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A Zero Energy Lab as a validation testbed: Concept, features, and performance

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ABSTRACT

The issues of fossil-fired energy shortage and global warming have aroused worldwide attention, and the renewable and sustainable energy sources, therefore, are playing an increasingly important role in future energy consumptions. Energy consumptions in buildings account for almost 40% of the primary energy use in the US. A novel research-based Zero Energy (ZØE) Lab as a validation testbed combining various kinds of renewable energies has been presented in this paper. The concept, unique features, and the operation performance by experiments have also been shown in detail. The results of the novel ZØE Lab can open up a good angle for the future development of zero energy buildings. After analyzing the operating data of the ZØE Lab, the energy consumption, energy generation, and energy allocation of the devices have been presented. A new HVAC system with higher performance is recommended to be used in the ZØE Lab to achieve an even lower energy consumption than the current use, as a necessary refinement.

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Introduction

Commercial and residential buildings are central in the aspects of the nation's energy savings, reduction of green house gases and pollution emissions, and environment protection, as they consume almost 40% of the primary energy and approximately 70% of the electricity in the United States [1]. Obviously, the energy consumption by the building sector is continuously increasing due to the fact that more and more buildings are being constructed, more quickly than ever, all which brings up energy use. Existing data indicate that electricity consumption in the commercial building sector doubled between 1980 and 2000, and it is expected to increase another 50% by 2025 [2]. The trend of drastically increasing energy consumption in commercial and residential buildings will not stop in the long run unless there are worldwide awakening of the people and governments, effective technological improvements, and preferential policies for the encouragement of renewable energy applications.

Technically, a direct and effective answer to save the buildings' energy is to construct zero-energy buildings (ZEB) or net-zero energy buildings (NZEB) [3]. A ZEB refers to a building with a net energy consumption of zero over a typical period of time. The energy consumption, i.e., consumption of heat, electricity, and fuel, is greatly reduced in a ZEB, and the utilization of renewable energy technologies, such as solar photovoltaic (PV) panel, solar heat collector, wind turbine, and ground source heat pump, can compensate for this reduced energy demand. The negative environmental impact of current building practices can be overcome by low energy houses. ZEB can be the pinnacle of saving energy and best standard for a sustainable near future houses. Here comes the appealing concept of ZEB which is envisioned as the technology of tomorrow towards a green and sustainable future. Enormous efforts are being made to make the ZEB more practical, and cost effective to make it a mainstream energy solution for future generations. These efforts are integrating various renewable energies [4–8], using insulated materials to avoid excessive energy dissipation [9–11], designing advanced HVAC systems [12–16], adopting various energy saving facilities and apparatuses [17–20], and studying the relation between occupant schedules and energy consumption in a building [21–26]. A detailed review on the development of two design strategies, i.e., energy-efficient measures to minimize the need for energy use in buildings (especially for heating and cooling) and renewable energy technologies to meet the remaining energy needs, has been presented by Li et al. [27].

Recently, the research on ZEBs/NZEBs has aroused worldwide attention. Iqbal [28] presented a feasibility study of a wind energy conversion system based on a zero energy home (ZEH) in Newfoundland. This study was based on annual recorded wind speed data, solar data, and power-consumed data in a typical R-2000 standard house in Newfoundland. National Renewable Energy Laboratory's software HOMER was used to select an optimum energy system. da Graca et al. [29] explored the feasibility of solar NZEB systems for a typical single family home in the mild southern European climate zone. Using a dynamic thermal simulation of two representative detached house geometries, solar collector systems were sized in order to meet all annual energy needs. The impact of building envelope, occupant behaviors, and domestic appliance efficiency on the final energy demand, and the solar NZEB system size was analyzed. After sizing a set of solar thermal (ST) and photovoltaic (PV) solar systems, an analysis was performed to identify the best system configuration from a financial and environmental perspective. The introduction in the analysis of a micro-generation government incentive scheme shows great potential for financially attractive NZEB homes in this climate zone. Nielsen and Moller [30], Marszal et al. [6], and Marszal and Heiselberg [31] presented a very detailed analysis on the application of NZEBs in Demark from the points of heat reduction, on-site or off-site renewable energy supply options, and life cycle cost analysis. Zeiler and Boxem [32] reported a ZEB school which was built in the Netherlands and presented a detailed analysis on the pros and cons of the NZEB buildings. The authors advanced some suggested ways to find different solutions which increases the advantages of ZEB while at the same time improve some of the ZEB disadvantages. Silva et al. [33] presented a new prefabricated retrofit module solution for the facades of existing buildings, and also the steps taken to optimize its performance, which included a judicious choice of materials, 3D modeling, cost-benefit analysis, and use of different simulation tools for performance optimization and prototyping. What is also shown is the implementation of the retrofit module within an integrated retrofit approach, whose final goal was to obtain a building with the minimum possible energy consumption and greenhouse gas emissions. The research above indicates that it is feasible to build ZEBs/NZEBs towards significant energy savings and emission reduction.

Madeja and Moujaes [34] numerically investigated the energy consumption to compensate the heating and cooling loads of two residential homes and compared them with their experimental values. In their research, one home was classified as a ZEH and employed advanced construction features, which was designed to consume significantly less energy than a normal home. The baseline home was of the exact same dimensions and floor plan as the ZEH, but used more traditional construction practices. The results showed that the ZEH reduced the cooling load by about 76% and the heating load by about 12% experimentally. To investigate the energy performance of net-zero energy homes (NZEHs) and nearly net-zero energy homes (NNZEHs) in New England, Thomas and Duffy [35] 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. They found that 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 their actual performance varies widely. Bucking et al. [36] presented a theoretical analysis to estimate and reduce building energy consumption at the design stage using optimization algorithms coupled with the powerful tool of Building Performance Simulation (BPS). However, the application of optimization approaches to building design is not common practice due to time and computation requirements. Then, they proposed a hybrid evolutionary algorithm which used information gained during previous simulations to