Effect of Setup Thermostat Schedule on Heat Pump Water Heater Energy Consumption, Coefficient of Performance and Peak Load

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ABSTRACT

The *Energy Conservation Standards for Residential Water Heaters* require residential electric storage water heaters with volumes larger than 55 gallons to have an energy factor greater than 2.0 after April 2015. While this standard will significantly increase the energy efficiency of water heaters, large electric storage water heaters that do not use heat pump technologies may no longer be available. Since utilities utilize conventional large-volume electric storage water heaters for thermal storage in demand response programs, there is a concern that the amended standard will significantly limit demand response capacity. To this end, Oak Ridge National Laboratory partnered with the Tennessee Valley Authority to investigate the load management capability by reducing the peak period energy consumption of heat pump water heaters that meet or exceed the forthcoming water heater standard. Energy consumption reduction during peak periods was successfully demonstrated, while still meeting other performance criteria. However, to minimize energy consumption, it is important to design load management strategies that consider the home's hourly hot water demand so that the homeowner has sufficient hot water.

Introduction

Due to energy conservation mandates, by 2015 electric storage water heaters with volumes larger than 55 gallons will be required to have an energy factor (EF) of higher than 2.0 (DOE 2010). Since utilities utilize conventional large-volume electric storage water heaters for thermal storage in demand response programs, there is a concern that the amended standard will significantly limit demand response capacity. To investigate this issue Oak Ridge National Laboratory (ORNL) and the Tennessee Valley Authority (TVA) used 50 gallon heat pump water heaters (HPWH), with rated EFs of 2.4, to determine the demand response capability of HPWHs. Although the heat pump water heaters being tested were below the 55 gallon minimum of the conservation mandate, the principles of using heat pump water heaters for demand response found in this research will be applicable for all sizes of storage tanks. In fact, it is expected that higher volume tanks will perform better than the 50 gallon tank tested in this research.

Two HPWHs with the capability to reach 170°F tank temperatures utilizing only the heat pump and to receive demand response signals were installed in two unoccupied research homes in east Tennessee. One home called the builder home, is of typical construction and meets the IECC 2006 code. The second home is called the high performance home, and was built to have the highest energy efficiency measures that the local market could support when built. The high performance home has an energy efficient clothes washer and a dishwasher where the builder house has standard appliances. This caused a reduction in the water consumption at the high performance compared to the builder house on days when the laundry and dishwasher were operated. To simulate real water draws the appliances and showers are operated automatically each day. More information on emulating an average family's water draws can be found in Boudreaux, et.al. (Boudreaux 2012). Table 1 shows the summer appliance and shower schedule. The TVA peak demand period for the summer is 1PM to 9PM. Notice that the washer cycles were moved out of the summer peak demand time to reduce hot water consumption during this time.

Since the washer and dishwasher are not operated every day of the week and the high performance house used less hot water for the washer there are different water draw profiles depending on the weekday and the home. Because the washer in the high performance house is ENERGYSTAR® it uses about 11 gallons of hot water less per cycle than the washer in the builder house.

Table 1. Appliance and shower occupancy simulation schedules for the summer

Time of Day	Summer Schedule
7:00	Shower (SMTWRFS)
7:30	Washer (TWR)
8:30	Shower (SMTWRFS)
9:30	Washer (TWR)
12:00	Shower (SMTWRFS)
17:00	Shower (SMTWRFS)
21:00	Shower (SMTWRFS)
22:30	Dishwasher (MTWR)

Table 2 shows the hot water draws for each house for laundry and non-laundry days. Non-laundry days in the builder house will be considered for the low hot water draw days (57 gal) and laundry days will be considered for the high hot water draw days (91 gal). Laundry days in the high performance home are used for the medium hot water draw days (68 gal).

Table 2. Hourly hot water draws for laundry and non-laundry days for the builder and high performance homes (for hours not shown there are no water draws)

	Non-Laundry Days (gallons) (Sun, Mon, Fri, and Sat)		Laundry Days (gallons) (Tues, Wed, and Thurs)	
	Builder	High Perf.	Builder	High Perf.
7 AM	18.7	17.8	33.6	22.5
8 AM	4.7	4.6	4.7	4.6
9 AM	0.2	0.1	15.2	4.3
10 AM	0	0	0.1	0
12 PM	4.7	4.6	4.7	4.6
5 PM	9.2	8.9	9.2	8.9
9 PM	18.2	17.7	18.2	17.7
10 PM	1	0.7	3.6	2.7
11 PM	0.5	0.6	1.8	2.5
Avg. Daily Usage (4/5 - 9/30)	57.2	55	91.1	67.8

This report will focus on the summer time performance of the water heaters since data is only available for this season. The water heater is located in the garage of the builder house and the conditioned space of the high performance house. Since the performance of the heat pump water heater is affected by ambient temperature this will have an effect on the measured energy consumption. The average daily temperature in the builder house garage ranged from 62-79°F during the cooling season. The average daily temperature in the utility room of the high performance house, where the HPWH is located, ranged from 64-74°F during the cooling season. The unit efficiency and energy consumption results included in this report were normalized to account for differences in ambient temperatures. The impact of the indoor HPWH on the space cooling energy was not considered in this report.

Methodology

In order to increase the thermal storage capacity, the thermostat set points of these HPWHs were adjusted to minimize the energy consumption during the peak demand hours. These water heater thermostat schedules were evaluated under the following performance criteria (as compared to the baseline cases of a standard electric water heater and/or the HPWH in standard electric hybrid mode):

- ability to meet all hot water demands,
- peak period energy consumption,
- overall efficiency, and
- overall energy consumption.

Six different tank temperature schedules were investigated at the builder and high performance homes. The first two schedules were used to "level set" the experiment and are therefore not discussed in this report. Figure 1 shows schedules 3 through 5, which investigated different pre-heating schedules. Schedule 6 has a temperature set point of 120 °F with the unit set to use only the heat pump. For each schedule there are three water draw profiles (low, medium and high) that were discussed above. For each schedule the three water draw profiles will be compared.

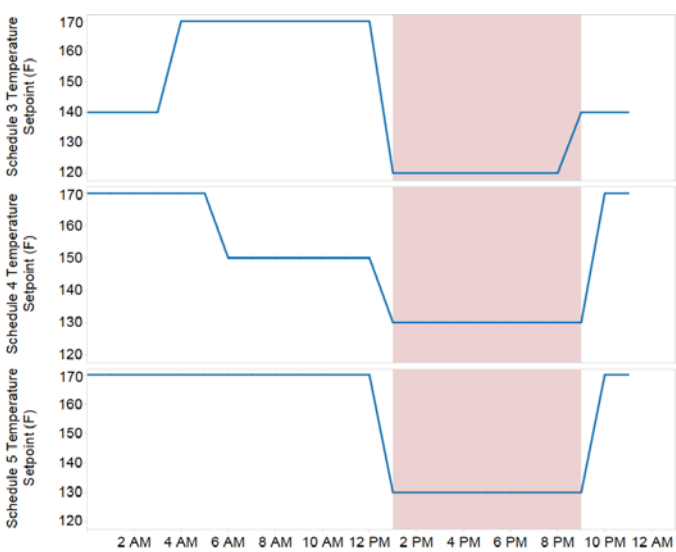

Figure 1. Tank temperature set points for schedules 3-5.

The water consumption discussed in the sections below is the water measured directly from the water heater tank before a mixing valve that tempers the water to approximately 120°F. The tank temperature is measured by a thermocouple attached to the tank near the thermocouple used by the manufacturer to control water heater operation. This position is about 8 inches below the top of the tank. Since the incoming cold water fills the bottom of the tank, while the water draw is pulled from the top of the tank, the tank can become significantly stratified such that the measured tank temperature does not reflect the energy stored in the tank.

Results

Baseline

As a baseline for comparison, the daily energy consumption for the conventional storage water heater originally installed in the builder house was measured at 13.2 kWh and 8.5 kWh for high and low water consumption days, respectively. This is shown in Table 3. During a water heating event, the electric water heater has a power draw of about 4.5 kW.

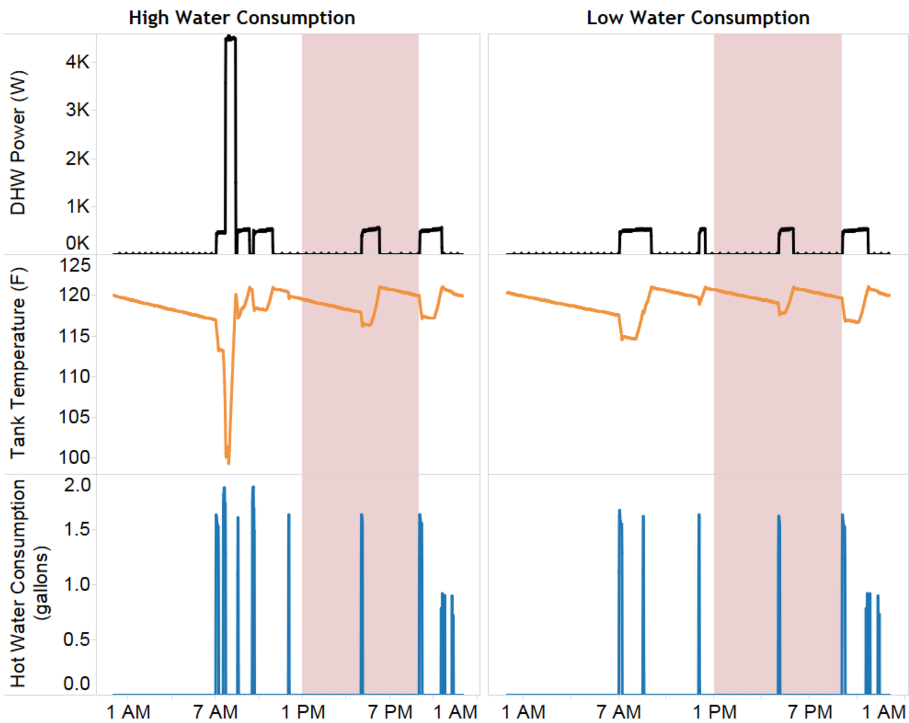

Figure 1. Water heater power, tank temperature and water consumption for the high and low water consumption profiles for the baseline HPWH schedule. For brevity, plots of the medium water consumption case are not presented, although the results are included in the tables.

In contrast, the HPWH installed in the builder house, with a factory default temperature setting of 120°F, consumed an average of approximately 510 Watts when the heat pump was used. On high water consumption days as shown in Figure 2, there was a water heating event that required heat from the resistance element with an output of 4500 Watts, similar to the electric resistance water heater. However, even though resistance heat was used, the energy saved in comparison to the conventional water heater was significant with average daily energy consumption for high and low water consumption days of 6 kWh and 2.3 kWh, respectively, as shown in Table 3. This is a savings of 54% and 83% for the high and low water draw profiles in comparison to the electric resistance water heater.

Table 3 also shows the energy consumed during the peak time (referred to as "Peak Energy") for each water draw profile for the baseline HPWH schedule. For all three water draw profiles, the baseline HPWH used energy during the peak time. Table 4 shows the time that the water heater might not provide hot water to the home. This is determined to be anytime that the average hourly tank temperature dips below 117°F. The daily coefficient of performance (COP) is also calculated for each representative day for each profile in Table 4. The high water draw profile has the lowest COP, because it was the only profile that required supplemental electric resistance heat, which reduces the efficiency of the water heater.

Table 3. Daily and peak energy consumption for the conventional electric resistance water heater and the heat pump water heater set to 120°F in hybrid mode

	Low Water Draw Profile (kWh)	Medium Water Draw Profile (kWh)	High Water Draw Profile (kWh)
Conventional WH	8.5	N/A	13.2
Baseline HPWH	2.3	2.7	6.0
Baseline HPWH Peak Energy	0.6	0.5	0.6

Table 4. Statistics on the baseline HPWH schedule

	Low	Medium	High
% time below 117°F	4%	21%	13%
Water Heater COP	2.8	3.0	1.9
Avg. Tank Temp. (F)	119	118	118

Schedule 3

Table 5 shows the daily energy consumption of each water draw profile for schedule 3. For all cases, schedule 3 consumes less energy than the conventional water heater (62% and 63% on low and high water consumption days respectively). In contrast, for the low water consumption profile, schedule 3 consumed 40% more energy than the baseline HPWH. However, there were energy savings of 20% for the profile with high water consumption compared to the baseline HPWH. This is because no electric resistance heat was used for the high water consumption case as it was for the baseline schedule. This energy savings is also despite the increased heat losses to the environment and decreased efficiency of the heat pump at higher tank temperatures.

Table 5. Schedule 3 daily and peak energy consumption with other performance metrics

	Low	Medium	High
Daily Energy (kWh)	3.2	3.9	4.8
Peak Energy (kWh)	0	0	0
Time below 117°F (%)	0%	0%	0%
Water Heater COP	2.0	2.1	2.4
Avg. Tank Temp. (F)	157	156	140

Figure 3 contrasts the water heater power, tank temperature, and water draws for a high water consumption day and a typical low water consumption day. During the high water consumption day, the high temperature set point at 170°F was not met. However, the hourly average tank temperature was always above 117°F. Consequently, even though the energy consumption was highest for the high water consumption day, the average COP was also the highest. This is due in large part to the lower average tank temperature during the high water consumption day, which results in a higher heat pump efficiency.

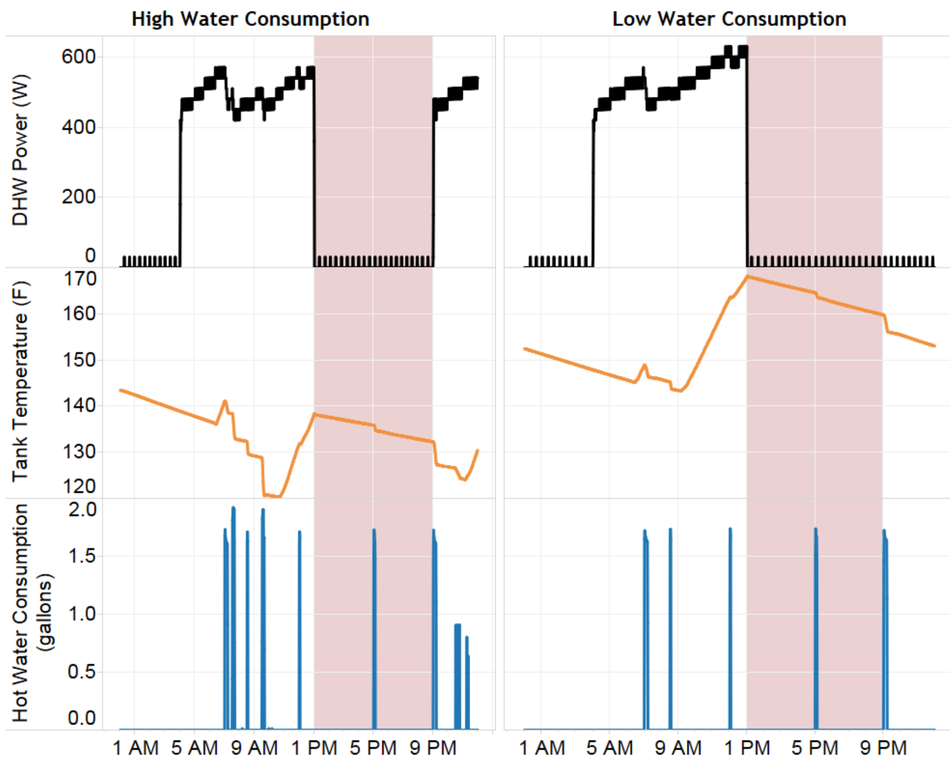

Figure 2. Water heater power, tank temperature and water consumption for the high and low water consumption profiles for schedule 3.

Schedule 4

Table 6 shows the daily and peak energy consumption of each water draw profile for schedule 4. For the high and low water draw profiles, schedule 4 saved energy (61 and 64% respectively) compared to the conventional electric resistance water heater. However, for the low and medium water draw profiles schedule 4 used more energy (33 and 58% respectively) than the baseline HPWH at 120°F hybrid mode. The high water draw profile saved energy over the baseline HPWH likely because no resistance heat was used. During high water use days there was also water heating energy used during the peak time of 1-9PM.

Table 6. Schedule 4 daily and peak energy consumption with other performance metrics

	Low	Medium	High
Daily Energy (kWh)	3.1	4.3	5.2
Peak Energy (kWh)	0	0	1.5
Time below 117°F (%)	0%	8%	0%
Water Heater COP	2.1	1.9	2.2
Avg. Tank Temp. (F)	154	149	145

Figure 4 shows the water heater power, tank temperature, and water draws for a high water consumption day and a low water consumption day. There is a large temperature decrease during the peak time of the high water consumption case, which requires the heat pump to turn on during peak hours. This is due to the combined effect of lowering the set point temperature, the stratified nature of the water temperatures in the tank, and the position of the temperature sensor near the top of the tank that is used to measure tank temperature. When the set point was lowered to 150 F from 170 F, and then 120 F from 150 F, the heat pump was never on for a sufficient amount of time to "de-stratify" the tank. During the water draw during the peak time this slug of cold water finally reached the thermostat and brought the tank temperature measurement below 120 F which turned on the heat pump during the peak time.

Table 6 shows that all schedule 4 water draw profiles had similar COPs with average daily tank temperatures. However for the medium water draw day the tank did go below 117 for 2 hours.

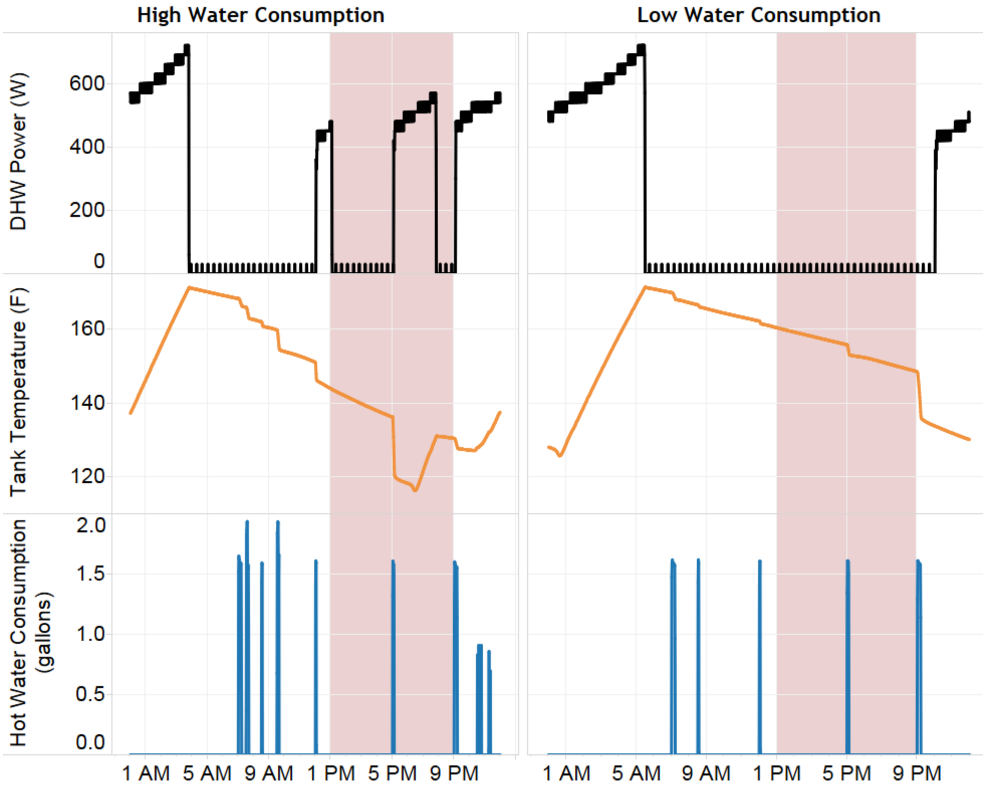

Figure 3. Water heater power, tank temperature and water consumption for the high and low water consumption profiles for schedule 4.

Schedule 5

Table 7 shows the daily and peak energy consumption for schedule 5 for each water draw profile. Schedule 5 saved 58% and 57% when compared to the electric resistance water heater for the low and high water draw profiles respectively. In comparison to the baseline schedule, schedule 5 used more energy for the low and medium water draw profiles (56 and 58% respectively). For the high water draw profile schedule 5 saved energy over the baseline schedule. No energy was used during peak times for low, medium, or high water consumption cases. Figure 5 shows the water heater power, tank temperature, and water draws for a representative high water consumption day and low water consumption day.

Table 7. Schedule 5 daily and peak energy consumption with other performance metrics

	Low	Medium	High
Daily Energy (kWh)	3.6	4.3	5.7
Peak Energy (kWh)	0	0	0
Time below 117°F (%)	0%	0%	0%
Water Heater COP	1.8	1.9	2.0
Avg. Tank Temp. (F)	164	162	152

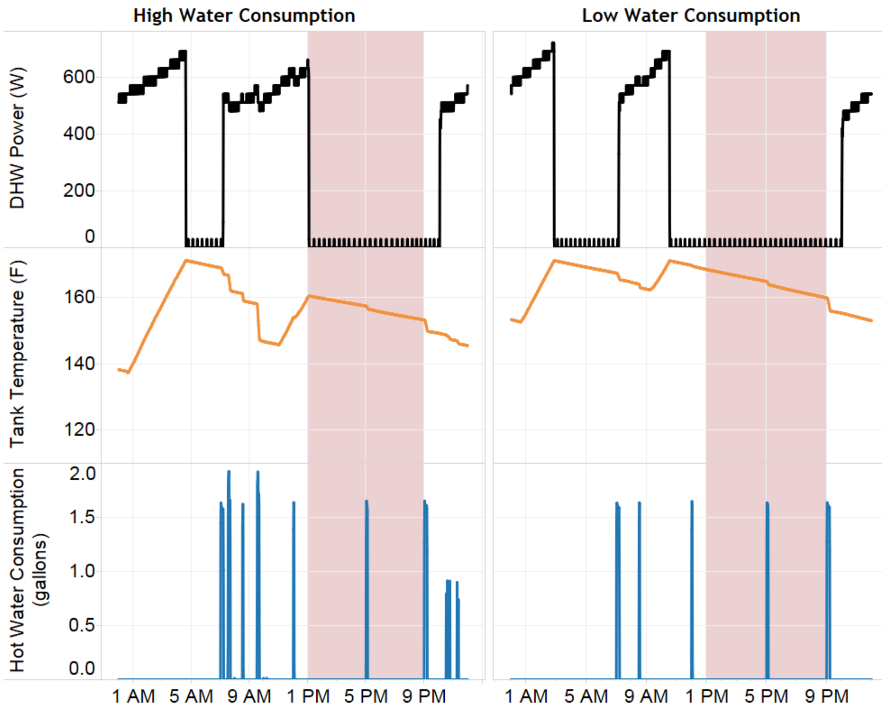

Figure 4. Water heater power, tank temperature and water consumption for the high and low water consumption profiles for schedule 5.

Table 7 shows that no hours during schedule 5 had average tank temperatures below 117°F. While the low water draw profile consumed less energy, the average COP was lower than in the high water consumption case. This can be attributed to high average tank temperatures for the low draw scenario.

Schedule 6

The primary difference between schedule 6 and the baseline HPWH schedule is the restriction that no supplemental electric resistance heat could be used for schedule 6. While this is not a load managed temperature schedule, it is useful as a further point of comparison and investigation of how heat pump water heaters respond to different water draw profiles. Table 8 shows the daily and peak energy consumption of each water draw profile for schedule 6. Similar to schedules 3-5, schedule 6 used significantly less daily energy than the conventional water heater. In contrast to schedules 3-5, schedule 6 used 34% less energy than the baseline HPWH schedule for high water consumption days, which required supplemental electric resistance heat. However, while less energy was required, there was a substantial amount of time when the hot water delivered to the home was below the minimal threshold of 117 F.

Table 8. Schedule 6 daily and peak energy consumption with other performance metrics

	Low	Medium	High
Daily Energy (kWh)	2.4	2.7	3.9
Peak Energy (kWh)	0.5	0.4	0.6
Time below 117°F (%)	8%	13%	17%
Water Heater COP	2.7	3.0	2.9
Avg. Tank Temp. (F)	120	118	117

Figure 6 shows the water heater power, tank temperature, and water draws for a representative high water consumption day and low water consumption day. On high water use days, the tank temperature fell significantly below the set point of 120 F. During both high and low water consumption days the heat pump was used during the peak energy time and there were times where the tank could not provide 117°F water to the home, similar to the baseline.

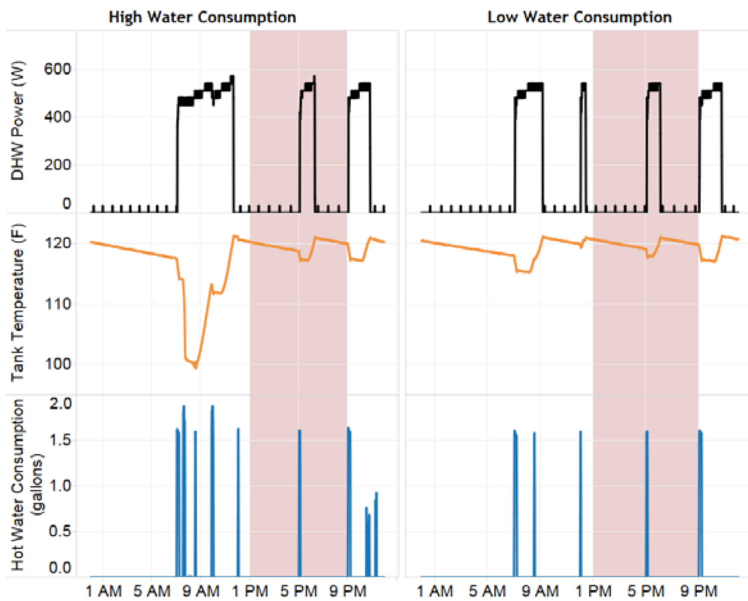

Figure 5. Water heater power, tank temperature and water consumption for the high and low water consumption profiles for schedule 6.

Discussion of Results

Energy Consumption

Table 9 shows the daily average energy consumption for each schedule and water draw profile. All HPWH schedules save energy over the conventional water heater even when the tank set point is 170°F. As expected, higher tank temperature resulted in higher energy consumption and lower efficiencies except for the high water draw profile where the higher tank temperatures enables the electric resistance heaters to stay off resulting in lower energy consumption and higher COP over the baseline

Table 9. Daily average energy consumption of each schedule for 3 water draw profiles

	Low (kWh)	Medium (kWh)	High (kWh)
Conventional WH	8.5	N/A	13.2
Baseline HPWH	2.3	2.7	6.0
Schedule 3	3.2	3.9	4.8
Schedule 4	3.1	4.3	5.2
Schedule 5	3.6	4.3	5.7
Schedule 6	2.4	2.7	3.9

Peak Energy Use

Schedule 3 and 5 were the only schedules that effectively eliminated all energy use during peak hours for all consumption profiles as is seen in Table 10. Therefore, while these schedules had higher energy consumption over the baseline (for low and medium draw profiles), they were able to successfully meet the project objective of eliminating peak energy use. Schedule 4 only had peak energy use during the high water consumption profile.

Table 10. Average peak energy consumption for each schedule and water draw profile

	Low (kWh)	Medium (kWh)	High (kWh)
Baseline HPWH	0.6	0.5	0.6
Schedule 3	0	0	0
Schedule 4	0	0	1.5
Schedule 5	0	0	0
Schedule 6	0.5	0.4	0.6

Efficiency

Table 11 shows the coefficient of performance (COP) for each schedule and water draw profile. Note that this calculation includes stand-by losses. As expected, the heat pump water heater efficiency decreases as the temperature in the tank increases for the low and medium water draw profiles. For the high water draw profile however the increase in tank temperature abated the need for electric resistance heat so the efficiency increased. Also, there is a general trend that shows with increased water consumption comes increased COPs, since higher water use results in a lower tank temperature and thus less heat loss to the ambient environment.

Table 11. Average COP for each schedule and water draw profile

	Low (COP)	Medium (COP)	High (COP)
Baseline HPWH	2.8	3.0	1.9
Schedule 3	2.0	2.1	2.4
Schedule 4	2.1	1.9	2.2
Schedule 5	1.8	1.9	2.0
Schedule 6	2.7	3.0	2.9

Ability to Meet Hot Water Demand

Table 12 shows the percentage of hours throughout the day where the tank temperature fell below 117°F. This metric was used to determine if the tank would supply sufficient hot water to the home. In all water draw profiles, the baseline HPWH and Schedule 6 had periods of time when the water temperature was below the desired threshold. Additionally, during the medium water draw profile, Schedule 4 also did not meet all hot water demand.

Table 12. Percent time per day that schedule was below 117°F

	Low (%)	Medium (%)	High (%)
Baseline HPWH	4%	21%	13%
Schedule 3	0%	0%	0%
Schedule 4	0%	8%	0%
Schedule 5	0%	0%	0%
Schedule 6	8%	13%	17%

Conclusion

To determine the ability to eliminate water heater peak period energy use by pre-heating water in the tank to increase the stored thermal energy, four different heat pump water heater tank schedules were tested. From a peak energy standpoint two of the elevated set point schedules (3 and 5) resulted in zero peak energy consumption, which shows that demand response is possible with heat pump water heaters. This would be beneficial to the utility but not necessarily to the homeowner, since for example Schedule 5 uses more energy than the baseline except during high water consumption days.

Other figures of merit were overall energy consumption, and hours below a minimal tank temperature threshold of 117 F. Shaded in red in Table 13 are schedules that resulted in hours below the minimal threshold and not considered as appropriate strategies, since a water heater's primary objective is to provide hot water when needed. It is important to note that particular temperature scheduling strategies were most appropriate for certain profiles (shaded in green). Of the elevated temperature schedules (3-5), Schedule 4 has the lowest total energy consumption with zero peak hour energy use for the low energy consumption profile. However, schedule 3 was the most appropriate strategy for the medium and high water consumption profiles in this study. This observation illustrates the importance of designing a temperature set point schedule to match the home's hot water consumption pattern. An optimal set point temperature scheduling strategy would require the ability to predict the home's hot water consumption usage and respond appropriately. This would be possible with HPWH units with built in flow-learning and temperature set point control algorithms, which the authors are currently working on. If this were implemented then this strategy for demand response could be implemented at scale.

Table 13. Load managed HPWH schedule comparison (cells shaded in green are considered most appropriate for the water consumption profile)

	Low	Medium	High
Baseline HPWH			
Schedule 3			
Schedule 4			
Schedule 5			
Schedule 6			

References

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