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

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ABSTRACT

Future utilities will emphasize home appliances to reduce greenhouse gas emissions while providing electric load shifting and demand profile management. Heat pump water heaters (HPWH) have demonstrated the ability to cut water heating energy by more than 65% compared with conventional electric resistance waters (ERWH). Laboratory research was conducted on the load shifting potential of grid-connected heat pump water heaters (HPWH), compared to ERWHs. Testing applied different CTA-2045 command designs. Highly-controlled laboratory experiments were conducted on one ERWH and four HPWHs, including a prototype incorporating the new CTA-2045-B protocol feature allowing 'advanced' load up above the tank setpoint. The prototype unit with the B-protocol increased tank temperature by 15°F (8.3C) under the advanced load up providing an increase of 1.8 kWh of storage for a 50-gallon (189 liter) tank. The prototype includes a built-in mixing valve to meet anti-scalding codes. With the load-shaping ability of CTA-2045-B, utilities might be able to store excess renewable energy in connected tanks when renewable wind and solar resource production is high. Tests were performed under baseline conditions (no load shift) and under several load-shifting schemes, including load up and advanced load up, ahead of shed commands. Grid-connected HPWHs reduced peak demand by as much as 0.5 kW, depending on tank volume, time of day, control scheme, and draw profile.

INTRODUCTION

Laboratory electrical load shifting experiments were conducted using the CTA-2045-A and -B standards to demonstrate the viability of grid-connected heat pump water heaters (HPWH) in comparison to conventional electric resistance water heaters (ERWH). The investigation applied different CTA-2045 shed control command designs under two different water draw profiles representing average and above-average hot water consumption in U.S. single-family homes (discussed in the section Implemented Experiments). Highly-controlled laboratory experiments were conducted on one ERWH and four HPWHs – including a special prototype allowing for the CTA-2045-B advanced load up command – from April through October 2021.

The research aimed to evaluate the load shifting potential of grid-connected HPWHs in a high-impact region, including the testing of a prototype unit with the CTA-2045-B protocol. A secondary objective was to evaluate energy efficiency implications of HPWHs compared with ERWHs that comprise greater than 73% of water heaters in the Southeastern U.S. (DOE/EIA, 2015). This high saturation of ERWHs in the Southeastern U.S. provides the region a unique opportunity for HPWH market penetration, offering significant energy savings potential. However, many of the large utility providers in these states do not offer HPWH incentives to their customers through their energy efficiency programs. On the other hand, most of these large utility providers have demand response and load management programs (Butzbaugh and Winiarski, 2020). This means these utilities may find value in promoting grid-connected HPWHs capable of load shifting if demonstrated as viable.

Two hot water draw profiles were implemented in the FSEC Hot Water Systems Laboratory (HWS) in Cocoa, Florida. Using electronically-controlled solenoids, all tested systems were simultaneously subjected to the same draws with flows and temperatures carefully measured as well as electrical power demand, room temperature, and outdoor

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temperature. Data were collected at a one-minute interval, which were then aggregated into 15-minute bins, commonly used for utility load evaluations across the U.S. Within the study, we define curtailment as the period during which a specific effort is made to limit water heater electric demand on the utility. A three-hour morning curtailment (6 – 9 AM) and four-hour evening curtailment (4 – 8 PM) were defined as the shed periods to reflect times when system-wide electric demand reductions are of high value to utilities.

Tests were performed under baseline conditions (i.e., no load shifting commands), and across multiple different load shifting schemes. These schemes are briefly outlined in the section Implemented Experiments. The general outline for tests was *n* hours of a morning load up (a period where the water was forced on to increase water storage temperature) followed by *n* hours of shed, then *n* hours of an afternoon load up followed by *n* hours of shed. The load up command calls on the water heater to raise the tank temperature up to its set point ahead of the shed period. 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 (8.3 C), in our experiments) above the tank set point with an integral mixing valve to bring the delivery temperature down to prevent scald danger.

BACKGROUND

Heat pump water heaters (HPWH) are a well demonstrated technology to dramatically reduce electricity consumption for meeting household hot water needs. A variety of monitored projects around the U.S. have shown savings of 50-70%, reflected by operational coefficient of performance (COP), relative to conventional electric resistance storage tank systems (Colon et al., 2016, Shapiro and Puttagunta, 2016, Willem et al., 2017). More recent systems have shown even higher operational COPs from improved compressors and other design enhancements.

Beyond the ability to save water heating electricity, such systems can also cut peak demand. However, few studies have quantified how load shifting capabilities with HPWH might help utilities meet load control objectives. This can be thought of as the ability to not only control utility-coincident peak loads, but also to 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 CTA-2045-A protocol (ANSI/CTA, 2018). This protocol has demonstrated electric demand flexibility in the Northwest, to provide a utility the ability to control when an appliance draws power from the grid (Metzger et al, 2018).

The CTA-2045 protocol standardizes both the hardware interface between a communications module and 'smart' appliance, as well as the language used by electricity providers to communicate with a connected device. Unitary Control Modules (UCM) can be attached to conforming appliances, enabling dedicated, digital control of the appliance using the CTA-2045 protocol, and allowing electricity providers to communicate with end uses over the standard interface. The communications standard specifies messages, called commands, which each CTA-2045-enabled device must support. The current CTA-2045-A communications commands used for this 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), and end shed (return to normal operation). Water heater manufacturers determine how different water heaters respond to the control commands (based primarily on the water temperature profile in the tank), and thus differences can exist in implementation. The CTA-2045-B protocol allows for an advanced load up, just described.

TESTED WATER HEATERS

The four water heaters characterized in Table 1 were all set to deliver temperatures of 125°F (51.7 °C) which is essentially identical to the average tank set points of 127°F (53°C) found in a sample of 138 Florida homes. (Masiello and Parker, 2002.)

Table 1. Test Facility Water Heater Model Numbers, Capacity and UEF

Technology	Capacity (Gallons/Liters)	Uniform Energy Factor
ERWH	50/189	0.93
HPWH (with CTA 2045-A)	50/189	3.45
HPWH (with CTA 2045-A)	80/303	3.45
HPWH (with CTA 2045-B)	50/189	N/A

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. For the discussed experiments, we allowed the tank set point to approach 145°F (63°C). Figure 1 demonstrates how the tank temperature of the heat pump with advanced load up (AHP) varied during a typical day under load control.

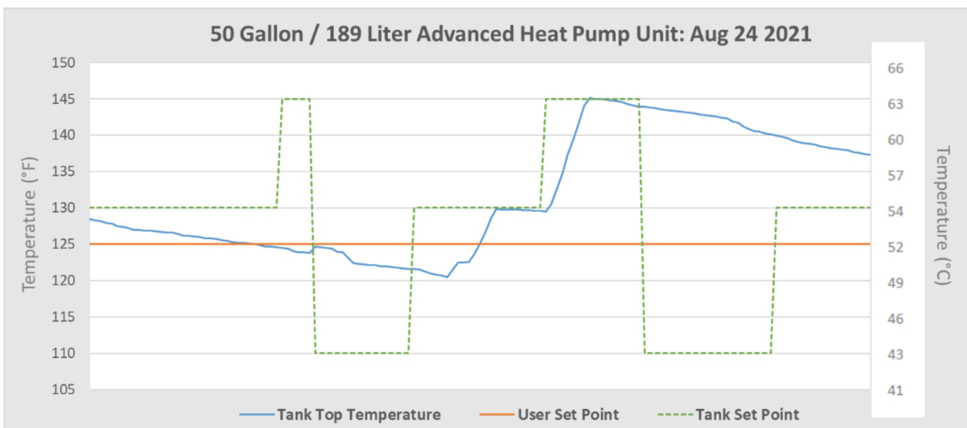


Figure 1 Temperatures for AHP unit with CTA-2045-B protocol capability including advanced load up capability.

INSTRUMENTATION AND MONITORING

Data were recorded on a multi-channel data logger, executing measurements every 12 seconds. Scanned data are then averaged into 1-minute intervals and stored. A custom program takes into consideration the hot water draw events that occur during the day (see next section). Inlet water temperatures are physically measured using ungrounded immersion well (stainless steel) type T thermocouples of special limit error (±0.5ºC). Hot water outlet temperatures are also measured with immersion thermocouples at the system positioned less than six inches 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 around North America, serves to reduce the magnitude of water heating in warmer months and warmer climates (Burch and Christensen, 2007).

IMPLEMENTED EXPERIMENTS

Draw Profile and Grid-Connected Command Schedules. For the test facility evaluation, different water heater models were compared in their responses to combinations of the two draw profiles and eight grid-connected command schedules. Each distinct test, as well as a baseline with no commands under each draw schedule, was run for one week at a time. The two draw profiles tested and reviewed in this report are 57 gallons per day (GPD) (216 Liter (L)) and 69 GPD (621 L), plotted in comparison in Figure 2. The shape of the draw profiles differ in important ways. The 57 GPD (216 L) profile aligns with common draw profiles with morning weighted draws, consistent with measured hot water energy demand and associated hot water consumption profiles seen in studies stretching back to the 1980s (Masiello and Parker, 2002; Fairey and Parker, 2004). The 69 GPD (261 L) profile has draws more tightly aligned with peak morning and evening hours. The differing shapes of the draw profiles are captured in Figure 2 in the cumulative gallons and liters over time for the vertical draw events shown.

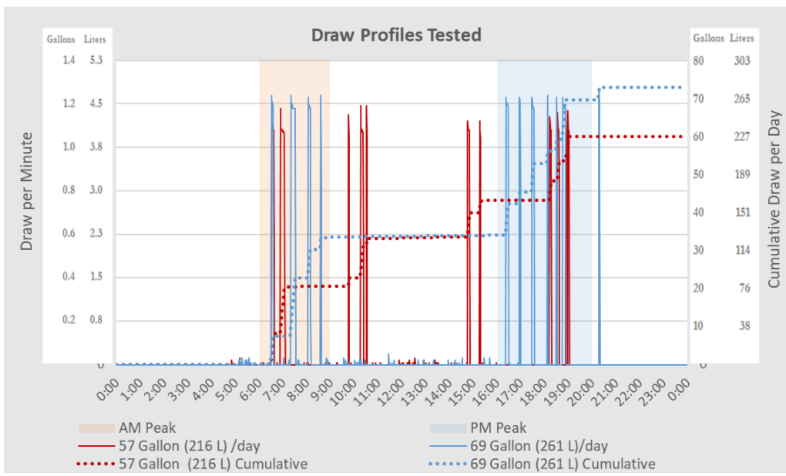


Figure 2 Hot water test facility draw profiles for connected water heater experiment.

Control Schemes. A total of eight different control schemes implemented during the experimentation from April to October 2021 were evaluated. These consisted of a morning load up period, a morning control window, an afternoon load up period and then a peak evening control window. Thus, a 0-12-2-10 test protocol would indicate a zero hour load up, a 12-hour morning curtailment window, a 2-hour afternoon load up, and then a 10-hour curtailment window during the evening hours. Load up commands are issued for the immediate hours ahead of the shed commands. Two test cases, (1-3-3-4) and (2-3-2-4) were designed to evaluate pre-heating and loading up to enhance the morning load shed.

Experimental Results. Table 2 shows the average measured water heater kW during the morning and evening peaks for the 50 G (189 L) electric resistance (ER 50), the 50 G (189 L) and 80 G (303 L) HPWH with CTA-2045-A (HP 50 and HP 80), and the 50 G (189 L) HPWH with CTA-2045-B (AHP 50). Daily energy is presented as well.

Table 2. Total Daily and Peak Hours Water Heater Energy and Demand

57 Gallon/216 Liter Profile								
	ER 50		HP 50		HP 80		AHP 50	
Temperature	Energy	Average Peak Demand	Energy	Average Peak Demand	Energy	Average Peak Demand	Energy	Average Peak Demand

						Energy			Energy			Energy	
Schedule	Average Outdoor °F	Daily kWh	AM Hours kW	PM Hours kW	Daily kWh	AM Hours kW	PM Hours kW	Daily kWh	AM Hours kW	PM Hours kW	Daily kWh	AM Hours kW	PM Hours kW
Baseline	80.4	6.39	0.68	0.47	1.56	0.20	0.11	1.50	0.19	0.17	3.00	0.26	0.54
0-12-2-10	83.2	5.99	0.55	0.00	1.36	0.13	0.00	1.33	0.18	0.00	1.49	0.00	0.00
0-3-3-4	80.0	5.95	0.11	0.00	1.54	0.04	0.00	1.58	0.03	0.00	1.83	0.05	0.00
0-6-4-7	79.9	6.38	0.00	0.00	1.55	0.00	0.00	1.55	0.00	0.00	1.85	0.00	0.00
0-7-0-8	79.1	6.39	0.00	0.00	1.54	0.02	0.02	1.66	0.00	0.00	1.89	0.00	0.00
0-7-3-8	79.0	6.35	0.00	0.09	1.60	0.00	0.02	1.61	0.00	0.02	1.85	0.00	0.00
1-3-3-4	82.9	6.13	0.11	0.15	1.55	0.04	0.03	1.54	0.04	0.04	1.89	0.00	0.00
2-3-2-4	73.0	7.53	0.00	0.00	1.98	0.04	0.02	1.95	0.03	0.00	2.21	0.00	0.00
69 Gallon/261 Liter Profile													
Baseline	75.8	8.15	3.65	3.98	1.89	0.88	0.91	1.83	0.62	0.73	2.14	0.56	0.52
0-5-4-6	75.7	7.36	0.57	0.66	1.80	0.32	0.44	1.76	0.01	0.01	2.01	0.58	0.01

One concern within water heater load control programs is that users may have insufficient hot water during large draw events or during lengthy control periods. Within the experiment, thermocouples at the tank outlet, measured outlet water temperature during draw events. We saw no evidence of the problem of low temperature hot water draws either with the 57 GPD (216 L) draws and limited 69 GPD (261 L) draws during summer conditions– an important consideration for using the CTA-2045 standard instead of traditional direct load control. This encouraging finding suggests manufacturers have engineered CTA-2045 water heater controls properly to limit hot water run outs for users. Further testing with 69 G (261 L) draws and under winter conditions will be important, however.

All of the control strategies other than no load up and 3 hour shed (0-3-3-4) showed substantial reduction in morning peak demand with the 57 GPD (216 L) draw profile. The observed hourly demand reduction for the Advanced Load Control Heat Pump (AHP) from 6-9 AM during the morning peak hours was 0.21 kW for this control scheme. There are 20 G (76 L) drawn during this peak window. The reduction during the evening peak window (0.54 kW) was larger given the 16 G (61 L) on-peak draw as well as other mid-day draws leading up to the evening peak.

Under the single 69 GPD (261 L) load control scheme, 0-5-4-6, only the 80 G (3030 L) HPWH avoided the peak demand windows nearly completely, dropping the morning peak from 0.62 kW to 0.01, and the afternoon peak from 0.73 to 0.01. The AHP was unable to curtail during the morning peak following a zero-hour load up, but performed effectively during the afternoon peak, dropping the peak from 0.52 to 0.01. The ERWH showed sizable reductions during both peak periods, and the 50 G (189 L) HPWH showed some curtailment, but less than the other units.

The total daily water heating energy without load control commands is 3.0 kWh/day for the heat pump water heater with advanced load up capability under the 57 G (216 L) draw. Meanwhile, the 50 G (189 L) electric resistance water heater meeting the same draws showed an average daily consumption of 6.39 kWh. Two other HPWH showed daily consumption of 1.56 kWh (50 G/ 189 L unit) vs. 1.50 kWh for an 80 G (303 L) unit. Thus, the AHP baseline showed more than a 50% daily energy savings against a standard electric resistance water heater -- higher than when not used to control water heating loads (the reason for this is still being explored). However, the AHP daily energy savings increased with all the load control schemes evaluated The AHP showed energy use performance that was similar to other HPWHs whether using load control or not due to the AHP's ability to keep tank temperature high enough to avoid using electric resistance. The reductions in daily water heating energy for the unit with advanced load up over its baseline was very large under the 57 GPD (216 L) draw profile —1.1 to 1.5 kWh per day. The AHP's 53% daily baseline savings (3.4 kWh) increased to 4.5 kWh saved for the 0-12-2-10 scheme. Summarized data for the 57 GPD (216 L) draw profile indicate that the HPWH decreased daily water heating energy by 53-78% without load control (on par with prior research noted in the section Background).

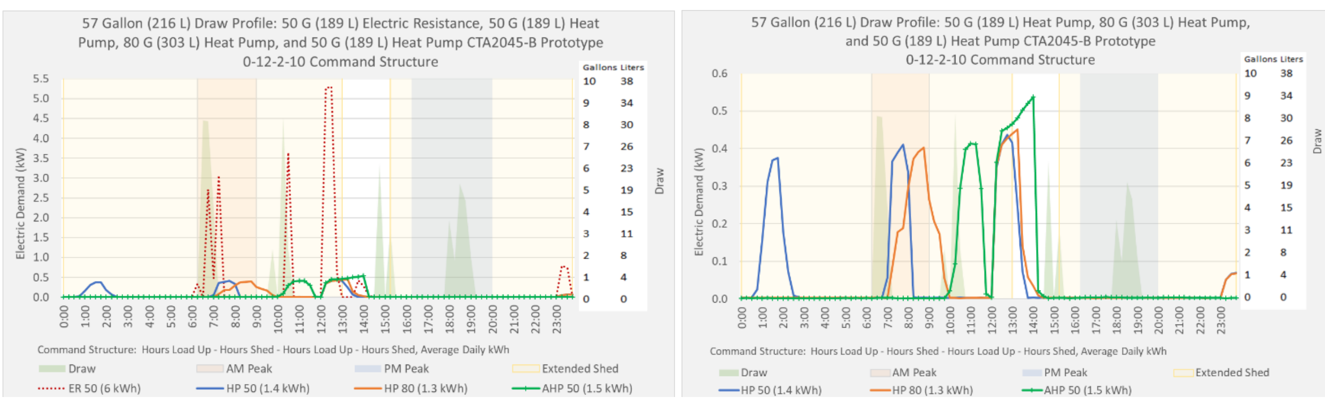
The ERWH under various load control strategies showed little impact on daily electricity consumption for heating hot water—a reduction of about 6-7% for 0-12-2-10 and 0-3-3-4. All the other strategies were largely neutral other than

2-3-2-4 with a 2-hour load up which showed an 18% increase in water heating energy. For the ERWH, the baseline morning peak demand of 0.68 is on par with findings for a 153 sample study of non-gas Florida homes, which found average water hearing morning demand of 0.71 kW and an average annual hot water energy consumption of 6.37 kWh (Masiello and Parker, 2002).

Under the 57 GPD (216 L) draw profile, under almost all load control strategies, the AHP showed greater effectiveness than the other electric resistance or HP systems—particularly for the longer load control windows. Other than the 0-12-2-10 scheme, all other strategies were effective in cutting energy during peak periods, with 0-6-4-7 looking particularly effective. Compared with the controlled HPWH with A control, the B control with advanced load up provided superior peak load reduction in all tested scenarios. For the AHP, all tested schemes under the 57 GPD (216 L) draw, other than 0-3-3-4, showed perfect load shed. And, under this draw pattern, all units curtailed peak use very well under all but the 0-12-2-10 scheme with extended sheds.

The wide success of the schemes across the control strategies suggests that summertime water inlet temperature and environmental conditions in Florida may not sufficiently challenge the load control dynamics to allow determination of the relative efficacy of the various schemes; further experiments during winter conditions may provide more insight.

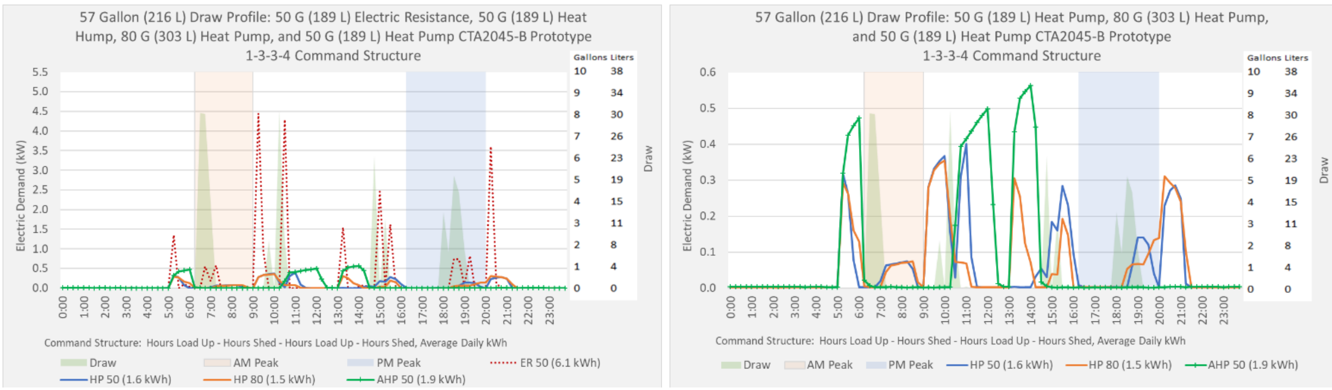
Graphic Results. In Figures 3, 4, and 5, we show daily water heating draw and water heater electric demand plots for different control schemes to illustrate results summarized in Table 3. The plots are composites of several days during the same command structure. Figure 3 (a) presents the electric demand daily load profile of the 50 G (189 L) electric resistance unit, 50 G (189 L) hybrid heat pump, 80 G (303 L) hybrid heat pump during an aggressive shed command structure comprised of no morning load up, a 12-hour shed, a 2-hour afternoon load up, and a 10-hour shed (i.e., 0-12-2-10). The unit with advanced load up capabilities is the only unit to avoid runtime during the peak periods. All units were able to avoid the afternoon peak and the extended afternoon shed, except for the 80 G (303 L) and the electric resistance model which operate briefly at 23:00. A graph of only the HPWHs is provided as Figure part b.



a) b)

Figure 3 (a) Comparison of three heat pump units during the 0-hour am load up, 12-hour shed, 2-hour pm load up, and 10-hour shed, relative to electric resistance and (b) same without electric resistance model.

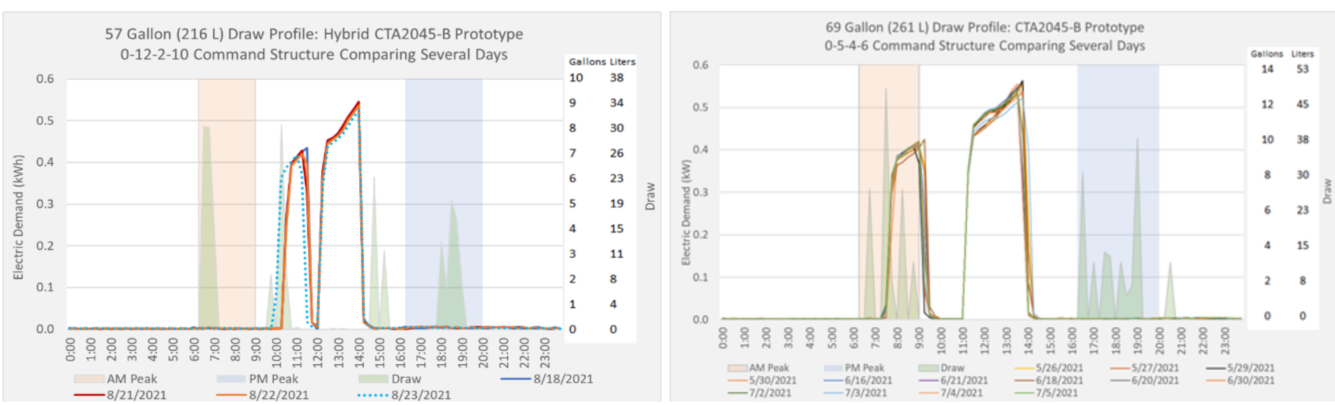
Figure 4 provides similar plots, but of a less aggressive shedding command structure, comprised of a 1-hour morning load up, 3-hour afternoon shed, 3-hour afternoon load up, and a 4-hour afternoon shed. In this case, all units are better able to avoid the peak periods. Only the AHP is able to completely avoid running during these windows, however. In Figure 4(b) we see the AHP prototype draw greater power and operate longer than the other HPWHs, as it attempts to either reach the tank set point of 130°F (54°C) during non-events, or 145°F (63°C) during load up. This explains why the overall daily energy use is greater for the AHP than for the other heat pump units.



a) b)

Figure 4 (a) Comparison of three heat pump units during the 1-hour am load up, 3-hour shed, 3-hour pm load up, and 4-hour shed, relative to electric resistance and (b) same without electric resistance model.

Experimental Reproducibility. One concern with the testing was repeatability of the experiments across the various solenoid-initiated draw patterns as well as the resulting electric demand of the water heaters under comparison. Draw profile and electric demand profiles were consistent, showing reliable reproducibility. Although these tests were successfully done for all of the tested water heaters, in Figure 5 (a) we show repeated tests for the AHP with the 0-12-2-10 load control profile evaluated on differing days. We also evaluated the 69 GPD (261 L) draw profile for impact on the AHP on 13 individual days. This demonstrated practical experimental repeatability giving confidence in measured results and differences. Measuring field impacts will require large samples for many of the small influences that were observed. This occurs because of the probabilistic nature of hot water draws and varying conditions across a population of water heaters. Based on earlier one-minute data in a previous project monitoring 50 electric water heaters, it will be possible to estimate variances for necessary samples (Fenaughty et al., 2017).



a) b)

Figure 5 (a) Repeated testing of 0-12-2-10 profile on CTA2045-B prototype unit and (b) of the 0-5-4-6 profile.

Thirteen repeated tests in Figure 5 (b) for 0-5-4-6 for the AHP show an average morning peak demand of 0.19 (±0.03) kW giving a good indication of the repeatability and experimental variation in the laboratory testing. Also, this repeatedly shows the 5-hour morning curtailment is not achieved by the AHP following a zero-hour load up, as indicated in Table 2.

Caveats. This laboratory evaluation of the potential impacts of load-controlled HPWHs has important limitations. First, the evaluations were conducted primarily with a 57 GPD (216 L) hot water draw profile. Two other draw profiles were evaluated in a limited fashion—a 47 GPD (178 L) draw profile and another at 69 GPD (261 L) reflecting intensive hot water consumption. However, testing performed under these profiles was not sufficient to report on intrinsic differences. We did see in limited evaluation with the higher 69 GPD (261 L) draw that HPWH with the A-protocol was unable to control demand during a 5-hour peak window unless the 80 G (303 L) storage tank size was in use. However, while the AHP was unable to reduce demand during the morning shed period, it showed advantageous demand control and a 0.51 kW afternoon peak reduction.

Secondly, the testing was done in Florida during summer and autumn conditions when daily average outdoor temperatures varied between 73 and 83°F (23 – 28°C), favorable operating conditions for heat pumps. This also means that inlet water temperatures were high, making it easier to interrupt the water heaters for longer periods than under cooler conditions. A final limitation is that the draws examined in the tests are necessarily deterministic for repeatability. In actuality, all household hot water draws are probabilistic and vary stochastically over time in a complex way depending on complex hot water draw event variations across households (e.g. Richie et al, 2021). Thus, results here are indicative, rather than predictive.

CONCLUSIONS

A series of laboratory tests were performed on four electric water heaters designed to provide load control from electric utilities to reduce energy demand during system peak periods. One was an electric resistance water heater (ERWH), and the other three were heat pump water heaters (HPWH). One of the HPWHs was a prototype designed and configured to allow "advanced load up" prior to an attempted utility load shed. Advanced load up raises the set point temperature before load control to provide longer and more reliable load reduction. The tests were highly controlled with detailed monitoring in 2021 at a testing laboratory in Florida.

Two control protocols were used, CTA 2045-A and CTA 2045-B, which allow water heater load up and shed periods. Most importantly, we tested a HPWH with the 2045-B protocol with advanced load up where the tank's water storage temperature was elevated by 15°F (8.3°C). As expected, all of the tests indicated energy savings of the HPWHs by 53-78% over the energy used for the electric resistance system. Grid-connected HPWHs reduced peak demand up to 0.5 kW, depending on CTA protocol, tank volume, control scheme, peak period, and draw profile.

As shown in the graphic data, standard load up feature (2045-A) as well as the advanced load up feature within protocol 2045-B demonstrated ability to remain in heat pump mode—and avoid back up resistance water heating -- for extended periods ahead of peak events under certain schemes. All 2045-A and 2045-B schemes worked well except for the 0-12-2-10 scheme. This scheme showed differences for the morning period, where the 2045-B protocol provided superior load reduction (0.55 kW vs. the ER tank; 0.13 vs. the 50 G (189 L) HPWH and 0.18 kW reduction vs. the 80 G (303 L) HPWH). Likely uncertainty in the measured values is approximately ± 0.03 kW based on repeated testing.

Results indicate that the longer 4-hour afternoon load up was most successful across the evaluated load shifting schemes (0-6-4-7) during summer conditions. The 2045-A did as well as the 2045-B results for this case. However, it seems likely that these results may differ significantly in winter or with profiles exhibiting more hot water demand. This hypothesis is substantiated by a single test of the 69 GPD (261 L) draw profile across the water heaters which showed the 2045-A protocol could not eliminate the evening peak demand with the 50 G (189 L) water heater, although both the 80 G (303 L) HPWH and the AHP using the 2045-B protocol showed excellent control.

Results indicated an energy penalty over unit baseline of the longer 2-hour load up across the water heater models (2-3-2-4) except for the 2045-B protocol. Daily energy use of the electric resistance tank increased by 18% (1.14 kWh), and the 50 G (189 L) HPWH showed an increase of 27%, (0.43 kWh). Meanwhile, the AHP showed a reduction in daily hot water energy use from 3.0 kWh/day to 2.21—a reduction of 26% (0.79 kWh). All of the water heaters show a “payback” of increased demand at the end of the control window. However, these resulting demand spikes markedly differ between ERWH (often 4-5 kW) versus the HPWH which show a “release demand” of only about 0.5 kWh—a very large difference for an electric utility that might face thousands of such water heaters operating in a diversified manner in the future.

Further laboratory testing will evaluate performance across winter conditions and for more and less demanding water heating draw profiles. One conclusion is that the summer 57 GPD (216 L) profile in Florida does not challenge the established load control system enough to further separate the success of the various schemes implemented, with the exception of the 0-12-2-10 scheme with the AHP demonstrating modestly better results than all other units tested.

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NOMENCLATURE

n = number of hours a CTA-2045 protocol command was issued for a given scheme

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