Water Heater Demand Response: Comparing Full Replacement and After-Market Controllers

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ABSTRACT

Customer acceptance, technical efficacy, grid flexibility, and cost-effectiveness are the four essential legs supporting any successful residential load shifting approaches. As utilities look to expand load shifting and demand response approaches beyond thermostats, many are looking to water heaters. However, water heaters face different challenges to connectivity and customer comfort. In addition, as a major appliance with a relatively long life, early replacement of a functioning standard model for a new connected model may not be attractive to customers or be cost-effective. Over two pilot phases, a southeastern utility is comparing the efficacy and customer experience with two approaches: 1) full-unit replacements and 2) after-market controllers that can be installed with existing eligible water heaters. The phase 1 test of full unit replacements found measurable impacts in summer and winter demand response events, explored the impact of load shift events, and assessed customer acceptance. Phase 2 will test the viability of after-market controllers to provide a more cost-effective approach and will test two types of controllers with different communication protocols – cell signal and Wi-Fi. Phase 2 will test consistency of connection, responsiveness to signals, and demand impacts during summer and winter months. This paper reports out the evaluation methodologies and findings of phase 1 with discussion of how those findings are informing the design of the ongoing phase 2 pilot.

Introduction

As a ubiquitous household appliance, many utilities are looking at water heaters as an expansion to their load-shaping strategies beyond thermostats. However, water heaters are a major appliance with a long life and customers have different expectations of comfort, aesthetics, and functionality compared to thermostats. Demand response (DR) through water heaters merits careful testing. This paper discusses two approaches to water heater DR – full unit replacement and after-market controllers. We present results from a pilot sponsored by a southeastern utility that tested installing brand-new Wi-Fi enabled water heaters and conducted both winter and summer events. The successes and challenges of that pilot spurred a second pilot to test two after-market controllers that use Wi-Fi and cell signal. We discuss the impetus and design for the second phase of the pilot considering expected impacts, connectivity challenges, customer experience, and cost. As of November 2021, the second phase of the pilot is in-progress with controllers installed and ready for suitable cold-weather mornings for events.

Background

In the phase 1 pilot, the pilot sponsor recruited 100 residential customers into its water heater demand response (WHDR) pilot. Pilot participants were utility employees, and friends and family of employees. The pilot installed 70 heat pump water heaters (HPWHs) and 30 electric resistance water heaters in the homes of participants. To be eligible for this pilot, participants had to:

- Own their single-family home and not have plans to move within the year,
- Have an active account with the utility with a standard electric residential rate,

- Have electric water heat or the ability to convert to electric water heat,
- Have an existing water heater that is at least five years old,
- Have Wi-Fi in their home, and
- Not be participating in an air conditioning switch program or other pilots.

The pilot sponsor also contacted eligible customers to have them provide a photograph of their existing water heater showing the space around it. If their current water heater was gas, eligible customers had to provide a photograph of their breaker box. The pilot sponsor used these photographs to determine if there was adequate space to meet the ventilation requirements of the HPWHs and/or space in the breaker box to add a circuit for the water heaters converted from natural gas. Many otherwise eligible customers were not able to participate in the pilot because there was not enough space around their water heater to install a HPWH.

Water heater installations began in late September 2018 and concluded the first week of January 2019. Installations started with an appointment to add a breaker for the water heater (where necessary) and to install a TED (The Energy Detective) monitoring device (in the homes of 15 participants). After any necessary electrical work, a plumber installed the new HPWH or electric resistance water heater and connected it to the mobile app. Most installations (64%) took at least two visits to complete, with one visit for the electrical work and one for the water heater installation. Most respondents (86%) reported installation visits took between two and six hours to complete. The pilot aimed to provide water heaters equal to or one size larger than the existing water heater to maintain customers experiences with hot water supply.

Each DR event consisted of two components: a load shift event during which the water was preheated by raising the setpoint to 140^{o} F, and a load shed event during which the water heaters' setpoints were reduced. During the load shed event, the pilot sponsor lowered the water heaters' setpoints to 110^{o}F until the end of the event, at which point they raised it back to the customers' selected pre-event setpoints.

The timing of the load shift events varied throughout the pilot as the pilot sponsor became aware of issues with the water heaters receiving the signal via Wi-Fi and the vendor made improvements to the platform and (API) call to water heaters. During the first two DR events, the pilot sponsor scheduled the load shift for one hour prior to the load shed event. However, not all devices received the signal to switch from the load shift event to the load shed event. For subsequent events, the pilot sponsor began scheduling the load shift events to begin 1.5 hours prior to the event. This created a 30-minute gap between the end of the load shift event and the beginning of the load shed event during which the water heaters could receive the signal. For the last two events, the pilot sponsor scheduled the load shift events to begin 1.25 hours prior, which left a 15-minute gap between the end of the load shift event and the beginning of the load shed event. The pilot sponsor held a total of ten DR events throughout the winter and summer of 2019. Table 1 displays the dates and times of these DR events as well as the percentage of customers who reported being at home during the events and the number who reported any negative experiences during the events.

Table 1. Winter and summer event details

Event date	Load shift	Load shed	Number of opt-outs	Percentage of customers at home	Reported any negative experience
Friday, January 18	7:00 a.m. to 8:00 a.m.	8:00 a.m. to 10:00 a.m.	4	47%	0
Thursday, February 7	6:00 a.m. to 7:00 a.m.	7:00 a.m. to 9:00 a.m.	4	58%	3

Monday, February 18	5:30 a.m. to 6:30 a.m.	7:00 a.m. to 9:00 a.m.	1	60%	1
Tuesday, February 26	4:30 a.m. to 5:30 a.m.	6:00 a.m. to 8:00 a.m.	1	82%	13
Wednesday, March 6	4:30 a.m. to 5:30 a.m.	6:00 a.m. to 8:00 a.m.	0	50%	NA
Friday, June 21	1:30 p.m. to 2:30 p.m.	3:00 p.m. to 5:00 p.m.	0	71%	0
Tuesday, June 25	2:30 p.m. to 3:30 p.m.	4:00 p.m. to 6:00 p.m.	2	68%	1
Tuesday, July 2	2:30 p.m. to 3:30 p.m.	4:00 p.m. to 6:00 p.m.	0	47%	2
Wednesday, July 10	1:45 p.m. to 2:45 p.m.	3:00 p.m. to 5:00 p.m.	0	47%	0
Monday, July 29	2:45 p.m. to 3:45 p.m.	4:00 p.m. to 6:00 p.m.	1	67%	

The pilot design tested how two variables may affect demand impacts and customer experience: (1) pre-notification of DR events and (2) preheating (through load shift event) of water heaters. To facilitate this testing, the evaluation team divided the 100 participants equally into four different treatment groups and developed a plan for rotating each group through all four different possible combinations of receiving notification and/or pre-heat twice—once during winter events and once during summer events. For the first four events of each season, the pilot sponsor notified half of the participants via email two to three days in advance of the event and implemented a load shift event to preheat half of the water heaters. For the fifth DR event of each season, the pilot sponsor notified all participants in advance of the event and preheated all water heaters. For the fifth summer DR event, the pilot sponsor also incorporated text notification which became available on the platform.

Methodology

The evaluation team estimated demand reduction and energy savings achieved during the DR events by using hourly AMI data for participating homes and an analysis of device-level event participation using water heater data. The team fielded online surveys to gather customer feedback about their experiences with the water heaters and the events.

Interval Meter Data Analysis

The evaluation team estimated the demand reduction achieved during the DR events using hourly AMI data for participating homes. Analysis steps included data cleaning and preparation, identifying baseline or counterfactual days, and regression modeling.

Within subject baseline. The evaluation team estimated a baseline for each event based on participants' energy use during non-event days. The following screening criteria was used to select three non-event days from those with the smallest temperature difference between the non-event day and event day: 1) within two weeks of the matching event day; 2) not a holiday or weekend day; 3) must not be another DR event day or test event day.

Modeling. Using data from the selected non-event days and event days in a linear fixed effects regression, the evaluation team modeled a treatment effect for each event period. The final model specification included terms that accounted for weather (as heating degree hours with a base temperature of 65°F and cooling degree hours with a base of 70°F), time of day, and interactions between weather and time of day. The team estimated peak demand reduction and energy savings during an event day by including variables in the model to identify treatment (i.e., taking the value of 1 for days, hours, and sites where treatment occurred and 0 otherwise). The team validated the modeling using five variations of the regression model specification, which all yielded similar results, as well as reviewing the average impacts from the event level results.

$$kW_{i,h,d} = \alpha_i + \sum \beta_{1,h} * Hr_h + \sum \beta_{2,d} * Event_d + \beta_3 * HDH.65_{i,h,d} + \beta_4 * CDH.70_{i,h,d} + \sum \beta_{5,d} * Event_d * HDH.65_{i,h,d} + \sum \beta_{6,d} * Event_d * CDH.70_{i,h,d} + \beta_7 * Trt.Day_d + \beta_8 * Shift.Hr_h + \beta_9 * Trt.Shift_{h,d} + \beta_{10} * Trt.Shed_{h,d} + \beta_{11} * Trt.Post_{h,d} + \varepsilon$$

Where:

kW_{avg}	= Hourly average demand for site *i* at hour *h* during day *d*.
α_i	= Site fixed effect for site *i*. This field captures site specific conditions that do not vary over time.
Hr_h	= Hourly dummy variables for hours 1-24, where Hr_1 takes a value of 1 for observations where the hour is 1 and 0 otherwise.
$Event_d$	= Event dummy variables, where $Event_1$ takes a value of 1 for the day of event 1 and its counterfactual days and 0 otherwise.
$HDH.65$	= Heating degree hours at base 65°F for site *i* at hour *h* during day *d*.
$CDH.70$	= Cooling degree hours at base 70°F for site *i* at hour *h* during day *d*.
$Trt.Day_d$	= Dummy variable for days where load shift and/or load shed was delivered, where this field takes a value of 1 during days where load shed was sent and 0 otherwise.
$Shift.Hr_h$	= Load shift dummy variable, where this field takes a value of 1 during hours where shift was delivered and 0 otherwise. This field captured unique characters of the hours for which Shift was delivered based on the counterfactual days. We added this additional field to better control for unobservable factors that could influence Shift savings. We only added this control for Shift treatment because the program is designed to only deliver shift for 50% of participants for most events.
$Trt.Shift_{h,d}$	= Load shift treatment dummy variable, where this field takes a value of 1 during days and hours where shift was delivered and 0 otherwise. This field captured shift impacts.
$Trt.Shed_{h,d}$	= Load shed treatment dummy variable, where this field takes a value of 1 during days and hours where load shed was intended to be delivered and 0 otherwise. This field captured shed impacts.
$Trt.Post_{h,d}$	= Post-shed treatment dummy variable, where this field takes a value of 1 for the hour after shed was intended to be delivered and 0 otherwise. This field captured post-shed snapback.

Water Heater Data Analysis

The evaluation team used interval data from the water heaters to provide insight into the estimated demand reduction and energy savings. Water heater data, stored in 5-minute intervals, included information on the operating mode, load shed and load shift status, setpoint, water heater use, kW draw, schedule modifications, and connectivity. Data was available for four winter DR events and all the summer DR events.

Participant Surveys

The evaluation team fielded three types of online surveys to understand the customer experience:

Post-installation survey. This short survey gathered initial feedback on the water heater, program enrollment, and installation experience. The evaluation team sent participants email invitations to complete the survey within two weeks of their water heater installation.

In-depth customer experience survey. This survey assessed motivations for participation, user experience with the pilot, customer satisfaction, and demographics. The team sent email invitations for the customer experience survey to all 100 unique participant emails after the January 18, 2019, event. Participants who had not yet responded to the customer experience survey continued to receive invitations to this survey after subsequent events.

Short follow-up surveys. The team used a shorter follow-up survey to provide a longitudinal perspective on the customer experience with DR events. Once a participant completed the customer experience survey, the team invited them to take this shorter follow-up survey after subsequent DR events. In total, 75% of participants completed the post-installation survey and 70% of participants completed the full customer experience survey. The proportion of participants completing post-event surveys dropped from over two-thirds after the first DR event to less than half after the last DR event. Few participants (15%) completed all nine post-event surveys, but 92% completed multiple surveys.

Results: Customer Experiences

Generally, respondents experienced few issues with their hot water, disruptions to routines, or negative effects due to any changes made to their water heater during the DR events. The largest number of respondents reported issues after the February 26, 6:00 a.m. to 8:00 a.m. event, the event for which the most participants were home. Neither pre-event notification nor preheating appeared to impact the number of respondents who reported any issues with hot water, disruptions to routines, or other negative effect from the DR event. The following subsections provide additional details.

Connectivity. Overall, respondents did not report having many issues with their new water heater. The most reported issue was connecting the water heater to Wi-Fi, with 15% reporting this issue. Of those with trouble connecting, five had issues with the Wi-Fi network itself. People described having low or spotty Wi-Fi signal which affected their water heater staying connected.

At-home rates. The percentage of respondents reporting that they were at home during an event ranged from 47% to 82%. Respondents were most likely to be home during DR events held in the early morning before people typically leave for work and in the early evening when they return home. In winter, respondents were significantly more likely to be home during the 6:00 a.m. to 8:00 a.m. DR event (February 26) than they were during the other winter DR events held later in the morning. In summer, respondents were more likely to be home during the 4:00 p.m. to 6:00 p.m. DR events than the 3:00 p.m. to 5:00 p.m. DR events. Table 1 provides additional detail on the percentage of respondents who were at home during part or all surveyed DR events.

Opt-outs. No participants opted out in advance and very few participants opted out during DR events.[1] Fewer participants opted out of the summer DR events than winter DR events. Summer results indicate that customers opting out of events had little effect on load impacts. Less than 1% of participants opted out of summer events on average. Even customers who opted out received the load shed signal for 83% of the event.

Hot water. The survey asked respondents if anyone in their home experienced any of the following issues with their water heater: water temperature would not get hot enough, ran out of hot water, water took too long to heat, or water was too hot. Few respondents reported these difficulties. The highest rate of issues related to water temperature was on February 26, when ten respondents reported experiencing problems, most often that the water would not get hot enough.

Impact to routine. Very few respondents reported that the DR events affected their routines. In fact, respondents noted disruption to their routines after only three of the nine surveyed events. The largest proportion of respondents reported disruption to their routines after the February 26 event, when 8% said their routines were affected. As noted previously, this event took place between 6:00 a.m. and 8:00 a.m. In general, respondents who reported that their routines were affected noted that getting ready for work or school was an issue and that the water not reheating in between showers affected their routines.

Preheating and pre-event notification. Looking across multiple survey questions and events, we found very little difference in the customer experience of those who received pre-notification and those who did not, and those who received preheating and those who did not across the following topics:

- Whether or not respondents recalled receiving email notifications
- Likelihood to be home during an event
- Events opt-out rates
- Rate of reporting any issues with their water temperature, routines, or any other negative effect
- Satisfaction with the pilot overall and the pilot sponsor
- Willingness to participate in a future water heater DR program

Results: Demand Impacts

In this section, we provide estimated demand impacts achieved during the summer and winter DR events and report on the effect of opt-outs and load shift on demand savings. It is important to note that results include all pilot participants, even those with connectivity issues, in the summary results to estimate the impacts the program achieved per *enrolled* water heater. For the event-level and customer-specific characteristics results, we constrained our analysis to only the water heaters we could verify were connected and active during events to provide insight into the potential savings per *connected* water heater.

[1] Participants could opt-out of an event prior to the event through the advanced email notification or during the event by manually or remotely adjusting water heater setpoints.

Winter DR Events

During winter DR events, the pilot achieved an average load shift demand increase of 0.18 kW, average load shed savings of 0.20 kW, and a post-event demand increase of 0.21 kW. These impacts apply to an average of 89.4 sites across five winter events. This corresponds to total program impacts per event of 16.1 kW pre-heat load increase, 17.9 kW load shed savings, and 18.8 kW of post-event load increase. Table 2 shows the average estimated household-level demand reduction achieved across all five winter DR events, as well as the average demand impact in pre- and post-event periods. We define the pre-event period as the load shift event held one to two hours prior to the load shed event and the post-event period as the one hour following the event.

Table 2. Estimated household-level average demand reduction for winter DR events

Period	Average Treated Sites per Event	Average Number of Sites per Event in Analysis	% Treatment Delivered (Estimated)	Number of Impacted Hours	Household kW Impact	Household confidence interval (high/low)
Load Shift	89.4	88.4	42%	1.6[a]	-0.18	-0.11/-0.25
Load Shed	89.4	88.4	94%, 75%[b]	2	0.20	0.28/0.13
Post-Event	89.4	88.4	-	1	-0.21	-0.11/-0.31

[a] Pre-event periods occurred for an hour in duration. However, with hourly usage data, the pre-event period may have spanned multiple hours (e.g., occurring from 5:30 a.m. to 6:30 a.m.). As a result, the modeling yields an estimate of the impacted kW over the impacted hours, which would be two hours for a pre-event occurring from 5:30a.m. to 6:30 a.m.

[b] Water heater data indicates that shed load action was not delivered February 26, 2019. Outside of that event and where water heater data exists (events 1 – 3), connectivity issues affected 6% of sites; including that event and the available data for event 5, connectivity issues affected 25% of sites.

Summer DR Events

During summer DR events, the pilot sponsor achieved an average load shift demand increase of 0.09 kW, average load shed demand reduction of 0.11 kW, and post-event savings of 0.05 kW. These impacts apply to an average of 97 sites across five summer DR events. This corresponds to total program impacts per event of 8.7 kW load shift load increase, 10.7 kW load shed savings, and 4.9 kW of post-event savings. While the post-event impacts are not statistically significant at the industry-standard 90% confidence level, the robustness checks of the results provide some evidence to the reliability of this approximate estimate.[2] Table 3 shows the average estimated household-level demand reduction achieved across all five summer DR events, as well as the average demand impact in pre- and post-event periods.

[2] Robustness checks support an overall estimate of 0.05 kW savings during the summer post-shed hour and some of the variance is likely due to load shifting, which was only intended to be applied to 60% of sites on average across the events. The difference in post-shed impacts between sites who did (0.23 kW) and did not (-0.14 kW) receive load shift event likely contributes to the large error band, and for an example of the robustness of this estimate, the average post-shed savings for customers who did and did not receive load shift is 0.05 kW.

Table 3. Estimated household-level average demand reduction for summer DR events

Period	Average Treated Sites per Event	Average Number of Sites per Event in Analysis	% Treatment Delivered (Estimated)	Number of Impacted Hours [a]	Household kW Impact	Household confidence interval (high/low)
Load Shift	97	94.0	54%	2	-0.09	-0.01/-0.18
Load Shed	97	91.6	90%	2	0.11	0.18/0.04
Post-Event	97	93.6	-	1	0.05	0.15/-0.04

[a] Pre-event periods occurred for an hour in duration. However, with hourly usage data, the pre-event period may have spanned multiple hours (e.g., occurring from 5:30 a.m. to 6:30 a.m.). As a result, the modeling yields an estimate of the impacted kW over the impacted hours, which would be two hours for a pre-event occurring from 5:30a.m. to 6:30 a.m.

Load Shift Impacts

As shown in Table 4, households that had load shift through preheating had greater demand reductions during the load shed period, suggesting that implementing a load shift may increase impacts during the load shed period. Winter and summer events show a similar trend, with load shift increasing load shed impacts by approximately one-third in each season. In addition, in winter, households that had load shift had lower snapback effects in the post-event period.[3] In summer, households that had load shift showed demand savings during the post-event period. This may be partially driven by the load shift period: the water heaters may be maintaining temperature through the load shed period and beyond.

Although the impact evaluation results have relatively large error bands due to sample size, this finding aligns with expectations. Water heaters are more likely to stay above their setpoint with load shift. In semi- or unconditioned spaces during hot summer afternoons, some water heaters may be able to stay above their setpoints beyond the two-hour shed event. In conditioned spaces during winter, some water heaters may be able to stay above setpoints beyond the two-hour shed event, thus diminishing the snapback load increase in the hour after the event.

Table 4. Load shift impacts on household-level average demand reduction

	Winter		Summer	
Period	Not Load Shifted/Preheated Households (confidence interval)	Load Shifted/Preheated Households (confident interval)	Not Load Shifted/Preheated Households (confidence interval)	Load Shifted/Preheated Households (confident interval)
Load Shift	NA	-0.29 (-0.19/-0.39)	NA	-0.19 (-0.04/-0.34)
Load Shed	0.29 (0.43/0.15)	0.37 (0.52/0.23)	0.11 (0.24/-0.04)	0.15 (0.26/0.05)
Post-Event	-0.40 (-0.17/-0.62)	-0.26 (-0.09/-0.44)	-0.14 (0.05/-0.33)	0.23 (0.39/0.07)

Discussion and Pilot Phase 2

The phase 1 pilot attained measurable demand impacts with positive customer feedback and satisfaction. However, the challenges and lessons learned from this pilot have informed planning for the

[3] Snapback is the increase in energy use or demand after a DR event due to the water heater returning to its previous setpoint.

phase 2 (in-progress) pilot. Table 5 summarizes the challenges and lessons learned and shows how the phase 2 pilot design will address these items.

Table 5. Phase 2 pilot design based on lessons learned From Phase 1

Eligibility	
Key Finding from Phase 1	Many otherwise eligible customers had to be screened from the pilot because there was not enough space around their water heater to install a HPWH.
Phase 2 Pilot Approach	After market controllers have fewer space limitations.
Connectivity	
Key Finding from Phase 1	Water heater connectivity issues negatively affected demand reduction achieved by the program and the customer experience. Through examining the number of water heaters connected during each DR event, ILLUME estimates that connectivity issues may have diminished load shed kW impacts by as much as 25% during the winter and 10% during the summer. Moreover, the most reported issue respondents reported having with their water heaters was connecting them to Wi-Fi. This was primarily due to issues with the Wi-Fi network, not the water heater itself.
Phase 2 Pilot Approach	The pilot is testing two communication protocols by randomly assigning participants to receive one of two different model controllers: one that uses Wi-Fi for communication and one that uses cell signal. This will allow a direct comparison of communication protocols and their impact on treatment delivery and customer experience. During the installation process, about one-third of customers receiving the Wi-Fi controller reported the installer had difficulty connecting the controller to their Wi-Fi. About 17% of customers receiving the controller that uses cell service reported that the installer had difficulty connecting the controller to call service.
Cost and Impact	
Key Finding from Phase 1	The pilot yielded measurable, but modest, demand savings. In addition to the cost of the water heaters, the pilot sponsor invested significant time and resources screening prospective pilot participants and installing water heaters in their homes. To vet participants, the pilot sponsor used a screening survey and required participants to provide photos of their current water heater. Most installations took at least two visits to complete, with one visit for the electrical work and one for the water heater installation. Customers reported installation visits took between two and six hours to complete.
Phase 2 Pilot Approach	To improve cost-effectiveness the Phase 2 pilot is testing after-market controllers. The pilot maintained a screening process and installed the controllers through qualified electricians. Most installations have been completed in one visit. 90% of installations took one hour or less and 50% took less than 30 minutes.
Customer Experience	
Key Finding from Phase 1	Respondents were highly satisfied with their water heater and the pilot throughout their participation in the pilot. Very few respondents reported issues with their hot water, disruptions to routines, or negative effects due to the DR events. Neither advance notice of the DR events nor preheating the water heaters affected the customer experience with the DR events. Furthermore, respondents that received the advance notice of events did not opt-out of any DR events prior to the event start.

Phase 2 Pilot Approach	Customers did not act differently after receiving event notifications but did report appreciating event notifications. The phase 2 pilot will send event notifications for all participants.

Conclusion

Water heater DR with full equipment replacement shows promise for measurable impacts and customer acceptance but still faces challenges due to cost, connectivity, and customer interest if equipment and installation are not being provided at no cost. Results from the in-progress phase 2 pilot will provide insight on the benefits of different communication protocols, customer acceptance of an after-market device, and relative cost-effectiveness of the two approaches.