Detailed Laboratory Evaluation of Electric Demand Load Shifting Potential of Controlled Heat Pump Water Heaters

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ABSTRACT

The demand profile management of electric end uses is vital research for utilities and government agencies attempting greenhouse gas emission reductions. In this study, detailed laboratory research was conducted on the load shifting potential of 4 grid-connected heat pump water heaters (HPWHs) and one electric resistance water heater (ERWH). The testing applied different CTA-2045 shed and critical peak command designs under three water draw profiles. Highly-controlled laboratory experiments were conducted in Florida. One of the four HPWHs was a prototype incorporating the new CTA-2045-B protocol feature allowing 'advanced' load-up above tank set point.

A 3-hour morning (6 – 9 AM) and 4-hour evening curtailment (4 – 8 PM) were defined as the shed or critical peak periods reflecting high-value control periods for utility coincident load for system-wide electric demand reductions. Tests were performed under baseline conditions (no load shift) and under varied load-shifting schemes, including load up and advanced load up, ahead of shed and critical peak commands. Data were collected from December 2020 – February 2022. Demand reductions for the controlled HPWHs compared with the uncontrolled ERWH were up to 1.64 kW with large hot water draws in winter. Grid-connected HPWHs were found to reduce peak demand by up to 0.31 kW compared to uncontrolled HPWH units, depending on time of day, control scheme, draw profile, and temperature cluster. The load up strategy demonstrated the ability of all units to utilize heat pump mode for extended periods ahead of peak events.

Introduction

Electric resistance water heating in U.S. homes in the Southeastern U.S. exacts a large impact on the energy use and electric peak demand for utilities in that region. Heat pump water heaters (HPWHs) are a well-demonstrated technology for very significantly reducing electricity consumption for household water heating. A variety of monitored projects around the U.S. have shown energy savings of 50-70% compared with conventional electric resistance storage tank systems (Colon et al. 2016; Shapiro and Puttagunta 2016; Willem et al. 2017). More recent HPWHs have shown even higher operational coefficient of performance (COP) from improved compressors and other design enhancements. The evolution of technical improvements seems likely to continue. There is also renewed effort to qualify very efficient electric water heating systems that will substitute for natural gas water heating in an effort to reduce U.S. greenhouse gas emissions.

The Southeastern U.S. represents a concentrated opportunity for the HPWH efficiency market, offering significant energy savings potential. Seventy-three percent of water heating in Southeastern states is accomplished with electricity with virtually all this done with inefficient electric resistance water heaters (EIA 2015). In Florida, approximately 85% of water heating is electric (Masiello and Parker 2002). In seeking energy reductions to cut greenhouse gas emissions, single-family homes with 30-gallon or larger electric resistance water heaters (ERWHs) are inviting for replacement with HPWHs. Many large utility providers have demand response and load management programs (Butzbaugh and Winiarski 2020) and southeastern utilities may find value promoting grid-connected HPWHs capable of load shifting.

However, most of the large utility providers in these states do not offer HPWH incentives to their customers through their energy efficiency programs. Against the global importance of cutting greenhouse gas emissions, there is a counterproductive desire by some southeastern utilities to not reduce electric resistance water heating energy use to preserve investor-own utility revenues. HPWH systems are not encouraged in spite of the fact that they can be quite cost effective for the public. This is a significant barrier to improved water heating efficiency.

Figure 1 shows the shape of the residential water heating electric load in 45 monitored homes in the Phased Deep Retrofit (PDR) Project in Florida (Fenaughty et al. 2018). Note the pronounced bi-modal peak (morning and evening) as well as the strong seasonality in load shape. Annual water heating energy consumption from this project was identified at approximately 1,770 kWh per year—although this is biased at least 10% low due to shallow retrofit interventions in the second half year in the PDR project. The findings compare to 2,325 kWh for a larger sample of 150 water heaters, sub-metered in Central Florida twenty years earlier in 2000 (Masiello and Parker 2002). Winter morning peak demand in that study from 7-9 AM was approximately 0.60 kW as seen in Figure 1.

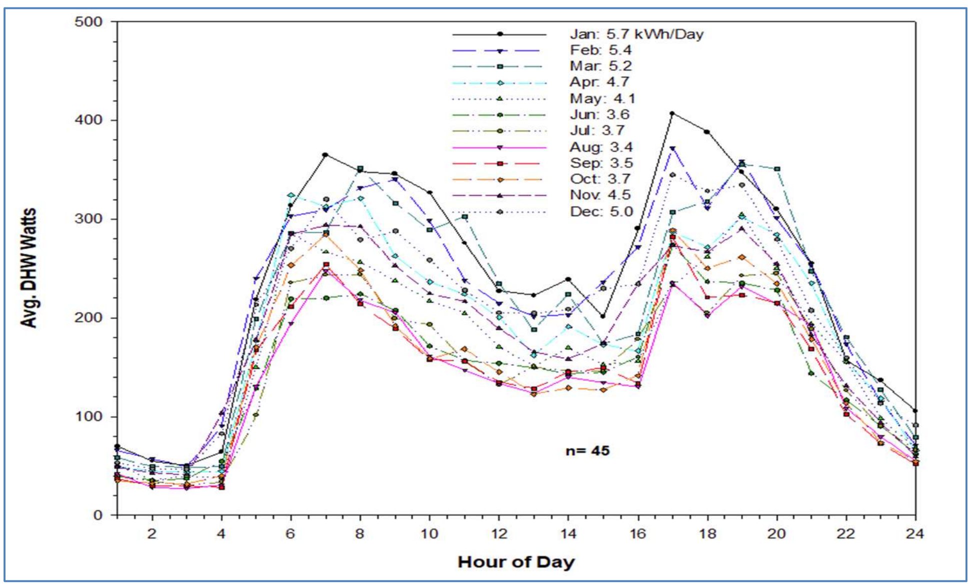

Figure 1: Load shape of 45 electric resistance water heaters in the Phased Deep Retrofit project in Florida. This is post shallow retrofits (low flow showerheads and hot water tank wraps). Magnitude of water heating likely biased low by ~ 10%.

Beyond saving water heating electricity, HPWHs also cut peak demand. However, few studies have quantified how HPWH load shifting capabilities might help utilities meet load control objectives. For instance, load shifting can potentially alter the water heating electrical demand profile in a significant fashion (e.g., consume greater amount of renewable energy). Current HPWHs and some ERWHs available for purchase are compatible with the CTA-2045-A protocol (ANSI/CTA 2018). This protocol has demonstrated utility flexibility in the Northwest, to provide ability to control when an appliance draws power from the grid (Metzger et al. 2018).

The CTA-2045 protocol standardizes the hardware interface between a communications module and 'smart' appliance to communicate with a connected device. Unitary Control Modules (UCM) can be attached to conforming appliances, enabling digital control of the appliance using the CTA-2045 protocol. The communications standard specifies messages commands which each CTA-2045-enabled device supports. The current CTA-2045-A communications commands used in the project include: load up (operate now and attempt to raise the water temperature to its set point), shed load (avoid operation to allow the present stored energy level of the tank to decrease), critical peak (CP) (more aggressively avoid of operation to allow the present stored energy level of the tank to decrease), and end shed (return to normal operation). Water heater manufacturers determine how different water heaters respond to the control commands, and thus differences exist in implementation. The newer CTA-2045-B protocol allows for an advanced load up where hot water is heated to a greater temperature to obtain greater shed capability, but is not yet supported by current models available for sale.

Laboratory Testing

Laboratory electrical load shifting experiments were conducted using the CTA-2045-A and -B control protocols to demonstrate the viability of grid-connected heat pump water heaters (HPWH) in comparison to conventional ERWHs in experiments stretching from December 2020 through February 2022. Three hot water draw profiles were implemented in the FSEC Hot Water Systems Laboratory (HWS) in Cocoa, two profiles developed by PNNL, a third is a modification of a profile developed by the Northwest Energy Efficiency Alliance (NEEA). The draws are not expected to mirror the load shape shown by real water heaters in Figure 1. Instead, such draw schedules must be used to preserve the intermittent, spike-like nature of hot water draws which are more challenging for HPWHs to meet with their limited capacity compressors. It is important to face HPWHs with such large water draws to see if they can operate without energizing higher-demand, less efficient backup resistance elements.

The advantage of the laboratory evaluation is that each water heating system is faced with identical draw quantities and flow rates. Evaluation was performed year round, including summer as well as Florida's mild winter conditions. Hot water draw quantities are known to vary strongly with seasonal variations in inlet water temperature (Parker, Fairey, and Lutz 2015). Accordingly, three different hot water draw quantities were exercised within the laboratory evaluation: 47 gallons per day (GPD), which would be appropriate for typical household summer draw quantities, 57 GPD which would approximate Florida's mild winter or shoulder month conditions for three person households and 69 GPD which would be similar to an extreme winter day in a household with three or more persons with heavier hot water use to arrive at proper bathing mix temperatures. In this paper we compare the largest and smallest draws.

Using electronically-controlled solenoids, all tested systems were simultaneously subjected to the same water draws and temperatures; electrical power demand, room temperature, and outdoor temperature were measured. Data were collected at a one-minute interval, which were then aggregated into 15-minute bins, commonly used for utility load evaluations. Within the study, a 3-hour morning curtailment (6 – 9 AM) and 4-hour evening curtailment (4 – 8 PM) were defined as shed periods to reflect times when system-wide electric demand reductions are likely of high value to utilities. We note that the resulting laboratory load demand profiles are expected to be larger than that shown in the concurrent field demand segment of this study—particularly for winter. The laboratory units were intentionally exercised under more demanding tests than conducted in the field segment, to best approximate peak demand days. The HPWHs were set to most efficient mode of operation.

The five water heaters evaluated were all set to deliver temperatures of 125 °F, which is similar to the average tank set points of 127 °F found in a sample of 138 Florida homes. (Masiello and Parker 2002.) The tested units are:

- A.O. Smith 50 gallon ERWH, 0.93 Uniform Energy Factor (UEF), EG12-50H55DV 200, Upper element 5500W, Lower element 5500W
- Rheem 50 gallon HPWH (CTA 2045-A), 3.55 UEF, XE50T 10H45UO, Upper element 4500W, Lower element 4500W
- A.O. Smith 50 gallon HPWH (CTA 2045-A), 3.45 UEF, HPTU-50N 130, Upper element 4500 W, Lower element 4500W
- A.O. Smith 80 gallon HPWH (CTA 2045-A), 3.45 UEF, HPTU-80N 130, Upper element 4500W, lower element 4500W
- GE Prototype 50 gallon HPWH (CTA 2045-B) N/A; Prototype

Data were recorded on a multi-channel data logger, executing measurements every 12 seconds. Scanned data were then averaged into 1-minute intervals and stored. Inlet water temperatures (which were uncontrolled) are physically measured using immersion well type-T thermocouples of special limit error ($\pm$0.5 ºC). Hot water outlet temperatures were also measured with immersion thermocouples a short distance from the outlet port. The annual weighted average inlet water temperatures experienced in the HWS in Florida reflect very moderate inlet water temperatures varying from 62-65 ºF in January-February to 83-85 ºF from June-September (see Colon et al. 2016 for specific data).

This seasonal phenomenon, widely observed throughout North America, serves to reduce the magnitude of water heating in warmer months and warmer climates (Burch and Christensen 2007). Figure 2 shows the measured draw-weighted inlet temperatures in the HWS which were

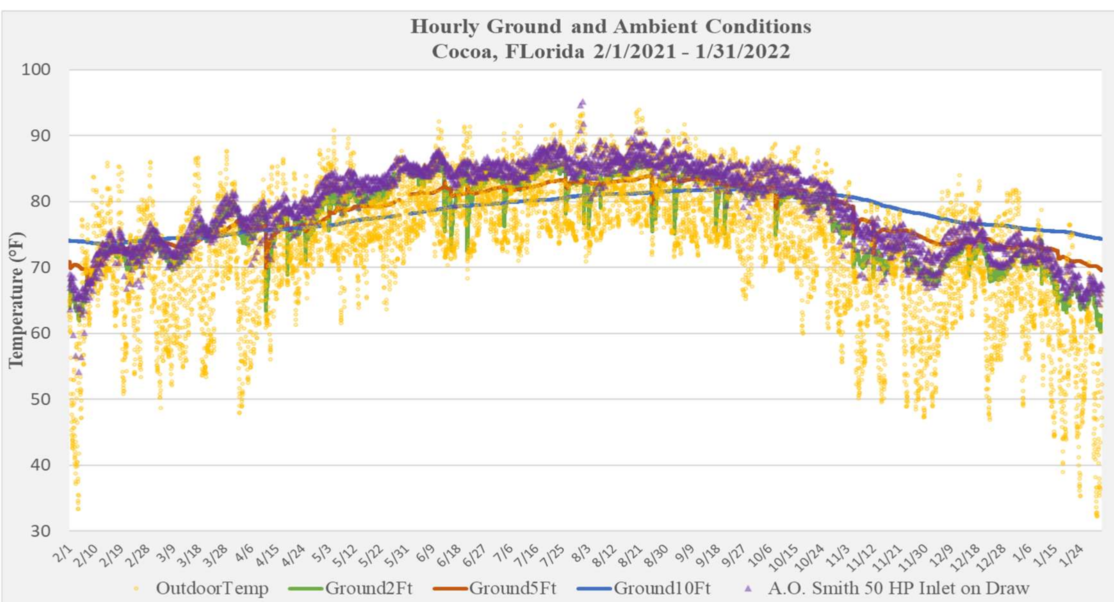

Figure 2. Measured draw-weighted inlet water temperatures (purple) against various weather conditions (2021) at HWS lab. Note correspondence of inlet water temperature with ground temperature at 2 foot depth.

found to be strongly tied to the ground temperature at a two-foot depth where the mains water piping is buried in Central Florida. Interestingly, we also found that the measured HWS inlet temperatures were very similar to one field verification site when this value was measured in the field. This likely means inlet temperature is a fundamental value driving both hot water energy use as well as mix temperature to reach 105 ºF for bathing end-uses.

Laboratory Test Results

More than 200 tests were conducted and are compared to both a baseline water heating electricity (ERWH) and a baseline HPWH use without load control. We used a summer draw profile of 47 GPD for summer and 69 GPD for winter to strongly challenge the various exercised control options in a laboratory environment. Repeated evaluation of similar control strategies and draw profiles showed excellent repeatability of recorded laboratory data. Uncertainty in test values is $\pm$ 0.03 kW based on repeated testing. Tests were run for one or two weeks.

Tests were performed under baseline conditions (i.e., no load shifting commands), and across different load shifting schemes. The general outline for tests was *n* hours of a morning load up (a period where the unit is encouraged to operate to increase water storage temperature) followed by *n* hours of curtailment, then *n* hours of an afternoon load up followed by *n* hours of curtailment. Thus, a 2-3-2-4 test protocol would indicate a 2-hour load up, a 3-hour morning curtailment window, a 2-hour afternoon load up, and then a 4-hour curtailment window during the evening hours.

The load up command calls on the water heater to raise the tank temperature up to its set point ahead of the shed or critical peak curtailment period. We issued load up commands immediately ahead of the curtailment commands. A longer load up period is intended to fully charge hot water storage. This longer duration is potentially important to HPWH compressors with a limited capacity compared to larger resistance elements in ERWHs. For the CTA-2045-B prototype unit, we sent an advanced load up command, which allowed the water to be heated 15 °F above the tank set point. This unit contains an integral mixing valve to bring the delivery temperature down to prevent scald danger.

The prototype HPWH enabling the CTA 2045-B protocol allowed advanced load up to allow the tank temperature to heat up beyond the tank set point. (A tank set point of 130 °F (5 °F above the user set point) was determined necessary to produce the desired user set point of 125 °F through trial and error.) For the discussed experiments, we allowed the tank set point to approach 145 °F. While the prototype is the only unit that can accept the advanced load up command, it is not capable of accepting critical peak commands. Thus, at times, different command strategies were tested on the on the prototype than on the other water heaters. Figure 3 shows how tank temperature of the heat pump with advanced load up (AHP) varied during a typical day under load control.

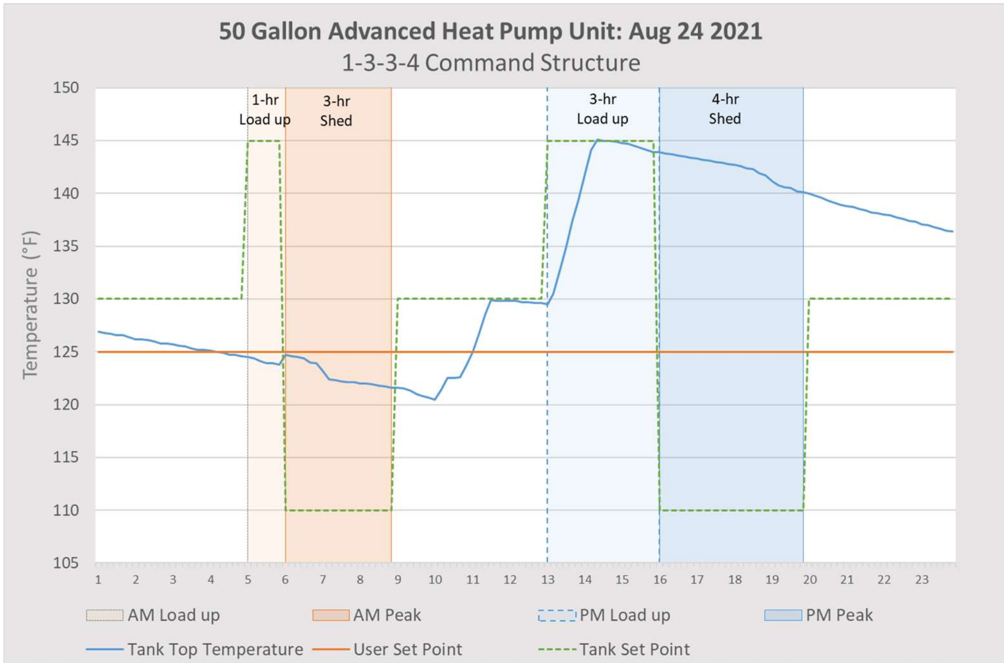

Figure 3. Temperatures for GE CTA-2045-B protocol with advanced load up capability.

Table 1 summarizes best performing command structure, first in terms of peak window curtailment and secondly in terms of daily energy consumption for each unit. As described in detail following Table 1, there were often competing tests for the best curtailment strategy and differences in energy use are sometimes explained by dissimilar test conditions. Winter comparisons are made with days where the average daily temperature was lower than 65 °F, and summer comparisons for days that were 65 °F or higher. Outlet temperatures were measured, and an evaluation of the minimum temperatures on a per-minute read shows that adequate

Table 1. Energy and peak demand for best summer and winter strategy versus baseline

Baseline or Best Summer/Winter Strategy	Summer			Winter		
	kWh/day (%)	AM kW (%)	PM kW (%)	kWh/day (%)	AM kW (%)	PM kW (%)
A.O. Smith 50G ER: Baseline	6.70	0.85	0.80	11.07	1.64	1.36
A.O. Smith 50G ER: 2-3-2-4 CP/2-3-2-4 CP	7.89	0.00	0.00	9.38	0.20	0.18
Reduction	-1.19 (-18%)	0.85 (100%)	0.80 (100%)	1.69 (15%)	1.44 (88%)	1.18 (86%)
Rheem 50G HP: Baseline	1.52	0.20	0.21	2.90	0.28	0.30
Rheem 50G HP: 2-5-2-6 CP/2-3-2-4 CP	1.53	0.00	0.00	2.40	0.08	0.09
Reduction	0.00 (0%)	0.20 (100%)	0.21 (100%)	0.50 (17%)	0.20 (72%)	0.21 (69%)
A.O. Smith 50G HP: Baseline	1.76	0.19	0.21	3.11	0.31	0.29
A.O. Smith 50G HP: 2-3-2-4 CP/2-3-2-4 CP	2.17	0.00	0.00	2.85	0.00	0.10
Reduction	-0.42 (-24%)	0.19 (98%)	0.21 (98%)	0.26 (8%)	0.31 (99%)	0.19 (66%)
A.O. Smith 80G HP: Baseline	1.79	0.11	0.19	2.90	0.16	0.21
A.O. Smith 80G HP: 1-3-1-4 S/2-3-2-4 CP	1.82	0.00	0.00	2.79	0.00	0.00
Reduction	-0.03 (-1%)	0.10 (97%)	0.19 (98%)	0.11 (4%)	0.16 (98%)	0.20 (99%)
GE 50G HP: Baseline	2.17	0.06	0.24	4.42	0.48	0.40
GE 50G HP: 2-5-2-6 S/1-3-3-4 S	2.41	0.00	0.00	3.42	0.01	0.00
Reduction	-0.24 (-11%)	0.06 (94%)	0.24 (99%)	1.01 (23%)	0.47 (99%)	0.39 (99%)

temperatures for all of the production units. Outlet temperatures were chiefly maintained above 115 °F, and always above 110 °F, with the exception of a few readings on the A.O. Smith 50 and 80 gallon HPWHs with temperatures of 108/109 °F during a very aggressive zero load up with a 12-hour critical peak curtailment strategy.

Summer Conditions Testing (47 GPD and temperatures ≥ 65ºF)

Average electrical demand for the ERWH under baseline conditions is compared to that under the 2-3-2-4 CP test in Figure 4. (The 1-3-1-4 CP test is not available under this temperature and draw profile at this time for comparison.) While peak demand load reduction was achieved with an electric resistance tank, there was a 1.19 kWh/day energy penalty showing that 2045-A control with a conventional ERWH may increase energy use over the uncontrolled configuration.

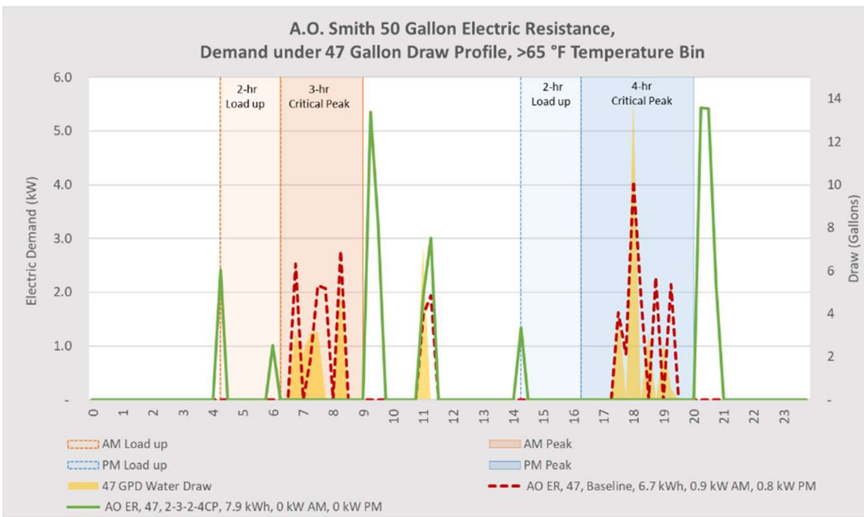

Figure 4. A.O. Smith 50 gallon electric resistance, baseline vs. 2-3-2-4 CP; Summer, illustrating load up and critical peak curtailment periods

Under all tests with a one or two hour load up, the Rheem 50 gallon HPWH unit was always able to avoid demand during the peak windows. While the 57 GPD draw profile is not a focus in this paper, the 1- and 2-hour load up tests showed equivalent results under this larger draw profile too. The 2-5-2-6 CP test provided perfect curtailment during the shed windows and with no energy penalty, as demonstrated in Figure 5. While the 1-3-1-4 shed test also yielded complete curtailment during the peak windows, there was an energy penalty of 0.27 kWh per day (18%). (The energy savings and curtailment of the HPWHs are relative to the baseline for each unit, unless a comparison to the ERWH baseline is specifically referenced.) Deeper investigation shows that while the daily average outdoor temperatures for the periods compared were nearly identical (69.5 °F during the 2-5-2-6 CP test and 70.5 °F during the 1-3-1-4 shed test) the inlet temperatures averaged a full 10 degrees warmer during the 2-5-2-6 CP test, explaining the energy penalty associated with the 1-3-1-4 shed test. This also speaks to the importance of ground temperatures over ambient temperatures, as demonstrated in Figure 3.

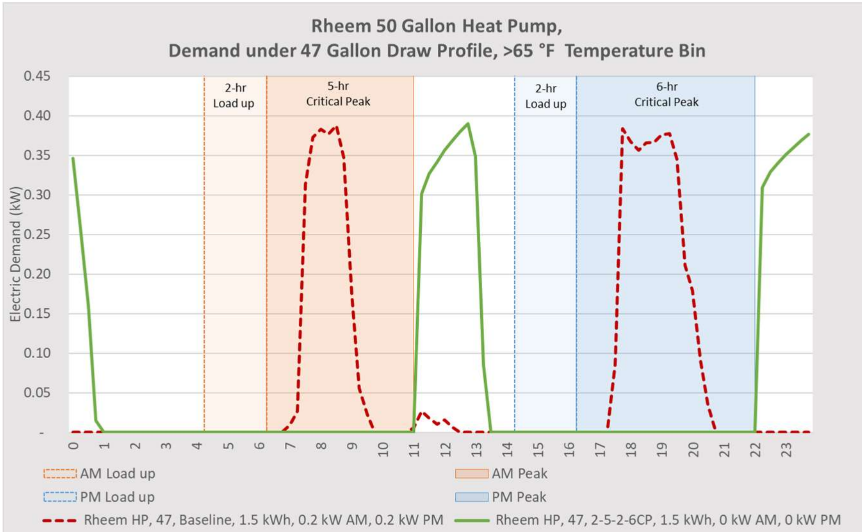

Figure 5. Rheem 50 gallon HPWH, baseline vs. 2-5-2-6 CP; Summer.

The best performing test for the A.O. Smith 50 gallon HPWH was the 2-3-2-4 CP, which is plotted against the unit's baseline in Figure 6. The strategy completely avoided demand during the peak control windows, although there was an energy penalty of 0.42 kWh (24%) per day. We note that the 1-3-1-4 CP and the 2-3-2-4 CP also completely avoided demand during the peak control windows under the larger 57 GPD draw profile. These each also had similar energy penalties.

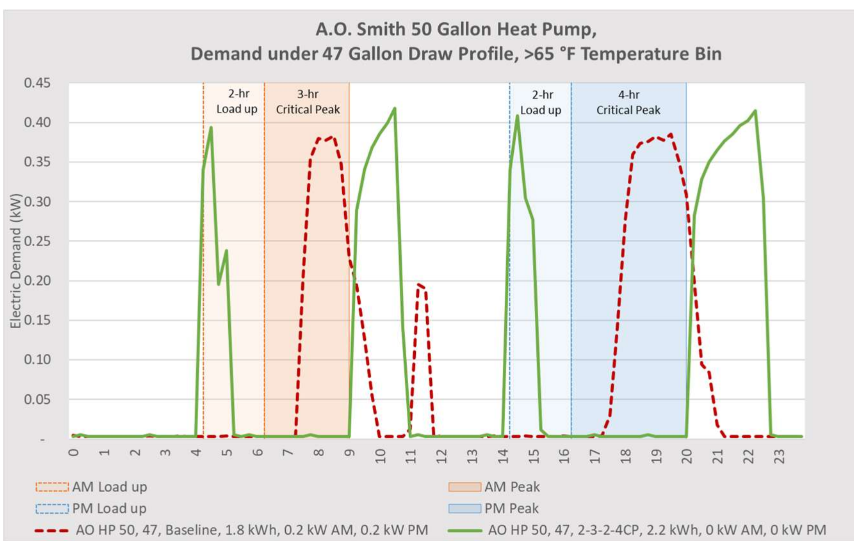

Figure 6. A.O. Smith 50 gallon HPWH, baseline vs. 2-3-2-4 CP; Summer.

Almost all tests run on the A.O. Smith 80 gallon HPWH avoided peak demand completely (including 2-5-2-6 CP, 2-3-2-4 CP, 1-3-1-4 shed, and 2-3-2-4 shed). However, the 1-3-1-4 shed was the best performing command with no statistically significant energy penalty. This test is plotted against the unit baseline in Figure 7. The only command structure examined that was unable to largely curtail morning demand during peak hours was the zero load up, 0-12-2-10 CP. This underscores the importance of some load up to achieve dependable load shed.

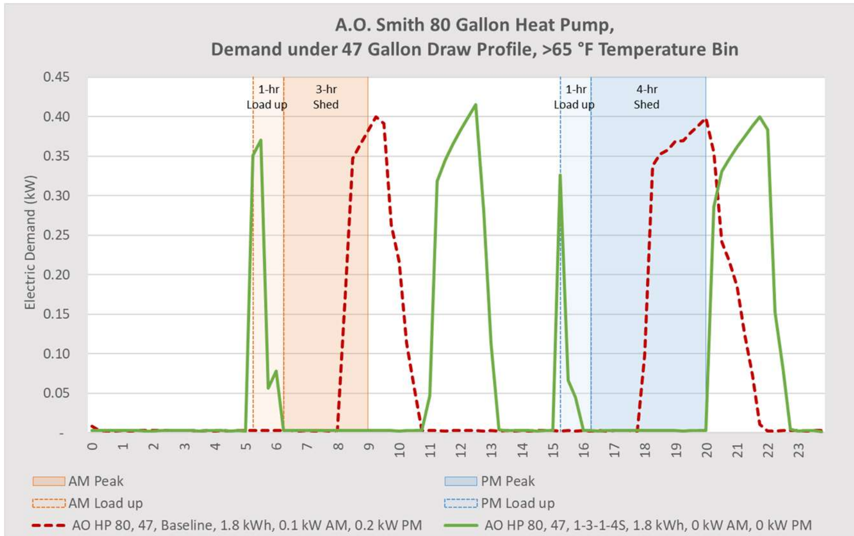

Figure 7. A.O. Smith 80 gallon HPWH, baseline vs. 1-3-1-4 Shed; Summer.

The GE 50 gallon advanced load up HPWH prototype was tested with the 2-5-2-6 shed and the 0-12-2-10 shed under the 47 GPD draw with warmer outdoor temperatures. There were no one-hour load up tests available for comparison during this draw and temperature profile. Curtailment during the 2-5-2-6 test was only slightly better than the 0-12-2-10. Of note: the zero load up 0-12-2-10 had an energy use reduction of 0.77 kWh (36%) per day**.** The 2-5-2-6 shed, plotted against the unit's baseline in Figure 8, completely eliminated demand during both curtailment windows, but with a 0.24 kWh/day (11%) energy penalty. (The critical peak command is not available with this 2045-B protocol prototype.)

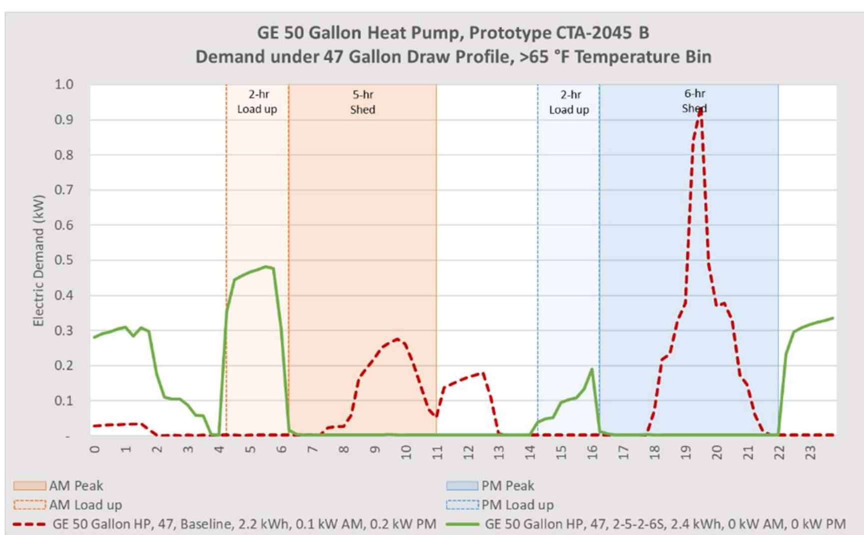

Figure 8: GE 50 gallon, CTA-2045B prototype HPWH, baseline vs. 2-5-2-6 Shed; Summer.

Testing for Winter Conditions (69 GPD and daily temperatures under 65ºF)

No test on the ERWH were able to completely avoid peak morning window demand during the 69 GPD draw with an outdoor temperature less than 65 °F. While there were large reductions in control window demand under the 2-3-2-4 CP, the unit was not able to completely curtail during either the morning or the evening peak windows, as demonstrated in Figure 9. Also, large daily water heating energy reductions were observed, 1.69 kWh per day (15%). Curtailment under the 1-3-1-4 CP test was similar to that of the 2-3-2-4 CP, but with less water heating energy use reduction (0.64 kWh per day, or 6%). Under deeper investigation we find that the inlet water temperatures during the 1-3-1-4 CP period were considerably colder, averaging 70.2 °F, versus 76.9 °F during the 2-3-2-4 period which explains the energy use difference.

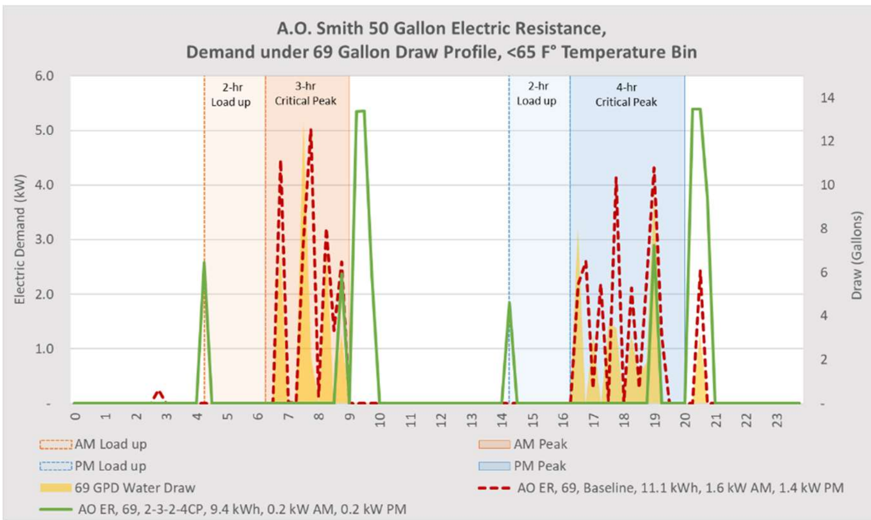

Figure 9. A.O. Smith 50 gallon electric resistance, baseline vs. 2-3-2-4 CP; Winter.

The best performing test for the Rheem 50 gallon HPWH under the winter profile was the 2-4-2-4 CP. Under this test, peak demand is sharply curtailed, but the unit is unable to make it through either the morning or afternoon peak windows without resuming compressor operation. This unit curtailed similarly under the 1-3-3-4 CP, the 1-3-1-4 shed, and the 2-3-2-4 CP. The 2-3-2-4 CP, plotted in Figure 10, had the greatest daily energy reduction of those investigated, 0.50 kWh (17%). Perhaps most interestingly, the load up command is not acted upon, as was the case for all tests mentioned here. While we don't know how the different manufactures handle the CTA-2045 commands, the Rheem unit appears to allow the tank temperature to drop slightly lower than the other units tested, likely explaining why the load up opportunity was sometimes passed up.

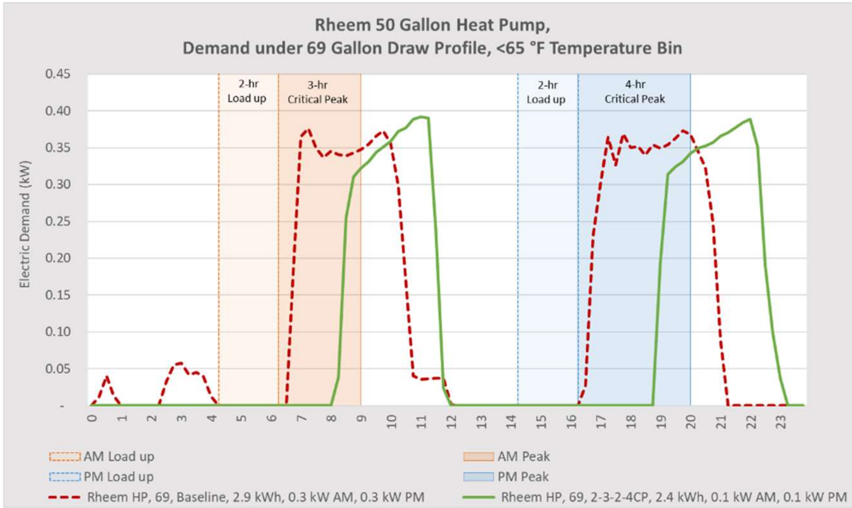

Figure 10. Rheem 50 gallon HPWH, baseline vs. 2-3-2-4 CP; Winter.

The A.O. Smith 50 gallon HPWH was subjected to several tests under the 69 GPD winter profile. The 2-3-2-4 CP was the only test examined to curtail during the whole *morning* peak window, as plotted in Figure 11. This test also produced a daily energy water heating energy reduction of 0.26 kWh (8%). When comparing this curtailment to that of the 50 gallon resistance unit of a similar size and the same manufacturer (excluded from graph due to scale), we were able to cut morning peak demand by 0.31 kW (99%).

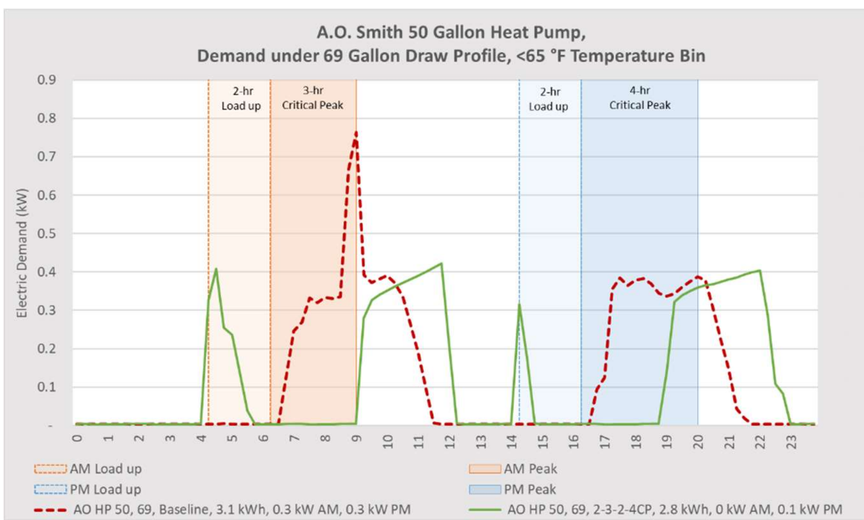

Figure 11. A.O. Smith 50 gallon HPWH, baseline vs. 2-3-2-4 CP; Winter.

The A.O. Smith 80 gallon HPWH performed about as well for the 1-3-1-4 CP, 1-3-3-4 CP, and the 1-3-1-4 shed tests. However, under the 2-3-2-4 CP command structure the unit also showed a small daily energy reduction of 0.11 kWh (4%). Results are plotted in Figure 12 and include the 1-3-1-4 CP test. This comparison demonstrates that only one hour of load up is needed to get through the curtailment period – under these weather conditions and this draw profile –, regardless of the load up length offered. Once again, the energy use difference between the 2-3-2-4 CP and the 1-3-1-4 CP tests is explained by different inlet water temperatures, which were considerably colder during the 1-3-1-4 CP period.

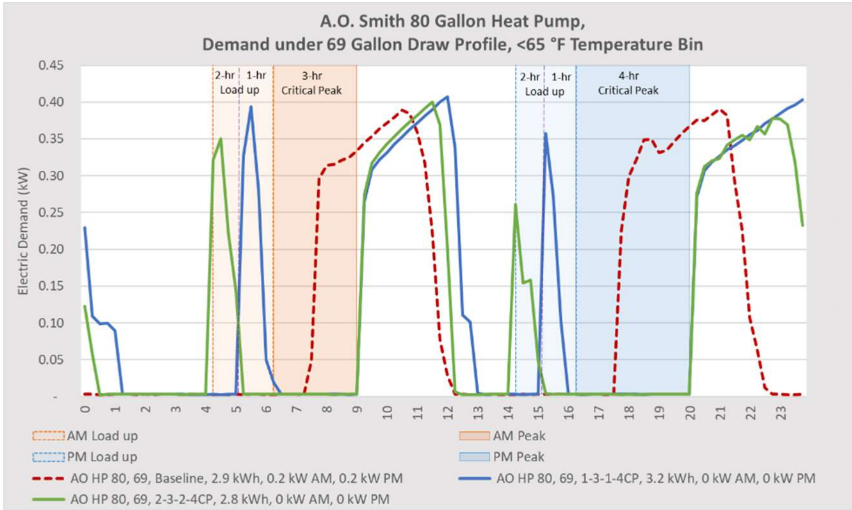

Figure 12. A.O. Smith 80 gallon heat pump, baseline vs. 2-3-2-4 CP and 1-3-1-4 CP; Winter.

The GE 50 gallon advanced load up (HPWH CTA-2045-B protocol) unit was tested with the 1-3-1-4 shed, 1-3-3-4 shed, and the 2-5-2-6 shed under the winter and 69 GPD draw profile. Curtailment was complete, or nearly so, under all tests; outperforming the similarly sized units without the advanced load up capability. However, the 1-3-3-4 shed test, presented in Figure 13, also showed a sizeable energy reduction (1.01 kWh per day, or 23%).

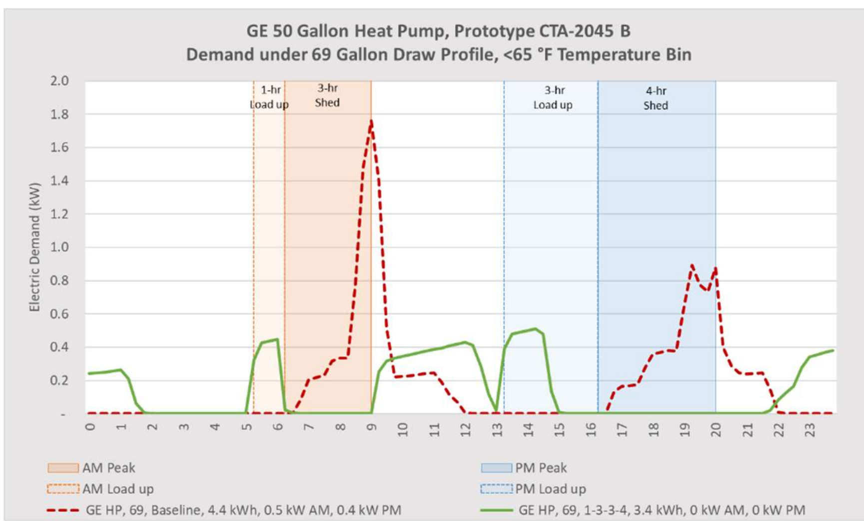

Figure 13. GE 50 gallon, CTA-2045-B prototype HPWH, baseline vs. 1-3-3-4 Shed; Winter.

The 0-12-2-10 CP summer test showed differences during the morning peak. Morning reductions over unit baselines were 0.38 kW for the ER tank; 0.08 kW for the Rheem, 0.11 kW for the A.O. Smith 50 gallon (over uncontrolled HPWH), and no reduction for the A.O. Smith 80 gallon; The GE, which was tested with the 0-12-2-10 shift command, showed load increase of 0.03 kW during the morning curtailment window.

A rough comparison of the laboratory tests with earlier field data shows approximate correspondence. In the Pacific Northwest, Metzger et al. (2018) measured an electric resistance tank peak load shed of approximately 0.325 kW with load control and 0.20 kW with HPWH. In our lab tests, across strategies, we saw larger drops (1.23 kW) from a strongly challenged ERWH system in the winter (69 gallon draw), but similar reductions to Metzger's study controlling HPWH -- 0.13-0.23 kW demand reduction among CTA-2045-A units, and 0.47 kW demand reduction with the CTA-2045-B prototype. These are average reductions among all tests evaluated. We hasten to add that the field data are given precedence as indicators of likely performance for utilities operating 2045-A or B control of water heaters. However, our tests yielded data on comparative strategy results and under highly controlled and repeatable circumstances.

Conclusions

Electric resistance water heaters (ERWH) are the most common water heating type in the Southeastern U.S—making up 73% of systems (EIA 2015). We evaluated how effective control of HPWHs might reduce household electric demand for heating hot water. Laboratory testing was conducted on five different electric water heaters designed to provide load control for electric utilities. Their design objective is to lower energy demand during system peak periods. One of the water heaters was an ERWH; the other four units were HPWH. Each of the HPWH systems had dispatchable load control that could feasibly cut demand on command during curtailment periods. This came in response to a load shed signal, or even more so with a critical peak signal.

Detailed monitoring was performed from 2020 - 2022 at the FSEC hot water systems laboratory (HWS) in Cocoa, Florida with over two hundred tests conducted. We found HPWH systems, when tested in the laboratory, provided reductions to energy use of 66-77% when compared to electric resistance storage water heaters.

When comparing a uncontrolled 50 gallon resistance to a controlled HPWH of a similar size and manufacturer, we were able to cut morning peak demand by up to 1.64 kW (99%) in winter (69 GPD draw). As expected, when the HPWH was controlled, the reduction was greater than for the uncontrolled water heater. Peak demand was reduce by up to 0.31 kW more for controlled compared to uncontrolled HPWH units. Demand reduction depended on numerous factors identified in the testing: the CTA control protocol, tank volume, control scheme, draw profile, and time of year. The 1-hour load up duration was often long enough to satisfy a 3- or 4-hour curtailment.

Within the various control configurations, we found many 1- and 2-hour load up strategies similarly effective in Florida's very warm summer. They provided perfect 100% load shed (0.85 kW morning and 0.80 kW evening) when evaluated at the 47 GPD draw profile, as compared to the uncontrolled ERWH. Only the A.O. Smith 80 gallon and the GE CTA 2045-B prototype were able to completely shed load during the winter tests under a 69 GPD draw profile (1.64 kW morning and 1.36 kW evening). Each unit successfully curtailed throughout the peak window demand, both during the1- and 2-hour load up strategies.

During both summer and winter, there were often other strategies that curtailed demand equally well, or nearly so, but with differences in daily energy use – sometimes explained by differences in inlet water temperatures. We found inlet water temperature are strongly associated with ground temperatures at two feet depth and slow to react to outdoor temperatures. Summary results are displayed graphically in Figure 14 (Summer) and Figure 15 (Winter), comparing peak window reductions and energy use changes for each unit's best strategy compared to its baseline.

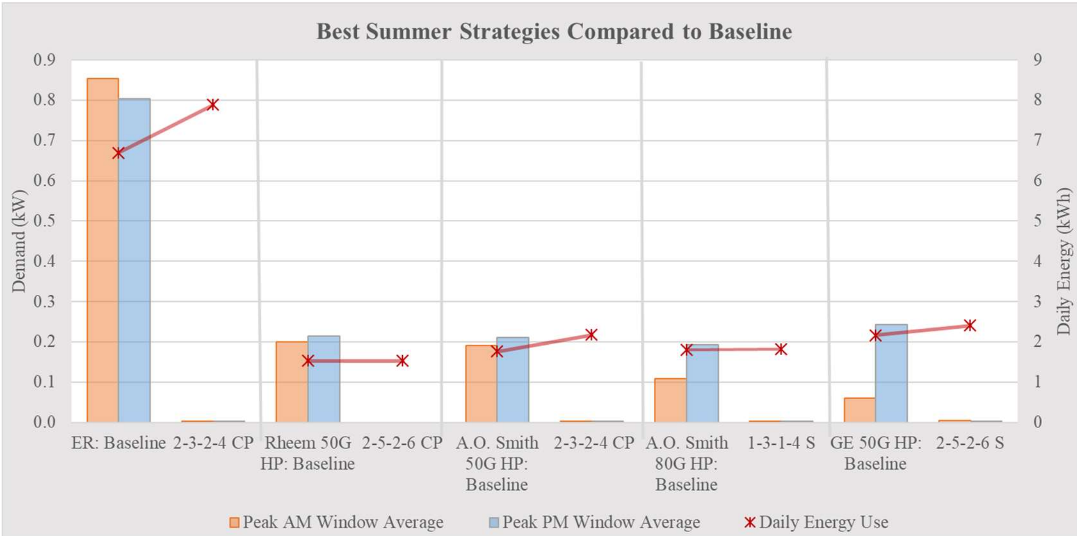

Figure 14. Demand and energy use changes for best summer strategy compared to its baseline.

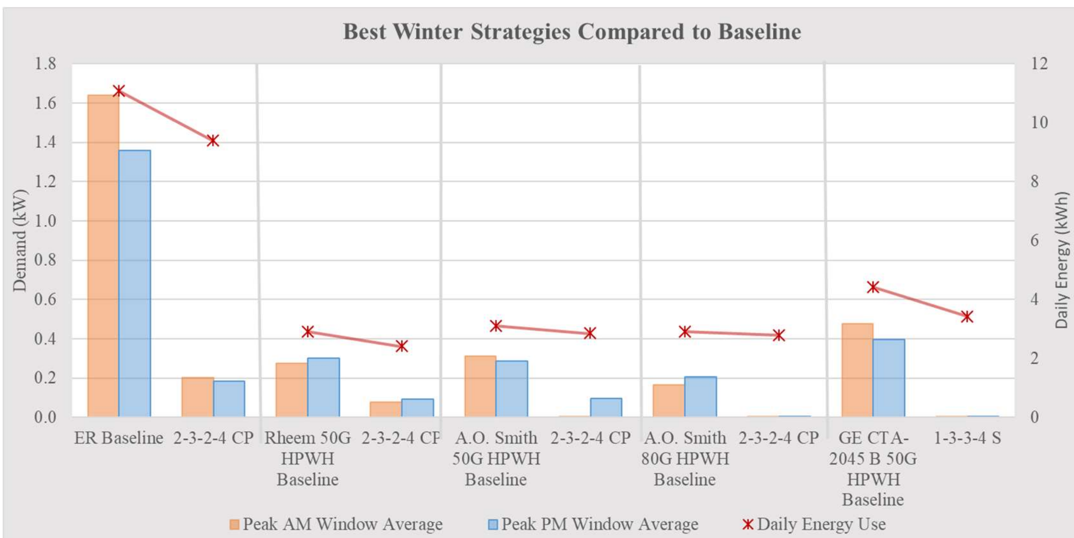

Figure 15. Demand and energy use changes for best winter strategy compared to its baseline.

Under load control, the ERWH was unable to perfectly curtail the load during the winter test, but did provide energy use reduction in winter (1.69 kWh, 15%) as compared to no load control. However, there was perfect peak load curtailment in summer, but with an energy penalty (-1.19 kWh/day, 18%).

We tried an aggressive 0-hour load up morning strategy of 0-12-2-10 in summer, which was unable to control demand the morning window although successful after a 2-hour load up preceding the evening control window. The 0-hour load up did provide some energy savings. Energy savings were similar for the 2045-A protocol units with this 0-hour load up test – 0.41 kWh for the Rheem 50 gallon, 0.50 kWh for the A.O. Smith 50 gallon, and 0.58 kWh for the A.O Smith 80 gallon.

One of these models was a prototype 50 gallon heat pump unit engineered to provide "advanced load up" prior to electric load shed. The advanced load up increases the hot water set temperature prior to load control in order to potentially provide longer and deeper load reductions during the curtailment window.

For the advanced load up unit in winter, we found either the 1-3-1-4, the 1-3-3-4, or the 2-5-2-6 provided essentially identical results with near perfect winter morning load shed. This unit demonstrated better shedding ability than the similarly sized units without the advanced load up capability. The superior load shed demonstrated by the advanced load up was during very large draw profiles in winter conditions, conditions that may not often be observed in Florida with its mild inlet water conditions. However, cooler climates might expect to see greater demand reduction over standard load up ahead of curtailment.

All 2045-A and 2045-B schemes worked well except for the 0-12-2-10 scheme without morning load up, which was only tested under summer conditions. All controlled water heaters show a "payback" of increased demand at the end of the control window. However, these control release demand spikes differ markedly between ERWH (often 5 kW) versus the HPWH which show a "release demand" of only about 0.5 kWh.

This is potentially a large difference for an electric utility in the future that might face many thousands of such water heaters operating under control in a diversified manner. Results suggested the 80 gallon compared with 50 gallon tank size was only marginally better for load shed purposes in Florida if there was at least a one hour load up prior to the control event. Findings may be impacted by different control modes for the HPWH and different draw patterns. Geographic variation is also expected to influence such conclusions as inlet water temperatures in northern climates can be expected to be much lower. The high efficiency mode was used for our testing and results may vary with units set to a less efficient hybrid mode.

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