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 ($\text{COP}_{\text{sys}}$) of 2.87. The heat pump water heater alone results in a $\text{COP}_{\text{sys}}$ of 1.9, while the baseline resistance water heater has a $\text{COP}_{\text{sys}}$ 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 $\text{COP}_{\text{sys}}$ 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 $\text{COP}_{\text{sys}}$, 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.

Keywords

Water heating; Residential; Solar; Heat pump water heater; Electric water heating

1. Introduction

Residential water heating was estimated to consume $3.04 \times 10^{18}$ J (2.88 quads) of source energy and $2.02 \times 10^{18}$ J (1.92 quads) of site energy in the US in the year 2015 \cite{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 \cite{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 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 measurements performed during the first year of operation of the NZERTF [20]. Parameters that were tuned to better match the data include the effectiveness of the heat exchanger, heat loss factors for the solar storage tank and HPWH, thermostat setpoints, HPWH performance map, water flow rates through the heat exchanger, and solar pump power parameters. The tuned model predicted the measured solar pump energy consumption to within 4% and the HPWH energy consumption within 11% of annual measured values. The majority of the discrepancy in the HPWH prediction arises from the resistance element, where the model under-predicted the measured energy by 45%. The overall annual predicted energy consumption is 7.7% less than the measured energy consumption. The delivered energy was predicted to within 3%. Balke et al. [27] note the challenges faced in matching experimental data on account of the uncertainty in the control scheme of the resistance element in the HPWH. The tuned models of the SWH and the HPWH were then used as part of this study of alternative configurations.
The eight water heating options considered are listed in Table 1. The first five options are single tank systems, and the last three are dual-tank systems. These options are based on the as-built configuration (Option 6: 303 L SWH + 189 L HPWH) and permutations of that configuration. The first set of permutations (Options 2 and 4) involve a single tank system using either component. The next permutation involves a larger SWH of 454 L (120 gal), which was installed in the facility but not used. This unit is simulated to assess whether the larger tank can reduce the need for backup heat in both a dual tank (Option 7) and a single tank configuration (Option 3). The next variation to the as-built situation, Option 5, models a larger stand-alone heat pump with a volume of 303 L (80 gal). This product is modeled to examine whether the larger storage volume lowers energy consumption by reducing the need for electric resistance heating. The last permutation, Option 8, incorporates an alternative backup water heater, an electric tankless, instead of the heat pump water heater. Since this unit has minimal standby losses, it is examined to compare its energy consumption to that of the other solar options. Finally, a baseline case of a 189 L (50 gal) electric resistance water heater of minimum efficiency is considered for comparison (Option 1).

2.2.1. Electric resistance water heater—The 189 L (50 gal) water heater is modeled as a cylinder with a height of 1.42 m. The EF of the water heater is the minimum value allowed by law in the US [28], 0.95. With a thermal efficiency of the heating element as 1, this EF is achieved through a heat loss coefficient from all sides of the water heater of 0.355 W/(m$^2$ K). The storage tank is partitioned into 15 equal volumes from top to bottom for simulation. The upper heating element (3800 W) is located in the 5th zone from the top, whereas the lower heating element is located in the second zone from the bottom. Cold water is introduced in the second element from the bottom, and hot water is removed from the third zone from the top to simulate a water heater with a side discharge of hot water. The upper element is activated when the temperature in its zone drops below 43.3 °C (110 °F) and turns off when the temperature reaches 51.7 °C (125 °F). The lower element does not energize when the upper element is on. When the upper element is off, the lower element energizes when the temperature drops below 48.9 °C (120 °F) and cuts off when the temperature reaches 51.7 °C (125 °F). These temperature setpoints were adjusted to ensure each water heating configuration delivered comparable amounts of thermal energy, thereby allowing for better comparisons.

2.2.2. Solar water heater—Fig. 3 shows a schematic of the solar thermal water heating system, including the solar panels, hot water storage tank, the piping between the components, the heat exchanger, and pumps. Two solar panels facing due south at a tilt angle of 18.4° are connected in parallel, with the total collector area of 2.1 m$^2$. A pump circulates a 50% by volume propylene glycol in water solution from the collectors to a heat exchanger, where heat is transferred to potable water circulated from the solar storage tank. All piping is insulated with the exception of the pipe from the main to the solar storage tank yielding an effective heat transfer coefficient of 1.96 W/(m$^2$ K).

Two different solar storage tanks are considered: a 303 L tank with a height of 1.59 m and a 454 L tank with a height of 1.63 m. Both tanks have heat loss coefficients of 1 W/(m$^2$ K). This value is computed based on an EF of 0.86, which was the minimum value allowed for a
303 L tank at the time of purchase of the solar water heater installed in the NZERTF. Mains water is introduced at the lowest zone in the tank, and water is drawn to the heat exchanger from the second lowest of the 15 zones in the tank. Water is returned from the heat exchanger at the second highest zone in the tank while water is removed as hot water from the highest node in the tank. This configuration is based on the installed solar storage tank in the NZERTF.

The 4500 W heating element, when used, is located in node 7 and is set to turn on at 46.2 °C (115 °F) and turn off at 51.8 °C (125 °F). The circulating pumps turn on when the differential between the temperature at node 14 and the solar panel outlet temperature is 10°C (18 °F) or greater, and they turn off when the differential is 3 °C (5 °F) or less. The pumps do not run if the temperature at node 14 exceeds 71 °C (160 °F). When a water draw occurs, the water exiting the solar storage tank is tempered to 49 °C (120 °F) if necessary using water from the mains. Table 2 lists other key parameters related to the solar thermal water heating system, including parameters that were tuned to match experimental data.

The 454 L tank is the largest one simulated in this work, and a preliminary study was conducted to assess the sensitivity of the number of nodes used on the results. This study considered the predicted electrical energy consumption and thermal energy delivery in the month of January. Simulations were conducted with the tank partitioned into equally sized zones numbering from 3 to 50. The results converged when 15 nodes were used to model the tank. Because this tank is the largest considered in this research, it is assumed that it is the most likely one to be stratified and that fifteen nodes will suffice for simulation of other tank configurations.

2.2.3. Heat pump water heater—The HPWH removes water from the bottom of the tank (node 13) at a rate of 454 kg/h and returns it to the same node after being heated by the heat pump component of the HPWH. Mains water is introduced in node 13, and hot water is delivered to the fixtures from the top node. Two tank sizes are considered: a 189 L (50 gal) tank with a height of 1.14 m and a 303 L (80 gal) tank with a height of 1.32 m. A 3600 W electric resistance heating element is located in the fifth node from the top of the unit. The heating element and heat pump do not operate at the same time. If the temperature sensor located in node 5 drops below 32.2 °C (90 °F), the element will be energized. That element will turn off when the temperature in that node reaches 53.4 °C (128 °F). When the heating element is off, the heat pump unit turns on when the temperature in node 13 drops below 47.9 °C (118 °F) and turns off when it reaches 50.1 °C (122 °F). These control points were determined based on information from the manufacturer and laboratory tests. Different HPWHs will likely have different control schemes.

Experimental data were collected on the same model of HPWH that was used in the NZERTF in order to provide test data to verify the simulations. The control algorithm noted in the previous paragraph was determined from these experiments. The measured standby power of 6.92 W is included in the model. Additionally, a laboratory test of the same model of water heater was carried out to determine the coefficient of performance (COP) as a function of stored water temperature for the heat pump as done by Sparn et al. [29]. These data were compared to the TRNSYS heat pump water heater performance map obtained
with an average inlet water temperature of 32.2 °C (90 °F), ambient air temperature of 21.7 °C (71 °F), and ambient relative humidity of 40%, which are representative of the conditions seen in operation. This map was adjusted to better match experimental data. Fig. 4 shows the small discrepancy between the measured COP and the COP predicted by the adjusted performance map in TRNSYS.

2.2.4. Tankless water heater—Option 8 of Table 1 includes an electric tankless water heater (TWH) used as a backup to the solar thermal system. This model has two stages of heating (12.5 kW and 25 kW) and a standby power draw of 2 W. The heat loss coefficient was determined based on data from Glanville et al. [30] for gas tankless water heaters when the power vent fan was off. Based on data observed during testing of such a unit, it was determined that the number is representative of the heat loss coefficient of the electric tankless unit being simulated.

2.2.5. Distribution piping—Distribution piping from the mains to the water heater and from the water heaters to the fixtures is identical for all configurations. The piping from the mains to the water heater has an inner diameter of 2.54 cm (1 in.) and a length of 7.4 m (24 ft). There is no insulation on this pipe, and the resulting heat loss coefficient is 13.1 W/(m²K). The piping from the water heater to the fixtures is modeled as two separate lines, one feeding the first floor and the second feeding the second floor. Both of these pipes have an inner diameter of 1 cm (0.4 in.). The pipe to the first floor has a length of 8.3 m (27 ft), and the pipe to the second floor has a length of 12.1 m (40 ft). The pipes are insulated with a resulting heat loss coefficient of 1.96 W/(m²K).

2.2.6. Usage pattern and ambient conditions—The water heaters are modeled to be in the basement of the NZERTF. Hourly average measured basement temperatures and relative humidity are used as inputs to the models. The basement is within the conditioned space of the house, with temperatures ranging between 19 °C (66 °F) in the winter and 22.5 °C (72.5 °F) in the summer. Relative humidity ranges from approximately 10% to 60%. The performance of the solar water heating system is dependent upon weather; for these simulations, typical meteorological year (TMY3) data [31] from Sterling, Virginia are used. Water mains temperature is estimated using soil properties provided by [32] and soil temperature data obtained from the United States Department of Agriculture [33].

Each water heating configuration is subject to the same usage pattern that was implemented in the NZERTF over the course of a year of testing to represent the usage of a typical family of four. The pattern is based on the work of Hendron and Burch [34] and consists of sink draws, showers, baths, clothes washer cycles, and dishwasher cycles. The total volume used per week is 2229 L (589 gal). Table 3 shows a breakdown of the water draw events per week [19]. The temperature setpoints of fixtures, 41 °C (105 °F) for sinks and 43 °C (110 °F) for showers and baths, are based on information from the ASHRAE Handbook [35]. The simulations use a 1 min timestep for a total duration of 13 months starting on January 1. The first month is a pre-conditioning period and is omitted from the analysis.
3. Results

3.1. Water heating efficiency

Each configuration was simulated as if it were operating in the NZERTF for a period of one year. The load met by each DHW system is calculated as \( Q_{\text{del}} = \int c (T_{\text{out}} - T_{\text{in}}) \, dt \), where \( c \) is the mass flow rate of water leaving the system before being mixed with cold water to meet the required set point, \( T_{\text{out}} \) is the specific heat of water, \( T_{\text{out}} \) is the outlet temperature from the water heating system prior to being mixed with cold water to meet the required set point, and \( T_{\text{in}} \) is the inlet water temperature to the water heating system. Fig. 1 displays sensor locations on the as-built SWH + HPWH configuration. The efficiency of each configuration will be expressed as a Coefficient of Performance of the system, \( \text{COP}_{\text{sys}} = Q_{\text{del}} / E_{\text{tot}} \), where \( E_{\text{tot}} \) is the total electrical energy used by the water heating system. Table 4 provides the annual load \( (Q_{\text{del}}) \), electrical energy usage \( (E_{\text{tot}}) \), and \( \text{COP}_{\text{sys}} \) for each water heating configuration that was studied. A key feature to note is that the load varies less than 0.7% among the options, indicating that the simulation imposes nearly identical demands on each one. The most efficient options are found to be the solar water heater paired with the heat pump water heater (Options 6 and 7), which is approximately 3 times more efficient than the base case; little difference is found between the use of the 189 L and the 303 L solar storage tank. It is noted that only a single, typical size solar collector pair was examined in this study and that the performance of the system would depend upon collector size. The heat pump water heaters (Options 4 and 5) are the next most efficient, followed by the pairing of the solar tanks and the tankless (Option 8) and the solar tanks with the internal resistance elements (Options 2 and 3). Little difference is observed between solar tanks or heat pump water heaters of different storage volume.

Fig. 5 plots the monthly \( \text{COP}_{\text{sys}} \) for each of the 8 systems simulated. The resistance water heater maintains a steady \( \text{COP}_{\text{sys}} \) throughout the year; its \( \text{COP}_{\text{sys}} \) drops slightly in the summer because \( Q_{\text{del}} \) decreases due to a higher value of the water mains temperature, \( T_{\text{in}} \), without a proportional decrease in \( E_{\text{tot}} \). The total electrical energy consumption, \( E_{\text{tot}} \), is comprised of energy required to both heat the delivered water and maintain the stored water at delivery temperature. Since the latter requirement is relatively stable throughout the year, that portion of \( E_{\text{tot}} \) changes little from winter to summer, and therefore its reduction is not proportional to the reduction in \( Q_{\text{del}} \) that occurs in the summer months. HPWHs also show a decrease in efficiency in the summer because of this effect. The \( \text{COP}_{\text{sys}} \) of the solar water heaters increase in the summer because of more hours of sunlight and higher panel efficiencies. In winter months, the systems must rely more on backup options to provide that load. The system inefficiency due to resistance heating is seen for the SHW and SHW + TWH configurations during these months.

Table 5 shows energy used by each component of the systems, including standby energy use of the HPWH controls. In all cases with a SHW, the heating element energy use exceeds that required by the circulating pumps. The pumps use less energy when heating elements are located inside the solar tanks since, at times, those elements do not allow the large temperature differential that activates the pumps. Results indicate that the heating elements
did not activate in the larger HPWH, but the heat pump energy is higher due to greater standby losses of the larger tank.

3.2. Impacts on space conditioning

In all systems, there is heat transfer to/from the surrounding air that will impact the space conditioning loads. Table 6 shows the annual values of heat flow from each component of the DHW system into the space for each configuration. Negative values mean that heat is added to the component or overall system from the surroundings. The tank loss from the solar and heat pump tanks is a positive number, with the number being greater for larger tanks. There is heat transfer from the surroundings into the pipe from the mains to the water heaters, as the water typically enters below the ambient temperature. The pipes between two tanks are generally hot and give up heat to the surroundings, and the heat pump unit pulls heat from the ambient. Pipes to fixtures lose heat to the surroundings. Overall, the configurations with only a HPWH draw heat from the ambient air, whereas all other configurations resulted in heat being added to the surroundings.

Fig. 6 displays this heat load by month for each system. The combination of solar and HPWH remove heat from the space in the cooler months (on account of heat pump operation), but they add heat to the space during the summer months (on account of higher temperatures in the SHW and lower use of the HPWH). Unfortunately, this trend is opposite of what would be desired from a space conditioning perspective in both the summer and winter. This behavior also appears to a lesser extent with the electric resistance water heater, where the cold water main draws heat from the surroundings in the winter, but that effect is lessened in the summer months due to the warmer mains temperature.

To assess the impact of the heat load from the water heating system on the heat pump used for space conditioning in the house, the average measured heat pump coefficient of performance, $COP_{hp}$, for each month is used to convert the DHW heat load to electric energy required by the space conditioning system to compensate for its operation. The heat pump is modeled to be in heating mode November through April and in cooling mode May through October. Table 7 displays the heat pump $COP_{hp}$ used in the calculations along with the electrical energy required in each month for each system. Total values of additional annual energy consumption by the HVAC system, $E_{HVAC}$, range from 49 kWh for the electric resistance water heater up to 364 kWh for the combination of a large SHW and HPWH.

Using these numbers, a modified annual $COP_{sys}$ is computed for each system that considers both the energy used by the water heater and the heat pump, $COP_{mod} = Q_{del} / (E_{tot} + E_{HVAC})$. Table 8 shows the original $COP_{sys}$ for each configuration computed using only the water heating energy consumption and adds two different $COP_{mod}$’s that also include the energy from the HVAC system when computing $E_{HVAC}$. The first $COP_{mod}$ accounts for heat losses or gains from all components of the water heating system described in Table 7 when calculating $E_{HVAC}$. The second $COP_{mod}$ omits space conditioning energy associated with heat losses or gains from the piping between the main and the water heater and the piping between the water heater and fixtures, as those distribution features can be considered to be outside the system that generates hot water. The electric resistance tank and solar water...
heaters show minor degradation in efficiency. The use of a heat pump leads to the largest decreases in COP, with the HPWH configurations showing a 13% decrease and the SHW + HPWH configurations averaging a 24% drop. Exclusion of pipe heat transfer from the distribution piping increases the modified COP between 2% and 3%.

4. Discussion

The results demonstrate the magnitude of differences from the use of a variety of water heating configurations in an all-electric home located in Gaithersburg, MD under a usage profile typical of a family of four. On an annual basis, the most efficient options considered are the combination of a solar water heater and a HPWH as a backup (Options 6 and 7 from) despite the larger surface area for heat loss from this two-tank solution. This conclusion depends upon the size of the solar collector, and only the size installed in the NZERTF is considered here. This option is also most efficient during every month of the year. Little difference is observed between the 303 L and the 454 L solar storage tanks, though it is acknowledged that this conclusion could vary if the loads were dramatically larger. The HPWH-only configurations are the next most efficient, delivering a steady COP through the year of slightly less than 2, with a dip during the summer months because of the lower thermal load. The solar water heater with an electric tankless backup has a higher efficiency than both configurations with a storage tank with internal resistance elements that are thermostatically controlled. These configurations saw large variations in the efficiency from winter to summer, with the COP dropping to approximately 1 in the winter and approaching 2.5 to 3 in the summer.

It is valuable to compare these results to those from Maguire [15], where electric resistance, solar with resistance backup, and HPWH performance were examined. The case that most closely resembles the present study is the one in which Maguire simulated performance in Atlanta with a high use water scenario. Annual estimates of the energy consumption of the electric resistance and HPWH in the two studies are within 20% of each other despite the difference in water consumption, weather conditions, and equipment specifications. The solar water heating system has a larger difference in estimated annual energy consumption, with the results here exceeding those in Maguire by 40%. A number of issues may lead to such a discrepancy: (a) the tilt angle of the solar panels in the current study is 18.4° compared to the more optimal 27° in the Maguire study, thereby making the solar fraction lower and the electric heating higher in the present work, and (b) the usage in the present study is larger, causing a greater need for resistance heat. Despite these differences, both the present study and [15] found the HPWH to be the best choice for this situation among the three options considered by both investigations. It should be noted, however, that Maguire found the solar option to be the most optimal for lower usage levels.

These water heating results should be considered along with space conditioning impacts, as HPWHs draw significant amounts of heat from the surroundings with the utilization of the air-to-water heat pump, while storage tanks continuously lose heat to the air. When considering these impacts, the performance of the best configuration was less favorable, especially considering that it drew heat from the space in the heating season and added it to the space in the cooling season. The findings suggest that there may be particular situations
where the HPWH would have higher efficiency if it were placed in an unconditioned space. That analysis would depend upon the availability of space, the need for freeze protection, the difference in standby heat loss, and the modified heat pump unit performance. Regardless, the efficiency of this system with a heat pump as space conditioning equipment still exceeded a standard resistance water heater by a factor of 2.4 and a standalone HPWH by a factor of 1.3.

This study considers selected water heating alternatives under a single use pattern in a single location implemented in the NZERTF. Further work could consider these options under alternative use cases and under different climatic conditions. Additionally, the HVAC system implemented in the NZERTF is a high efficiency heat pump, and different results would likely be obtained with other types of space conditioning equipment. Finally, heat pump water heaters have been introduced with Coefficients of Performance exceeding 3, and this level of performance will likely alter the overall system efficiency.

5. Conclusion

A computer model of a water heating system used in a net-zero energy residence was developed and used to assess the performance of alternative configurations under the same use pattern. The original setup, with a solar thermal water heater feeding a heat pump water heater, was found to be the most efficient, with a COP$_{sys}$ of 2.87. Use of a larger solar thermal tank made negligible difference in the results. The heat pump water heaters were the next most efficient option, with minimal difference between the 189 L and 303 L sizes. A drawback of the solar + HPWH configuration is the additional space conditioning load, where heat is added to the space in the summer from losses from storage tanks and piping, while heat is removed from the space in the winter because of the long runtimes of the HPWH’s refrigeration system. This factor lowers the effective COP of the system, which considers HVAC energy consumption, by 24%, while the effective COP for a standalone HPWH is reduced by 13%. Regardless, the solar + HPWH was still the most efficient approach even when HVAC energy consumption is considered, with its modified COP exceeding that of the HPWHs by 35%.

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Fig. 1.
Schematic of solar thermal and heat pump water heaters installed in NZERTF. Diamonds with a “T” indicate temperature measurement locations in the stream of fluid flow and diamonds with “F” show flow measurement locations.
Fig. 2.
Monthly energy consumption of each portion of the Domestic Hot Water (DHW) system.
Notes: (1) the solar thermal pumps were not operational from Aug. 24 to Sept. 3 and (2) the HPWH ran only in resistance mode from Nov. 25 through Dec. 5.
Fig. 3.
Schematic of solar water heating system.
Fig. 4.
Measured COP vs. TRNSYS estimate of the COP.
Fig. 5.
Monthly COP for Each DHW System.
Fig. 6.
Thermal Energy Transferred to Ambient Air by DHW System.
## Table 1

Water heater options considered.

| Option | Primary Water Heater | Secondary Water Heater |
|--------|----------------------|------------------------|
| 1      | 189 L (50 gal) electric resistance water heater, 3800 W heating element | n/a |
| 2      | 303 L (80 gal) solar water heater (SWH), 4500 W electric heating element | n/a |
| 3      | 454 L (120 gal) solar water heater, 4500 W electric heating element | n/a |
| 4      | 189 L (50 gal) heat pump water heater (HPWH), 3600 W electric backup heating element | n/a |
| 5      | 303 L (80 gal) heat pump water heater, 3600 W electric backup heating element | n/a |
| 6      | 303 L (80 gal) SWH, electric heating elements disabled | 189 L (50 gal) HPWH, 3600 W electric backup heating element |
| 7      | 454 L (120 gal) SWH, electric heating elements disabled | 189 L (50 gal) HPWH, 3600 W electric backup heating element |
| 8      | 303 L (80 gal) SWH, electric heating elements disabled | 25 kW Electric Tankless Water Heater |
### Table 2

Parameters for simulation of solar water heating system.

| Parameter                                      | Value                  |
|------------------------------------------------|------------------------|
| Piping Length                                  |                        |
| From Mains to water heater                     | 7.4 m                  |
| Outdoor to/from collector                      | 6.1 m                  |
| Indoor to/from solar storage tank              | 15.2 m                 |
| From water heater to first floor fixtures      | 8.3 m                  |
| From water heater to second floor fixtures     | 12.1 m                 |
| Piping Heat Loss Coefficient, insulated        | 1.96 W/(m$^2$ K)       |
| Piping Heat Loss Coefficient, uninsulated      | 13.1 W/(m$^2$ K)       |
| Heat Exchanger Effectiveness                   | 0.44                   |
| Brine pump rated flow rate                     | 196 kg/h               |
| Brine pump rated power                         | 80 W                   |
| Water pump rated flow rate                     | 999 kg/h               |
| Water pump rated power                         | 80 W                   |
| Heat Loss Factor, solar tank                   | 1.0 W/(m$^2$ K)        |
|            | Water Draw per Event (L) | Length of Water Draw (min) | Number of events per week | Water Temperature (°C) |
|------------|--------------------------|----------------------------|---------------------------|------------------------|
| Sinks      | 2.4                      | 1                          | 280                       | 40.6                   |
| Bath       | 113.6                    | 10                         | 2                         | 43.3                   |
| Short Shower | 33.1                    | 5                          | 21                        | 43.3                   |
| Long Shower | 53.0                     | 8                          | 5                         | 43.3                   |
| Clothes Washer | 56.7                   | 7                          | 6                         | 23.8                   |
| Dishwasher | 6.8                      | 3                          | 5                         | 48.9                   |
Table 4

Annual Performance of each DHW System.

| DHW System | Load, Q del [kWh] | Total Energy Consumed, E tot [kWh] | COP<sub>sys</sub> |
|------------|-------------------|-----------------------------------|-----------------|
| Option     | Description       |                                   |                 |
| 1          | Baseline          | 3420                              | 3613            | 0.95            |
| 2          | 303 L SHW         | 3398                              | 2451            | 1.39            |
| 3          | 454 L SHW         | 3403                              | 2451            | 1.39            |
| 4          | 189 L HPWH        | 3409                              | 1795            | 1.90            |
| 5          | 303 L HPWH        | 3412                              | 1852            | 1.84            |
| 6          | 303 L SHW + HPWH  | 3402                              | 1184            | 2.87            |
| 7          | 454 L SHW + HPWH  | 3402                              | 1187            | 2.87            |
| 8          | 303 L SHW + TWH   | 3408                              | 1986            | 1.72            |
Table 5

Analysis of Annual Energy Consumed by Each DHW System (kWh).

| DHW System          | Total Energy | Circulating Pump Energy | Heating Element(s) Energy | Heat Pump Energy | TWH Energy | HPWH Standby Energy |
|---------------------|--------------|-------------------------|---------------------------|------------------|------------|---------------------|
| Option              | Description  |                         |                           |                  |            |                     |
| 1                   | Baseline     | 3613                    | 3613                      |                  |            |                     |
| 2                   | 303 L SHW    | 2451                    | 300                       | 2151             |            |                     |
| 3                   | 454 L SHW    | 2451                    | 327                       | 2124             |            |                     |
| 4                   | 189 L HPWH   | 1795                    | 49                        | 1698             | 48         |                     |
| 5                   | 303 L HPWH   | 1852                    | 0                         | 1805             | 48         |                     |
| 6                   | 303 L SHW + HPWH | 1184                | 410                       | 2                | 716        | 56                  |
| 7                   | 454 L SHW + HPWH | 1187                | 412                       | 2                | 717        | 56                  |
| 8                   | 303 L SHW + TWH | 1986                | 408                       |                  |            | 1583                |
Table 6

Thermal energy transfer from different components of each system; positive numbers indicate heat transfer to ambient air (kWh).

| Option | Description       | DHW System | SHW Tank | HPWH Tank | TWH | Mains Pipe | Pipe Btw Tanks | PG Pipe | Heat Pump | Pipes to Fixtures | Net  |
|--------|-------------------|------------|----------|-----------|-----|------------|----------------|---------|-----------|------------------|------|
| 1      | Baseline          |            | 184      |           |     |            |                |         |           |                  |      |
| 2      | 303 L SHW         |            | 594      |           |     |            |                |         |           |                  | 835  |
| 3      | 454 L SHW         |            | 761      |           |     |            |                |         |           |                  | 981  |
| 4      | 189 L HPWH        |            | 240      |           |     |            |                |         |           |                  | 919  |
| 5      | 303 L HPWH        |            | 338      |           |     |            |                |         |           |                  | 1782 |
| 6      | 303 L SHW + HPWH  |            | 338      | 267       |     |            |                |         |           |                  | 160  |
| 7      | 454 L SHW + HPWH  |            | 430      | 269       |     |            |                |         |           |                  | 160  |
| 8      | 303 L SHW + TWH   |            | 341      | 274       |     |            |                |         |           |                  | 812  |
Table 7
Electrical Energy Required by HVAC System to Make Up DHW System Losses for each option considered.

| HVAC Heat Pump COP |  |  |  |  |  |  |  |  |
|-------------------|---|---|---|---|---|---|---|---|
|                   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Conv. Water Heater (kWh) | 303 L SHW (kWh) | 454 L SHW (kWh) | 189 L HPWH (kWh) | 303 L HPWH (kWh) | 303 L SHW + HPWH (kWh) | 454 L SHW + HPWH (kWh) | 303 L SHW + TWH (kWh) |
| January 1.72 | 6 | -18 | -24 | 111 | 110 | 67 | 66 | -12 |
| February 2.17 | 5 | -17 | -22 | 83 | 83 | 34 | 34 | -11 |
| March 2.19 | 6 | -26 | -30 | 91 | 90 | 16 | 14 | -20 |
| April 2.23 | 3 | -33 | -38 | 79 | 77 | -5 | -7 | -30 |
| May 3.39 | 0 | 28 | 32 | -45 | -44 | 18 | 21 | 28 |
| June 3.05 | 3 | 36 | 40 | -40 | -38 | 32 | 36 | 38 |
| July 3.03 | 5 | 41 | 46 | -34 | -32 | 40 | 45 | 44 |
| August 2.89 | 7 | 42 | 46 | -31 | -29 | 41 | 45 | 45 |
| September 2.71 | 7 | 40 | 44 | -34 | -32 | 32 | 36 | 42 |
| October 2.15 | 6 | 42 | 48 | -52 | -49 | 20 | 23 | 42 |
| November 2.1 | -2 | -28 | -34 | 63 | 61 | 16 | 15 | -26 |
| December 2.32 | 2 | -18 | -23 | 73 | 71 | 39 | 39 | -15 |
| Total | 49 | 89 | 85 | 264 | 267 | 349 | 364 | 122 |
Table 8
COP for each configuration with and without consideration of HVAC energy consumption.

| DHW System | COP<sub>sys</sub> | Modified COP (including heat transfer from distribution piping) | Modified COP (excluding heat transfer from distribution piping) |
|------------|------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| 1 Baseline | 0.95             | 0.93                                                          | 0.95                                                          |
| 2 303 L SHW| 1.39             | 1.34                                                          | 1.36                                                          |
| 3 454 L SHW| 1.39             | 1.34                                                          | 1.37                                                          |
| 4 189 L HPWH| 1.90             | 1.66                                                          | 1.70                                                          |
| 5 303 L HPWH| 1.84             | 1.61                                                          | 1.65                                                          |
| 6 303 L SHW + HPWH| 2.87 | 2.22                                                          | 2.29                                                          |
| 7 454 L SHW + HPWH| 2.87 | 2.19                                                          | 2.26                                                          |
| 8 303 L SHW + TWH| 1.72 | 1.62                                                          | 1.65                                                          |