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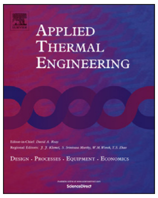

Research Paper

Energy use consequences of ventilating a net-zero energy house

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HIGHLIGHTS

- HRV saved 7% in annual heat pump energy compared with no heat recovery.
- Savings calculated using measurements are consistent with simulations in literature.
- HRV increased heat pump energy 5% in cooling & decreased 36% in heating.
- Fan power of HRV paid for itself with savings in heat pump energy in mixed-humid climate.

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ABSTRACT

A Net-Zero Energy Residential Test Facility (NZERTF) has been constructed at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, to demonstrate that a home similar in size, aesthetics, and amenities to those in the surrounding communities can achieve net-zero energy use over the course of a year while meeting the average electricity and water use needs of a family of four in the United States. The facility incorporates renewable energy and energy efficient technologies, including an air-to-air heat pump system, a solar photovoltaic system, a solar thermal domestic hot water system, and a heat recovery ventilation system sized to meet American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 62.2-2010 ventilation requirements. The largest energy end use within the home was space conditioning, which included heat loss through the building envelope, ventilation air supplied by the heat recovery ventilator (HRV), and internal loads. While HRVs are often described as being able to save energy when compared to ventilating without heat recovery, there have been no studies using a full year of measured data that determine the thermal load and energy impacts of HRV-based ventilation on the central heating and cooling system. Over the course of a year, continuous operation of the HRV at the NZERTF resulted in an annual savings of 7% in heat pump energy use compared with the hypothetical case of ventilating without heat recovery. The heat pump electrical use varied from an increase of 5% in the cooling months to 36% savings in the heating months compared with ventilation without heat recovery. The increase in the cooling months occurred when the outdoor temperature was lower than the indoor temperature, during which the availability of an economizer mode would have been beneficial. Nevertheless, the fan energy required to operate the selected HRV at the NZERTF paid for itself in the heat pump energy saved compared with ventilation without heat recovery.

1. Introduction

Buildings consumed 41% of all energy used in the United States in 2011, with residential buildings and commercial buildings accounting for 22% and 19% [1], respectively. In addition to consuming more energy than the transportation or industrial sectors, buildings represent the fastest growing sector of energy usage [1]. Thus, goals for achieving net-zero energy performance have been established in the U.S. and around the world. A net-zero energy building (ZEB) is an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy [2]. Under the Energy Independence and Security Act of 2007, U.S., federal buildings are mandated to eliminate fossil fuel-generated energy consumption by 2030 [3]. For federal buildings to be built in 2020 and beyond, they must be net-zero by 2030 [4]. The American Institute of Architects set a goal for all new and renovated buildings to be carbon-neutral by 2030 [5]. The American Society of Heating, Refrigeration, and

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Air-Conditioning Engineers (ASHRAE) issued a visit to develop tools by 2020 that enable the building community to produce market-viable net-zero energy buildings by 2030 [6]. In 2010, the Energy Performance of Buildings Directive stated all buildings in the European Union to be nearly net-zero by 2020 [7]. Melbourne, Australia has set a goal to be a carbon neutral city by 2020 [8]. Thus, buildings have been designed, constructed and monitored throughout the world to demonstrate the feasibility of achieving net-zero energy. Parker [9] presents a history of low energy homes, including annual performance data from a dozen very low energy homes in North America. Musall et al. [10] summarizes the research of the International Energy Agency's Annex 52 "Towards Net Zero Energy Buildings" and states that "during the last 20 years more than 200 reputable projects with the claim of a net-zero energy budget have been realized all over the world." Rosta et al. [11] report on the construction and performance of a net-zero energy house in the Desert Southwest region of the United States. Boleyn [12] reports on a residence in Portland, Oregon that is approaching net-zero in a relatively cloudy climate. Sherwin et al. [13] present the performance of four near net-zero energy homes in Florida instrumented to provide data on electrical consumption and generation, indoor conditions, and outdoor weather. Norton et al. [14] report on the design and performance of a three-bedroom Habitat for Humanity net-zero energy home near Denver, Colorado that produced 24% more energy than it consumed during its first year of operation. Of these six studies, only four mentioned that ventilation was provided to maintain acceptable indoor air quality (IAQ) and none of them mentioned the design ventilation rate. Further, the energy use consequences of ventilation were not discussed in any of these studies.

The studies of net-zero energy buildings cited above report data on energy usage with little or no discussion of IAQ. ASHRAE has a standard containing minimum ventilation rates to achieve acceptable IAQ based on the floor area and number of bedrooms, ASHRAE Standard 62.2 [15]. The Standard does not, however, dictate how the ventilation air has to be delivered. There are many ways to deliver the air, including exhaust-only systems, supply-only systems, systems that are integrated with the central heating and cooling system, and heat recovery and energy recovery ventilators (HRV, ERV). The difference between an HRV and ERV is that HRVs recover only sensible heat and ERVs recover both heat and moisture.

Lstiburek et al. [16] simulated high-performance houses in six U.S. climate zones and with various mechanical ventilation systems, including an HRV/ERV and supply-only ventilation. For all the climates simulated, the use of an HRV/ERV saved on average 3% (ranging from no savings to 7%) in space conditioning and ventilation fan energy combined compared with a supply-only ventilation system. Sherman and Walker [17] and Rudd et al. [18] performed simulation studies on similar houses in six U.S. climate zones. Sherman and Walker [17] found that the use of an HRV/ERV saved on average 1% (ranging from a 4% energy increase to a 6% savings) in space conditioning and ventilation fan energy combined compared with a supply-only ventilation system. Rudd et al. [18] found that the use of an HRV/ERV saved on average 7% (ranging from a 2% energy increase to an 11% savings) for a house with a Home Energy Rating System (HERS) index [19] of 50 compared with a central space conditioning system with outdoor air intake. Walker and Sherman [20] performed simulation studies on houses in California climates and modeled an HRV in the "cold climate". They found that the use of an HRV saved 5% compared with a supply-only ventilation system. The HRV was modeled to operate on a 50% duty cycle because the minimum flow rate exceeded the minimum requirements of ASHRAE 62.2. On average, the fan power required to operate the HRV/ERV studied was 7% of the energy required by the space conditioning system.

Turner and Walker [21] presented simulation results of using a proposed control system to determine the optimal time, based on time-of-use pricing and outdoor temperature, to run an HRV without compromising indoor air quality (IAQ) and occupant health. The control system also monitors the operation of local exhaust fans and does not activate the HRV when the flow rates from local exhaust fans meet the required minimum whole-building ventilation rate. The use of the controller in conjunction with an HRV saved on average 31% in space conditioning and ventilation fan energy combined when compared with using an HRV without the proposed controller.

Dodoo et al. [22] simulated supply-only ventilation and an HRV in an apartment building in Europe built to conventional building standards and also one built to passive house standards, which had a building envelope that was twice as tight. They found that in the building built to conventional building standards, the use of an HRV saved 21% in space heating only and ventilation fan energy combined compared with a supply-only ventilation system. In the building built to the passive house standards, the use of an HRV saved 55% in space heating only and ventilation fan energy combined compared with a supply-only ventilation system.

These studies demonstrate the wide range of savings HRVs and ERVs can have on ventilation-related energy (fan power plus heating and cooling) depending on ventilation rate, building size, building envelope leakage, and climate. However, they all have been based on simulated data. This study used actual energy data collected for one year for an air-to-air heat pump and an HRV in order to determine the impact of ventilation air on the heating and cooling loads of a very low energy house. The purpose of this manuscript is to examine the energy use consequences of different options for ventilating a net-zero home. Similar analysis was performed previously by the authors in Fanney et al. [23], but the analysis in this manuscript provides greater detail.

2. Test house

The NZERTF is a unique facility that resembles a residence yet is truly a laboratory (Fig. 1). The house is comprised of two stories of living area (252 m^2), a full basement (135 m^2), and a conditioned attic (108 m^2). The water, lights, and appliance usage utilized by a family of four were simulated in the NZERTF according to occupancy schedules. Details of these control schedules can be found in Omar and Bushby [24] and Kneifel [25]. Sensible heat generated by occupants was simulated in various rooms, but the latent loads generated by occupants were all located in the kitchen. Details can be found in Fanney et al. [23]. Though natural gas is supplied to the house, during the first year of operation all of the equipment and appliances were powered by electricity supplied by either the 10.2 kW (direct current) solar photovoltaic (PV) system or the main power grid.

The building envelope was constructed using a continuous air barrier system to minimize infiltration, and ventilation was provided by an HRV. The exterior walls were constructed of wood studs, a fully-adhered membrane applied to plywood sheathing, two layers of polyisocyanurate foam board, fiber cement lap siding, and blow-in cellulose insulation. The calculated U-factor of the exterior above grade walls, including framing members, is 0.13 W/m^2-°C. The windows are double-hung units (rated U-factor of 1.14 W/m^2-°C). Five blower door tests were conducted at various stages of construction (Fig. 2). The first three (NZERTF w/o windows, NZERTF predrywall, and NZERTF substantial completion) were conducted by third-party testing companies [26]. The final tests (#4 and #5) were performed by NIST after the house was complete. Test #4 was performed with the kitchen and dryer vents sealed. Test #5 was performed with those vents not sealed, which yielded a leakage rate of 802 m^3/h at 50 Pa corresponding to 0.63 h^{-1}.