

Field Study of Grid-connected Heat Pump Water Heaters in the Southeast U.S.: The Next Right Thing

*Josh Butzbaugh, Ebony Mayhorn, Travis Ashley, and Cheryn Metzger,
Pacific Northwest National Laboratory*

Karen Fenaughty and Danny Parker, Florida Solar Energy Center

ABSTRACT

The integration of grid-connected functionality and advanced control algorithms into heat pump water heaters (HPWH) offers the capability to shift load with minimal customer impact. This ability provides a flexible grid resource to utilities, while the increased energy efficiency of HPWHs offers customers a lower electric bill. The combined utility/customer value from grid-connected HPWHs is compelling in the Southeast U.S. where residential electric water heating is prevalent and utility load management is common.

This paper presents the results of a HPWH load shifting study conducted in Central Florida using the CTA-2045 standard. Building upon previous research in the Pacific Northwest, this study consisted of approximately 50 occupied homes equipped with HPWHs undergoing load shifting strategies on weekdays for over a year. Curtailment periods and durations coincided with high-value periods for utility system-wide electric demand reductions. During the morning and afternoon, load-up events preceded curtailment.

Results from traditional load shifting strategies were analyzed across temperature bins and used to devise unique load shifting approaches to theoretically increase renewable energy use during periods of high solar energy generation and reduce energy use during peak load periods. Findings from this study showed that certain strategies could result in a peak power reduction of up to 76% per hour of curtailment, and a per-unit energy reduction as much as 0.74 kWh during peak load periods. Peak load reductions were estimated for grid-connected HPWHs compared to a forecasted ERWH baseline, and scaled up to approximate benefits in Florida.

Introduction

Heat pump water heaters (HPWH) are an important technology for the decarbonization of the U.S. economy. By transferring heat rather than creating it, HPWHs typically consume 60–70% less energy than electric-resistance water heaters (ERWH), offering considerable energy savings and permanent load reduction, reducing greenhouse gas emissions (Butzbaugh 2018).

Despite significant energy savings and more than 180 product models available on the market, HPWHs only make up about 2% of annual U.S. residential electric water heater sales (ENERGY STAR 2021). This is due to a myriad of market barriers undermining HPWH market adoption, such as high first cost, lack of immediate product availability, and lack of installer awareness/interest. Even with these challenges, manufacturers have remained committed to the long-term promise of the technology and continue to innovate their HPWH product lines.

The recent integration of grid-connected functionality and advanced control algorithms into HPWHs offers the capability to shift load with minimal impact to hot water users. By utilizing connected HPWHs to conduct load shifting, utilities and grid operators can request

HPWHs to load up thermal energy storage, herein “load up”, during periods of high renewable energy generation (e.g., solar peak). They can also request connected HPWHs to cease operation (i.e., curtail) to achieve peak load reduction. To prevent load shifting from having a negative impact on hot water service, manufacturers have embedded algorithms within the HPWH’s control scheme to determine whether it is suitable to load up or curtail based on the water heater’s status (e.g., storage temperature profile) when using the CTA-2045 Standard. This is especially advantageous for daily load shifting because it addresses variation in hot water use and temperature conditions that can increase the risk of hot water run outs when undergoing load curtailment.

In 2017, the Bonneville Power Administration, Portland General Electric, Northwest Energy Efficiency Alliance, and Pacific Northwest National Laboratory (PNNL) collaborated on the first large-scale, grid-connected HPWH demonstration in the Pacific Northwest (Hunt 2020, Metzger 2019, Metzger 2018). The objective of the Pacific Northwest field study was to understand and compare the performance of a population of grid-connected HPWHs with a population of grid-connected ERWHs while undergoing daily load shifting events to reduce peak load and increase renewable energy integration. The study demonstrated that grid-connected HPWHs are an effective resource to shift load. To build upon this success, the U.S. Department of Energy called on PNNL to help transfer lessons learned and best practices by conducting a similar study in a high impact region.

The Southeast region of the U.S. has both the largest number and highest percentage of homes using electric water heaters. Just four states alone (Florida, Texas, North Carolina and South Carolina) account for more than 30% of the U.S. residential installed base of electric water heaters (Butzbaugh 2020). 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 particular, the state of Florida has the largest percentage (85%) of electric water heaters installed in the residential housing stock. Florida has more than 3.1 million homes that are strong candidates for a straightforward HPWH replacement, the most of any state in the U.S. (Butzbaugh 2020). The Southeast offers a major opportunity for HPWH market penetration through the direct replacement of ERWHs with HPWHs, making it an untapped treasure trove of energy savings, and thus greenhouse gas emission reductions.

One of the reasons that HPWH market adoption is unremarkable in the Southeast, despite favorable housing and water heating characteristics, is the lack of energy efficiency programs promoting the technology. As of 2020, there were no large utility providers promoting HPWHs to their customers in Florida, Texas, and Virginia (Degan and Butzbaugh, 2022). These three states alone account for more than 24% of the U.S. residential installed base of electric water heaters; yet HPWH incentives are sparse. None of Florida’s five largest electric utilities, in terms of number of residential customers,¹ offers incentives for HPWH installations. While these utility providers don’t offer incentives for HPWHs, all have demand response and load management programs, meaning they see the value in promoting load shifting.

The reason for the lack of HPWH incentives in Florida is attributed to its use of the Rate Impact Measure (RIM) test as the primary screening method for energy efficiency measures. Using the RIM test, even if a technology has a negligible incremental cost and provides large potential energy savings to customers, it can still fail RIM because the average costs of generated

¹ Accounting for 80% of total Florida residential electric utility customers.

electric power (\$/kWh) would increase for non-participants when accounting for fixed costs (Parker 2017).

This paper presents the results of a HPWH load shifting study conducted in ~50 Central Florida homes using the CTA-2045 standard. The primary research objective was to identify effective HPWH load shifting strategies to reduce morning and afternoon peak demand for utility coincident load as well as increase renewable energy consumption during periods of high solar energy generation. These strategies were evaluated for specific temperature bins. A secondary research objective was to provide information and data that can help determine whether grid-connected HPWHs pass the RIM test.

Study Set-up

Recruitment for the field demonstration included postal mailing and emailing of the project recruitment flyer. Compensation for project participation was \$125 upon the homeowner's formal consent, survey submission, and e-Radio connectivity. Another \$125 is paid to all participants that conclude the study.

A targeted recruitment effort was deployed. Intuitional Review Board-approved recruitment flyers and emails were sent to owners of HPWHs, as identified by contact lists supplied by two partners. Periodic contact lists of residential ENERGY STAR® Heat Pump Water Heater rebate program participants were obtained through a partnership with a local utility, Orlando Utilities Commission. Additionally, contacts lists were obtained from a local builder, Lifestyle Homes, installer of many HPWHs as part of their smart design concept.

This field evaluation included 46 single-family owner-occupied homes located in Central Florida – thirty-two in Orlando, nine in Saint Cloud, two in Melbourne, two in Sebastian, and one in Harmony. Occupancy ranged from 1 to 8, averaging 3.17 occupants per home. The most common water heating unit capacity was a 50-gallon tank. Thirty-seven of the HPWHs were located in unconditioned space, typically in a garage. Among those located in conditioned space, a utility room with a clothes dryer was the most common location (n=6). Water heater capacities by home occupancy size is provided in Table 1.

Table 1. Water Heater Nominal Capacity by Occupancy

		Nominal Capacity (gallons)				
		40	50	66	80	Total
Occupancy	1		3			3
	2	1	16	1	1	19
	3		4	1		5
	4		9		2	11
	5		4			4
	6		1	1	1	3
	8		1			1
Total		1	38	3	4	46

The field data were collected using the ANSI/CTA-2045-A (CTA-2045) protocol. The CTA-2045 protocol standardizes both the hardware interface between a communications module

and ‘smart’ appliance, as well as the language for communication. CTA-2045 operates at the physical network layer to interface with the proprietary programming of a smart grid device (SGD) proprietary programming, and at the data link layer for data transfer. SGDs have CTA-2045 adapter ports built into the tank input/output board in which Universal Communication Modules (UCMs) can connect to enable receipt of FM broadcast signals and return internet communication over the Wi-Fi. The manufacturer of the UCMs used in this study was e-Radio Inc. (ERI). Figure 1 shows an example of an ERI UCM. Some units also required an adapter for the UCM connectivity. ERI maintained a continuous connection to the water heaters through these UCMs and collected the raw data which was logged by the module at one-minute intervals.



Figure 1. e-Radio CTA-2045 communications module

The field data were retrieved from the ERI cloud storage by PNNL via the web application programming interface. The CTA protocol provided performance data including the instantaneous power in watts, operational state (e.g., idle, running normal, cycling), and curtailment type (e.g., none, Load-Up, Shed, Grid Emergency, Critical Peak). In a previous study in the Pacific Northwest, approximately 40 water heaters were monitored with power meters to determine the reliability and accuracy of the reported instantaneous power field (Hunt et al., 2021). Using this data, it was determined that one HPWH manufacturer was found to report pre-programmed values based on the HPWH mode, so correction factors were applied to the instantaneous power field for this manufacturer based on the subset of monitored power data. To account for the cases in which participants may be away from home for extended periods, data was excluded for sites in which the measured instantaneous watts remained close to zero for a specific week.

Methodology

HPWH energy use is driven primarily by hot water consumption, air temperature surrounding the HPWH, and inlet water temperature. Researchers were limited in their ability to account for all three in this study. Air temperature, and inlet temperature by proxy, were factored into the analysis results. However, participant hot water consumption was not measured or forecasted in this study.

Sixteen load shifting strategies were investigated to understand their impacts on HPWH power and energy use. The strategies are a combination of a one-, or two-hour morning Load-Up immediately followed by a three- four-, or five-hour curtailment; and a one-, two-, three-, or five-hour afternoon Load-Up immediately followed by a four- or five-hour curtailment. The curtailments commands were either Shed (i.e., avoid operation to allow the present stored energy level of the tank to decrease) or Critical Peak (i.e., more aggressively avoid operation to allow the present stored energy level of the tank to decrease).

The chosen curtailment periods reflect periods of maximum utility coincident load when system-wide electric demand reductions are of high value. Based on insight from regional utility providers, peak demand periods of 6-9 a.m. and 4-8 p.m. were prioritized for curtailment. Morning curtailment always began at 6 a.m. and evening curtailment always began at 4 p.m. Curtailment periods were always immediately preceded by load-up periods.

A string of numbers and characters was created to denote the different strategies, for the sake of concise communication. The Load-Up duration was always the first (morning) and third (evening) number in the string. Curtailment duration was always the second (morning) and fourth (evening) number, and this is followed by a “C” for Critical Peak and an “S” for Shed.

The following strategies were repeated from previous work done in the Pacific Northwest: 1-3S-1-4S, 2-3S-2-4S, 1-3C-1-4C, and 2-3C-2-4C. A series of newly designed load shifting strategies were also assessed, as identified in Table 2. These 12 new strategies are categorized by structure similarities using the variable “x” to denote the differences within each column.

Table 2. New Load Shifting Strategy Designs

1 - 3 x - x - 4 x	1 - 4 x - x - 5 x	2 - 4 C- x - 5 C	1 - 5 x - x - 5 x
1. 1-3S-3-4S	4. 1-4S-1-5S	7. 2-4C-2-5C	9. 1-5S-5-5S
2. 1-3S-3-4C	5. 1-4C-1-5S	8. 2-4C-3-5C	10. 1-5S-3-5S
3. 1-3C-1-4S	6. 1-4C-5-5C		11. 1-5C-5-5C
			12. 1-5C-3-5C

Results

The results of the field study were analyzed by temperature (i.e., cool, warm, and hot) for daily energy consumption, and morning and evening load-up, curtailment, and rebound. The determination of these temperature bins is described below, and are defined as: less than 59°F (Cool), 59°F up to 78°F (Warm), and 78°F and greater (Hot). The sample size for each load shifting strategy by temperature bin is the number of participants multiplied by the number of days that strategy was conducted on their HPWH (shown in Figure 2).

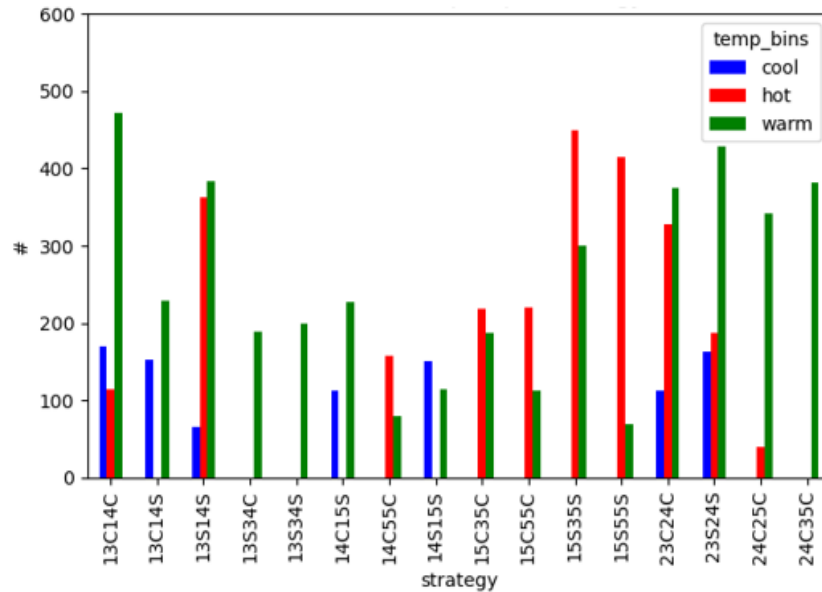


Figure 2. Number of samples (events) by load shifting strategy by temperature bin

As indicated in Figure 2, the Cool (temperature bin) sample size was the smallest with a maximum of 169 events over the seven load shifting strategies with a Cool bin. Florida air temperatures limited the extent to which HPWH performance could be studied in this bin. Thus, due to the small sample size, these results offer lower confidence in their conclusions. The Warm temperature bin has the largest sample size, with a maximum of 472 events for a given strategy. We conducted 15 load shifting strategies during the Warm temperatures. The Hot temperature bin had a maximum sample size of 460, and 10 load shifting strategies were conducted under Hot conditions.

Baseline

To account for the impact that surrounding air temperature has on HPWH energy use, temperature-binned HPWH baselines were generated from the field data. Average daily temperature (°F) was downloaded for Orlando International Airport and daily energy consumption was computed by averaging the energy consumption of all HPWHs participating in the study for each baseline day considered. Because a strong correlation between daily energy consumption and average daily temperature was observed, with a regression of $r^2 = 0.86$, these data were used to establish temperature-binned baselines. The temperature bins (less than 59°F for Cool, 59°F to 78°F for Warm, and 78°F and greater for Hot) were determined using frequencies in the histogram of average daily temperature. To compute the three baselines, the hourly power profiles for all HPWHs were averaged for each day and grouped into the respective temperature bins and averaged over each hour of day. Figure 3(A) provides the hourly temperature profiles of the three baselines and Figure 3(B) provides the hourly power profiles of the three baselines. The power profiles are typical for daily water heater energy consumption with one peak in the morning and a second peak in the evening. For this study, the evening peak

was higher than the morning peak, indicating that participants used more hot water in the evenings.

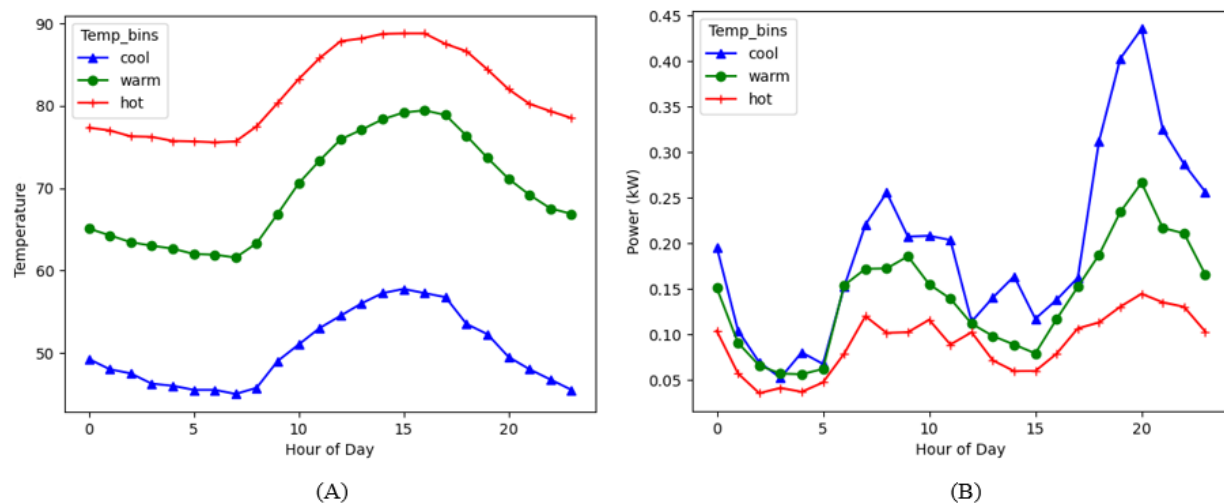


Figure 3. (A) Temperature (°F) profiles by hour of day for each baseline
(B) Average hourly power (W) by baseline temperature bin

To compare grid-connected HPWH energy use to the ERWH technology that dominates the market, an ERWH baseline was prepared using measured energy use data from a 2010 Duke Energy Florida end-use load study (Gurlaskie 2017). The 2010 ERWH power and temperature data were averaged by hour and by month to develop ERWH power regression lines based on temperature for each hour by month. Hourly average Orlando temperatures were applied to the regression coefficients to generate a normalized ERWH daily power profile. Since the participants in the 2010 Duke Energy Florida study had larger morning peak loads than evening, the load shapes were inadequate for a direct comparison of load shifting power and energy use for this study. However, the measured daily energy consumption of studied HPWHs relative to the normalized ERWH daily energy consumption can serve as multipliers, as shown in Table 3, for the temperature-binned baseline. These multipliers can help approximate load shifting performance of grid-connected HPWHs relative to unconnected ERWHs by hour during peak periods.

Table 3. Baseline HPWH and ERWH Energy Use by Temperature Bin

Temperature Bin	ERWH Daily Energy (kWh)	HPWH Daily Energy (kWh)	HPWH-to-ERWH Energy Multiplier
Warm	6.96	3.40	2.05
Hot	5.14	2.17	2.37
Cool	9.95	4.68	2.13

Daily Energy Consumption

Daily energy consumption of each load shifting strategy by temperature bin is shown in Figure 4(A). The difference between each load shifting strategy and its baseline – that is the baseline for the same unit under no strategy – is shown in Figure 4(B). The temperature impact on HPWH energy consumption is clear across different strategy types, indicating that with colder temperatures, energy consumption increases. Among the load shifting strategies studies, 1-4S-1-5S had the greatest energy consumption for the two temperature bins in which it was studied, Cool and Warm. The strategies with the lowest energy consumption were 1-5C-3-5C and 1-5C-5-5C during the Warm bin, and 1-3S-1-4S during the Cool bin. In general, strategies with longer afternoon load-up duration tended to have less daily energy consumption, especially when paired with a one-hour morning load-up.

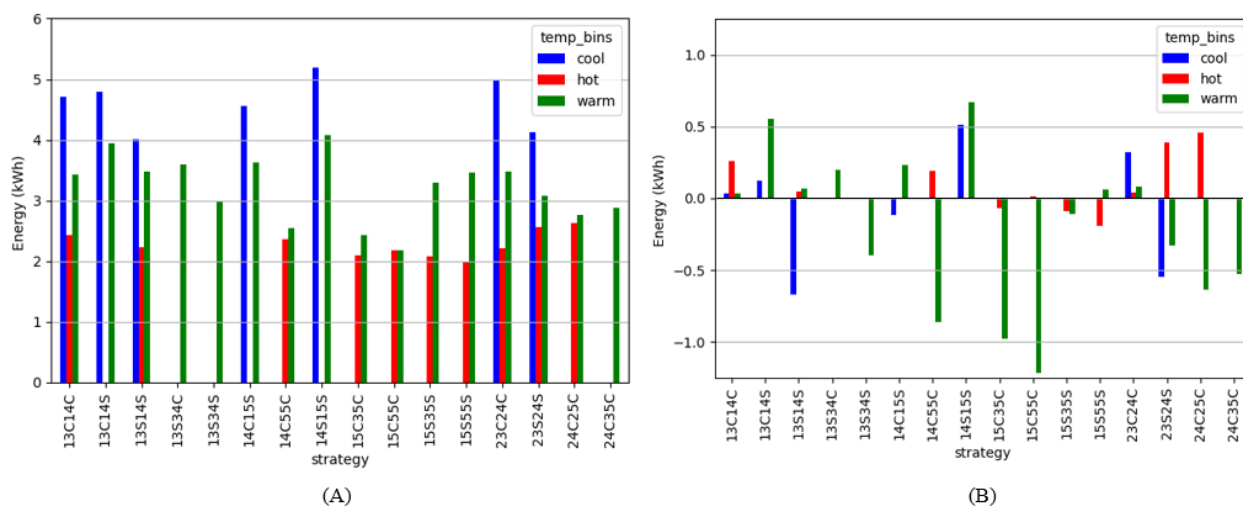


Figure 4. (A) Average daily energy consumption (kWh) by load shifting strategy by temperature bin (B) Average daily energy consumption (kWh) increase over baseline by load shifting strategy by temperature bin

Morning Load Shifting

This section focuses on the results of the morning load shifting events. Morning curtailment always began at 6 a.m. with Load-Up occurring prior and rebound measured as the first hour after the curtailment event. For completeness, morning and evening strategy labels are included in the figures. However, the results are presented separately for the load-up, curtailment, and rebound time periods associated with each experiment.

The average load-up power-per-hour by temperature bin for the morning period is shown in Figure 5(A). The total load-up energy by temperature bin for the morning period is shown in Figure 5(B). The results show that the two-hour load-up (e.g., 2-3S-2-4S) provides some additional total thermal storage benefit compared to the one-hour load-up (e.g., 1-3S-1-4S), particularly in the Cool temperature bin. However, the two-hour load-up provides lower energy-per-hour toward thermal storage.

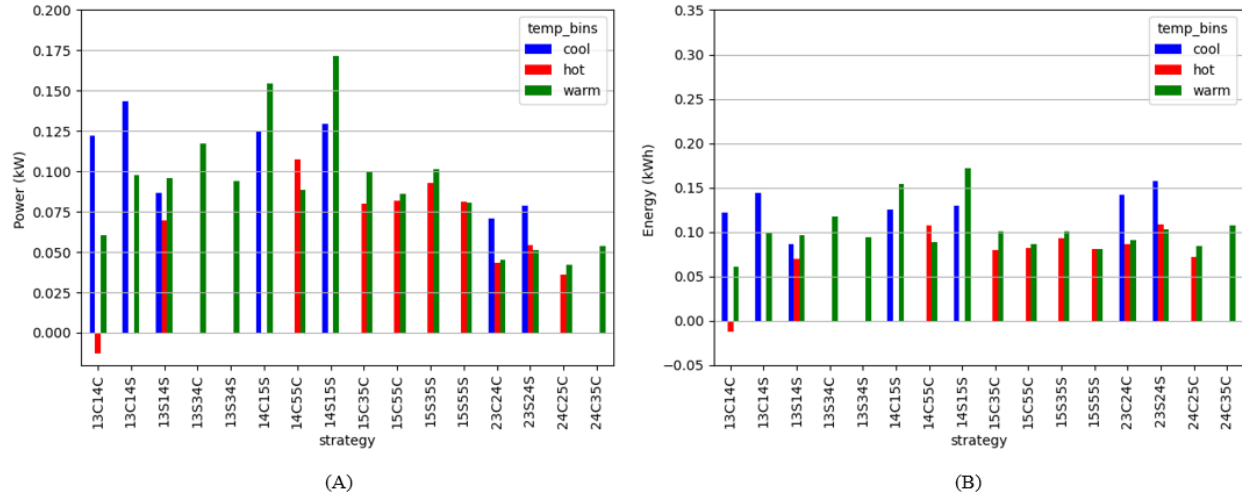


Figure 5. (A) Average load-up power (kW) per hour by temperature bin for the morning period
(B) Total load-up energy (kWh) by temperature bin for the morning period

The average curtailed power-per-hour by temperature bin for the morning period is shown in Figure 6(A) and percent of curtailed power-per-hour by temperature bin (relative to baseline) for the morning period is shown in Figure 6(B). For the Warm temperature bin, the Critical Peak command over a four- or five-hour duration (e.g., 1-4C-1-5S, 1-4C-5-5C, 1-5C-3-5C, and 1-5C-5-5C) provided the largest curtailment, both on an average power-per-hour and percentage basis. For the Hot temperature bin, average curtailed power-per-hour is relatively consistent across all strategies whether using the Shed or Critical Peak command or extending curtailment duration. In the Cool temperature bin, more total energy can be curtailed because of the larger hot water load, but due to the relatively small sample size, there is not a discernable difference in the curtailed energy for a three-hour versus four-hour curtailment period with exception to the 1-4C-1-5S strategy.

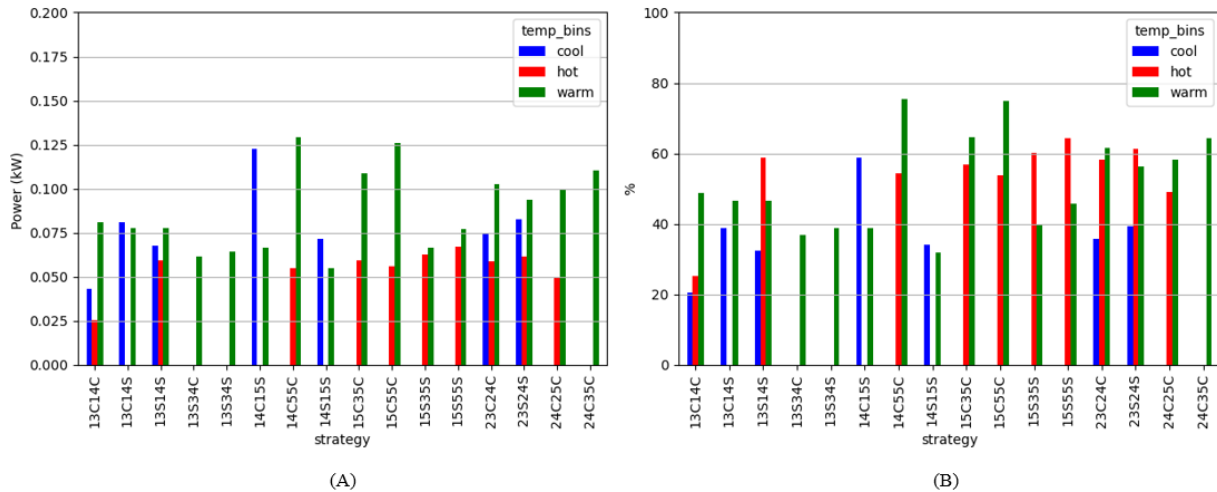


Figure 6. (A) Average curtailed power (kW) per hour by temperature bin for the morning period (B) Percent (%) of curtailed power per hour by temperature bin for the morning period

Tables 5-7 provide the average rebound power in the hour following curtailment in the morning. After the morning curtailment period, for the Warm temperature bin, the rebound is relatively similar across all load shifting strategies. In the Hot temperature bin, the primary trend is that the longest curtailment periods resulted in the highest rebound power. In the Cool temperature bin, the Critical Peak command consistently resulted in a larger rebound than the Shed command for the otherwise same load-up and curtailment strategies.

Evening Load Shifting

This section will focus on the results of the evening load shifting events. For completeness, morning and evening strategy labels are included in the figures. The results are provided separately for the load-up, curtailment, and rebound time periods associated with each experiment.

The average load-up power-per-hour by temperature bin for the evening period is shown in Figure 7(A). The total load-up energy by temperature bin for the evening period is shown in Figure 7(B). The longer evening load-up duration appears to add beneficial storage due to capturing the rebound from morning curtailment. This becomes apparent when comparing strategies with five-hour curtailment in the morning. For example, 1-5C-5-5C and 1-5S-5-5S load-up over three-times as much energy as 1-5C-3-5C and 1-5S-3-5S because they have two additional hours of load-up which capture morning rebound. Thus, the evening load-up performance of strategies 1-4C-5-5C, 1-5C-5-5C, and 1-5S-5-5S are not on equal footing as the others. However, their performance is indicative of the potential to capture energy storage when solar energy generation is higher on the grid. Otherwise, when the evening load-up did not capture morning rebound, total evening load-up energy was lower than morning load-up energy.

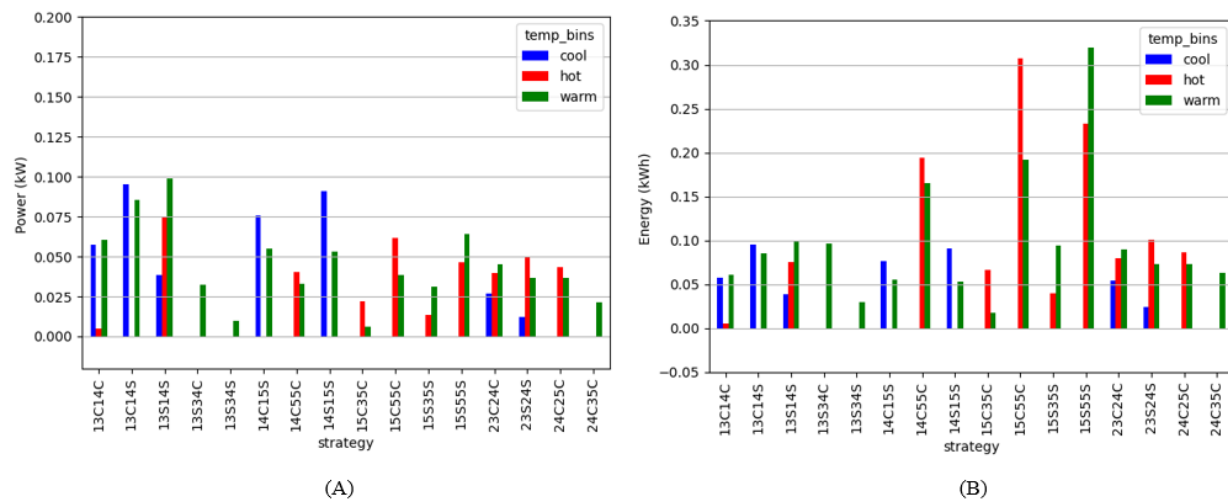


Figure 7. (A) Average load-up power (kW) per hour by temperature bin for the evening period
(B) Total load-up energy (kWh) by temperature bin for the evening period

The average curtailed power-per-hour by temperature bin for the evening is shown in Figure 8(A), and the percent of curtailed power-per-hour by temperature bin for the evening

period is shown in Figure 8(B). Evening curtailment was greater in magnitude than morning curtailment, but otherwise exhibited similar behavior.

For the Warm temperature bin, the Critical Peak command over a five-hour duration (e.g., 1-5C-3-5C and 1-5C-5-5C) provided the largest curtailment, both on an average power-per-hour and percentage basis. For the Hot temperature bin, like the morning, the evening curtailment is relatively consistent across all strategies whether using the Shed or Critical Peak command or extending curtailment duration. As with morning curtailment, this may indicate there's an opportunity to increase curtailment duration beyond five hours before diminishing returns become apparent. For the Cold temperature bin, the Shed command over a four- or five-hour duration (e.g., 2-3S-2-4S and 1-4C-1-5S) provided the largest curtailment, both on an average power-per-hour and percentage basis.

As was the case with morning curtailment, each strategy was fairly consistent on a percentage of curtailed power per hour basis across all three temperature bins with strategy 1-3S-1-4S demonstrating the most similarity across temperature bins. This indicates that strategies with the greatest percentage of curtailed power per hour (e.g., 1-5C-3-5C and 1-5C-5-5C) may offer the most curtailment potential across all temperatures.

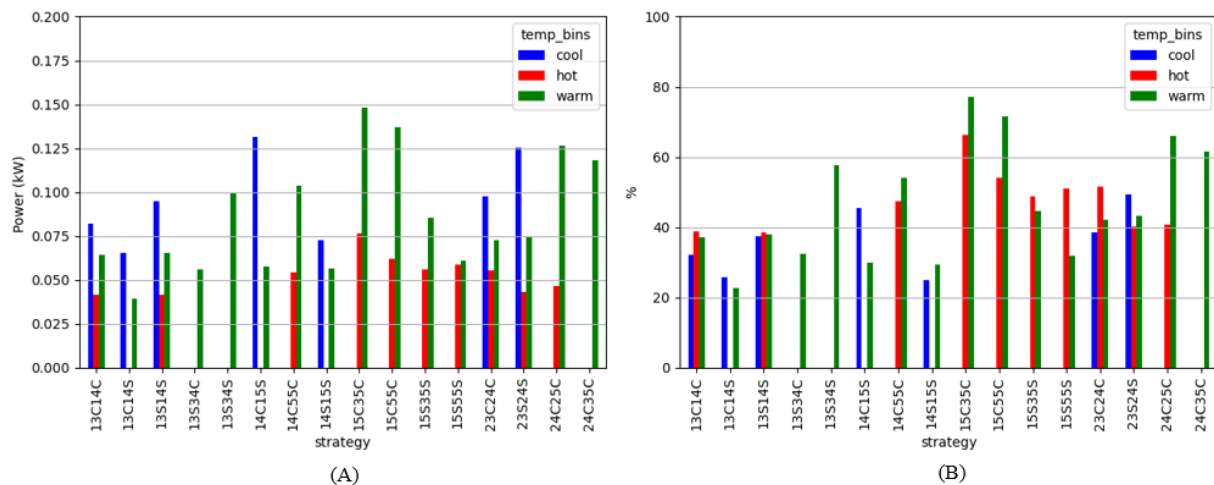


Figure 8. (A) Average curtailed power (kW) per hour by temperature bin for the evening period (B) Percent (%) of curtailed power per hour by temperature bin for the evening period

Tables 5-7 provide the average rebound power in the hour following curtailment in the evening. The magnitude of the evening rebound is larger than the magnitude of the morning rebound, which is consistent with the load shape for study participants, who have a much larger evening peak load than morning (as shown in Figure 3B). Often, for a given temperature range or curtailment period duration, the Critical Peak command tended to result in a larger rebound than the Shed command except for the five-hour curtailment periods that included long load-up durations in the Warm and Hot bins, and the four-hour curtailment period after a one-hour load-up in the Warm bin.

Summary of Results by Temperature Bin

Table 4 is a summary of the HPWH baseline data for each temperature bin. This baseline uses a three-hour morning and four-hour evening peak period for comparing load shifting among strategies. For the values shown in Figures 2-8, each strategy was compared against a matched load-up and curtailment period. In other words, a strategy with a five-hour morning curtailment period was compared against the same five hours for the baseline HPWH profile. For sake of table size, not every combination of load-up and curtailment period for the HPWH baseline is shown.

Table 4. HPWH Baseline Energy Use Disaggregated by Temperature Bin

Temperature Bin	Sample Size	Daily Energy (kWh)	Energy (kWh) 6-9 a.m.	Energy (kWh) 4-8 p.m.
Warm	1,102	3.4	0.5	0.69
Hot	604	2.17	0.3	0.43
Cool	167	4.68	0.62	1.02

The results from the load shifting events are summarized in Tables 5-7 for the Warm, Hot, and Cool temperature bins, respectively. For the tables below, AM=morning, PM=evening, Lu=load-up period, Sh=shed period, Re=rebound period, and Ev=event. Using the multipliers from Table 1, an ERWH baseline for a three-hour morning and four-hour evening peak period was estimated for each temperature bin for comparing the HPWH baselines as well as each strategy's daily energy consumption and load shifting performance.

For all three temperature bins, the load-up power-per-hour (fourth column from the left) and energy over the duration of the load-up event (fifth column from the left) trends show that the energy use over the population of HPWHs went up by a factor of at least two compared to the HPWH baseline when the HPWHs were signaled to turn on and prepare for a curtailment event. On the other hand, the sixth and seventh columns from the left show that generally, during the curtailment period, the average power and energy use over the population of HPWHs went down by approximately half or more compared to the HPWH baseline. Lastly, the general trend for the one-hour rebound period (rightmost column) shows that on average, rebound power increases compared to the HPWH baseline.

Table 5. Load Shifting Results for Warm Temperature Bin

Control Strategy	Sample Size	Daily Energy (kWh)	AM/PM Lu Pwr/hr (kW)	AM/PM Lu Energy/Ev (kWh)	AM/PM Sh Pwr/hr (kW)	AM/PM Sh Energy/Ev (kWh)	AM/PM Re Pwr/hr (kW)
ER Base	NA	6.96	0.12/0.16	0.12/0.16	0.35/0.35	1.03/1.40	0.39/0.55
HP Base	1102	3.4	0.06/0.08	0.06/0.08	0.17/0.17	0.50/0.70	0.19/0.27
13S14S	383	3.47	0.16/0.18	0.16/0.18	0.09/0.11	0.27/0.43	0.27/0.43
23S24S	429	3.07	0.11/0.12	0.22/0.24	0.07/0.10	0.22/0.39	0.23/0.35

13C14C	472	3.43	0.12/0.14	0.12/0.14	0.09/0.11	0.26/0.43	0.22/0.37
23C24C	375	3.48	0.10/0.13	0.21/0.26	0.06/0.10	0.19/0.40	0.26/0.49
15S55S	138	3.4	0.16/0.18	0.16/0.91	0.09/0.13	0.44/0.63	0.39/0.40
15S35S	300	3.29	0.16/0.12	0.16/0.36	0.10/0.11	0.51/0.53	0.31/0.44
15C55C	112	2.18	0.15/0.14	0.15/0.71	0.04/0.05	0.21/0.27	0.30/0.31
15C35C	188	2.42	0.16/0.09	0.16/0.28	0.06/0.04	0.30/0.22	0.27/0.35
24C25C	342	2.76	0.10/0.12	0.20/0.24	0.07/0.07	0.29/0.33	0.26/0.41
24C35C	382	2.87	0.11/0.11	0.23/0.33	0.06/0.07	0.24/0.37	0.28/0.39
13S34S	200	3.0	0.16/0.10	0.16/0.30	0.10/0.07	0.31/0.29	0.24/0.38
13S34C	189	3.6	0.18/0.12	0.18/0.36	0.11/0.12	0.32/0.47	0.29/0.49
13C14S	228	3.95	0.16/0.16	0.16/0.16	0.09/0.13	0.27/0.54	0.39/0.44
14S15S	114	4.07	0.23/0.13	0.23/0.13	0.12/0.14	0.47/0.68	0.42/0.50
14C15S	227	3.63	0.22/0.13	0.22/0.13	0.10/0.13	0.42/0.67	0.37/0.47

Table 6. Load Shifting Results for Hot Temperature Bin

Control Strategy	Sample Size	Daily Energy (kWh)	AM/PM Lu Pwr/hr (kW)	AM/PM Lu Energy/Ev (kWh)	AM/PM Sh Pwr/hr (kW)	AM/PM Sh Energy/Ev (kWh)	AM/PM Re Pwr/hr (kW)
ER Base	NA	5.14	0.12/0.14	0.12/0.14	0.24/0.26	0.71/1.02	0.24/0.33
HP Base	604	2.17	0.05/0.06	0.05/0.06	0.10/0.11	0.30/0.43	0.10/0.14
13S14S	363	2.22	0.12/0.13	0.12/0.13	0.04/0.07	0.12/0.26	0.22/0.26
23S24S	188	2.56	0.10/0.11	0.19/0.22	0.04/0.06	0.12/0.26	0.17/0.29
13C14C	115	2.43	0.03/0.07	0.03/0.07	0.08/0.07	0.23/0.26	0.06/0.18
23C24C	328	2.21	0.09/0.10	0.17/0.20	0.04/0.05	0.13/0.21	0.19/0.32
15S55S	460	2.05	0.13/0.13	0.13/0.64	0.04/0.06	0.21/0.30	0.29/0.31
15S35S	449	2.08	0.14/0.08	0.14/0.23	0.04/0.06	0.21/0.29	0.27/0.33
14C55C	237	2.42	0.15/0.12	0.15/0.61	0.04/0.07	0.18/0.35	0.25/0.31
15C55C	221	2.18	0.13/0.14	0.13/0.69	0.05/0.05	0.24/0.26	0.30/0.34
15C35C	219	2.10	0.13/0.09	0.13/0.26	0.04/0.04	0.22/0.19	0.26/0.32
24C25C	39	2.63	0.08/0.1	0.16/0.21	0.05/0.07	0.21/0.34	0.21/0.35

Table 7. Load Shifting Results for Cool Temperature Bin

Control Strategy	Sample Size	Daily Energy (kWh)	AM/PM Lu Pwr/hr (kW)	AM/PM Lu Energy/Ev (kWh)	AM/PM Sh Pwr/hr (kW)	AM/PM Sh Energy/Ev (kWh)	AM/PM Re Pwr/hr (kW)
ER Base	NA	9.95	0.15/0.23	0.15/0.23	0.45/0.53	1.34/2.17	0.45/0.94
HP Base	167	4.68	0.07/0.11	0.07/0.11	0.21/0.25	0.63/1.02	0.21/0.44
13S14S	66	4.01	0.15/0.16	0.15/0.16	0.14/0.16	0.43/0.64	0.29/0.49

23S24S	163	4.13	0.15/0.15	0.31/0.31	0.13/0.13	0.38/0.51	0.29/0.48
13C14C	169	4.71	0.19/0.17	0.19/0.17	0.17/0.17	0.50/0.69	0.36/0.49
23C24C	113	5.0	0.15/0.17	0.29/0.34	0.13/0.16	0.40/0.62	0.44/0.67
13C14S	152	4.8	0.21/0.21	0.21/0.21	0.13/0.19	0.39/0.75	0.38/0.48
14S15S	151	5.19	0.20/0.21	0.20/0.21	0.14/0.22	0.55/1.09	0.42/0.62
14C15S	113	4.56	0.19/0.19	0.19/0.19	0.09/0.16	0.35/0.79	0.51/0.59

Table 8 summarizes the strategies with the greatest percent reduction in average power-per-hour curtailment for the morning and evening peak periods compared to the HPWH baseline by temperature bin.

Table 8. Summary of Most Impactful Strategies for Hourly Peak Load Reduction

Temperature Bin	Morning Load Shifting		Evening Load Shifting	
	Impactful Strategy	Peak Reduction (%)	Impactful Strategy	Peak Reduction (%)
Warm	15C55C	76%	15C35C	76%
Hot	Many ²	60%	15C35C	64%
Cool	14C15S	57%	23S24S	48%

Table 9 provides a summary of strategies with the greatest total energy reduction for the morning and evening peak periods compared to the HPWH baseline and estimated ERWH baseline, accounting for the curtailment duration (meaning a strategy with a five-hour curtailment period was compared against the same five hours for the baseline).

Table 9. Summary of Most Impactful Strategies for Total Peak Energy Reduction

Temperature Bin	Morning Load Shifting			Evening Load Shifting		
	Impactful Strategy	Peak Reduction (kWh) – HP	Peak Reduction (kWh) – ER	Impactful Strategy	Peak Reduction (kWh) - HP	Peak Reduction (kWh) – ER
Warm	15C55C	0.66	1.57	15C35C	0.74	1.75
Hot	15S55S	0.32	1.02	15C35C	0.30	1.00
Cool	14C15S	0.47	1.40	23S24S	0.48	1.60

The peak reduction results per grid-connected HPWH in Table 8 can scale up to estimate the peak reduction benefits to the state of Florida if the 3.1 million homes that are strong candidates for straightforward HPWH replacement were to replace their ERWHs with grid-connected HPWHs enrolled in a load shifting program. For the Warm temperature bin, which typifies most Florida days by average daily temperature, the 15C55C strategy could provide an

² A number of strategies resulted in similar morning curtailment due to lower load on the HPWH at this time.

energy reduction of 4.9 gigawatt-hours (GWh) during the morning peak period whereas the 15C35C strategy could provide an energy reduction of 5.4 GWh during the evening peak period for the state of Florida. These are substantial peak energy reductions, commensurate with significant monetary savings to utility providers and customers, if just the strongest candidates were to install grid-connected HPWHs in their homes and enroll in load shifting programs.

Conclusions

In conclusion, heat pump water heaters provide inherent peak load reduction compared to electric-resistance water heaters due to their improved energy efficiency. They can also effectively shift load through grid-connected functionality, providing additional peak load reduction.

Findings from this study showed that strategies tested in this project could result in a peak power reduction of up to 76% per grid-connected heat pump water heater per hour of curtailment. Additionally, results showed that the peak energy reduction over the duration of a curtailment event could be as much as 0.74 kWh per event compared to the heat pump water heater baseline and 1.75 kWh per event compared to the estimated electric-resistance water heater baseline. When scaling up these results solely for Florida homes best suited for grid-connected HPWHs, energy reductions of 4.9 GWh during the morning peak period and 5.4 GWh during the evening peak period are potentially achievable when replacing electric-resistance water heaters with grid-connected HPWHs enrolled in load shifting programs.

Researchers plan to continue the field study during the summer of 2022. Further investigation will focus on how occupancy (low versus high) and water heater location (conditioned versus unconditioned space) impact the daily energy consumption and load shifting performance of grid-connected HPWHs.

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