The Performance of an Auxiliary Heat Pump Water Heater Installed in a Dual-Tank System in a Net-Zero Energy Residence

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ABSTRACT

In the effort to achieve low-energy operation of residential buildings, advanced water heating technologies are vitally important. This paper explores the year-long performance of a 189 L (50 gal) heat pump water heater (HPWH) serving as an auxiliary unit to an active, indirect solar thermal water heater with a 303 L (80 gal) storage tank in a net-zero energy test home located in Gaithersburg, MD, USA. The systems were subjected to a representative water use schedule for a virtual family of four between July 2013 and June 2014. We investigate the effect of inlet water temperature on the overall system Coefficient of Performance (COP_{sys}) of the HPWH and the unit's space conditioning impact, as these factors can vary substantially depending on the extent to which hot water demand is met by the solar thermal water heater. Field testing showed that the installed HPWH used 1104 kWh in the year and had a COP_{sys} of 1.41, not reaching the manufacturer's reported Energy Factor (EF) of 2.33 over the course of the 12-month testing period. The difference was largely due to the fact that the hot water load delivered by the unit was much less than if it were the sole water heater. The study of a HPWH in this unique configuration is valuable considering regulatory trends away from electric resistance storage water heaters, such as current standards in the United States that require EFs greater than 1.9 for electric water heaters with storage volumes greater than 208 L (55 gal).

INTRODUCTION

Water heating is the second largest energy consumer in homes, amounting to 18 % of the total energy use in residences (DOE 2012). For a high performance home, particular attention needs to be paid to minimizing all loads such that renewable technologies can provide the energy required to operate space heating and cooling equipment, water heaters, appliances, lighting, and plug loads. The Net-Zero Energy Residential Test Facility (NZERTF), a detached single-family test home built in Gaithersburg, Maryland, used the most energy efficient commercially-available water heating technologies. The primary means of water heating is accomplished with a solar thermal water heater. During times when solar irradiance is low or when hot water demand is high, this system would normally engage electric resistance elements in its storage tank for auxiliary heating. However, in the case of the NZERTF, auxiliary heating is instead provided by a heat pump water heater (HPWH) located downstream of the solar storage tank, making this a dual-tank water heating system. A two-tank configuration with an electric resistance water heater is not unusual, but the purpose of this paper is to provide data on how a HPWH performs in this scenario.

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HPWHs use a vapor compression cycle to draw heat from the ambient air to heat water. Their recent popularity is highlighted by a U.S. Department of Energy (DOE) report stating that shipments of Energy Star® qualified integrated HPWHs increased 630 % between 2006 and 2009 (DOE 2010b). The presence of HPWH technology will increase furthermore in upcoming years due to DOE efficiency standards that require electric storage water heaters above 208 L (55 gal) to have a minimum Energy Factor (EF) of at least 1.9, depending upon storage volume (DOE 2010a).

In this paper, data from a field-tested HPWH in a dual-tank solar water heating system are provided to show how the increased inlet temperature affects its overall performance, and estimates are provided for comparison to an electric resistance unit that could be installed for auxiliary water heating in its place.

NZERTF DOMESTIC WATER HEATING

The NZERTF uses an active, closed-loop solar thermal system as its primary method for water heating. The system utilizes two solar collectors (1.1 m (3.8 ft) by 2.0 m (6.6 ft)) aperture dimensions, facing true south at an 18.4° tilt) and a 303 L (80 gal) storage tank with its auxiliary heating element disabled. In its stead, a 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 source heat pump and two 3800 W electric elements.

The HPWH was operated in the "Hybrid" mode with a temperature set-point of 48.9 °C (120.0 °F). The control logic of the HPWH in Hybrid mode is as follows: When the differential between the set-point temperature and the reading of a temperature sensor located in the top portion of the tank is 16.7 °C (30.0 °F) or more, the heat pump will turn off and the 3800 W top element will be energized. Once the top temperature sensor reading reaches the set-point, the element turns off and the heat pump comes on to heat the remainder of the tank (i.e., until the reading of the sensor at the bottom portion of the tank also reaches the set-point). While the HPWH has a second 3800 W electric element, it is not energized in this mode.

Hybrid mode ensures that the heat pump provides a majority of the hot water load while electric resistance is enlisted only when the heat pump cannot provide enough hot water. In the Hybrid mode, under test conditions of 57.2 °C (135.0 °F) set-point temperature and 19.7 °C (67.5 °F) ambient temperature, the manufacturer-reported EF, Coefficient of Performance (COP), and standby loss are 2.33, 2.36, and 0.20 °C/h (0.36 °F/h), respectively.

WATER USE CONTROL AND MONITORING

The NZERTF was used to demonstrate that a home similar in size and amenities to those in the surrounding community could generate as much energy through onsite renewable sources as used by a typical family of four (Fanney et al. 2015). The family was in fact a virtual family whose water-use and electricity-use behaviors were automated according to a weekly schedule derived from the Building America Research Benchmark Definition (Hendron and Engebrecht 2008). Over the course of each day, 44 water draws were initiated at the sinks, showers, and baths in the house by a real-time event controller according to a water draw schedule described by Omar and Bushby (2013). The clothes washer was initiated for two cycles each on three days of the week, and the dishwasher was initiated for a single cycle five days a week. Approximately 2570 L (680 gal) of mixed hot and cold water were utilized in the house per week.

The water temperature at the inlet and outlet of the HPWH storage tank and the ambient temperature were measured with immersed Type-T thermocouples with a calibrated uncertainty (k=2) of ± 0.1 °C (± 0.2 °F). The water flow through the solar thermal storage tank and the heat pump water heater was measured by pulse-output paddle-type flow meters with a resolution of 0.013 gal/pulse (0.049 L/pulse) and a calibrated uncertainty (k=2) within ± 1.7 % of reading. HPWH power was measured at the circuit breaker using current transformers with an uncertainty (k=2) that did not exceed ± 2 % of reading, and electrical energy use was determined from a time integration of power. Solar irradiance was measured with a pyronometer in the plane of the thermal collector array. Temperature and flow data were collected by the house data acquisition system and thermal energy calculations were made at 3-s intervals during water draw events, while the electrical energy data and ambient conditions were recorded every minute.

RESULTS AND DISCUSSION

Heat Pump Water Heater Efficiency

Table 1 shows monthly HPWH performance data for the year of testing. As a result of solar insolation and, thus, the water heating contribution of the solar thermal system varying monthly, the average HPWH inlet water temperature, $T_{HPWH,in}$, during times of draws ranged from a minimum of 23.3 °C (74.0 °F) in December to a maximum of 46.1 °C (114.9 °F) in June. This inlet temperature impacted the amount of time the heat pump and the heating elements operated according to the control logic explained above. The heat pump monthly total runtime ranged from a minimum of 57 h in June to a maximum of 178 h in January. The heating elements were inactive for all of June and active most often in November (partly on account of a defect with the heat pump unit). Likewise, the total electrical energy used by the HPWH, E_{HPWH}, ranged from 45 kWh in July to 156 kWh in December. The result was that the thermal energy contributed by the HPWH, $Q_{del,HPWH}$, reached its low in the summer (35 kWh in June) and peaked in the winter (244 kWh in December), as the solar thermal water heater's capacity to meet the virtual family's hot water demand changed seasonally. Q_{load} is the total energy in hot water delivered to fixtures and water-utilizing appliances.

The overall system Coefficient of Performance, COP_{sys}, is an efficiency metric that is the ratio of thermal energy delivered by the HPWH, $Q_{del,HPWH}$, to the electrical energy used to produce it, E_{HPWH}, computed as follows:

$$COP_{sys} = \frac{m \cdot c_p \cdot (T_{HPWH,out} - T_{HPWH,in})}{E_{HPWH}} \tag{1}$$

where m is the mass of hot water delivered to the fixtures, c_p is its specific heat, $T_{HPWH,out}$ is the outlet water temperature of the HPWH, and $T_{HPWH,in}$ is the inlet water temperature. The COP_{sys} is akin to the EF, although the rated EF is measured under specific test conditions outlined below from which the present HPWH operation deviates. HPWHs generally have EFs above 2.0 since the work done by the heat pump extracts heat from the surrounding air for water heating and the manufacturer of the NZERTF unit reports an EF of 2.33. Monthly COP_{sys} indicate that this level of efficiency is never reached; the COP_{sys} did not surpass 1.68 (January).

According to the DOE test method for rating residential water heaters in place at the time of the manufacturer's rating (DOE 2010a), HPWHs were subjected to a 24-h simulated use test where 243 L (64.3 gal) of hot water was drawn, maintaining the inlet temperature at 14.4 °C (58.0 °F) and the set-point at 57.2 °C (135.0 °F), for a target temperature rise of 42.8 °C (77.0 °F). As shown in Table 1, the average temperature rise (difference between the inlet and outlet water temperatures) was as low as 4.6 °C (8.3 °F) and as high as 25.4 °C (51.2 °F). As the mass of water drawn on a daily basis also changed depending on the day of the week, the daily thermal output of the HPWH, $Q_{del,HPWH}$, ranged from -2.0 kWh to 12.7 kWh, rather than being fixed at $Q_{del,sim\ use}$ = 11.9 kWh as it is during the 24-hour simulated use test. Figure 1 shows the daily COP_{sys} between July 2013 and June 2014 as a function of $Q_{del,HPWH}$. It should be noted that these data do not account for any changes in stored energy within the tank from the start to the end of the day. The hollow diamond symbols serve to differentiate the days in which electric resistance was used from the days in which only the heat pump operated (solid diamonds). The manufacturer-reported EF at $Q_{del,sim\ use}$ is placed on the plot (solid circle) as a reference to the HPWH performance under rating conditions.

Table 1. Monthly Heat Pump Water Heater Performance, July 2013 – June 2014

Month	Solar Insolation [kWh/m²]	$T_{basement}$ [°C] ([°F])	RH [%]	$T_{HPWH,in}$ [°C] ([°F])	$T_{HPWH,out}$ [°C] ([°F])	HP Run Time [h]	Elmnt. Run Time [h]	Q_{load} [kWh]	$Q_{del,HPWH}$ [kWh]	E_{HPWH} [kWh]	COP_{sys}
Jul[a]	152	21.6 (70.8)	52.2	43.2 (109.8)	51.6 (124.9)	56	0	252	42	45	0.93
Aug[a,b]	123	21.7 (71.0)	51.4	35.7 (96.3)	51.8 (125.3)	86	2	218	108	71	1.52
Sep	158	22.1 (71.9)	51.9	41.8 (107.2)	51.5 (124.7)	69	1	238	68	57	1.20
Oct	114	21.2 (70.2)	51.6	37.6 (99.6)	51.6 (124.9)	105	1	269	119	82	1.44
Nov[c]	102	20.4 (68.8)	41.2	30.5 (86.9)	52.0 (125.6)	113	11	283	172	130	1.32
Dec[c]	73	20.1 (68.1)	38.0	23.3 (74.0)	51.8 (125.2)	160	10	326	244	156	1.56
Jan	101	19.8 (67.6)	31.4	23.7 (74.6)	51.3 (124.4)	178	4	343	240	143	1.68
Feb	98	19.5 (67.2)	30.7	25.6 (78.0)	51.3 (124.3)	153	4	330	208	125	1.66
Mar	117	19.5 (67.1)	30.6	28.8 (83.9)	51.3 (124.3)	149	4	341	187	121	1.55
Apr	153	19.6 (67.3)	40.0	38.9 (102.1)	49.9 (121.9)	92	1	300	84	73	1.16
May	161	20.8 (69.4)	51.6	44.2 (111.5)	50.9 (123.6)	69	0[d]	277	55	55	0.99
June	164	21.3 (70.3)	53.3	46.1 (114.9)	50.7 (123.2)	57	0	251	35	46	0.77
Year Total	**1518**					**1287**	**38**	**3428**	**1563**	**1104**	
Year Avg		**20.6 (69.1)**	**43.6**	**34.9 (94.9)**	**51.3 (124.4)**						**1.41**

[a] Data loss on 7/1/2013 and 8/2/2013 – 8/6/2013; therefore, monthly values in table exclude these days.
[b] Between 8/24/2013 and 9/3/2013, the pumps of the solar thermal water heater heat exchanger were not operational due to failure of electrical connection to glycol circulating pump.
[c] Between 11/25/2013 and 12/5/2013, the heat pump of the heat pump water heater was not operational due to a control wire being disconnected.
[d] Resistance element run time in May was not "0" but a very small value rounded to 0.

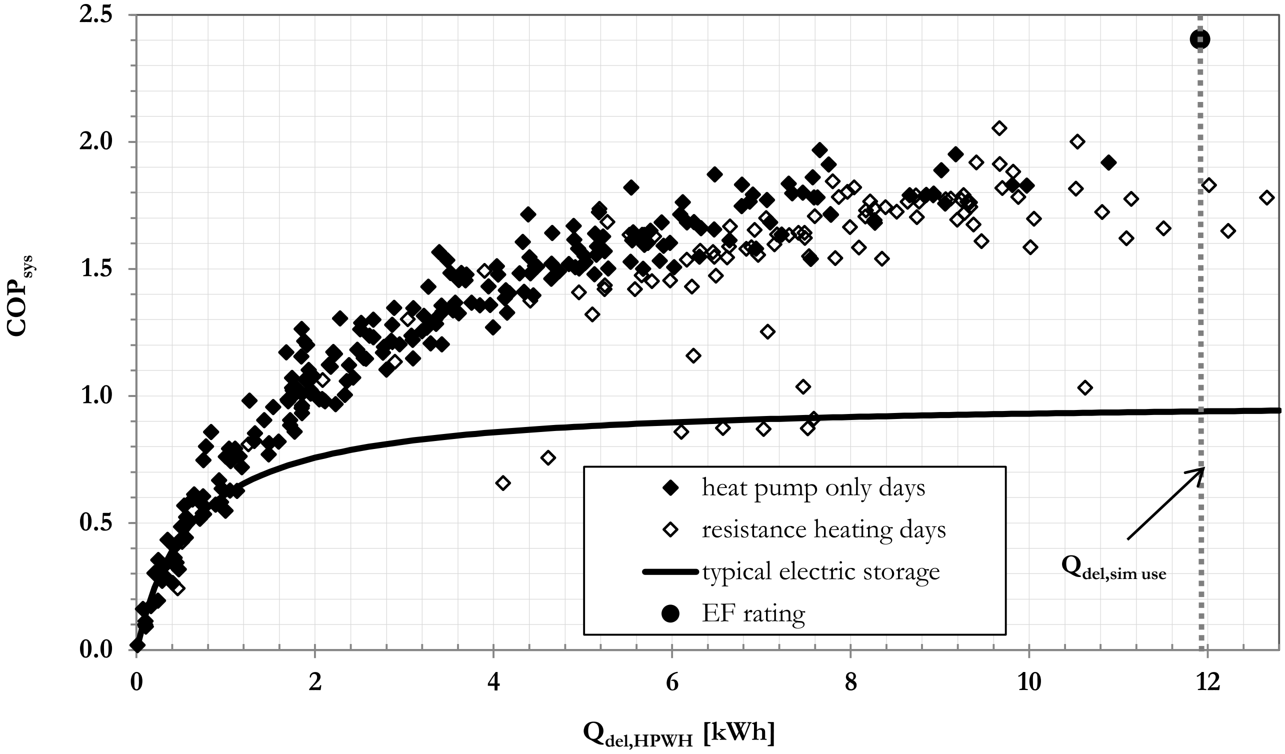

Figure 1 Daily averaged overall system Coefficient of Performance (COP_{sys}) of the heat pump water heater as a function of its thermal output, July 2013 – June 2014.

The overall COP_{sys} of any storage-type water heater will decline as the thermal output of the water heater goes to zero, i.e., as the temperature entering the unit nears the set-point temperature. This condition happens because of two factors: (1) the numerator in Equation 1 goes to zero, and (2) the water heater heater must have a minimum amount of electrical energy input on a daily basis to make up for thermal standby losses. For HPWHs, an added effect is that the refrigerant-to-water heat exchange efficiency decreases as the temperature of the water entering the heat pump compressor increases. While the installed unit is capable of reaching its rated efficiency, it does not operate under the conditions that would allow it to do so for most days of the year.

In addition to the daily COP_{sys} shown in Figure 1, the data are compared to a COP_{sys} curve (solid black line) that has been calculated for a typical electric storage water heater using equations from the Water Heater Analysis Model (WHAM) (Lutz et al. 1998). This theoretical unit has a rated EF of 0.95 and recovery efficiency, η_{rec}, of 0.98, but it operates with a tank temperature set-point of 48.9 °C (120.0 °F) as is the case for the HPWH under test. At $Q_{del,sim\ use}$, the COP_{sys} of the NZERTF HPWH is 2.5 times greater than the COP_{sys} of an electric storage water heater determined using WHAM to adjust for the different stored water temperature. However, that factor diminishes as the HPWH delivers less thermal energy; at approximately $Q_{del,HPWH} \approx 1$ kWh and below, the COP_{sys} data for the HPWH (diamond symbols) and the electric storage curve (black line) converge. In this range of water heater delivered energy, the HPWH no longer is more efficient than an electric storage water heater. For the period between July 2013 and June 2014, the HPWH delivered less than 1 kWh of thermal energy as hot water for 68 d (19 %) out of the 359 d examined.

Overall Energy Use

The expected benefit of an air-to-water heat pump is that energy usage for water heating can be cut by a factor of 2 or more as determined by rating tests. An electric storage water heater with an EF of 0.95 uses 4622 kWh of electrical energy per year when subject to conditions specified in the DOE test procedure in effect prior to July 2014, and a HPWH with an EF of 2.33 uses 1866 kWh under those same conditions. However, the field-testing discussed here of a HPWH serving as an auxiliary heater to another water heater under typical use conditions indicates that the heat pump water heater efficiency can vary significantly because of deviation from rating test conditions.

For the July 2013 to June 2014 period, the HPWH in the NZERTF used 1104 kWh. To compare to an electric resistance unit, it is estimated using the WHAM model that an electric resistance water heater would have consumed 1851 kWh to deliver the same amount of energy if it were installed in the NZERTF as an auxiliary unit to the solar thermal water heater. At an average residential retail electricity price of $0.12 per kWh (EIA 2015), the heat pump water heater would cost $133 to operate for the year while the electric resistance unit is estimated to cost $222. The HPWH exhibited an overall system Coefficient of Performance of 1.41 for the year, while the electric resistance unit would have had a COP_{sys} of 0.86.

The HPWH fell short of its rating for a number of reasons. First, the delivered energy was much lower than at the rated value. Second, the rated value likely does not include situations when the electric resistance element was activated, since the water draws conducted during the test method do not always activate the elements. Figure 1 shows that for a significant number of days in the year, resistance heating was needed at the NZERTF. Finally, the efficiency of the heat pump's vapor compression system is lower at the higher inlet water temperatures experienced at the NZERTF as compared to the simulated use test. While the rated EF of the HPWH was 145 % greater than the rated value of a resistance water heater, the measured COP_{sys} of the HPWH over the year of operation was only 64 % greater than the estimated COP_{sys} of the resistance water heater. Nevertheless, the use of the HPWH saved $89 over the year compared with an electric resistance unit.

Space Conditioning Impact

Air-to-water heat pump operation extracts heat from the zone in which the water heater is installed. While a detailed analysis of the impacts of the HPWH on space conditioning loads is beyond the scope of this paper, a few points on this topic are worth mentioning. Figure 2 shows how space conditioning is impacted by the temperature of the water entering the HPWH. As detailed in Sparn et. al (2013), $Q_{net,space}$, the net energy added to the space, is determined as follows:

$$Q_{net,space} = Q_{loss} - Q_{air} = E_{HPWH} - Q_{del,HPWH} \qquad (2)$$

where Q_{loss} is energy lost from the tank surface and Q_{air} is heat transferred from the air to the tank via the heat pump. A negative $Q_{net,space}$ means that more energy is being transferred to heat water than is lost to the zone. In Figure 2, the triangular symbols indicate days in which the whole house air-to-air heat pump was in heating mode, while the circular symbols represent days in which the air-to-air heat pump was in cooling mode. Furthermore, the hollow symbols differentiate days in which the electric elements were engaged from the days in which only the air-to-water heat pump alone supplied heat to the water (solid symbols).

The net space conditioning predicted by a linear regression of all data in Figure 2 indicates that, at the test condition of inlet temperature $T_{inlet,sim\ use}$ = 14.4 °C (58.0 °F), 4.34 kWh of heat will be removed from the space (negative $Q_{net,space}$). Thus, 4.34 kWh more energy would have to be supplied to the space by the HVAC system to maintain the basement ambient temperature. Inlet water temperature would only ever be that low when solar thermal water heater output is low in the heating season. There are only 3 d in which the inlet water temperature is at or below $T_{inlet,sim\ use}$ and the $Q_{net,space}$ at the minimum average daily inlet temperature during the testing period was -5.21 kWh.

Additionally, the data indicate that at a daily average inlet water temperature of approximately 43.3 °C (110.0 °F), a changeover occurs where the energy losses from the tank begin to outweigh the energy transfer by the heat pump of the water heater (a positive $Q_{net,space}$). While the HPWH receives incoming water from the solar thermal storage tank over a wide range of temperatures, 13.1 °C (55.5 °F) to 54.7 °C (130.5 °F) between July 2013 and June 2014, respectively, the HPWH inlet temperature exceeded 43.3 °C (110.0 °F) 95 d (26 %) out of 359 d. Those days occurred mostly in the cooling season and, thus, more energy would have to be extracted from the space by the HVAC system as a result of HPWH operation. $Q_{net,space}$ = 1.68 kWh was added to the space by the HPWH on the day of highest inlet water temperature in the testing period.

It should be noted that an electric resistance water heater would only add heat to the space and would not have the ability to remove it. In other words, the $Q_{net,space}$ associated with an electric resistance water heater would always be positive, whereas sometimes the $Q_{net,space}$ associated with a HPWH is positive (generally cooling season) and sometimes it is negative (generally heating season). While the net space conditioning impacts of the HPWH on the zone has been quanitifed above, the degree to which this impacts the heating and cooling loads of the whole house air-to-air heat pump will be studied in the future.

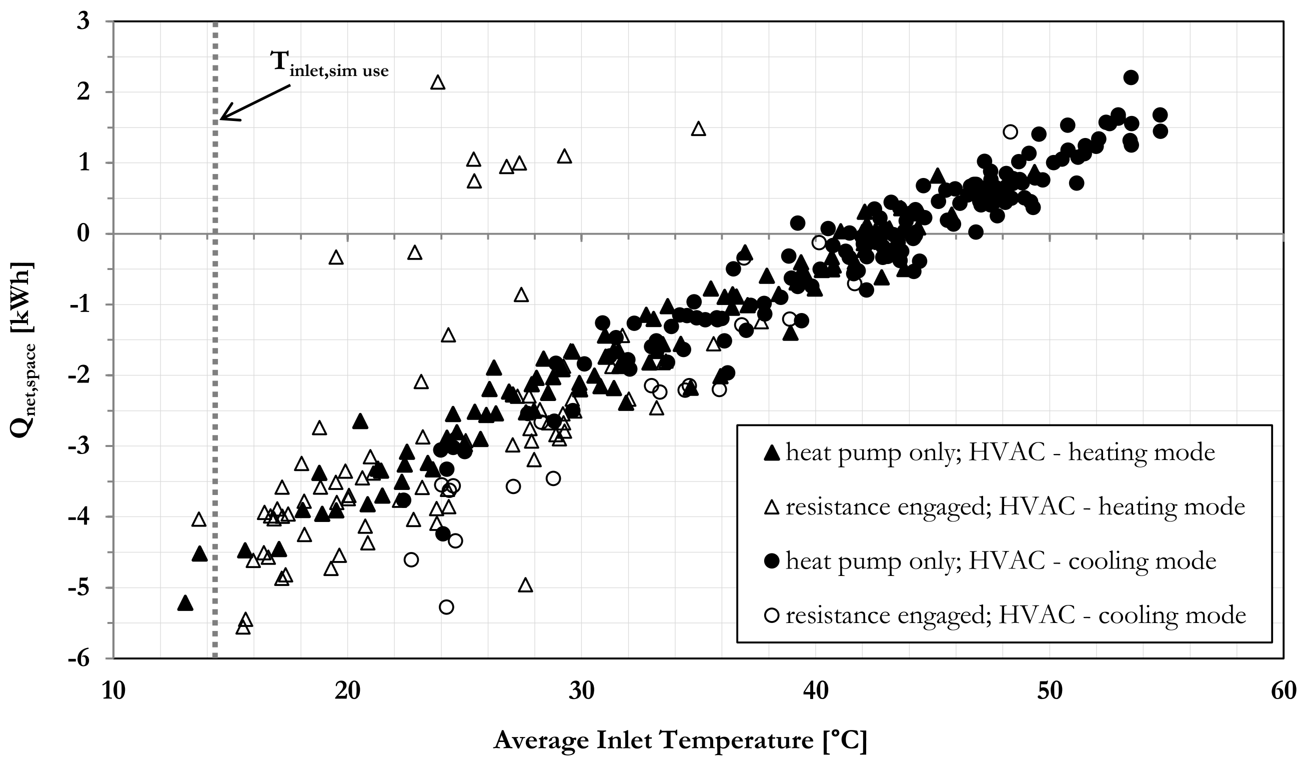

Figure 2 Net thermal energy transferred to basement zone as a function of inlet water temperature, July 2013 – June 2014.

CONCLUSIONS

A dual-tank water heating system that employs a heat pump water heater (HPWH) for auxiliary heating to a solar thermal system used less energy than would be expected with an electric resistance water heater, but exhibited overall system Coefficients of Performance (COP_{sys}) below what ratings data indicate during times when the solar thermal system was providing the majority of hot water required for occupant use. While the rated EF of the unit is 2.33, the average COP_{sys} of the HPWH over a year-long period was 1.41. This decrease is partially due to the fact that the amount of thermal energy delivered by the water heater is much lower than is required during the rating test given a lower temperature rise from inlet to outlet and a lower volume of delivered hot water. The average inlet water temperature of the HPWH was 34.9 °C (94.8 °F) compared to 14.4 °C (58.0 °F) as prescribed in the test procedure, and the average delivered water temperature was 51.3 °C (124.4 °F) compared to the value of 57.2 °C (135 °F) prescribed in the test procedure. An added factor is that the performance of the heat pump unit drops with higher inlet water temperature. With this reduced thermal energy demand, it was estimated that an electric resistance water heater would have operated at an efficiency of 0.86. The average COP_{sys} of the HPWH of 1.41 makes it only 64 % more efficient than a standard electric storage water heater rather than 145 % more efficient as suggested by the ratings. Nevertheless, the annual energy consumption of the HPWH was estimated to be 747 kWh less than what would have been expected if an equivalently sized electric resistance water heater having an EF of 0.95 were installed as an auxiliary water heater to the solar thermal system as opposed to the HPWH. The net energy transferred to the space, $Q_{net,space}$, was found to follow a linear trend with the inlet water temperature. The data indicate that the maximum thermal energy removed from the basement zone during a single day due to HPWH operation is 5.21 kWh, and that day occurred in the heating season. Additionally, the maximum thermal energy added to the basement zone during a single day due to HPWH operation is 1.68 kWh, which occurred in the cooling season. The extent to which $Q_{net,space}$ has an impact on whole-house HVAC operation is to be determined in future research.

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