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An assessment of efficient water heating options for an all-electric single family residence in a mixed-humid climate

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ABSTRACT

An evaluation of a variety of efficient water heating strategies for an all-electric single family home located in a mixed-humid climate is conducted using numerical modeling. The strategies considered include various combinations of solar thermal, heat pump, and electric resistance water heaters. The numerical model used in the study is first validated against a year of field data obtained on a dual-tank system with a solar thermal preheat tank feeding a heat pump water heater that serves as a backup. Modeling results show that this configuration is the most efficient of the systems studied over the course of a year, with a system coefficient of performance (COP_{sys}) of 2.87. The heat pump water heater alone results in a COP_{sys} of 1.9, while the baseline resistance water heater has a COP_{sys} of 0.95. Impacts on space conditioning are also investigated by considering the extra energy consumption required of the air source heat pump to remove or add heat from the conditioned space by the water heating system. A modified COP_{sys} that incorporates the heat pump energy consumption shows a significant drop in efficiency for the dual tank configuration since the heat pump water heater draws the most heat from the space in the heating season while the high temperatures in the solar storage tank during the cooling season result in an added heat load to the space. Despite this degradation in the COP_{sys}, the combination of the solar thermal preheat tank and the heat pump water heater is the most efficient option even when considering the impacts on space conditioning.

1. Introduction

Residential water heating was estimated to consume 3.04×10^{18} J (2.88 quads) of source energy and 2.02×10^{18} J (1.92 quads) of site energy in the US in the year 2015 [1]. That number amounts to 13.7% of primary energy use and 16.9% of site energy use in US homes, a number that is comparable to the 16% of site energy reported by the International Energy Agency for countries in the Organization for Economic Cooperation and Development [2]. In the US, water heating makes up the second largest residential site energy use behind space heating [1]. Therefore, domestic water heating is a critical end use that must be investigated in order to reduce the energy consumption of residential buildings.

The water heater market in the US has traditionally been dominated by conventional electric resistance and gas storage water heaters [3]. This market is driven by both new construction and replacements, with water heaters being replaced on average every 13 years [4]. While many homeowners may simply replace an existing unit with a similar one, a number of developments in the water heater market have added more options. First, a number of high efficiency technologies have emerged and are beginning to gain greater market share. For example, heat pump water heaters (HPWHs) [5] and tankless (i.e., instantaneous) water heaters [6] have gained popularity and offer significant energy savings over conventional water heaters. In addition to these emerging technologies, solar water heaters (SWH) are an available efficient water heating option as documented by a number of sources [7–11].

The second major development relates to regulatory requirements. In the US, minimum standards for residential water heaters mandated in 2015 by the Department of Energy (DOE) require the regulated efficiency, Energy Factor (EF), to be at least 1.9 for electric water heaters with rated storage volumes greater than 208 L (55 gal) [12]. Given the technologies that are currently commercially available, this requirement essentially mandates heat pump technology. It would be expected that this standard will lead to an

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increase in the number of HPWHs sold, thereby decreasing their costs and increasing familiarity with the technology.

With all of these possibilities, it is important to investigate which option, or combination of options, uses the least amount of energy in particular situations. Merrigan and Parker [13] presented one of the first studies of various options, investigating HPWHs, solar hot water systems, electric resistance water heaters, and desuperheaters in a mild climate (Florida, USA). They found solar hot water systems had the lowest energy consumption among the technologies available at the time. Biaou and Bernier [14] evaluated four different configurations numerically, including electric resistance water heaters, a desuperheater of a ground-source heat pump, solar thermal with electric backup, and a HPWH coupled with a ground source heat exchanger. Of these options, the solar thermal system required the lowest peak power and the least amount of annual energy in both Montreal and Los Angeles. Maguire [15] modeled a range of options in six cities across the US, in both conditioned and unconditioned spaces and subject to three levels of hot water demand. For electric water heating, solar water heaters with electric resistance backup inside the solar storage tank were the most efficient options in 26 of the 36 cases studied, with HPWHs being the most efficient in the other ten. (Solar with HPWH backup was not considered.) Two key trends that were found were that solar was more advantageous in low use situations, and solar was more advantageous in unconditioned spaces. This work was followed up with a report that documented the benefits of HPWHs compared to standard electric resistance water heaters across the US [16].

In this work, we examine a broad range of options for an all-electric home located in a mixed humid climate. The configurations are largely based on those installed in an experimental home located in Gaithersburg, MD. Data collected over the course of a year in this test facility are first used to validate a simulation model. The validated model is then used to examine alternative techniques for providing hot water to the home to determine which option performs the best in terms of energy usage and thermal energy delivered by the entire water heating system, during different months and over the entire year. Additionally, the impact on space heating and cooling loads is considered in these analyses. The focus of this work is on energy use, with a discussion of life cycle costs and best performance from an economic perspective being beyond the scope of this report. The interested reader is referred to Kneifel [17] for a comparison of the life-cycle costs of the NZERTF compared to a code-compliant home.

2. Experimental and computation description

The Net-Zero Energy Residential Test Facility (NZERTF) located in Gaithersburg, MD, USA provides the basis for this analysis. The NZERTF serves as a test-bed to evaluate the performance of building technologies and operational schemes from energy usage and indoor environmental quality perspectives. The detailed design of the facility is described in Pettit et al. [18], and the description of the simulation of occupant behavior on a minutely basis is given by Omar and Bushby [19]. A test was run for an entire year between July 2013 and June 2014, and net-zero operation was confirmed with energy consumption within the house of 13039 kWh and a net energy export to the electric grid of 484 kWh [20]. The following discussion focuses on the domestic hot water (DHW) systems in the facility, as well as the computational approaches to simulate those systems.

2.1. Experimental facility

The DHW system used during the first year of operation was a dual tank configuration, with a solar thermal preheat tank feeding into a HPWH as shown in Fig. 1. The solar hot water (SHW) system consists of two solar collectors, a 303 L (80 gal) storage tank with its auxiliary heating element disabled, and an external heat exchanger with an effectiveness of 0.44 to transfer heat from a 50% by volume propylene glycol/water solution to the potable water. Each solar collector array consists of two SRCC OG-100 [21] certified single-glazed flat plate solar thermal collectors with individual aperture dimensions of 1.1 m by 2.0 m. The collectors are located on a roof facing due south at a tilt of 18.4°. The HPWH provides hot water in the event that the solar thermal water heating system cannot meet the demand. The unit consists of a 189 L (50 gal) storage tank with an integrated air-to-water heat pump. The system is operated in "Hybrid" mode whereby the heat pump adds heat to the bottom of the tank, and an electric resistance element located in the top portion of the tank is energized when the temperature of water in the upper portion of the tank falls below a certain threshold. The manufacturer-reported EF, COP, and standby loss of the unit are 2.33, 2.36, and 0.20 °C/h, respectively, when tested in accordance to methods specified by DOE [22].

Over the course of the year, the water heating system was measured to have used 1422 kWh ± 28 kWh, which represents 11% of the total energy consumption of the house (uncertainties presented here are based on a propagation of Type B uncertainties as described in [23]). Fig. 2 displays the energy consumption of the different components of the domestic hot water system, which include the HPWH resistance elements (EHPWH,resistance), the heat pump unit of the HPWH (EHPWH,HP), and the pumps for the solar water heater (ESWH). Fig. 2 shows that the majority of the energy was used by the HPWH. Less energy is used in summer months on account of the larger contribution from the solar water heater and the higher mains temperature. The solar fraction throughout the year was 0.54 ± 0.01, and the solar energy factor, defined here as the thermal energy delivered divided by the total electric energy consumption was 2.41 ± 0.05.

The measurements shown in Fig. 2 indicate that the dual tank SHW system plus HPWH system (SHW + HPWH) performed efficiently over the first year of operation of the NZERTF. This paper examines the energy consumption of the current configuration compared to a number of alternative systems that could be installed. The combination of a solar thermal system and a HPWH is expensive, and the performance of a HPWH degrades as the inlet temperature rises [24], meaning that introduction of solar preheated water may negate the advantages expected of a HPWH. To investigate those and other issues, a computer model has been used to assess how other electric water heating approaches would work compared to this case.

2.2. Computer model

A computer model of the water heating system was created in the TRNSYS modeling program [25]. An overview of the model will be presented here; see Balke et al. [26,27] for a more complete description.

The water heating system model includes the point where water enters the building at the main ("Cold Water Supply" in Fig. 1) to the fixtures (located beyond the "Hot Inlet Manifold" in Fig. 1). The model includes the piping between the main and the first water heater, the water heaters, piping between water heaters when two are used, solar panels, piping between the panels and the solar storage tank, a thermostatic mixing value, the heat exchanger to transfer heat from the solar panels to the potable water, and piping from the water heater to fixtures. Electrical energy consumption was calculated for the solar pumps, resistance elements, heat pump compressor and fans, and water heater controls.

Prior to modeling hypothetical configurations, a baseline model of the actual system configuration was evaluated and tuned against