughout the year. The table below (figure 6) provides an overview of the construction elements for each house.

Advances in building envelope specifications have the potential to radically reduce total energy demand in a building. While the energy and environmental

FIGURE 6. Envelope specifications in H-1 and P-1.

ENVELOPE SPECIFICATIONS	H-1 Home	P-1 Home
Slab Floors	R-35 (6 °C-m2/W)	None
Foundation Walls	R-35 (6 °C-m2/W)	R-19 (3 °C-m2/W)
Basement Ceiling	None	R-19 (3 °C-m2/W)
Above Grade Walls	R-35 (6 °C-m2/W)	R-40 (7 °C-m2/W)
Roof	R-35 (6 °C-m2/W)	R-56 (10 °C-m2/W)
Windows	R-3 (0.5 °C-m2/W)	R-10 (2 °C-m2/W)
Relative Humidity	40–45%	40–45%
Infiltration Rate	5.0 ACH50	2.0 ACH50

impacts of building materials themselves must be minimized, attention must be given to improved construction practices to maximize efficiency gains. New building material production methods may lead to better control of heat and mass flux by the building envelope (foundation, roof, walls, doors, windows) and to reductions in the resource intensity of the high-tonnage materials comprising the structure (frame and floors). However, the success of the envelope in thermally insulating the building, providing a barrier to moisture penetration, and minimizing air leakage is critically dependent on the building crew's expertise in construction, installation, and detailing. High performance materials will only perform as intended if they are properly handled. The building envelopes for the two homes in this study were constructed from locally available materials by local construction crews. What is significant about their performance is level of detailing that was required to construct the envelope. The owners/designers specified precisely how the systems were to be constructed and oversaw the process to ensure their standards were being met. This attention was the primary reason why the building envelopes performed well enough to reduce demands on each home's electromechanical systems.

Electromechanical Systems

The construction of a Zero Energy Home involves materials and technologies familiar to the building trades and homeowners. Opportunities to reduce energy use exist in many areas. The first priority is to reduce energy loads. This is done by taking advantage of design features discussed in section 1, like minimizing building footprint, designing for passive solar heating and daylighting, and using low impact building materials. As discussed in previously, it also means buildings are constructed with thermally efficient envelopes—more insulation is required, with attention given to issues such as air infiltration and moisture barriers. In this section, the third and final metric for constructing zero energy homes is analyzed—the electromechanical systems. This includes energy consuming equipment as well as the energy generation systems.

The first consideration is to size the major equipment in the home correctly and select systems that are very efficient. This includes the furnace, air-conditioner, and water heater as well as the duct and piping systems that deliver air and water to the outlets. The next opportunity to reduce energy loads is to use higher efficiency lighting and appliances. Once the home's energy demand is reduced, a renewable energy production system (PV or wind) is installed to provide the electricity used in the home and offset electricity supplied by the utility when averaged over the course of one year. The table (figure 7) below provides an overview of the systems that were installed in each house.

Energy Consumption Systems

In the H-1 home, the owners worked to eliminate or find less energy intensive alternatives for household major equipment. For example, replacing the motor for the blower in the air handling unit with an Energy Star-rated motor and a Hitachi variable speed controller, saved 1900 KWh per year. They also replaced the 80 gallon (300 liter) electric water heater with the solar hot water system. Then, by using a Kill-A-Watt meter, they determined that

FIGURE 7. Electromechanical systems in H-1 and P-1.

ENERGY SYSTEMS	H-1 House	P-1 House
Energy Consumption		
Heating	Air (AHU) + Radiant (Solar Thermal)	Radiant (GHP)
AC	None	None
Water Heating	Solar Thermal	Instantaneous (on-demand)
Ventilation	Natural	HRV
Energy Generation		
Passive Solar Heating	Yes	No
PV	9.8 KW	None
Wind	None	10 kW
Solar Thermal	Yes	Hybrid (GHP + on-demand)

the 12-year-old refrigerator had to be replaced with a new Energy Star-rated unit that uses less than half the energy. At the same time the dishwasher was replaced with an Energy Star-rated dishwasher. Almost all lighting in the house is florescent and plug loads are unplugged or put on a switched outlet strip. The total distribution of loads for the H-1 house is provided in figure 8a.

The P-1 House is in Vermont, which is known for its especially unforgiving winters and conventional wisdom says it is impossible to heat a house in the northeast without burning fossil fuels. The P-1 house proves otherwise. To reduce energy demand, the house uses only Energy Star appliances and fluorescent lighting. The home uses a heat recovery system to transfer waste heat from exhaust air stream to an incoming fresh air stream. This strategy is important for indoor air quality due to the building's efficient envelope. A heat recovery ventilator supplies fresh air and exhausts stale air to prevent moisture and pollutants from accumulating. Also, a waste water heat recovery system brings heat from the shower drain back to the domestic hot water tank.

To provide domestic hot water, a ground source heat pump (GHP) was installed. Rather than installing an additional conventional hydronic or forced hot air system for space heating, the GHP also provides radiant heat to occupied zones. The ground source heat pump extracts water from a nearby well and heats it in one of two storage tanks. From there, the water circulates throughout the house as part of the radiant floor heating system, which remains at a consistent 61–66 °F (16–19 °C) year-round. The other tank is the domestic hot water tank, which is preheated by the GHP and then brought up to temperature using an electric resistance coil (in the instantaneous water heater) powered by the wind turbine. Figure 8b shows the average distribution of electric demand for the home.

FIGURE 8. (a) H-1 Total Energy Consumption. (b) P-1 House Total Energy Consumption.

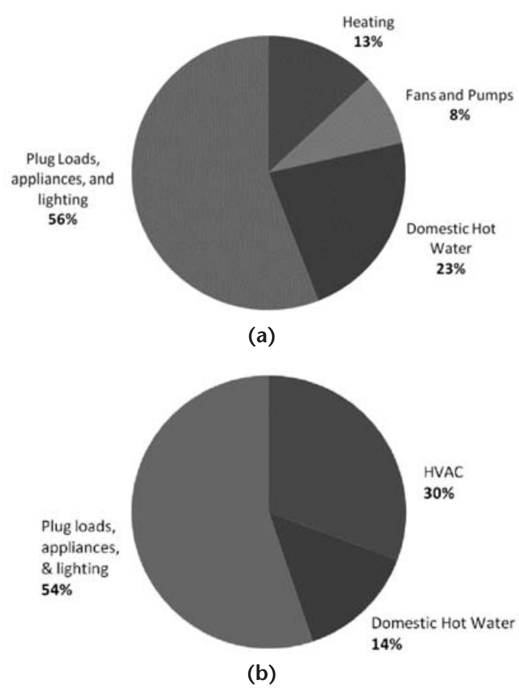
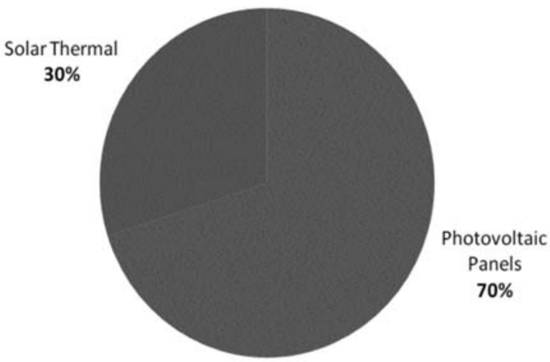


FIGURE 9. H-1 Total Energy Production.



culator pump was installed. The collector loop uses non-toxic anti-freeze. The system has four zones. One for each of the two hot water storage tanks, one for the house heat, and one for garage heat. Once the two tanks are have met the set point temperature, any excess hot water from the collectors is used for either house heat or garage heat. The garage PEX (cross-linked polyethylene) tubing is embedded in the concrete and this is used as a dump load in the summer. In the winter, the extra heat from the collectors is diverted to heat the house through a water-to-air heat exchanger in the variable speed air handling unit. Figure 9 shows the distribution of energy production between the solar thermal system and the PV system for the H-1 house.

Energy Production Systems

The energy production system in the H-1 house is a 9.8 KW dual axis tracking PV system that generates all the home's electrical power. The PV trackers maximize yearly power output and achieve the lowest cost per watt. Two SunnyBoy 2500-watt inverters and one Beacon 5000-watt grid-tie battery backup inverter are used. A 100-amp hour 48 volt battery pack enables the Beacon inverter to power the critical loads during a power outage when the sun is not shining. The inverters are mounted inside the building envelope in the basement. The waste heat generated by the inverters contributes to heating the house in the winter.

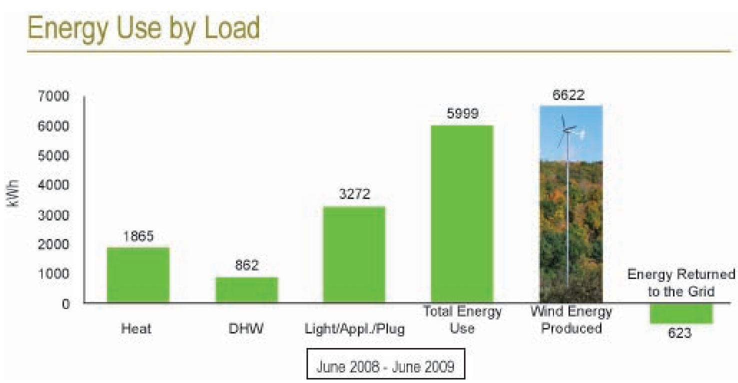
For the H-1 home's domestic water load, a solar hot water system using 110 evacuated glass tube collectors (112 square feet; 10 square meters), two 60 gallon (227 liters) indirect-fired (integral heat exchanger) stainless steel hot water tanks, and a circulator pump was installed.

The renewable energy production system in the P-1 house is wind powered. Wind turbines change the kinetic energy of the wind into electric energy by converting the rotational movements of the blades into electricity. Wind speed determines the amount of energy available while turbine size determines how much of that energy is actually harvested. In the H-1 house, a 10KW net-metered wind turbine that generates enough electricity to power all appliances, lighting, heating, and hot water. This small wind turbine—with a rotor of 50 ft (15 m) in diameter and a tower of 120 ft (35 m) tall produces all the required energy for the P-1 house, which is approximately 6500 kWh per year (figure 10).

CONCLUSION

Every building, no matter how well-conceived, designed, and operated, loses and gains heat, moisture, and air as a result of differences between

FIGURE 10. P-1 Total Energy Production (credit David Pill).



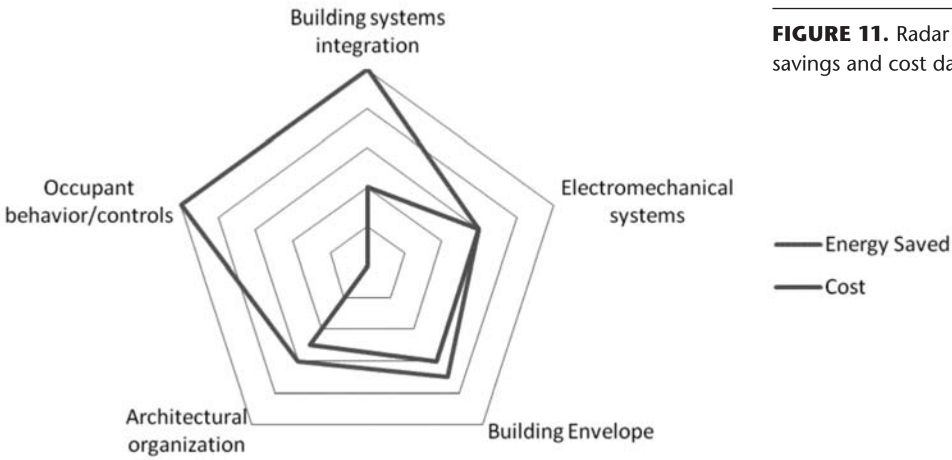


FIGURE 11. Radar diagram of energy savings and cost data for metrics.

indoor and outdoor conditions. These factors, to a large extent, determine the amount of energy a building will consume. There is a growing interest, driven by changes in the global climate, rising fuel prices, and attitudes of the public, in the design and construction of buildings that consume less energy. The two homes analyzed in this study illustrate that there are considerable variations in the strategies to achieve net zero energy for homes. The significance of this analysis, showing a wide range of possible strategies, indicate that there are a variety of different ways to reduce energy demand and produce renewable energy in the northeastern United States.

In both homes, the owners worked closely with the builders to ensure that site design, lighting, window fenestration, energy delivery systems, etc., were considered *together*, rather than discrete parts of the project. The results of such coordination (called integrated design) contributed to lowered first costs (use of wind power in P-1 rather than solar power) and produced long term benefits (better humidity control in H-1 due to efficient thermal envelope). Furthermore, occupant behavior and conservative use of energy were significant factors in reducing overall energy consumption. While integrated design, high efficiency appliances and equipment, and renewable systems make it possible for a home to function at net zero energy use, it is not possible without homeowner awareness. In P-1 for example, meters on the heating system, the wind turbine, and hot water system were used to keep track of real time energy consumption. These monitoring tools enabled a kind of energy consciousness to emerge that allowed the occupants to reduce their overall energy use by 1781 kWh/year (the difference between the modeled energy use and the actual). In the following radar diagram (figure 11), the energy savings from passive solar considerations (based on orientation, geometry, and spatial organization), detailed envelope design and construction, and improved electromechanical systems are compared to the effort required for each. Effort is quantified in terms of average number of hours (average total cost) for each particular task, and is derived from feedback based on a larger subset of net zero energy homes that were built in the northeast in the last five years. It was found that the effort per energy savings were relatively well-matched for the three metrics analyzed in this paper. For integrated design and occupant behavior, however, the data was insufficient to provide conclusive results. However, other studies have shown that one can achieve significant energy savings from integrated design and that modified occupant behavior has the potential to reduce energy loads. Further study is needed to better quantify the energy savings that can be achieved through integrated design and behavior modification.

Future improvements in residential energy efficiency can be made by better modeling and monitoring of energy consumption data to determine where to make changes and how these decisions impact the environment. Simply accounting for net zero site energy use does not fully encompass the scope of the sustainable building movement. Other categories for concern, such as occupancy patterns and behavior, site selection and building location, water efficiency, indoor air quality, and construction resources, must be addressed. The development of accurate energy models that are dynamic and can calculate the complex interactions between various components ought to be used to propose energy conservation measures (ECMs). The process is iterative and necessary at all stages of design to inform the development of energy efficient housing and the systems within them. In the coming years, providing examples of successful net zero energy buildings and an accurate means to evaluate their environmental impact will help to facilitate the widespread acceptance of and enthusiasm about Net Zero Energy.

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