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Energy performance of net-zero and near net-zero energy homes in New England

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ABSTRACT

Objective: To investigate the energy performance of net-zero energy homes (NZEHs) and near net-zero energy homes (NNZEHs) in New England. NZEHs produce at least as much energy as they consume on site in a year, while NNZEHs are designed to come close to net-zero.
Methods: We gathered construction and occupational statistics on 20 homes; measured 12 months of energy consumption, cost and production data; developed custom models to predict consumption and production; and compared measured performance to modeled predictions.
Results: Six out of ten NZEHs achieved net-zero energy or better, while all the NNZEHs achieved an energy density (kW h/m^2/person) at least half as low as a control house; measured energy consumption averaged 14% below predictions for the NZEHs and 38% above predictions for the NNZEHs; and generated energy was within ±10% of predicted for 17 out of 18 on-site PV systems.
Conclusion: Even in cold New England, these types of homes, using very diverse systems and designs, can meet or exceed their designed-for energy performance, though actual performance varies widely.
Practical implications: Architects, engineers, and policymakers now have quantifiable evidence in support of increasing energy conservation requirements and renewable energy incentives in residential building codes in New England.

1. Introduction

There are several definitions of a net-zero energy home (NZEH). Marszal et al. reviewed many of these definitions for net-zero buildings used in various countries, and discussed the calculation methodologies used to determine whether a building is net-zero energy [1]. The definition used in this research is that a NZEH produces as much energy on-site as it consumes during the course of a year, i.e., net energy use equals zero. Near net-zero energy homes (NNZEHs) are simply homes built to minimize net energy—essentially a super-efficient home that may also include an on-site renewable energy system that does not produce enough energy for the home to reach net-zero.

Most NZEHs and NNZEHs share several common design elements. These include a well-sealed, well-insulated building envelope, energy efficient appliances and lighting, right-sized heating, ventilating and air conditioning (HVAC) systems and domestic water heating equipment, and an on-site electrical generation system. Nearly all will incorporate elements of passive solar design, from day lighting to passive heating and cooling. These include the long axis of the home running east to west in order to maximize southern exposure, exterior and/or interior shading elements that shade southern glazing in summer but not in winter, and possibly thermal mass to store heat and help reduce temperature swings. Of course, a critical question for a designer of a NZEH home is what will be more cost effective—taking measures to reduce the load of the house or simply adding more on-site energy generation? Anderson et al. outline the least-cost method of determining the most cost-effective mix of energy efficiency measures and renewable energy generation to achieve net-zero status [2].

Interest in NZEHs and NNZEHs has increased in the US over the past few years mainly due to rising energy prices, decreasing costs for on-site renewable energy systems, and increasing concerns over climate change. For example, California now requires that all new residential construction be "zero net energy" by 2020 [3]. By 2011, several dozens of these homes had been built in New England, a relatively cold and less-sunny region in the northeastern US, consisting of six states: Connecticut, Maine, Massachusetts, New

Abbreviations: ASHP, air source heat pump; CEM, custom energy model; DHW, domestic hot water; FFA, finished floor area; GSHP, ground source heat pump; HERS, home energy rating system; HVAC, heating, ventilation and air conditioning; MEL, miscellaneous electronic load; NESEA, Northeast Sustainable Energy Association; NREL, National Renewable Energy Laboratory; NZEH, net-zero energy home; NNZEH, near net-zero energy home; PV, photovoltaics; SHGC, solar heat gain coefficient; TMY, typical meteorological year.

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Hampshire, Rhode Island and Vermont. However, though architects, energy engineers and builders spent considerable time (and homeowner money) in designing these homes, the first author of this work could find only three published studies on their actual performance, once built and occupied.

The first was a yearlong study on eight small homes on Martha's Vineyard that were designed to be affordable NZEHs [4]. The results of this study indicated that two of the eight homes were net-zero, three others within 25% of net-zero, and three well off target. The author of this study concluded that achieving net-zero appeared to be dependent more on occupant behavior than building design, since the eight homes were more or less identical in terms of location, building specifications, and energy production potential. The second study, also for one year, was on 13 NNZEHs built as a moderate-income development in Greenfield, MA [5]. This study focused on the annual energy cost of these homes, and the results were promising, as the average annual energy cost for the 13 homes (ranging in size from 105 to 164 m^2) was just $337. As in the Vineyard study, occupant behavior was the dominant reason for the range in annual energy cost. In addition, the authors found that modeled natural gas consumption was much greater than measured, and measured electricity use was much lower than one model's prediction but higher than a different model's prediction. The third study was on a single 3-bedroom, two-story house built in Townsend, MA [6]. This home was one of several net-zero energy homes built by a local builder as part of a 20 home development. During the year in which it was studied, this home came close to being net-zero, with just 1000 kW h net consumed.

Other studies have been done on NZEHs in other parts of the US [7,8] and the world [9] that do not reflect the climate, energy costs, incentives, environmental sensitivities, and building codes of New England. The homes from the three MA studies above do show that NZEH and NNZEHs are quite possible in New England. However, the homes studied were very homogeneous in design, still relatively small by New England standards, and all in Massachusetts. Thus, none of the published studies indicated how a more diverse group of New England NZEHs (varying in design, size, system components and geographic location) would perform.

Therefore, the primary objectives of this research were to determine how closely homes of this type, built and occupied in New England, could actually achieve the net-energy performance for which they were designed, and to examine common factors influencing performance. To meet these objectives, the authors measured the energy consumption and production of a representative number and diverse population of these homes for 12 months, and then compared these actual performance measurements to designed-for and/or modeled consumption and production levels. A simplified design approach was developed based on these comparisons. The authors also undertook numerous analyses of energy cost savings and estimated carbon dioxide emissions reductions during this [10]. However, for brevity, only the energy performance of the homes is discussed in this paper.

2. Methodology and calculation

The authors conducted this investigation in overlapping steps. The first involved the solicitation and selection of a set of suitable homes. The next was the collection of construction specifications, costs and incentives, occupation statistics, weather data, and on-site production system specifications. The third step was a 12-month-long period of measuring the energy performance and cost for the selected homes. In addition, the authors developed energy production and consumption models, against which the measured performance of each home was compared.

2.1. Participant selection

A list of NZEHs and NNZEHs in New England was created, mainly by using homes that had competed in various "zero energy challenges" that had taken place in the region. The authors found other potential homes via internet searches, as several of these homes had been written about and/or had their own on-line presence (e.g., homeowner blog). Criteria for houses was simply that they had to be designed to be either net-zero energy or near-net zero energy and that they had to be located in one of the six New England states. The authors also solicited participants via an appeal to members of the Northeast Sustainable Energy Association (NESEA) using its monthly on-line newsletter. Between this solicitation and direct solicitation by the authors, approximately 30 homeowners expressed interest by the fall of 2011.

After some homeowners later declined or were removed for non-response, the number of homes fell to 20. As complete anonymity was one condition of participation, the authors kept homeowner names and the exact addresses of the homes strictly confidential. Hence, the homes are simply referred to as House A, House B, etc. Ten were designed as NZEHs, nine were designed as NNZEHs, and one fell into neither group but served as a "control" house. This last one was the home of one of the authors. Since it was a certified Energy Star home and contemporaneous with the other participants, he decided its performance would serve as a good baseline against which the other homes could be compared. The first author performed this self-funded research as part of the degree requirements for a Ph.D. in energy engineering at the University of Massachusetts Lowell [10]. Thus, no sponsor could influence the results. The authors conjecture that having no sponsor was one of the key reasons that such a high number of homeowners volunteered for the study.

2.2. House specifications, occupation statistics, and other collected information

Each participating homeowner completed an initial survey. This survey gathered construction specifications (location, lighting, appliances, HVAC equipment, etc.), occupation statistics (number of occupants, number of days living in the home, temperature settings for heating and cooling, etc.), cost information (cost of installed PV system, cost of additional energy efficiency measures beyond code, etc.) and energy production system specifications (size of PV system, components, orientation, etc.).

Various other input parameters were used in the developed models. First, the authors used irradiance data (hourly levels of beam normal, global horizontal and diffuse irradiance, in W/m^2) from the Typical Meteorological Year 3 (TMY3) data set, using the closest available site for each house [11]. Second, they collected three sets of local temperatures: 30-year "normal" temperatures [12]; "typical" temperatures from the aforementioned TMY3 database; and measured temperatures (indoor and ambient) at 13 of the 20 homes. For the latter, indoor temperatures were collected hourly using HOBO U10-003 data loggers manufactured by Onset, placed on the first floor, away from heat sources and direct sunlight. Outdoor (ambient) temperature values were collected hourly using Lascar EL-USB-2 data loggers, located to the north of each home, shaded from direct sunlight. Third, the authors received estimated annual energy consumption predictions for several homes, created by the various home designers and generated from energy modeling software. The authors assumed the modeling was performed correctly, and that the houses were built per the specifications used in the models.