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Selecting HVAC systems to achieve comfortable and cost-effective residential net-zero energy buildings

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HIGHLIGHTS

- Use a validated model to compare various HVAC options for a net zero energy residence.
- Compare energy/comfort/economy of ventilation/dehumidification/heat pump options.
- Heat and energy recovery ventilator reduced the HVAC energy by 13.5% and 17.4%
- Ground source heat pump with 2 and 3 boreholes reduced HVAC energy by 26.0% and 29.2%
- Economics analysis using installation cost data and two electricity price structures.

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Net-zero energy building
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ABSTRACT

HVAC is responsible for the largest share of energy use in residential buildings and plays an important role in broader implementation of net-zero energy building (NZEB). This study investigated the energy, comfort and economic performance of commercially-available HVAC technologies for a residential NZEB. An experimentally-validated model was used to evaluate ventilation, dehumidification, and heat pump options for the NZEB in the mixed-humid climate zone. Ventilation options were compared to mechanical ventilation without recovery; a heat recovery ventilator (HRV) and energy recovery ventilator (ERV) respectively reduced the HVAC energy by 13.5% and 17.4% and reduced the building energy by 7.5% and 9.7%. There was no significant difference in thermal comfort between the ventilation options. Dehumidification options were compared to an air-source heat pump (ASHP) with a separate dehumidifier; the ASHP with dedicated dehumidification reduced the HVAC energy by 7.3% and the building energy by 3.9%. The ASHP-only option (without dedicated dehumidification) reduced the initial investment but provided the worst comfort due to high humidity levels. Finally, ground-source heat pump (GSHP) alternatives were compared to the ASHP; the GSHP with two and three boreholes reduced the HVAC energy by 26.0% and 29.2% and the building energy by 13.1% and 14.7%. The economics of each HVAC configuration was analyzed using installation cost data and two electricity price structures. The GSHPs with the ERV and dedicated dehumidification provided the highest energy savings and good comfort, but were the most expensive. The ASHP with dedicated dehumidification and the ERV (or HRV) provided reasonable payback periods.

1. Introduction

Buildings accounted for 40% of the total energy consumption in the U.S. in 2016, with residential buildings accounting for 21% of the energy consumption [1]. Residential buildings accounted for approximately 38% of the retail sales of electricity in 2016 [2]. This large amount of energy consumption resulted in the residential sector accounting for approximately 20% of the total carbon dioxide emissions in the U.S. [1]. Therefore, advancements in the energy efficiency of residences could significantly reduce greenhouse gas emission [3].

It is toward this end that interest in net-zero energy buildings (NZEB) is increasing, where NZEB are defined here as buildings that produce at least as much energy as they use in a year when accounted for at the building site [4]. The US Department of Energy aims to achieve “marketable zero energy homes in 2020 and commercial zero energy buildings in 2025” [5]. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) assigned a target of market-viable NZEBs by 2030 [6].

Advances in NZEBs are mainly accomplished by minimizing the building energy demand and increasing on-site renewable energy generation.

Minimizing the building energy demand includes improving

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Nomenclature

A	area, m^2
C	cost, \$
E	energy consumption, kWh
f	ratio
h	convective heat transfer coefficient, W/(m^2·°C)
I	thermal resistance, m^2·°C/W
M	metabolic rate, W/m^2
m	mass flow rate, kg/s
P	power, W
p	pressure, Pa
Q	thermal load, kWh
t	temperature, °C
V	velocity, m/s
W	work, W/m^2
η	effectiveness

Abbreviations

ASHP	air source heat pump
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CHP	combined heat and power
COP	coefficient of performance
DHW	domestic hot water
ERV	energy recovery ventilator
ESR	energy saving ratio
GSHP	ground source heat pump
HP	heat pump
HPWH	heat pump water heater
HRV	heat recovery ventilator
HVAC	heating, ventilation, and air conditioning
NIST	National Institute of Standards and Technology
NZEB	net-zero energy building
PMV	predicted mean vote
PPD	percentage of people dissatisfied
PV	photovoltaic
SHW	solar hot water
TRNSYS	Transient System Simulation Tool

building design, using efficient appliances, integrating more efficient heating, ventilation, and air conditioning (HVAC) systems, using smart control technologies, and encouraging energy-efficient occupant behaviors [7,8]. Improved building designs include enhanced thermal insulation, higher levels of airtightness, optimized orientation/shape, solar shading, etc. [9–11]. Adopting energy-saving lighting and efficient appliances (refrigerators, washing machines, dryers, etc.) can not only directly cut the electricity consumption but also lower the cooling load imposed on HVAC systems [12,13]. Alternative HVAC systems, such as ventilators with heat recovery [14], ground-source heat pumps (GSHP) [15], and integrated heat pumps (providing both space-conditioning and water heating) [16], can play an important role in energy efficiency. Using smart control technologies, such as smart meters and smart controllers, can also contribute greatly to the efficient operation of NZEBs [13]. Occupant behaviors, which affect indoor setpoints and load schedules, also have a great influence on the ability to achieve the NZEB goal [17].

Increasing on-site renewable energy generation includes the advances in solar, wind, and biomass [7]. Elkinton et al. [18] addressed the feasibility of wind power for NZEB developments in U.S. and found that wind turbines would be more cost beneficial in large-scale installations. Marszal et al. [19] compared a biomass/biofuel micro-combined heat and power (CHP) system with other renewable resources, and found that the micro-CHP systems were a rather costly technology and had a relatively short lifetime. On-site electricity generation with a solar photovoltaic (PV) system is currently the dominant technology [20] due to its easy integration with building roofs and facades, and the fact that there is an insignificant marginal cost difference between small and large-scale installations [19]. Furthermore, PV production is improving through the adoption of advanced photovoltaic technologies [21].

The literature review indicated that it was important to explore efficient HVAC technologies for NZEBs. Even with advanced envelope construction, the HVAC system remains responsible for the largest share of energy use in residential buildings, greater than 40% [22]. Although prior research has analyzed the advantages and disadvantages of different HVAC systems [14,23–25], the studied HVAC options were limited, and the evaluation criteria mainly focused on energy performance or economic benefit without considering thermal comfort.

In this work, we studied various HVAC configurations for a residential NZEB constructed on the National Institute of Standards and Technology (NIST) campus in Gaithersburg, Maryland, USA (ASHRAE Climate Zone 4, mixed-humid [26]). Using a validated building energy model, the house and each HVAC subsystem were considered in detail, including the ventilation, dehumidification, and heat pump equipment. We compared three commercially-available options for each subsystem based on energy performance, thermal comfort, and economic performance. The goal of this study was to identify the relative merits of alternative HVAC technologies and provide recommendations for HVAC system design, in support of broader implementation of residential NZEBs in North America.

2. Description of the residential NZEB

2.1. General information

The studied residential NZEB, which is the basis for the model described in Section 3, was constructed on the NIST campus in Gaithersburg, Maryland, USA in 2012 (Fig. 1). The single-family house had two stories (251 m^2) of living area and a full conditioned basement (135 m^2). The first floor comprised the kitchen and dining room, a family room, an office, and a full bathroom. The second floor included a master bedroom with adjoining bathroom, two additional bedrooms and two bathrooms. The house featured a wide array of energy efficient technologies. Increased insulation, double-paned windows, and very tight construction (0.63 air change per hour measured by a blower-door test at 50 Pa) were used in the building envelope to reduce heating and cooling loads [10].

The house was unoccupied, but the activities associated with a family of four were emulated by computer activating appliances, plug loads, lighting, water draws, and devices that generate sensible and

Fig. 1. Residential NZEB on NIST campus.