Take a Load Off Showering: How Much Might Heat Pump Water Heaters Help?

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ABSTRACT

Many states are on a path to electrify the water-heating end use but must do so while managing peak loads. Grid-enabled heat pump water heaters (HPWHs) allow utilities to not only reduce energy consumption, but to shift water-heating loads to times when renewable energy is plentiful or energy demand is otherwise low.

To assess the performance of high-efficiency HPWHs during simulated peak demand events, we reviewed product data to determine the median Uniform Energy Factor (UEF). These results were combined to develop building-energy models that simulated typical hot-water loads in a single-family home with the HPWH located in an unconditioned space. Finally, we varied the HPWH size and the criteria of peak demand events by elevating the setpoint during times when hot-water loads are typically low and either: 1) renewable energy sources prevail (midday) or 2) overall energy demand is low (nighttime).

The modeled peak demand reductions produced by the load-shifting strategies simulated were estimated using two sizes of HPWHs and two pre-event setpoint ramp-up strategies. In doing so, it was possible to assess benefits and drawbacks of each strategy. While the additional infrastructure costs of installing HPWHs with temperature-regulated mixing valves—to mitigate the scalding risk of increased setpoints—are considerable, the benefits in resource-constrained regions include reducing peak energy demand, improving grid reliability, and shifting the energy usage to periods when power generation produces fewer GHG emissions.

Introduction

With the advent of HPWHs, it became possible to deliver domestic hot water (DHW) about three times more efficiently than had ever been possible with standard electric resistance storage water heaters. That said, during periods of very high demand for DHW in residential buildings—when perhaps multiple occupants shower simultaneously—the heat pump cannot always fully meet the demand. For this reason, residential HPWHs are usually manufactured with one or more back-up electric resistance heating elements and sophisticated control strategies built in to meet the loads on an as-needed basis. While these are sometimes referred to as "hybrid" HPWHs, they are referred to as HPWHs throughout this paper.

More recently, WiFi-enabled HPWH technology has made it possible to remotely shift DHW loads from periods of high electric energy demand to those with lower demand. The paper explores the feasibility of doing so during two periods of the year:

- On hot afternoons, when high hot water and HVAC cooling loads coincide, between the hours of 4 and 9 PM
- On cold mornings, when high hot water and HVAC heating loads coincide, between the hours of 5 and 8 AM

The feasibility and impacts of shifting these DHW loads were studied using building energy modeling to simulate the performance of HPWHs in a prototypical 2,100 sq. ft., single-family residence located in Sacramento, CA or climate zone 12 (CEC 1995) as shown in Figure 1.

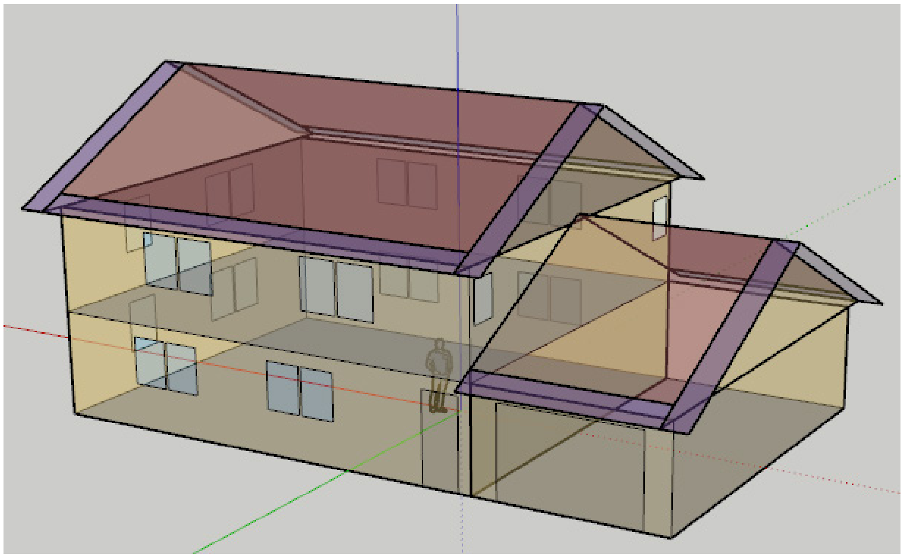

Figure 1. 2,100 sq. ft., 3-bedroom, 2-bath single-family residence prototype. *Source*: California Building Energy Code Compliance software;[1] SketchUp™ software was used to produce image.

Residential Heat Pump Water Heaters

The energy efficiency improvement from a HPWH is due to its ability to transfer more heat from the air to the water than the energy consumed by that transfer process. The performance of the heat pump depends on both the temperature and humidity of the air surrounding the HPWH. The coefficient of performance (COP) is used to measure the useful energy transfer to the water divided by the input energy to the system as shown in Equation 1.

$$COP = \frac{Q_{thermal}}{W_{input}} = \frac{m \times C_p \times \Delta T}{W_{input}} \qquad \text{Equation 1}$$

where

COP = coefficient of performance (a measure of efficiency)

$Q_{thermal}$ = heat transferred to water

W_{input} = work input to heat water

m = mass of water heated

C_p = specific heat capacity of water

ΔT = water temperature increase due to heat transfer

Residential HPWHs manufactured today typically have a COP[2] of 3 or higher while the heat pump is in use at optimal temperatures and can drop to a COP of 2 or so at cold temperatures. On the other

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[1] The original model, *2022_CZ12_2011ft2_std_HP – Std.rbd22i*, is from the CEC's CBECC-Res 2022 RV 2022.0.5 software package (Research Version).

[2] While the COP is an easily calculated and directly comparable efficiency metric used for many types of heating/cooling equipment, it is not the metric used for Federal and State standards for residential water heaters; Uniform Energy Factor (UEF) is the efficiency metric around which residential water heater standards are written. The UEF rating is designed to reflect the performance of multiple operating characteristics at typical residential hot water usage patterns over a 24-hour period. As a blended metric, it is less directly comparable than the COP metric.

hand, the COP drops to 1 when the back-up electric resistance element(s) is in use. The controls in most residential HPWHs only engage either the heat pump or the electric resistance components at any one time.

To guide the selection of the HPWHs to model, all currently “in production” units were downloaded from AHRI’s website. After removing duplicates from the list of the available products, 50-gallon HPWHs were divided into categories: medium, high, and very high efficiency as shown in Figure 2. Larger HPWHs having a nominal tank capacity of 65-66 gallons were also divided into three categories as shown in Figure 3.

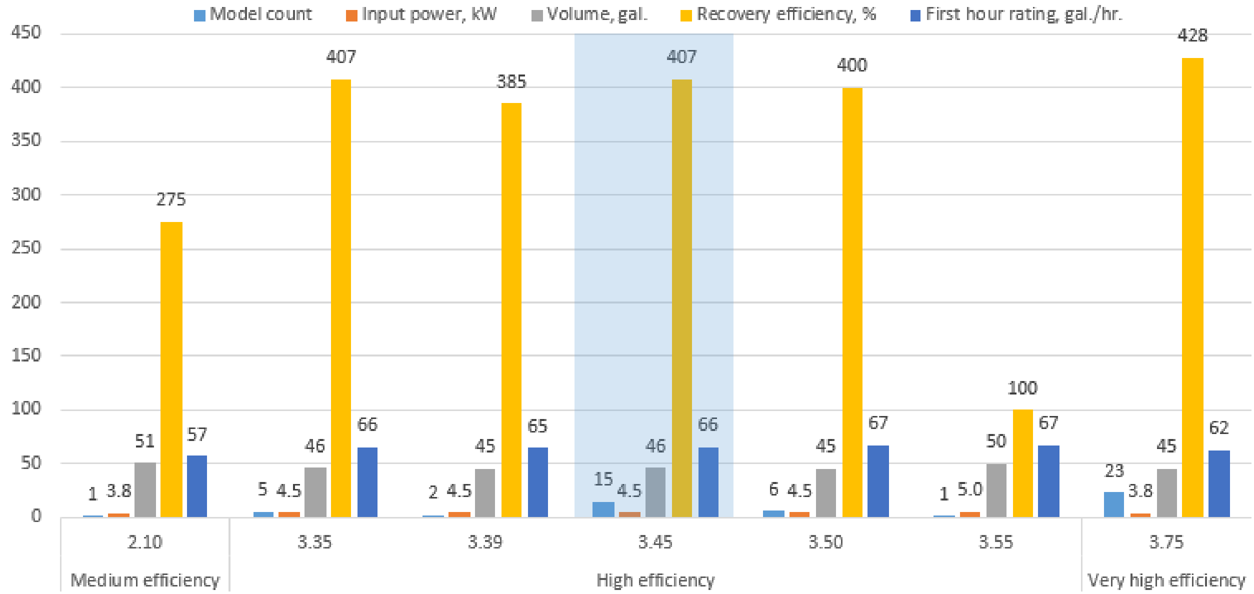

Figure 2. 50-gallon HPWH product data from AHRI website, clustered by UEF values. *Source*: www.ahri.com (September 2021)

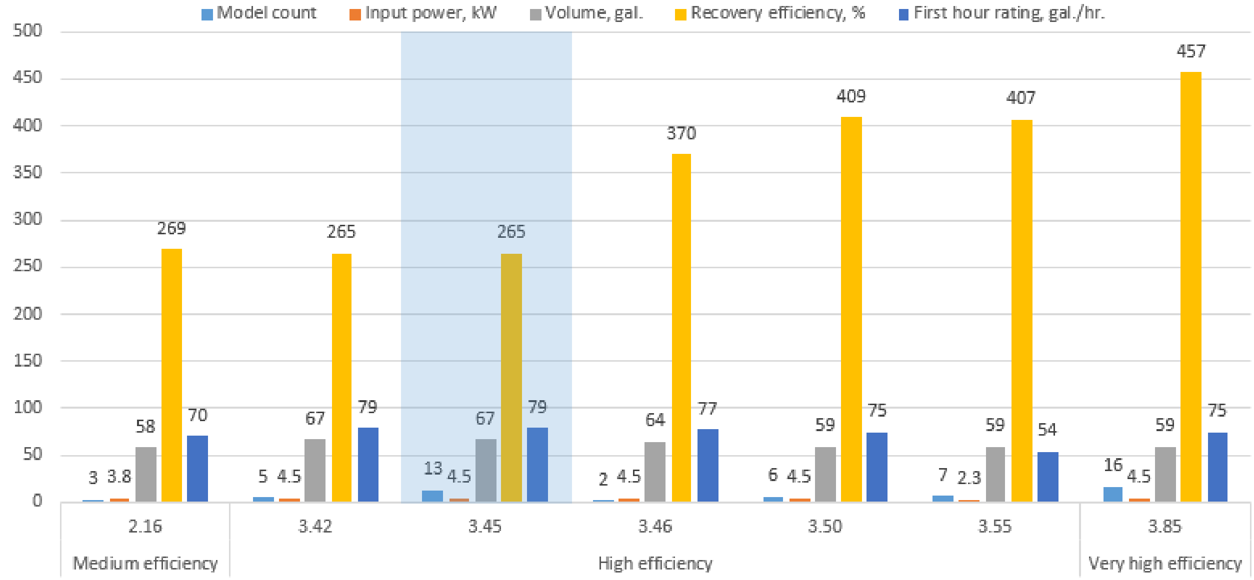

Figure 3. 66-gallon HPWH product data from AHRI website, clustered by UEF values. *Source*: www.ahri.com, (September 2021)

After careful review of manufacturer data available from the AHRI website, the characteristics listed in Table 1 were selected to represent residential HPWHs that includes a CTA-2045-A[3] compliant communication port in two storage capacities: 50 gallons and 66 gallons. For this effort, the building simulation models were run using the performance characteristics of two models found to be within the high efficiency cluster with an overall rated efficiency of 3.45 UEF.

Table 1. Performance characteristics of modeled HPWHs

HPWH characteristic	**50-gallon HPWH**	**66-gallon HPWH**
Manufacturer	A. O. Smith	A. O. Smith
Model	HPTU-50CTA	HPTU-66CTA
Nominal storage capacity, gallons	50	67
Rated storage capacity, gallons	46	59
Draw pattern/usage	Medium	High
Uniform Energy Factor (UEF)	3.45 (NEEA Tier 3)	3.45 (NEEA Tier 3)
Estimated COP	2.9	3.1
CTA-2045-A compliant port	Yes	Yes
Input energy (each element), kW	4.5	4.5
Tank insulation UA-value, Btu/hr·°F	4.2	4.2
Recovery efficiency	407%	265%
First-hour rating of HP, gallons/hr	44.4	62.5
First-hour rating of ER, gallons/hr	57.3	78.6
First-hour rating of hybrid, gallons/hr	70	80
Tank height, inches	40.5	38.0
Tank diameter, inches	15.0	23.0
Maximum temperature, °F	150	150

Source: AHRI. (HP=heat pump component; ER=electric resistance elements)

Residential Hot Water Loads

Until fairly recently, residential hot water load profiles were typically constructed to represent the average hourly demand with only a few variations to account for differences between weekday, weekend, and holiday usage. For the benefit of the CEC's code compliance software packages, hot water load profiles were greatly improved "based on analysis of a large data set of measured draws from more than 700 California single-family homes" (Kruis et al. 2019, 1). Kruis et al. (2019) make the point that the actual draws of hot water only occur during about 8% of the day and that averaging those draws over each hour of the day provides a poor representation of the varying demand on a water heater during periods of high and sustained draws, such as filling bathtubs or taking showers. Kruis et al. (2019) provide a compelling comparison of the average daily profile and the actual draws as shown in Figure 4.

Upon reviewing Figure 4, it becomes apparent that any attempt to estimate the energy used by a water heater that relies on an average daily profile will significantly underestimate the occasional bursts

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[3] CTA-2045-A is an ANSI/CTA standard for communication ports for appliances to facilitate demand response events (though the results of the simulations can be applied to units both with and without this communication port).

of heating energy demanded of the water heater. While this shortcoming would impair the accuracy of the hourly energy use estimates, it would be exacerbated when attempting to determine the peak energy demanded during lengthy draws of hot water.

When possible, Kruis et al. (2019) produced 30 representative days for each occupancy level that ranged from one to 6+ people. Of these, 10 represent weekdays, 10 represent weekend days, and 10 represent holidays. Since the CEC's CBECC-Res 2022.0.5 software package (Research Version) estimates the number of occupants based upon the number of bedrooms, the model used for this effort assumes that 2.64 occupants reside within the 2,100-sq.ft., single-family residence shown in Figure 1. The hot-water draws of the representative days for weekdays, weekend days, and holidays are scattered throughout the year in an accompanying data file that provides these values in one-minute intervals. Using discrete 1-minute hot water draws rather than hourly draws better accounts for the intermittent nature of the load on the water heater. While this comes at a cost of longer processing times, it offers a much more realistic representation of the performance and energy usage patterns of water heaters.

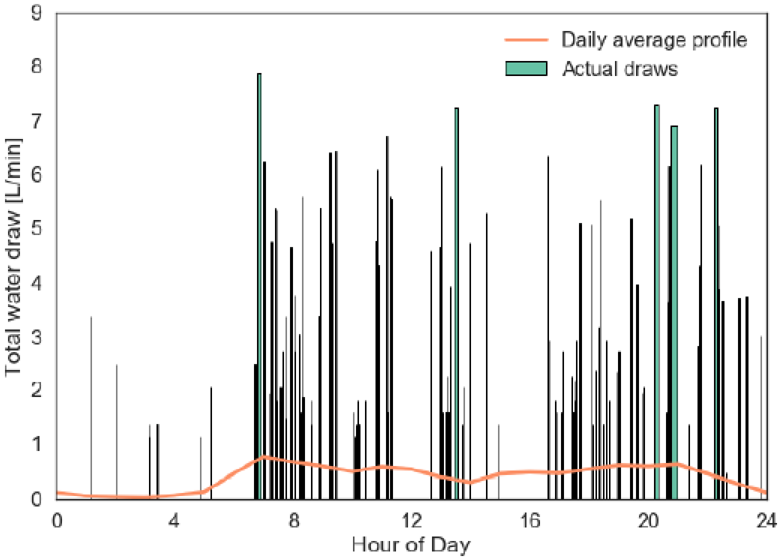

Figure 4. Example comparison between average daily profile and actual draws. Source: Kruis et al. 2019.

EnergyPlus™ Model

The EnergyPlus models developed for this effort originated from the CEC's CBECC-Res 2022.0.5 (Research Version) compliance software and was used as a starting model for the following reasons:

- The previously-described residential hot water load shapes—in one-minute intervals—are embedded into the model.
- The performance curves for the HPWHs have been updated more recently than those provided in EnergyPlus.

The weather data used for this effort were developed by White Box Technologies, Inc. (2019) and are referred to as CZ2022[4] files. They were updated to reflect the gradual warming that is occurring

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[4] This effort used the CZ2022 EnergyPlus file for the Sacramento Metropolitan Airport named: CA_SACRAMENTO-METRO-AP_724839S_CZ2022.epw.

throughout California. Although water heating is not typically treated as a weather-dependent end use, CZ2022 was used in case this work may be further developed to allow for alternate installation of HPWH within the conditioned space where interaction with the space-heating and cooling equipment would result. As currently built, the applicability of this model where the HPWH is located within an uconditioned space is somewhat limited to the southwest United States where above-freezing temperatures are the norm and construction practices are tailored to the relatively warmer climate. That said, an interested and motivated reader will be able to download the modeling files used for this effort,[5] modify them by moving the water heater to within the conditioned space of the dwelling, update the building envelope characteristics, and study the interactions with the space conditioning equipment.

The plant loop line diagram in Figure 5 shows where a thermostatic valve is installed between a branch from the water main and the hot water delivered by the HPWH. This cold-water, make-up bypass is necessary to ensure that the water delivered to the nearest plumbing device never exceeds that of the HPWH setpoint of 125°F during normal operations.

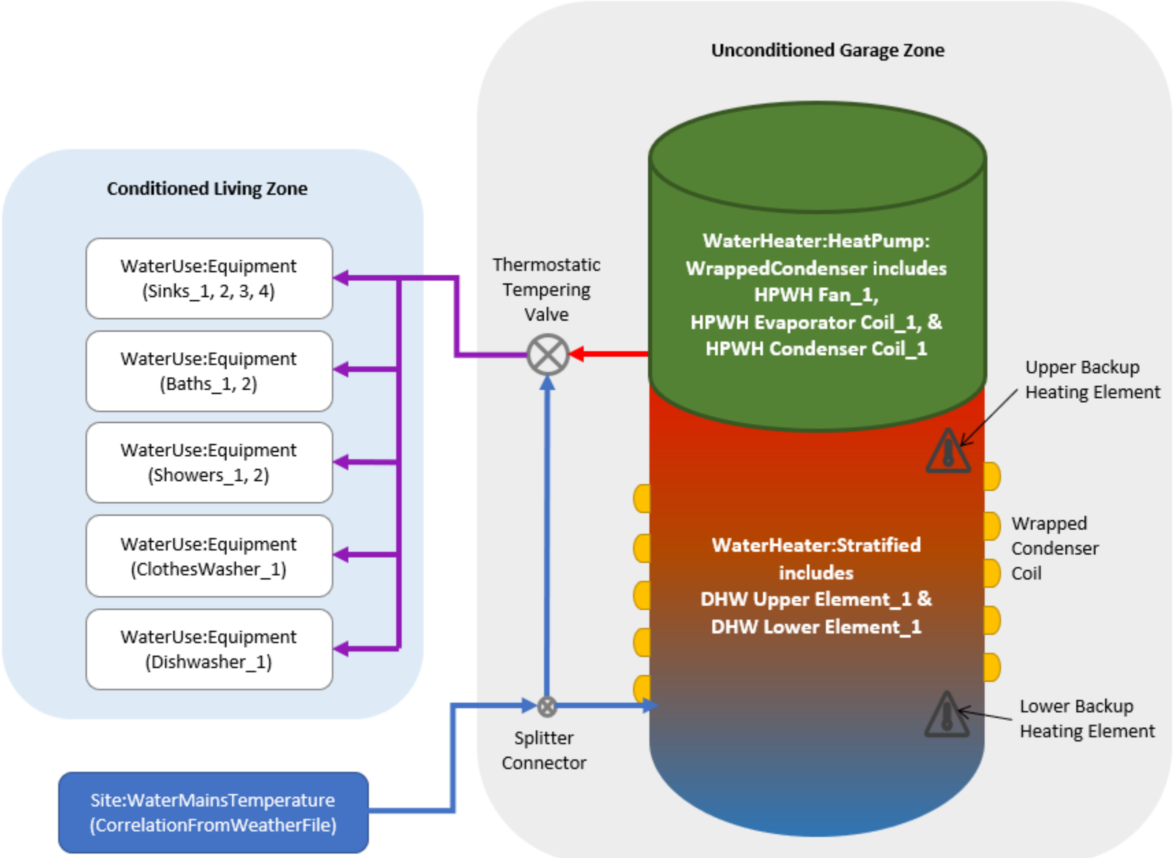

Figure 5. Line diagram of plumbing for EnergyPlus model with HPWH located in unconditioned garage

To increase the suitability of the existing CBECC-Res model for this effort, the following additional revisions were made:

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[5] The following input files used for this effort are available at https://github.com/RVMurrayPE/HPWH-LoadShifting.git: EnergyPlus input design files for each scenario, the hot water fixture draw file (with and without vacation days), the miscellaneous electric and gas loads, the HPWH setpoints files for each scenario, and the CZ2022 weather file for Sacramento, CA.

- The setpoints for the HPWH compressor components and both electric-resistance heating elements (upper and lower) were modified from using the built-in Energy Management System (EMS) controls to drawing from a series of HPWH_setpoints-*.csv files, where the “*” wild character is replaced with the scenario descriptor. Using .csv files allowed for nuanced variations to each of the setpoints to assess their effects on the energy usage of the HPWHs.
- Most of the time, the setpoints for the upper and lower back-up electric resistance heating elements were typically set to be 15°F and 55°F, respectively, less than the HPWH compressor setpoint. When the mean air temperature in the garage fell to below 52°F, however, those differences were narrowed to 5°F and 45°F, respectively.
- All vacation days were removed so that they no longer coincided with either the hottest summer days or the colder winter nights, when demand-response events were more likely. The hot water draws for those days that previously had none were replaced with non-vacation days—for the same day of the week—during which an average volume of hot water was drawn.

When it is particularly hot in the afternoon or particularly cold in the very early morning, the model gradually elevates the HPWH compressor setpoint to 150°F for the three to five hours that precede 5 PM or 5 AM, respectively. The setpoints for the HPWH compressor system and the upper and lower electric-resistance heating elements are provided to the EnergyPlus models via the previously described .csv files.

The setpoints for the HPWH compressor, the upper electric-resistance element, and the lower electric-resistance element were modified whenever the garage air temperature either exceeded or fell below the summer or winter thresholds, respectively. Two methods of ramping up the setpoints before the beginning of the peak demand period were attempted: a sawtooth-shaped ramp-up and a stepped ramp-up. Both shapes were selected to allow the HPWH to gradually achieve the elevated setpoint just as the peak demand period began as shown in Figure 6. Modeling both ramp-up strategies enabled comparisons between them to gage whether the benefits of the sawtooth ramp-up shape were sufficient to warrant the more complicated demand event control strategy that would be required.

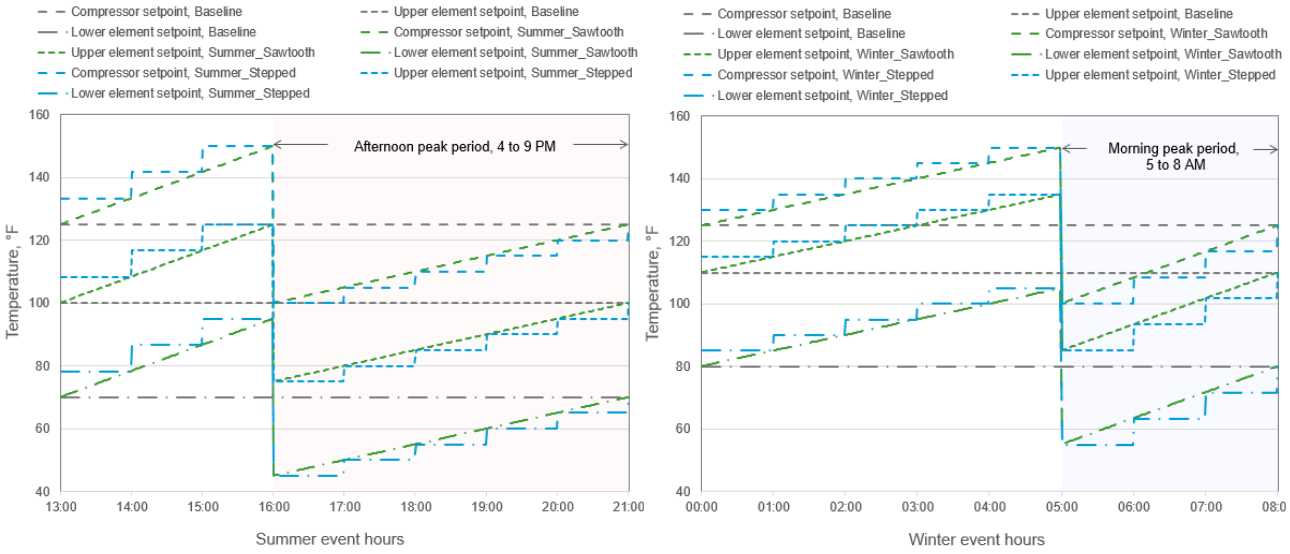

Figure 6. Gradual setpoint adjustments made in advance of the start of demand event were established to reduce the calls for back-up electric resistance element(s). In advance of the winter events (shown to the right), the ramping up was spread out over more hours (5 hours compared to 3 hours).

Simulation Results

Prior to establishing the final settings for the EnergyPlus simulations, the start times, temperature thresholds, and hot water setpoints were varied rather extensively to gain a sense of how the resulting energy usage and hot water temperature would respond. Further exploration of how to modify the setpoints for the components of HPWHs was also done. The described EnergyPlus model was run using a variety of simulation settings and control scenarios before arriving at the final settings as summarized in Table 2.

Table 2. EnergyPlus simulation scenarios and results for 2,100 sq. ft., single-family residence in Sacramento, CA with HPWH having typical setpoint of 125°F and located in an unconditioned garage

Scenario characteristics and simulation results	**Baseline**		**Summer demand events**				**Winter demand events**			
	50 gal.	**66 gal.**	**50 gal.**		**66 gal.**		**50 gal.**		**66 gal.**	
Garage air temperature threshold for modified setpoint, °F	-	-	≥ 103				≤ 51			
Peak demand period start time	-	-	4 PM				5 AM			
Time of start of gradually raising the setpoint	-	-	1 PM				12 AM			
Time of end of adjustments to setpoint	-	-	9 PM				8 AM			
Standard HPWH setpoint, °F	125									
Target HPWH setpoint during demand response event, °F	-	-	150				150			
Setpoint ramp-up shape	-	-	Saw-tooth	Step-ped	Saw-tooth	Step-ped	Saw-tooth	Step-ped	Saw-tooth	Step-ped
Number of days involving demand response events	-	-	27				31			
Annual energy use by HPWH, kWh	1,418	1,281	1,425	1,426	1,286	1,287	1,421	1,422	1,284	1,285
Percent difference from corresponding "Baseline" scenario	-	-	0.5%	0.6%	0.5%	0.5%	0.2%	0.3%	0.3%	0.3%
Peak demand event load shifted, kW	-	-	0.08	0.08	0.07	0.08	0.15	0.14	0.18	0.17
Proportion of time that electric-resistance heating is in use, annually	2.5%	1.6%	2.5%	2.5%	1.6%	1.6%	2.4%	2.4%	1.5%	1.6%
Annual hot water delivered, gallons	20,012	20,285	19,860	19,855	20,122	20,115	19,886	19,874	20,165	20,154

Source: EnergyPlus output reports

The results shown in Table 2 demonstrate both the benefits and drawbacks of calling anticipatory demand events based on the local weather conditions. While California does not have morning demand events, these were simulated to be of use in other regions of the country. While it is possible to enable and pre-program such controls within some of the more sophisticated HPWH systems, it is more likely that utilities or system operators would issue their own demand-response (DR) notifications to HPWHs to adjust setpoints several hours in advance of anticipated events.

In Figure 7, a twelve-hour segment of 1-minute data for a simulated summer afternoon demand event is shown for the 50 gallon HPWH. In this case the setpoint is raised by 25°F and at no point has any difficulty keeping up with the hot water draws surrounding the afternoon peak demand event. In fact, the back-up electric resistance elements are never invoked during these simulated events. The results for the 66-gallon HPWH were very similar and thus not shown separately.

While both setpoint ramp-up strategies presented in Figure 6 were used, there appeared to be no significant benefit to using the sawtooth ramp-up compared to the stepped ramp-up. Hence, for ease of calling summer demand events, increasing the pre-event setpoints in one-hour increments seemed to work quite well. When the mean garage ambient air temperature is high, the amount of heat that can be transferred to the HPWH condenser coils is very high and dramatically alters the garage air temperature (see Navy blue line in Figure 7).

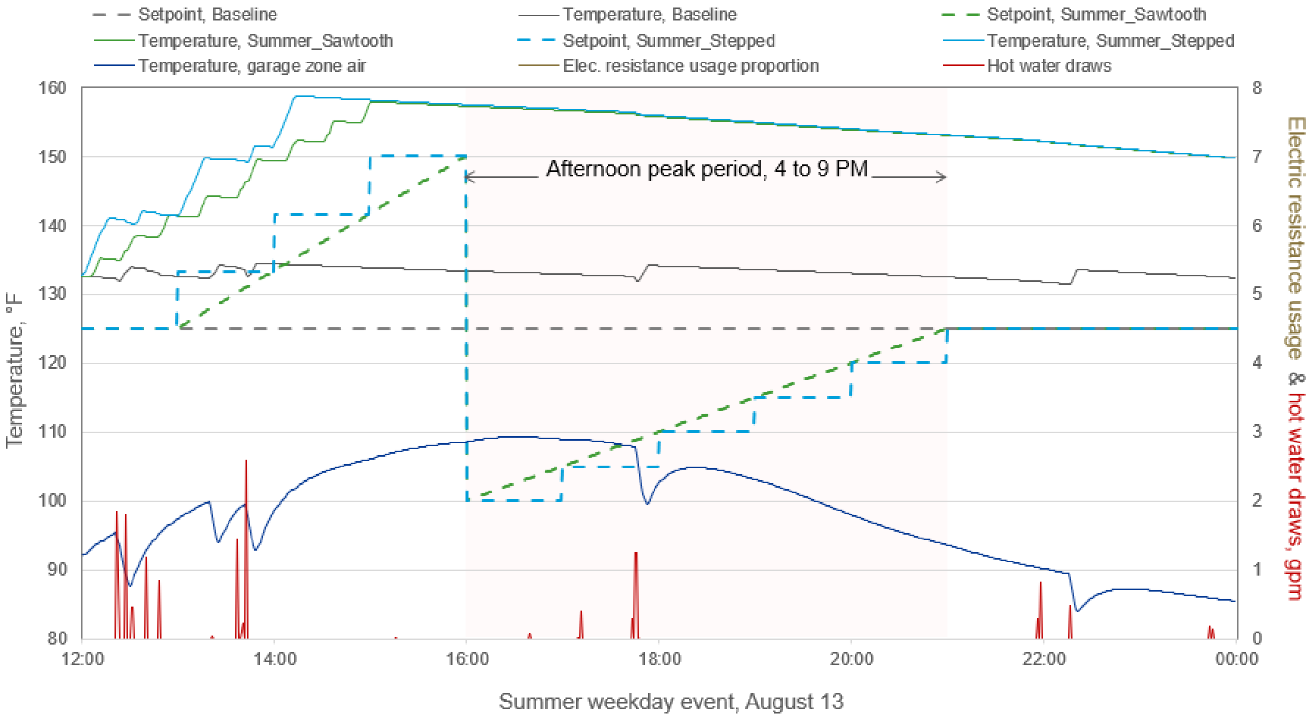

Figure 7. HPWH setpoints and HPWH and garage air temperatures (see left axis) are shown before, during, and after a simulated summer peak demand event for the 50 gallon unit; the proportion of back-up electric resistance element usage (none in this case) and hot water draws are shown along the bottom (see right axis).[6]

In Figure 8, a second twelve-hour segment of 1-minute data for a simulated winter morning demand event is shown for the 50-gallon HPWH. In this case, however, the setpoint is more slowly

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[6] EnergyPlus appears to misapply the setpoint shifts in advance of the scheduled ramp up by about one hour. This could not be resolved by the author and may warrant an inquiry to Big Ladder Software.

increased but the hot water still fails to reach the elevated setpoints—using either the heat pump or the back-up electric resistance elements. The elevated water temperature in the HPWH was able to remain above the standard setpoint for smaller hot water draws, but dropped well below it during a long hot water draw (a shower) occurring at about 7:30 AM. Even with the back-up electric resistance elements operating 100% of the time for about twice as long as the duration of the shower, it took several hours for the hot water temperature to return to the standard setpoint. (It was due to this observation that a second set of duplicate models were developed using a HPWH with a larger tank capacity of 66-gallons.)

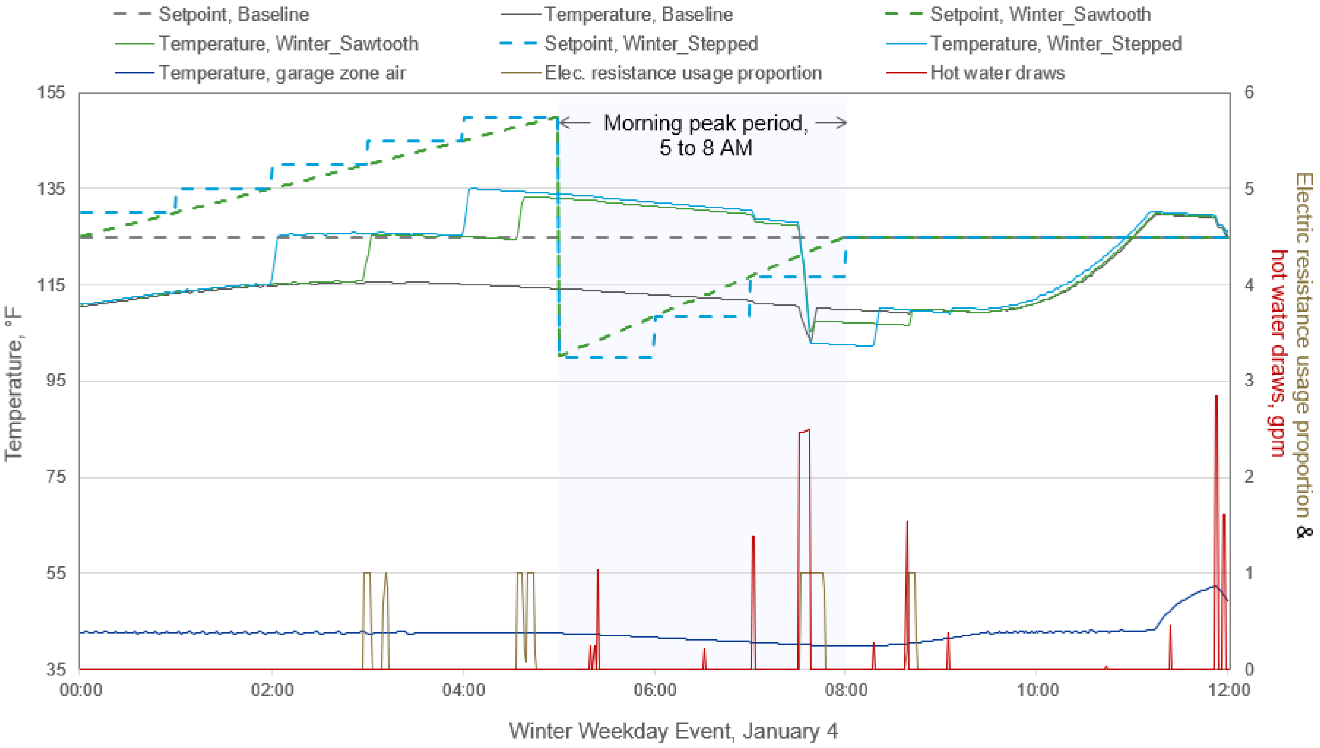

Figure 8. HPWH setpoints and HPWH and garage air temperatures (see left axis) are shown before, during, and after a simulated winter peak demand event for the 50-gallon unit; the electric resistance element usage proportions and hot water draws are at the bottom (see right axis).

In Figure 9, the same twelve-hour segment of 1-minute data for a simulated winter morning demand event is shown using a 66-gallon HPWH from the same product line by the same manufacturer as the previously simulated 50-gallon HPWH. Again, the setpoint is slowly increased over a five-hour period, but the tank temperature—even when invoking the back-up electric resistance elements—still fails to reach the elevated setpoint temperatures. That said, the tank water temperature recovered from hot water draws slightly more quickly than the 50-gallon HPWH.

As can be seen in Table 2, the 66-gallon HPWH used less annual electric energy to meet the simulated hot water load—both with and without demand events in the summer and winter—and offers a shorter recovery time. While these are expected results, it is nonetheless useful to have side-by-side comparisons that demonstrate a nearly 10% annual electric savings is possible by selecting the next size up. According to NEEA's *HPWH Qualified Products List* (2021), the 50-gallon HPWH modeled for this effort is appropriate for a home with 2-3 occupants whereas the 66-gallon HPWH is appropriate for 3 occupants.

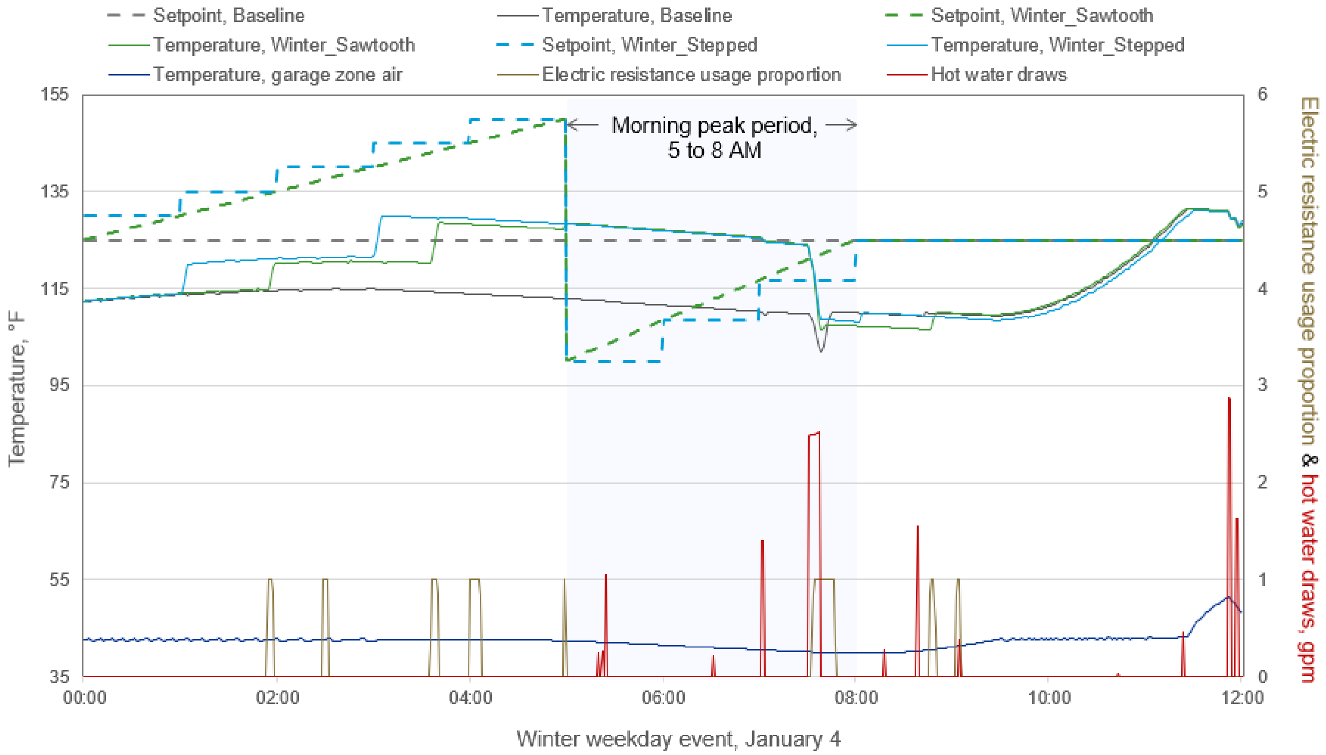

Figure 9. HPWH setpoints and HPWH and garage air temperatures (see left axis) are shown before, during, and after a simulated winter peak demand event for the 50-gallon unit; the electric resistance element usage proportions and hot water draws are at the bottom (see right axis).

The results demonstrate the extent to and frequency with which the ability to shift peak hot-water electric energy demands to the hours that precede the potential demand-response events might be helpful to utilities and grid operators on the the hottest afternoons and/or the coldest mornings. For example, the California ISO 2021 1-in-2 peak demand forecast is 45,837 MW[7] (CAISO 2019, 5); by enrolling 100,000 load-shifted HPWHs at single-family homes in a demand-response program, California could potentially offset the forecasted peak demand by approximately 0.02 percent on the hottest afternoons and evenings of the year.

While the simulations show that shifting the DHW loads is possible for both summer and winter peaks, they also show that it is much more difficult to do so in the winter. To successfully do so on the coldest mornings, the duration of the demand event must remain short when located in unconditioned spaces. In fact, the 50-gallon HPWH has difficulty delivering water that is at least 110°F *without* increasing the baseline setpoint. Issuing demand-response events without compromising occupant needs or comfort has been difficult to achieve; shifting loads for domestic hot water uses offers a promising means for achieving both as long as the HPWHs are appropriately sized for the number of home occupants and the duration of the events consider the effects on them—particularly on chilly winter mornings.

Future Considerations

For those planning to apply the results of this effort or the associated HPWH EnergyPlus models, the following should be considered:

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[7] A 1-in-2 peak demand forecast is the forecast of peak demand that is statistically expected to be reached once every two years.

- On hot summer days, it takes much less time for HPWHs located in unconditioned spaces to reach the pre-event elevated setpoints than it does during cold winter mornings.
- Further, the HPWH's tank will retain its pre-event elevated water temperature throughout a five-hour event since tank heat loss rates are far lower than during cold winter mornings.
- When HPWHs are located in unconditioned spaces, the duration of morning demand events should be kept as short as possible to minimize customer complaints due to a lack of sufficiently hot water.
- Since EnergyPlus does not appear to handle rapidly-changing setpoints well, further investigation into the cause of sometimes misaligned setpoints and HPWH tank water temperatures is warranted.
- Since each manufacturer utilizes its own proprietary control strategy for hybrid HPWHs, it would be beneficial for manufacturers to generate and release their own EMS controls subroutines for utilities or third-party implementers to use with EnergyPlus models. Doing so would eliminate the need to "guess" at the setpoints and controls of the back-up electric resistance element(s).

References

AHRI (American Heating and Refrigeration Institute). 2020. Directory of Certified Product Performance. https://www.ahridirectory.org/NewSearch?programId=24&searchTypeId=3 (accessed September 2021).

ANSI/CTA (American National Standards Institute/Consumer Technology Association). 2018. *Modular Communications Interface for Energy Management (ANSI/CTA 2045-A).*

CEC (California Energy Commission). 1996. *California Climate Zone Descriptions for New Buildings*.

CEC (California Energy Commission). 2020. CBECC-Res 2022.0.5 software package (Research Version). http://www.bwilcox.com/BEES/cbecc2022.html.

CAISO (California Independent System Operator). 2021. *2021 Summer Loads and Resources Assessment.* http://www.caiso.com/Documents/2021-Summer-Loads-and-Resources-Assessment.pdf.

Kruis, N., B. Wilcox, J. Lutz, and C. Barnaby. 2019. *Development of Realistic Water Draw Profiles for California Residential Water Heating Energy Estimation—Revised (March 2019).*

NEEA (Northwest Energy Efficiency Alliance). 2021. *HPWH Qualified Products List.* https://neea.org/img/documents/HPWH-qualified-products-list.pdf (accessed September 2021).

White Box Technologies, Inc. 2019. *Update of California Weather Files for Use in Utility Energy Efficiency Programs and Building Energy Standard Compliance Calculations.* http://weather.whiteboxtechnologies.com/pdf/PGE0450.pdf.