Factors Influencing Grid-connected Heat Pump Water Heater Performance in the Southeast U.S.

Karen Fenaughty and Danny Parker, FSEC
Josh Butzbaugh and Travis Ashley, Pacific Northwest National Laboratory

ABSTRACT

Grid-connected heat pump water heaters (HPWH) can shift electrical load while minimizing impacts to hot water availability for occupants. This capability provides a flexible grid resource to utilities seeking to manage peak loads. Such load control also can feasibly improve renewable utilization within the utility electric production mix, for instance using off-peak generation during periods with high renewable energy generation. The increased efficiency of HPWHs offers lower electric bills to customers and cuts greenhouse gas emissions. The Southeast U.S. presents a particularly promising opportunity for grid-connected HPWHs due to the region's high penetration of electric water heating.

This paper builds upon the results of an extensive HPWH load shifting field study conducted in 51 occupied homes in Florida using EcoPort technology (Butzbaugh et al, 2022). In 2022 an initial evaluation was available. Here, long term load results are provided as well as an examination of various control strategies and influences. Analysis is conducted for HPWH energy use and load shifting performance based on home occupancy (i.e., low and high) and water heater location (i.e., conditioned and unconditioned) across different temperature profiles. An unexpected outcome of this analysis was increased overall daily energy consumption of HPWHs under demand control located in conditioned spaces, possibly because of inadequate air volume from improper installation. We did find higher demand reductions from 2-hour over 1-hour load ups and slightly improved demand reductions for critical peak over shed signals. As expected, higher occupancy households showed greater load reductions.

Introduction

Heat pump water heaters (HPWH) have the potential to achieve substantial carbon emission reductions. By transferring heat rather than creating it, HPWHs typically consume 60–70% less energy than electric-resistance water heaters (ERWH), offering permanent load reduction. The displacement of ERWHs with HPWHs is a low-hanging fruit among energy conservation opportunities because homes with ERWHs already have the electrical infrastructure to accommodate a HPWH. The retrofit costs of switching from a ERWH to a HPWH at time of natural replacement are modest and can often be recovered through utility bill savings.

In 2018, grid-connected functionality and advanced control algorithms were integrated into HPWHs, thereby offering the capability to shift load using the CTA-2045 standard with minimal impact to hot water users. (As of the time of this writing, there are some issues with the standardization of CTA-2045.) Using this functionality, utility providers 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), and cease operation (i.e., curtail) to achieve peak load reduction. To prevent load shifting from negatively impacting a home's hot water service, water heater manufacturers have embedded algorithms within the HPWH's control scheme to determine whether it is suitable to load up or curtail upon receiving CTA-2045 load shifting commands. These control algorithms evaluate the water heater's thermal status, which reduces hot water depletion risk when implementing daily load shifting because it addresses variation in hot water use and temperature conditions.

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 (Metzger et al. 2019). This study demonstrated that grid-connected HPWHs are an effective resource to shift load. To build upon this success, the U.S. Department of Energy sought to conduct a similar study in a high impact region.

The Southeast U.S. offers a significant energy savings and load reduction opportunity through the replacement of ERWHs with HPWHs. The states of Alabama, Florida, Georgia, North Carolina, South Carolina, Tennessee, and Virginia account for 34% of the U.S. residential electric water heaters (US EIA 2023). In this region, approximately 75% of homes have an electric water heater, and the vast majority are ERWHs. Florida has both the highest number of homes (seven million) and highest percentage of homes (88%) in the U.S. with electric water heaters. Even though the Southeast is dominated by electric water heating, many of the large utility providers there do not offer incentives for HPWH installations. However, these utility providers find value in shifting load, given they have demand response and load management programs (Butzbaugh et al. 2020). For instance, Duke Energy Florida has one of the largest demand response programs in the U.S. with more than 400,000 participants who allow the control their HVAC, water heaters, and pool pumps (Gurlaskie 2017).

In 2020, PNNL and the Florida Solar Energy Center (FSEC) partnered on a HPWH load shifting study conducted in 51 single-family homes in Central Florida using the CTA-2045 standard. This study investigated 16 load shifting strategies across three temperature bins, and initial findings were published in the proceedings of the ACEEE 2022 Summer Study for Energy Efficiency in Buildings (Butzbaugh et al. 2022). A complement to this field study was a laboratory evaluation completed earlier in Central Florida that assessed various HPWH demand control strategies (Fenaughty et al, 2022). Findings indicated that the state of Florida could potentially reduce morning and afternoon peak load periods by five gigawatt-hours each through the replacement of ERWHs with grid-connected HPWHs undergoing load shifting.

Our paper builds upon this research by introducing novel results of the PNNL/FSEC study by investigating whether HPWH load shifting with CTA 2045 is affected by certain home characteristics. For this analysis, participant homes were segmented and analyzed based on occupancy and water heater location to understand how these factors impact HPWH load shifting. Prior research involving occupancy-based analysis was prepared for the 2017-2020 Pacific Northwest HPWH load shifting study, indicating how occupancy and season influence HPWH energy consumption and power demand in that region (Hunt et al. 2021). This paper builds upon the PNNL analysis by investigating how both occupancy and water heater location affect HPWH load shifting in the climate of the Southeast U.S., given its immense potential for HPWH market adoption.

Table 1 provides a breakdown of occupancy for Florida single-family homes with electric water heaters. Of Florida single-family homes with electric water heaters, approximately 78% have either one, two, or three occupants whereas 22% have four or more occupants. Of Florida single-family homes with electric water heaters, approximately 35% have the water heater location in conditioned space whereas 65% have it located in unconditioned space.

Table 1. Occupancy of Florida single-family homes (SFH) with electric water heaters

Occupants	Number of SFHs	Weight
1	879,000	20%
2	1,790,000	40%
3	813,000	18%
4	558,000	13%
5	313,000	7%
6	65,000	1%
7+	37,000	1%
Total	4,455,000	100%

Study Design

Participants and Water Heater Characteristics

Participants were recruited for the field demonstration via postcard and email, with an offer of a project participation stipend of up to $300. Targeted participants included Orlando Utilities Commission residential ENERGY STAR® Heat Pump Water Heater rebate program recipients and recent purchasers of homes from a local builder. A total of 51 homeowners were recruited, connected their water heaters to an Ecoport controller device, and completed occupant surveys. Participants were all located in central Florida, primarily in Orlando, with a few in the outlying areas of Saint Cloud, Melbourne, Sebastian, and Harmony.

Home occupancy among study participants ranged from one to nine persons, with a median of two. The most common water heating system among participants was a 50-gallon nominal capacity, and most the units were in unconditioned space – most typically the garage. Seven homes had HPWHs in conditioned space. Table 2 provides water heater capacities by home occupancy size where occupancy was determined at the outset of the monitoring.

Table 2. HPWH nominal capacity by occupancy

	Nominal Capacity (gallons)				
Occupancy	40	50	66	80	Total
1		3			3
2	1	17	1		19
3		4	1		5
4		11		3	14
5		4			4
6		1	1	1	3
8		2			2
9			1		1
Total	1	42	4	4	51

Methodology and Field Testing

Electrical load shifting experiments were conducted in the field using the ANSI/CTA-2045-A (CTA-2045) control protocols to demonstrate the viability of grid-connected HPWHs from December 2020 through June 2022. And it is through this protocol that data were collected for the evaluation. The CTA-2045-A communications commands used in this field study included: load up (operate now and seek to raise the water temperature to set point), shed (avoid operation, allowing the present stored energy level of the tank to decrease), critical peak (more aggressive avoidance of operation to allow the present stored energy level of the tank to decrease), and end shed (return to normal operation). How the specific water heater models respond to these commands is determined by the water heater manufacturers.

The field tests were performed under baseline conditions (i.e., no load shift), and across different load shifting schemes. The structure for tests was *n* hours of a morning load up period immediately followed by *n* hours of curtailment, then *n* hours of an afternoon load up period immediately followed by *n* hours of curtailment. Thus, a 2-3-2-4 test protocol would indicate a 2-hour morning load up, 3-hour morning curtailment, 2-hour afternoon load up, and a 4-hour afternoon curtailment.

Within this evaluation we assess strategies with a 1- or 2-hour morning load up (these were issued from 5 – 6 or 4 – 6 AM, respectively) and 1-, 2-, or 3-hour afternoon load up (3 – 4, 2 – 4, or 1 – 4 PM, respectively). The hot water tanks are intended to be fully charged by the longer load up periods. A longer duration may be important to HPWH compressors given limited capacity relative to the larger resistance elements in electric resistant tanks. Curtailment periods immediately followed the load up periods, and were 3-, 4-, or 5-hour windows for morning and 4- or 5-hours windows for afternoon. The curtailment periods reflect times when system-wide electric demand reductions are likely of high value to utilities. The curtailment signals used were shed (S) and critical peak (C). The strategies evaluated herein are presented in Table 3.

Table 3. Morning strategy (left), afternoon strategy (right)

Morning					Afternoon			
		Curtailment					Curtailment	
		3-hour	4-hour	5-hour			4-hour	5-hour
Shed Strategies					Shed Strategies			
Load Up	1-hour	1-3S-1-4S		1-5S-3-5S	Load Up	1-hour	1-3C-1-4S	1-4C-1-5S
		1-3S-3-4C					1-3S-1-4S	
		1-3S-3-4S				2-hour	2-3S-2-4S	
	2-hour	2-3S-2-4S				3-hour	1-3S-3-4S	1-5S-3-5S
Critical Peak Strategies					Critical Peak Strategies			
Load Up	1-hour	1-3C-1-4C	1-4C-1-5S	1-5C-3-5C	Load Up	1-hour	1-3C-1-4C	
		1-3C-1-4S				2-hour	2-3C-2-4C	2-4C-2-5C
	2-hour	2-3C-2-4C	2-4C-2-5C			3-hour	1-3S-3-4C	1-5C-3-5C
			2-4C-3-5C					2-4C-3-5C

Strategy terminology indicates: AM load up hours; AM curtailment hours; (S)hed or (C)ritical Peak; PM load up hours; PM curtailment hours; (S)hed or (C)ritical Peak

Results

The dataset for this evaluation is 51 homes; all sites may not have data for every test scheme conducted. Given the variations in weather, many control strategies may have uneven coverage across the temperature bins evaluated. Data were segmented considering unit capacity and daily average outdoor temperature. A prior publication on this field demonstration evaluated results according to daily average outdoor temperature ranges – *cool* (<59 °F); *mild* (59 °F - 77 °F); and *warm* (>77 °F) (Butzbaugh et al. 2022). This current work preserves these temperature categories. The cool and mild temperature bins are the subject of this paper, as the water heaters were unchallenged during warmer weather and showed little variation in energy use or demand regardless of test.

The baseline dataset for the cool temperature bin includes 44 homes and up to 4 days per home for a total of 103 site days (number of evaluation days across all sites). The test dataset includes up to 41 sites, depending on strategy tested, and up to 7 days. Sample size per strategy ranges from 63 to 162 site days. The baseline dataset for the mild temperature bin includes all 51 homes and up to 41 days per home for a total of 1320 site days. The test datasets include up to 45 homes and up to 17 days depending on strategy, with site days ranging from 145 to 371. While performance during challenging colder periods is of interest, the Florida location of this study provided much less data in the *cool* temperature bin. Thus, much of this paper focuses on the *mild* temperature bin, with a much larger dataset and subsets of these data.

Quality control measures included identifying periods of occupant reported system operation failures. We also examined the individual demand plots for sites with unexpectedly high energy use and identified – and confirmed with homeowners – one site with a recirculation loop pump in constant use and one site using electric resistance mode only.[1] These records were included in the full seasonal evaluations as they are part of real-world energy use. However, they were excluded from the subsample evaluations of occupancy and tank location influences.

Evaluation of Load Control Under Mild Temperatures

Energy use is an important metric to consider when implementing demand control as homeowners' energy costs are directly affected. The *mild* temperature bin demonstrated that average daily energy use was similar during the combined test scheme periods relative to the baseline, although differences were observed. Daily energy use averaged 3.26 kWh for the baseline period and averaged 3.22 kWh for the various test periods. Given the limited samples, we included median values for overall differences in daily energy consumption since medians may be superior to averages, however demand is evaluated in averages since the median value for specific periods is often zero. Daily energy use - among all strategies as a whole - was lower by 5% over baseline. Table 4 provides the sample sizes and a summary of daily energy use (averages and medians) and morning and afternoon load up and curtailment demand for the baseline and 12 test schemes. Sample sizes are provided both in terms of number of homes tested (Sites) and total test days (Site Days) for each scheme. The average and median daily energy use for each test scheme is presented in Figure 2, with the baseline use in dashed lines. The median values plotted in Figure 2 are consistently lower than the averages, though medians reliably

[1] Since the initiation of the study, manufacturers, in technical advisory notes, have come out not recommending HPWH for household with recirculation loops since the excessive losses in such systems can result in continuous compressor operation and sometimes in early compressor failure (Rheem 2019).

follow the trend of the averages. Test schemes 1-5C-3-5C and 1-5S-3-5S, with the longest morning curtailment, had median daily energy use reductions of 19% and 16%, respectively.

Table 4. Mild period: Overall energy and demand results

	Sample Size		Daily Mean	Daily Median			Hourly Average AM Loadup			Hourly Average AM Curtailment			Hourly Average PM Loadup			Hourly Average PM Curtailment		
Mild Temp	Sites	Site Days	kWh	kWh	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %
Baseline	51	1320	3.26	1.96			0.06			0.17			0.10			0.15		
13C14C	29	349	3.56	1.90	-0.06	-3	0.14	0.09	130	0.08	-0.08	-49	0.15	0.05	44	0.11	-0.04	-23
13C14S	42	246	3.66	2.50	0.53	27	0.16	0.10	148	0.08	-0.09	-51	0.15	0.05	48	0.12	-0.03	-18
13S14S	24	366	3.41	1.77	-0.19	-10	0.16	0.10	157	0.09	-0.08	-48	0.18	0.07	69	0.11	-0.04	-24
13S34C	37	183	3.53	2.21	0.25	13	0.18	0.12	184	0.10	-0.07	-40	0.12	0.02	18	0.12	-0.03	-19
13S34S	39	195	2.93	1.97	0.00	0	0.15	0.09	144	0.10	-0.07	-41	0.10	-0.01	-5	0.07	-0.07	-46
14C15S	45	251	3.35	2.12	0.16	8	0.17	0.11	166	0.09	-0.08	-49	0.14	0.03	31	0.12	-0.03	-19
15C35C	37	145	2.44	1.59	-0.38	-19	0.17	0.11	169	0.06	-0.10	-63	0.09	-0.01	-12	0.05	-0.10	-68
15S35S	42	284	3.00	1.65	-0.31	-16	0.16	0.10	155	0.10	-0.07	-42	0.11	0.00	4	0.09	-0.06	-38
23C24C	24	365	3.59	1.91	-0.05	-2	0.11	0.05	86	0.07	-0.10	-58	0.13	0.03	30	0.10	-0.04	-26
23S24S	24	293	3.28	1.65	-0.32	-16	0.12	0.06	100	0.08	-0.09	-54	0.12	0.02	20	0.11	-0.03	-20
24C25C	38	294	2.72	1.70	-0.27	-13	0.10	0.04	75	0.07	-0.10	-57	0.12	0.02	19	0.07	-0.08	-56
24C35C	38	371	2.77	1.79	-0.18	-9	0.11	0.05	89	0.06	-0.10	-63	0.11	0.01	5	0.07	-0.08	-55
All Tests	419	3,342	3.22	1.87	-0.09	-5	0.14	0.08	137	0.08	-0.09	-51	0.13	0.03	26	0.10	-0.05	-35

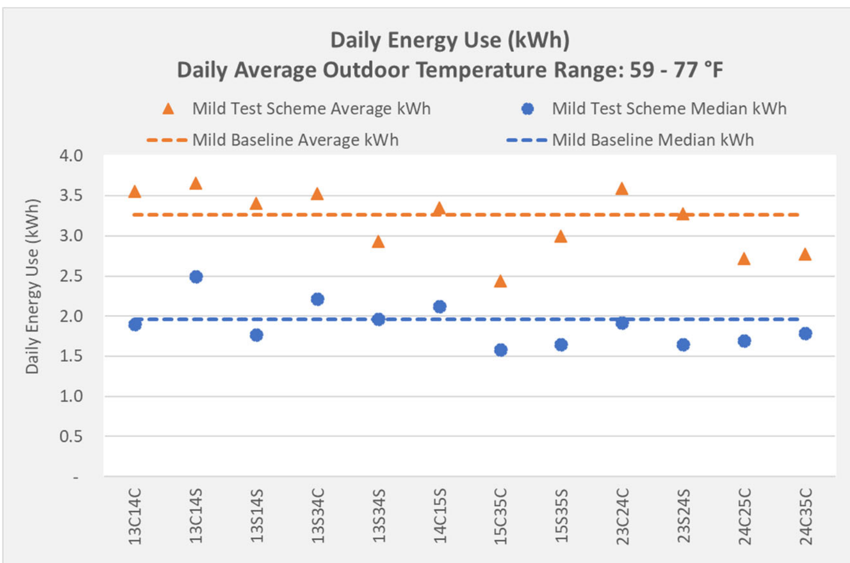

Figure 1. Average (orange) and median (blue) daily energy use during test schemes relative (point) to baseline (dashed line), mild temperature bin.

Figure 2 plots the change in load up and curtailment demand relative to a zero baseline when no commands were given for each test scheme average. Demand during the morning load up was always higher than baseline. The average load up demand for the 1-hour test schemes were consistently about 50% higher than that for 2-hour. This result aligns with the laboratory tests which showed consistently reduced demand in the second hour of a load up command, as tanks have achieved water temperature settings (Fenaughty et al. 2023). However, the schemes with the 2-hour load up tended to produce the largest demand reductions during morning curtailment.

The baseline demand during curtailment test windows for the HPWH was 0.17 kW and 0.15 kW, for morning and afternoon, respectively. Average demand during the morning curtailment period was consistently lower than during the same hours when no commands were given and generally reduced by about 50%, with average reductions by scheme ranging from 0.07 to 0.10 kW. The afternoon curtailments were generally about half that of morning curtailments. They were less consistent across strategies than those exercised in the mornings, ranging from 0.03 to 0.10 kW, but averaging 35%.

Multi-hour load ups appear more successful than the 1-hour at achieving demand reductions. Morning curtailment demand reductions averaged 0.10 kW (58%) for the 2-hour versus 0.08 kW (48%) for the 1-hour; afternoon reductions averaged 0.06 kW (42%) for the multi-hour versus 0.03 kW (22%) for the 1-hour. There were also indications that the "critical peak" strategy can provide slightly greater load reduction compared with "shed" signal. Where the preceding load up and the curtailment lengths where the same, morning curtailment demand reductions averaged 0.09 kW (55%) with critical peak versus 0.07 kW (45%) with shed; afternoon reductions averaged 0.05 kW for both signals but represented 36% with critical peak and 31% with shed. Generally, strategies with the longest load ups, longest curtailments, and critical peak commands produced the greatest demand reductions.

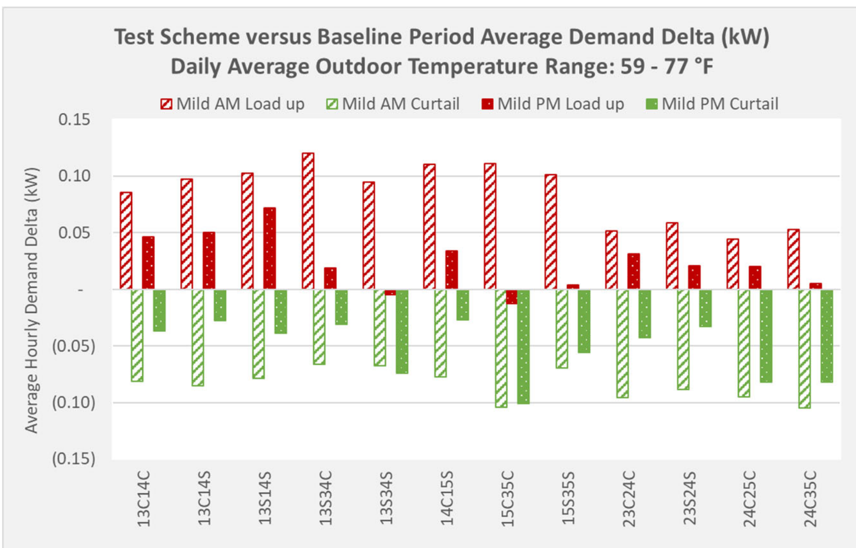

Figure 2. Average test scheme demand changes for morning (hash) and afternoon (polka dot), load up (red) and curtailment (green), relative to same period during baseline, mild temperature bin.

Notably, the afternoon load up demand is slightly reduced for 1-3S-3-4S and 1-5C-3-5C. The sample for these tests were the smallest. However, in almost all tests the afternoons show less load up and curtailment than they do in the mornings. This may be partially explained by the less-predictable water heating needs in the afternoon.

Evaluation Under Cool Temperatures

The cool weather dataset, composed of days when the daily average outdoor temperature was less than 59 °F, are summarized in Table 5 for the six test schemes evaluated. The limited sample sizes are indicative of the few cool days available in central Florida. Daily median energy use per strategy relative to its baseline are shown in Figure 3. The average daily energy use was 4.62 kWh (median 2.48 kWh) for the baseline and 4.46 kWh (median 2.80 kWh) for test days. The test schemes increased daily energy use under cool conditions by an average of 11%.

Table 5. Cool period overall energy and demand results

	Sample Size		Daily Mean	Daily Median			Hourly Average AM Curtailment			Hourly Average PM Curtailment		
Cool Temp	Sites	Site Days	kWh	kWh	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %
Baseline	44	103	4.62	2.48			0.19			0.20		
13C14C	24	162	4.67	2.57	0.08	3	0.16	-0.03	-15	0.16	-0.04	-17
13C14S	41	157	4.58	3.01	0.53	21	0.12	-0.07	-37	0.17	-0.03	-13
13S14S	21	63	3.99	2.19	-0.30	-12	0.14	-0.05	-29	0.16	-0.04	-18
14C15S	40	119	4.46	3.08	0.59	24	0.08	-0.11	-57	0.16	-0.03	-18
23C24C	22	65	4.91	2.98	0.49	20	0.12	-0.07	-35	0.16	-0.04	-18
23S24S	24	156	4.11	2.30	-0.19	-7	0.13	-0.07	-35	0.12	-0.07	-35
All Tests	172	722	4.46	2.76	0.28	11	0.13	-0.06	-34	0.16	-0.03	-17

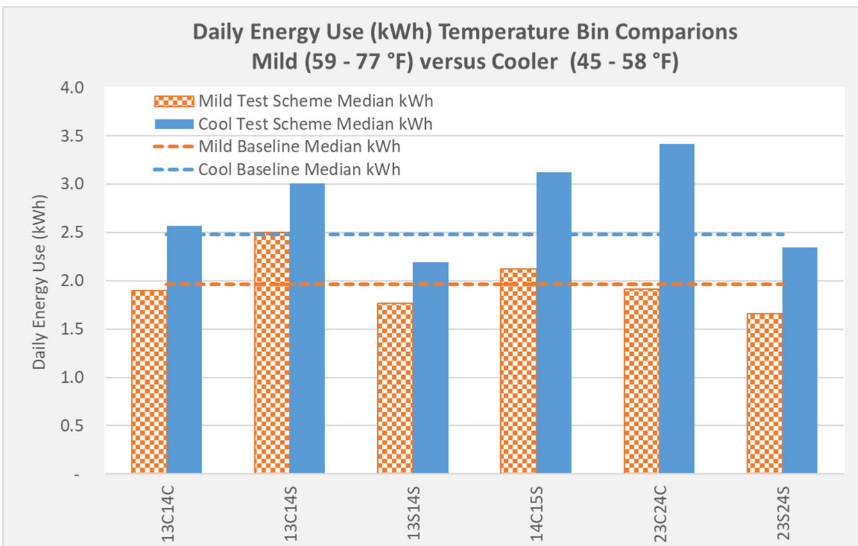

Figure 3. Median daily energy use during test schemes (bar) relative to baseline (dashed line), for cool (blue) versus mild (orange) temperature bins.

As expected, energy use was higher among the cooler days for all cases. The 2-3C-2-4C strategy was especially energy intensive, up 37% over its baseline. This is in stark contrast to the results of the mild temperature test, which had reduced energy use overall. Since 65% of HPWH are in the unconditioned space—typically the garage—the likely reason for elevated consumption is that the compressor is operating against lower ambient temperatures and the tank and piping is also losing heat to surroundings more rapidly than during mild conditions. The baseline demand during the morning load up windows was similar for both temperature bins. During the cooler weather, morning load up demand consistently exceeded that of baseline by about 0.11 kW (or 53%) and the increases over baseline were greater than during the warmer weather.

The per test average demand for morning and afternoon curtailment relative to each baseline is provided in Figure 4. During cool weather, the demand during morning curtailment tests was consistently lower than baseline, with load shift test scheme reductions averaging 34%. This was generally much lower than the morning curtailment during warmer weather. The average demand during the afternoon curtailment hours for the cool bin during the baseline condition was 0.20 kW – 33% higher than that baseline for the warmer weather (0.15 kW). This suggests that HPWH in unconditioned spaces under cooler temperatures may provide much lower curtailments during morning periods where outdoor temperatures are lowest and hot water demand is often elevated.

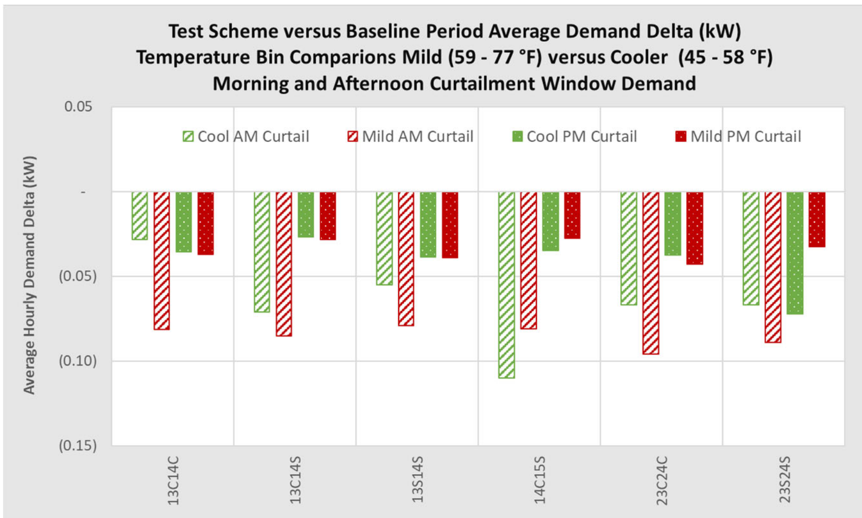

Figure 4. Average test scheme demand changes for morning (hash) and afternoon (polka dot) curtailment, relative to same period during baseline, cool (green) vs. mild (red) temperature bin.

Low Versus High Occupancy Evaluation, Mild Temperatures

The mild temperature data were subdivided into a *low occupancy* subset (sites with three or fewer occupants) and *high occupancy* (homes with four occupants or more). For clear comparison, the occupancy comparison dataset includes only homes with a 50-gallon nominal tank capacity, and it excludes high energy use outliers during times of reported water heater system operation failures and the site with constant recirculation pump use. Also excluded are sites where the occupancy changed between high and to low during the study period. The full dataset available for this evaluation was 17 low occupancy homes and 16 high occupancy homes.

Table 6 provides the energy use and demand summary for the baseline and 12 test schemes for the low occupancy homes, and Table 7 for the high occupancy dataset. The median daily energy use among the load shift test schemes for homes with low occupancy showed an average reduction of 8% over the baseline average of 1.41 kWh. High occupancy results averaged a 1% reduction from the 1.97 kWh baseline.

The median daily water heating energy for the high occupancy homes was 0.57 kWh (40%) more than for the low occupancy. The median daily energy use values are displayed in Figure 5, contrasting energy use between the higher and lower occupancy households. There is little variation among the test schemes, with 1-3S-3-4C being an outlier, where the higher occupancy homes responded with twice the energy use.

The average baseline demand during the curtailment windows were similar between groups – mornings were 0.16 kW (low occupancy cohort) versus 0.14 kW (high) and afternoons, 0.10 kW (low) and 0.12 kW (high). Average morning curtailment was greater for the higher occupancy homes, 0.09 kW (66%) versus 0.07 kW (40%). However, average demand reduction in afternoon was similar for both cohorts - 0.05 kW, 46% and 43% for the lower and higher occupancy homes, respectively. Figures 6 presents the average curtailment demand changes by test, relative to a zero baseline, for the low (green) and high (red) occupancy datasets.

Table 6. Mild period, low occupancy, energy, and demand results

	Sample Size		Daily Mean	Daily Median			Hourly Average AM Curtailment			Hourly Average PM Curtailment		
Low Occupancy	Sites	Site Days	kWh	kWh	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %
Baseline	17	550	2.48	1.41			0.16			0.10		
13C14C	13	150	2.06	1.23	-0.18	-12	0.11	-0.05	-31	0.05	-0.06	-51
13C14S	17	102	3.38	2.03	0.63	45	0.12	-0.04	-26	0.10	0.00	-3
13S14S	11	160	2.36	1.14	-0.27	-19	0.11	-0.05	-30	0.06	-0.04	-37
13S34C	15	75	2.64	1.50	0.09	7	0.11	-0.06	-34	0.09	-0.02	-16
13S34S	16	80	2.33	1.46	0.05	4	0.10	-0.06	-38	0.05	-0.06	-48
14C15S	17	98	2.97	1.64	0.24	17	0.13	-0.04	-23	0.10	0.00	0
15C35C	17	66	2.02	1.16	-0.24	-17	0.08	-0.09	-52	0.03	-0.07	-71
15S35S	18	123	2.24	1.21	-0.19	-14	0.10	-0.06	-38	0.05	-0.06	-54
23C24C	11	163	1.72	1.22	-0.18	-13	0.06	-0.11	-64	0.03	-0.08	-67
23S24S	11	128	1.89	1.21	-0.19	-14	0.09	-0.07	-45	0.05	-0.05	-45
24C25C	16	123	2.26	1.23	-0.18	-13	0.10	-0.06	-39	0.04	-0.06	-57
24C35C	16	153	2.31	1.21	-0.20	-14	0.08	-0.09	-52	0.06	-0.05	-46
All Tests	178	1421	2.30	1.29	-0.12	-8	0.10	-0.07	-40	0.06	-0.05	-46

Table 7. Mild period, high occupancy, energy, and demand results

	Sample Size		Daily Mean	Daily Median			Hourly Average AM Curtailment			Hourly Average PM Curtailment		
High Occupancy	Sites	Site Days	kWh	kWh	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %
Baseline	16	410	2.43	1.97			0.14			0.12		
13C14C	9	95	2.31	1.80	-0.17	-9	0.03	-0.10	-76	0.06	-0.06	-47
13C14S	15	85	3.04	2.48	0.51	26	0.05	-0.09	-65	0.10	-0.02	-15
13S14S	7	102	2.21	1.98	0.01	1	0.03	-0.11	-77	0.07	-0.05	-39
13S34C	12	58	3.75	3.03	1.06	54	0.12	-0.01	-10	0.15	0.03	22
13S34S	13	65	2.54	1.90	-0.07	-3	0.11	-0.03	-20	0.07	-0.05	-39
14C15S	17	88	2.46	1.99	0.02	1	0.04	-0.09	-68	0.07	-0.04	-38
15C35C	12	47	2.26	1.92	-0.05	-3	0.04	-0.10	-73	0.05	-0.06	-55
15S35S	13	87	2.33	1.92	-0.05	-3	0.08	-0.06	-40	0.08	-0.03	-28
23C24C	6	95	2.64	2.04	0.07	4	0.08	-0.06	-42	0.07	-0.04	-34
23S24S	7	82	2.24	1.86	-0.11	-6	0.04	-0.09	-69	0.07	-0.05	-39
24C25C	13	98	2.11	1.90	-0.07	-4	0.02	-0.11	-82	0.06	-0.06	-47
24C35C	12	120	2.15	1.89	-0.08	-4	0.03	-0.11	-77	0.04	-0.08	-65
All Tests	136	1022	2.46	1.96	-0.01	-1	0.05	-0.09	-66	0.07	-0.05	-43

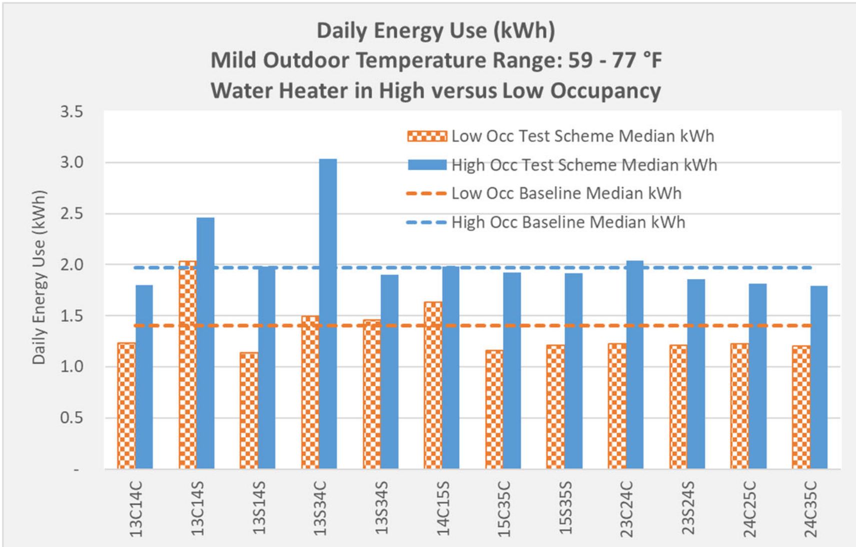

Figure 5. Median daily energy use during test schemes (bar) relative to baseline (dashed line), low (orange) vs. high (blue) occupancy homes.

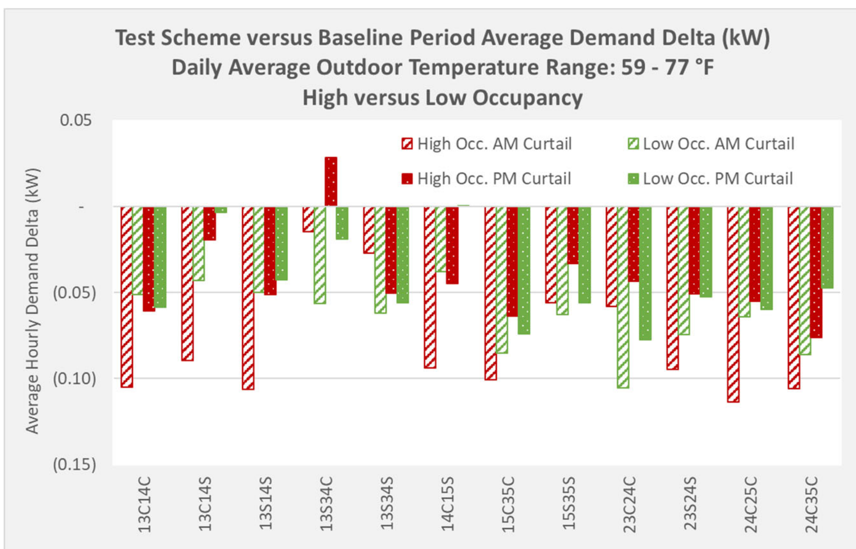

Figure 6. Average test scheme demand changes for morning (hash) and afternoon (polka dot) curtailment, relative to same period during baseline, low (green) vs. high (red) occupancy homes.

The 2-hour morning load ups resulted in greater curtailment than the 1-hour scheme, and were greater for the higher occupancy homes. Demand reduction during curtailment windows for the 1-hour load ups averaged 0.06 kW (34%) for the lower and 0.07 (54%) for the higher occupancy homes; 2-hour load ups averaged 0.08 kW (50%) for the lower and 0.09 (68%) for the higher. The afternoon demand reduction was generally smaller than morning for both cohorts, and the lower occupancy group showed more reliable reductions than the higher occupancy homes. For lower occupancy households, the longer load ups tended to produce larger afternoon curtailments.

The morning critical peak signal tended to produce greater demand reductions than the shed signal, for both cohorts. Morning critical peak curtailments where morning schemes were otherwise the same, averaged 0.07 kW (43%) for the lower and 0.09 kW (64%) for the higher occupancy homes; shed curtailments averaged 0.06 kW (37%) for the lower and 0.06 kW (43%) for the higher occupancy homes. The reductions for afternoon critical peak signals were mixed, averaging 0.06 kW (55%) for the lower and 0.03 kW (30%) for the higher occupancy homes; shed curtailments averaged 0.04 kW (40%) for the lower and 0.04 kW (35%) for the higher occupancy homes.

The notable case of high use during afternoon curtailment for high occupancy cohort under the 1-3S-3-4C test scheme may be related to the cooler average ambient temperatures, 65.4 °F (the coolest conditions among all test), versus the average baseline conditions of 68.8 °F.

Evaluation of the Impact of HPWH Location

Water heater location was examined to identify energy and demand differences based on the tank's location. This compared those in conditioned space to those in unconditioned space – which in Florida is typically in a garage. The tank location evaluation was limited by the small number of sites with the HPWH in the conditioned space. The dataset is 44 homes with water heaters in unconditioned space and six with water heaters in conditioned space.

Summary results for the water heaters in unconditioned space are presented in Table 8, and the results for the systems in conditioned space are in Table 9. We contrast energy use among these two groups graphically in Figure 7. While the baseline average energy use was higher among sites with water heaters in conditioned versus unconditioned space, the median daily energy use was the same for unconditioned and conditioned tanks, 1.96 kWh. During demand response tests, the average energy use was slightly greater among the homes with tanks

Table 8. Unconditioned space, energy, and demand results (mild)

	Sample Size		Daily Mean	Daily Median			Hourly Average AM Curtailment			Hourly Average PM Curtailment		
Uncondi-tioned	Sites	Site Days	kWh	kWh	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %
Baseline	44	1058	2.65	1.96			0.14			0.10		
13C14C	23	264	2.88	1.67	-0.18	-10	0.04	-0.09	-68	0.07	-0.03	-29
13C14S	35	205	3.13	2.50	0.65	35	0.04	-0.09	-67	0.08	-0.02	-20
13S14S	19	281	2.65	1.56	-0.29	-16	0.04	-0.10	-72	0.06	-0.05	-42
13S34C	30	148	3.06	2.04	0.19	10	0.07	-0.07	-50	0.08	-0.02	-22
13S34S	32	160	2.55	1.91	0.06	3	0.06	-0.07	-53	0.06	-0.05	-41
14C15S	38	209	2.72	2.05	0.20	11	0.05	-0.09	-66	0.08	-0.03	-25
15C35C	31	121	2.20	1.51	-0.34	-18	0.03	-0.10	-75	0.04	-0.06	-60
15S35S	35	221	2.34	1.44	-0.42	-22	0.06	-0.08	-59	0.06	-0.04	-42
23C24C	18	277	3.10	1.70	-0.15	-8	0.05	-0.09	-67	0.06	-0.04	-36
23S24S	19	228	2.69	1.45	-0.41	-22	0.03	-0.11	-79	0.07	-0.03	-27
24C25C	32	241	2.36	1.64	-0.21	-11	0.04	-0.10	-74	0.05	-0.05	-48
24C35C	31	302	2.38	1.64	-0.22	-12	0.03	-0.10	-75	0.05	-0.05	-51
All Tests	343	2657	2.68	1.71	-0.26	-13	0.04	-0.09	-68	0.06	-0.04	-39

Table 9. Conditioned space, energy, and demand results (mild)

Condi-tioned	Sample Size		Daily Mean	Daily Median			Hourly Average AM Curtailment			Hourly Average PM Curtailment		
	Sites	Site Days	kWh	kWh	Delta kWh	Delta %	kW	Delta kWh	Delta %	kW	Delta kWh	Delta %
Baseline	6	189	4.32	1.96			0.30			0.23		
13C14C	5	54	4.16	1.97	0.02	1	0.31	0.01	3	0.17	-0.06	-22
13C14S	6	36	5.48	1.82	-0.13	-7	0.28	-0.02	-8	0.24	0.02	7
13S14S	4	58	5.17	3.61	1.66	85	0.33	0.02	8	0.23	0.00	1
13S34C	5	25	5.08	3.17	1.22	63	0.30	0.00	-1	0.29	0.07	26
13S34S	5	25	3.87	1.61	-0.34	-17	0.32	0.02	5	0.13	-0.09	-37
14C15S	6	36	5.29	2.17	0.22	11	0.32	0.02	5	0.21	-0.01	-5
15C35C	5	20	3.55	1.51	-0.44	-23	0.23	-0.07	-24	0.07	-0.16	-69
15S35S	5	44	3.92	1.72	-0.23	-12	0.27	-0.04	-12	0.13	-0.10	-43
23C24C	4	54	3.58	2.00	0.05	3	0.23	-0.07	-23	0.14	-0.08	-32
23S24S	4	43	4.18	2.18	0.23	12	0.30	0.00	-2	0.19	-0.04	-14
24C25C	5	40	3.98	1.64	-0.31	-16	0.29	-0.02	-5	0.11	-0.12	-52
24C35C	5	50	4.06	1.87	-0.08	-4	0.22	-0.08	-28	0.14	-0.08	-36
All Tests	59	485	4.36	1.98	0.02	1	0.28	-0.02	-7	0.17	-0.05	-23

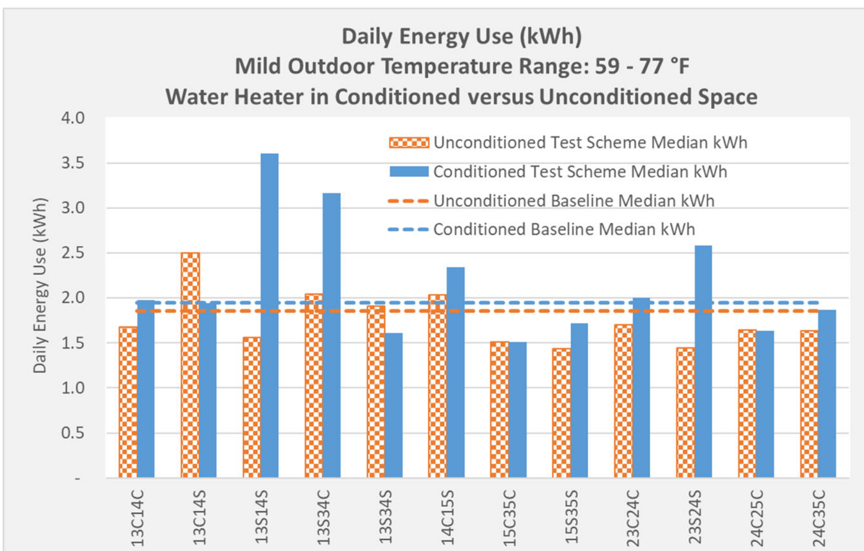

Figure 7. Median daily energy use during test schemes (bar) relative to baseline (dashed line), water heaters located in conditioned (blue) vs. unconditioned (orange) space.

in conditioned space – 1.98 kWh (a 1% increase), while those with tanks in unconditioned space had energy use savings – 1.71 kWh (a 13% decrease).

Baseline demand during the load up windows was much lower for the unconditioned cohort – 0.04 kW (unconditioned cohort) versus 0.14 kW (conditioned) in the morning, and 0.08 kW (unconditioned) versus 0.12 kW (conditioned) in the afternoon. For the conditioned sites, not only was the baseline demand during the morning load up window relatively high, morning curtailment was also less productive, with reductions averaging 0.02 kW (7%) for conditioned and 0.09 kW (68%) for unconditioned sites. The average afternoon load up demand was also higher for the conditioned versus the unconditioned locations, and the curtailment response greater for the unconditioned cohort, though the difference between cohorts was less extreme than during the morning curtailment (0.5 kW and 23% reduction for conditioned versus 0.04 kW and 39% for unconditioned.) Given the limited sample for conditioned locations, reasons for these findings remain unclear.

The longer versus the 1-hour load up periods did more to improve curtailment for the conditioned than for the unconditioned sites. The conditioned cohort experienced an average morning curtailment period demand reduction of 0.04 kW (14%) with the 2-hour load up, versus 0.01 kW (3%) with the 1-hour period tests. Longer afternoon load ups also proved more valuable for the conditioned sites, which experienced average curtailment period demand reduction of 0.07 kW (33%) versus 0.01 kW (5%) with the single hour load up. The critical peak signal showed a slightly greater curtailment demand reduction over the shed signal for the conditioned units –morning demand reduction was 0.04 kW (13%) with the critical peak signal versus no reduction with shed, and for the afternoon it was 0.06 kW (25%) with critical peak versus 0.04 kW (18%) with shed. This same trend existed for the unconditioned units, though more subtlety.

There are a couple of notable contrasts to the demand results for the homes with water heaters in conditioned locations. 1. Demand during curtailment often *increased over* baseline, and sometimes dispite a large load up demand, and 2. Afternoon curtailment was almost always larger than the morning curtailment – a reversal of the profile seen in the unconditioned home sample. The reasons for these differences are unknown, but the small unbalanced sample make conclusions suspect. We show these values since people aware of the evaluation expressed interest in knowing how tank locations influenced results. We do not claim significance.

Conclusion

We present the results of a HPWH electric load shifting study conducted in central Florida using the CTA-2045 standard. Key aspects evaluated were how load demand reduction varied with occupancy and water heater location as well as impacts on energy. Findings include:

- Mild Weather Evaluation:
  - Load control schemes typically reduced daily hot water energy use from the baseline median of 1.96 kWh, by as much as about 25% in the most extreme case, and often with lower energy use for long control periods. Reductions were typically on the order of 10 to 15% or 0.20 to 0.30 kWh/Day.
  - Morning demand curtailments during the peak hours were generally reduced by about 50%. The afternoon curtailments were not as great, averaging 35%.
  - Multi-hour load ups achieved slightly greater demand curtailments than did 1-hour.
  - There were indications that the “critical peak” strategy can provide slightly greater load reduction compared with “shed” signal.
- Cool Weather Evaluation:
  - Energy use during load control schemes generally varied greatly related to the baseline median daily use of 2.48 kWh, ranging from 30% less to 59% greater use.
  - Demand during morning curtailment testing was consistently lower than baseline, averaging 0.06 kW (34%) – generally curtailment was less than during warmer weather. The average demand during the afternoon curtailment hours during the baseline condition was 0.20 kW – 33% higher than that baseline for the warmer

weather (0.15 kW). However, afternoon curtailment for the cool weather testing was generally similar to that during warmer weather.

- High versus Low Occupancy Evaluation:
  - The lower occupancy group averaged 0.12 kWh (8%) reduction in daily consumption during load shifting tests, whereas the higher occupancy cohort's use was essentially unchanged.
  - Average morning curtailment was greater for higher occupancy homes, 0.09 kW (66%) versus 0.07 kW (40%) for the lower occupancy group. Average afternoon curtailment saw demand reductions of 0.05 kW for both cohorts.
  - Higher occupancy homes were more likely to use electric resistance to recover from curtailment.
  - The 2-hour morning load ups resulted in greater curtailment than the 1-hour, and provided greater reductions for the higher occupancy homes; though the longer load up periods tended to produce larger afternoon curtailments only for the low occupancy homes.
- Tank Location Evaluation:
  - The six sites with interior tank location showed increased daily energy consumption associated with demand control relative to unconditioned tanks. Average energy use increased 0.02 kWh, or 1% for those in conditioned space, versus a 0.26 kWh or 13% reduction for the unconditioned tank cohort.
  - The average morning and afternoon curtailments were greater for the unconditioned than they were for the conditioned tank sites. This difference between cohorts was especially stark for the morning curtailments, when reductions averaged 0.02 kW (7%) for conditioned versus 0.09 kW (68%) for unconditioned sites.
  - While both cohorts showed greater curtailment demand reduction during longer versus shorter load up strategies, homes with conditioned tanks showed greater improvement with longer load ups – for both morning and afternoon curtailments.
  - The critical peak signal showed a slight benefit to curtailment demand reduction over the shed signal for the conditioned units.

The reason for the reduced demand reductions of the HPWH in the conditioned spaces is unknown, but lack of sufficient air flow is suspected. However, there could be other influences such as setting tanks into a hybrid or electric resistance mode due to noise or other factors. The conditioned tank sample size of six homes was too small to support an evaluation between tank location among strategies.

Our field study found that both load up and curtailment of demand was generally greater in the morning than in the afternoon. The authors speculate that the greater response in the morning is related to the condensed and more predictable morning water use pattern. Further, the multi-hour load up control strategies were able to increase the load reduction from controlled HPWH by 25-30%, and without a hot water energy use penalty. This level of "demand profile sculpting" may represent an enticing potential for utility load control programs, particularly in the southeastern U.S with a very large saturation of electric resistance water heating.

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