WatterSaver Beta test: Use of Water Heater Thermal Storage to Manage TOU Peak Periods

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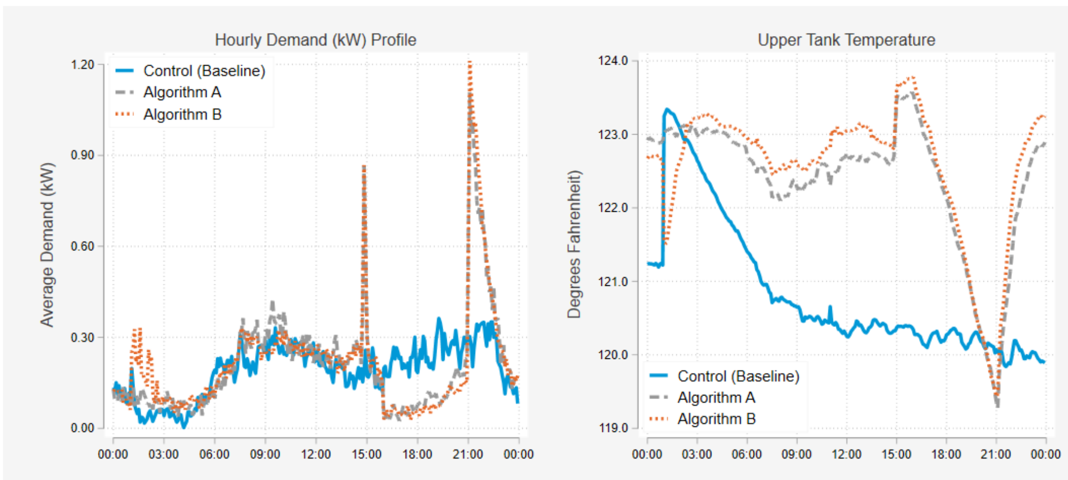

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ABBREVIATIONS AND ACRONYMS

EE	Energy Efficiency
HPWH	Heat Pump Water Heater
TOU	Time-of-Use

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EXECUTIVE SUMMARY

In 2018, PG&E proposed a behind-the-meter thermal storage project, known as WatterSaver, using smart electric water heaters and control devices.

The WatterSaver program has several objectives, including:

- Reduce peak demand by 5 MW by 2025
- Drive the adoption of heat pumps in both early and emergency replacement cases
- Provide customers with connected devices that enable them to align their energy use with the TOU price signal
- Assess if water heaters can be used to provide daily and permanent load shifts
- Test the integration of load shifting resources and rates with energy efficiency

By design, the roll-out of the program included a testing phase before scaling the program, known as a Beta test. The main goal of this phase was to test technologies, resolve any technical and implementation hurdles, and make program adjustments as needed. Because the technology and programs are new, PG&E expected that experimentation and adjustments would be necessary to understand how to control the water heaters and how to manage them to reduce demand over the 4-9 pm peak period.

PROJECT GOAL

The main objective was to shift the energy use profile of water heaters on a daily basis from the 4 to 9 pm peak period to lower-cost hours thus, avoiding congestion on the grid and aligning with time of use (TOU) rates. The study assessed two different water heater technologies: smart control devices and smart hybrid heat pump water heaters.

PROJECT DESCRIPTION

Water heaters can function as batteries by effectively storing energy in the form of pre-heated water. Customers experience similar hot water temperatures, but energy use is shifted to off-peak periods by using thermal storage. Two different intervention bundles were assessed, replacing less efficient water heaters with smart hybrid heat pump water heaters and retrofitting existing electric water heaters with smart devices. For each intervention bundle, devices were assigned to one of four groups based on enrollment order and each group alternated between baseline and different control operations.

For the smart control device intervention, the groups were rotated daily between three different operation strategies:

- **Control.** The devices operate without interference, based on user preferences.
- **Algorithm A**. Allows the water heater to draw more power in advance of the peak and limits energy use during the 4-9 PM window.
- **Algorithm B**. Similar to Algorithm A, but is specifically tailored to deliver steady reductions from 4-9 PM, including the fifth hour from 8-9pm.

For the smart hybrid heat pump water heater intervention, the groups were rotated on Mondays of each week between three different operation protocols:

- **Control (Baseline).** The water heater is set to operate on electric resistance mode, with the internal water temperature set to 120°F for all hours. This protocol mimics the energy use of a traditional electric water heater with efficient insulation. It produces a baseline of energy use absent a hybrid heat pump water heater.
- **Efficiency only.** The water heater is set to operate on Energy Saver mode (the default), and the internal water temperature is set to 120°F. The settings mimic the use of the water heater without storage operations.
- **Efficiency with storage.** The water heater is set to operate on Energy Saver mode (the default), and the water temperature is set to 120°F. However, during the three hours preceding the peak period (1 pm to 4 pm), the water heater internal temperature settings are increased to 140°F, and the water heater is only allowed to operate using the heat pump. The approach effectively converts energy into hot water (storage) and reduces the use of energy during the 4 pm to 9 pm peak period.

The alternating treatment approach enabled the evaluation team to estimate the change in energy use and peak demand change due to how the water heaters were operated. Customers did not know which group they were assigned to and, with a few exceptions, were unaware of the water heater operation schedule for a given day. Because of the alternating treatment, the weather and customer behavior were similar for the baseline and treatment options. While the experiment set the water heater settings, participants can override the default modes through their mobile devices and change the water heating set-points or other settings. Few customers did so.

PROJECT FINDINGS/RESULTS

Table 1 summarizes the main research questions and findings from the final testing phase of the Packetized smart control device intervention.

TABLE 1: KEY FINDINGS SUMMARY–WATER HEATER SMART DEVICES

Research Question	Findings
Did the technology work?	Yes. The technology enabled electric water heaters to control water heater operations and recorded granular information about water heater energy use, temperature setting, operation modes. The process for dispatching and monitoring water heaters was fully automated, and allowed testing of multiple algorithms. The algorithms clearly reduced peak demand over all five hours in the 4-9 pm window while avoiding increases in total daily energy use. The effect of the impacts was consistently observable for nearly all devices.

What are the peak demand reductions resulting from the installation of smart water heater devices?	When operating under Algorithm A, the devices reduced peak demand by 62% ± 21% (95% confidence), saving 0.15 kW ±0.05 (95% confidence) on average. When operating under Algorithm B, the devices reduced peak demand by 68% ± 20% (95% confidence), saving 0.17 kW ±0.05 on average.
Does overall energy use change due to using water heaters for storage and load shifting?	While the timing of energy use changed, storage and shifting operation did not lead to a statisticaly significant increase in energy use. The results are nuanced because the treatment effect lingers. On baseline days, between 12 am and 9 am, the water heaters benefit from storage – in the form of higher tank temperatures – from the prior day when a storage algorithm was in place. For Algorithm A, the control devices increased overall usage by 8.0% ± 9.0% (95% confidence), and under Treatment B, the control devices increase overall energy use by 6.2% ± 6.9% (95% confidence). Neither increase is statistically significant, but there is a noticeable increased in water heating activity immediately before and after the peak period.
How well do the algorithms perform?	Both algorithms resulted in statistically significant peak demand savings overall and at the customer level. Algorithm B delivered slightly more peak demand savings o and more consistent reductions for individual sites.

Figure 1 visualizes the results of the second intervention bundle. The impacts of both treatments were statistically significant overall and at the customer level, indicating that the installation of water heater control devices (cause) led to reductions in peak demand (effect), while the impacts on overall energy use were minimal.

FIGURE 1: SMART CONTROL DEVICE ENERGY AND PEAK DEMAND IMPACTS SUMMARY

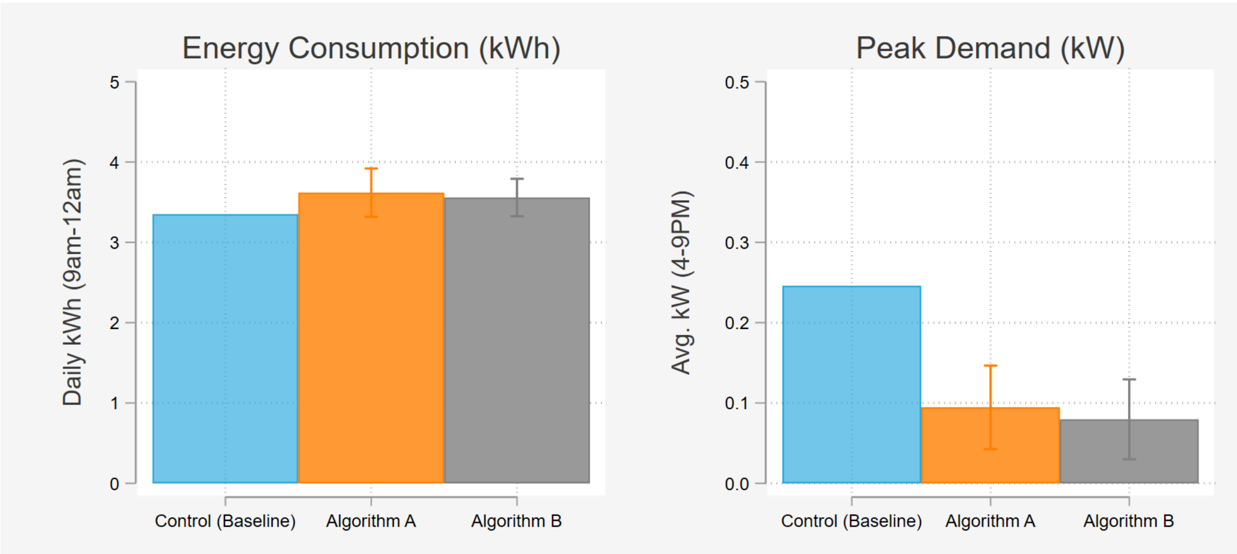


Table 2 summarizes the main research questions and findings from the final testing phase for the smart hybrid heat pump water heater intervention. Figure 2 visualizes the results. There is strong evidence that the higher efficiency of hybrid heat pump water heaters (cause) led to reductions in energy use and peak demand (effect).

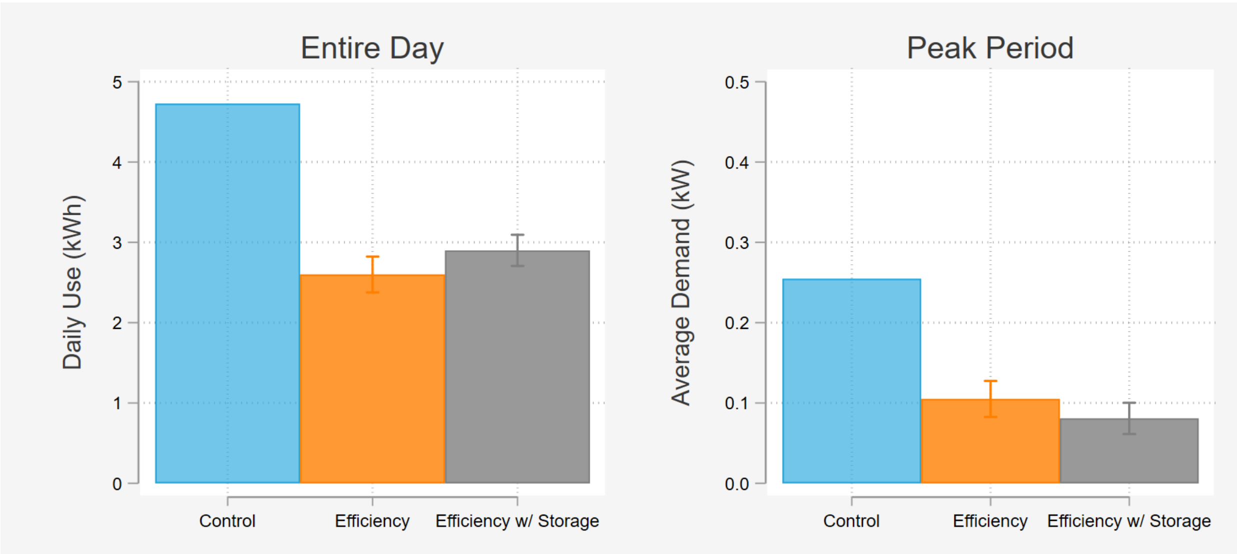
TABLE 2: KEY FINDINGS SUMMARY – SMART HYBRYID HEAT PUMP WATER HEATERS

Research Question	Findings
Did the technology work?	Partially. The technology provides the ability to schedule how water heaters operate. They also provide granular information about water heater energy use, temperature setting, operation modes, and use of the heat pump versus the electric resistance element. The process for automating the dispatch of water heaters was not fully automated and required manual scheduling, which generated implementation challenges. While the devices can be managed, the algorithms to manage the devices need additional refinement to deliver larger peak demand reductions and avoid increases in energy use.
What are the energy savings resulting from the installation of hybrid heat pump water heaters?	When placed in efficiency-only mode, the hybrid heat pump water heaters reduced daily energy use by 52.8% ± 4.9% (95% confidence), saving 2.59 kWh per day, or 947 kWh of annual savings.

	When placed in efficiency-plus-storage mode, the hybrid heat pump water heaters reduced daily energy use by 44.5% ± 4.2% (95% confidence), saving 2.19 kWh per day or 798 kWh annually. The effiency-plus-storage mode led to higher energy use than the effiency only mode, although that was largely due to poor implementation of the control algorithm. Further refinement of the dispatch algorithms and better implementation is likely to deliver the peak demand reductions without increases in energy use.
What are the peak demand reductions resulting from the installation of hybrid heat pump water heaters?	When placed in efficiency-only mode, the hybrid heat pump water heaters reduced peak demand (5-10 pm) by 58.8% ± 8.8% (95% confidence), or 0.150 kW on average.[1] When placed in efficiency-plus-storage mode, the hybrid heat pump water heaters reduced peak demand by 68.3% ± 7.7% (95% confidence), or 0.174 kW on average.
Do storage operations lead to incremental peak demand reduction?	Storage operations did lead to statistically significant incremental peak demand reductions. Storage operations resulted in an average 0.02 kW in additional peak demand savings compared to efficiency only operations. While the impact of storage is statistically significant, it is small in comparison to the peak demand reduction due to the efficiency of the smart hybrid heat pump water heater.

[1] As explained in Appendix A, the dispath strategy was not updated when daylight saving time went into effect on March 8, 2020. Before daylight savings, the water heaters were controlled from 4-9 pm, after daylight savings, they were controlled from 5-10 pm.

FIGURE 2: SMART HYBRID HEAT PUMP WATER HEATER ENERGY AND PEAK DEMAND IMPACTS SUMMARY



PROJECT RECOMMENDATIONS

Both interventions achieved statistically significant peak demand reductions and have the potential for successful program implementation. PG&E should continue its efforts to develop programs and incentives targeted towards water heaters, due to their significant loads and potential for electrification and improved efficiency. If California is to meet decarbonization targets, electric water heating will need to shift from natural gas to electricity as a fuel source.

The main recommendations are:

- Refine and automate the smart hybrid heat pump water heater storage algorithm.
- Conduct research on how to sustain connectivity rates with water heaters.
- PG&E should continue to perform and refine automated assessments of proper storage operations with water heaters.
- Incentivize the high penetration of smart hybrid heat pump water heaters to drive down costs.
- Systematically test incentive levels and distribution channels.
- Increase the pool of trained smart hybrid heat pump water heater installers.
- Explore fast-response applications of water heater smart controllers.

INTRODUCTION

California is undergoing a rapid transformation of its electric supply mix and demand. The introduction of large amounts of bulk and distributed solar is leading to changes in grid operating and planning needs. In parallel, the State of California has mandates to decarbonize transportation, space heating, and water heating via electrification of those end-uses. Over the course of 2021-2024, PG&E is also defaulting most residential customers onto time-of-use rates with a peak period between 4-9 pm on all days. Electric water heating technology is central to the above transformations. As California's decarbonizaton and electrification efforts mature, electric water heating will become more common. Water heaters are a good candidate for flexible load response, capable of meeting key operational needs of the grid and able to allow customers to better manage their enery use and shift loads away from TOU peak periods.

In 2018, PG&E proposed a behind-the-meter thermal storage project, known as WatterSaver, using smart electric heat pump water heaters and control devices. The water heaters effectively store energy in the form of pre-heated water. Customers experience similar hot water temperatures, but energy use is shifted to off-peak periods by using thermal storage. The main objective was to modify the energy use profile to align with time-of-use (TOU) rates and to shift loads from the 4 to 9 pm peak period to lower-cost hours and avoid congestion on the grid.

The WatterSaver program has several objectives, including:

- Reduce peak demand by 5 MW by 2025
- Drive the adoption of heat pumps water heater in both early and emergency replacement cases
- Provide customers connected devices for water heaters that enable them to align their energy use with the TOU price signal
- Assess if water heaters can be used to provide daily and permanent load shifts
- Test integration of load shifting resources with energy efficiency

By design, the roll-out included a testing phase before scaling the program, known as a beta test. The main goal was to test the technology, resolve any technical and implementation hurdles, and make program adjustments as needed. Because the technology and programs are new, PG&E expected that experimentation and adjustments would be necessary to understand how to control the water heaters and how to manage them to reduce demand over the 4-9 pm peak period.

The Beta test includes two distinct interventions:

- **Installing smart control devices on existing electric water heaters**. This variant involves the installation of controllers on existing electric water heaters. The control enables the fleet of water heaters to be used as a virtual battery, enabling storage and making the loads flexible. The controllers are supplied by Packetized Energy, which provides a virtual battery portal. The devices also collect data on water heater energy use and temperature settings. During the beta test phase, 38 devices were installed and 33 remained connected throughout the side-by-side testing phase.

- **Replacing less efficient water heaters with smart hybrid heat pump water heaters**. This variant involved the replacement of existing electric resistance water heaters with more efficient, smart hybrid heat pump water heaters (HPWH). The new water heater enables the use of the water heater as a storage device. They provide customers and PG&E the ability to schedule/shift water heating and also collect data on water heater energy use and temperature settings. There were 46 total beta test participants who had their electric water heaters replaced with smart, more efficient water heaters that enable thermal storage. 33 of these remained connected and were included in the final analysis.

All participating customers in the beta test were required to have electric water heating, meaning that none of them would be shifting from gas to electric water heating. All participating customers also were placed on PG&E's TOU-C rate plan (with peak period 4 – 9 p.m.) and some were provided additional light touch energy efficiency (EE) measures such as a smart thermostat and smart power strips, at no cost.

ASSESSMENT OBJECTIVES

While there were multiple interventions (a simultaneous water heater installation, a change to TOU rate, and installation of light touch EE measures), the focus is on the performance of the smart water heater technology. The main goal was to estimate the effect of the technology on energy consumption and peak demand. In this beta test phase, we seek to answer four key research questions for each intervention bundle.

For the smart controllers, the key research questions are:

- Did the technology work as intended?
- What are the peak demand reductions resulting from the installation of water heater smart control devices?
- Does overall energy use change due to using water heater for storage and load shifting?
- How well do the algorithms perform?

For the smart hybrid heat pump water heater, the key research questions are:

- Did the technology work as intended?
- What are the energy savings resulting from the installation of more efficient heat pump water heater?
- What are the peak demand reductions resulting from the installation of more efficient heat pump water heaters?
- Do storage operations lead to incremental peak demand reduction?

- Does overall energy use change due to using water heater for storage and load shifting?

BACKGROUND

As noted earlier, California is undergoing three large scale changes in its electric supply mix and demand:

- The introduction of large amounts of bulk and distributed solar is leading to changes in net load peak patterns and, thus, changing grid operating and planning needs.
- Mandates to decarbonize transportation, space heating, and water heating via electrification of those end-uses.
- The roll out of default time-of-use rates with a peak period between 4-9 pm on all days.

Electric water heating technology is central to the above transformations. In addition, the WatterSaver Beta test served as a test of integrated demand side management (IDSM) by combining energy efficiency measures with flexible load control and time-varying pricing. This section provides additional context regarding PG&E peaking load.

PG&E NET LOADS AND PEAKING PATTERNS

PG&E provides natural gas and electric service to approximately 16 million people throughout a 70,000-square-mile service area in northern and central California. PG&E delivers electricity to over 4.9 million residential accounts and natural gas to over 3.9 million residential accounts. In 2019, PG&E delivered 78,479 GW of electricity, with a peak demand of 21,079 MW.[2, 3]

Historically, utility infrastructure has been sized to meet the aggregate demand of end users when it is forecasted to be at its highest—peak demand. However, the California electric grid is evolving rapidly due to the introduction of large amounts of bulk and distribution connected renewable resources, which are intermittent by nature. The shift towards large amounts of renewable resources has created new operational and planning issues, including:

- A shift in the focus of planning and operations from gross to net loads – actual system demand minus intermittent renewable resources;

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[2] PG&E customer and energy sales data is from EIA Form 861 Early Release: https://www.eia.gov/electricity/data/eia861/

[3] PG&E Load data is available at: https://www.eia.gov/opendata/qb.php?category=3390291&sdid=EBA.CISO-PGAE.D.HL

- Changes in the timing of when system net loads peak, which have shifted from the mid-afternoon to evening hours;
- Increased need for fast response resources to follow net loads and counterbalance variability in solar and wind resources;
- Increased need for resources to meet much longer and larger sustained upward and downward ramps in net loads; and
- Resources capable of absorbing over-generation during the middle of the day, particularly on weekends in spring and fall months.

Figure 3 shows the hourly distribution of PG&E system loads by hour of day and shows that peak demand tends to occur in the evening hours.

FIGURE 3: DISTRIBUTION OF HOURLY PG&E ELECTRIC DEMAND

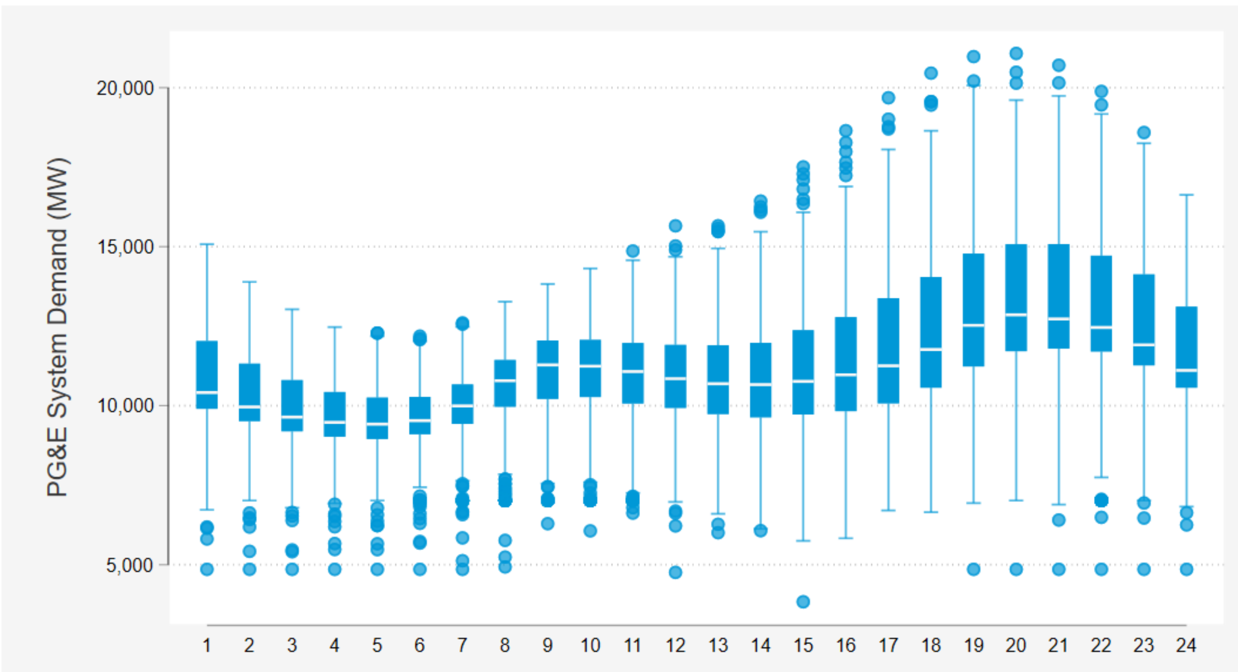
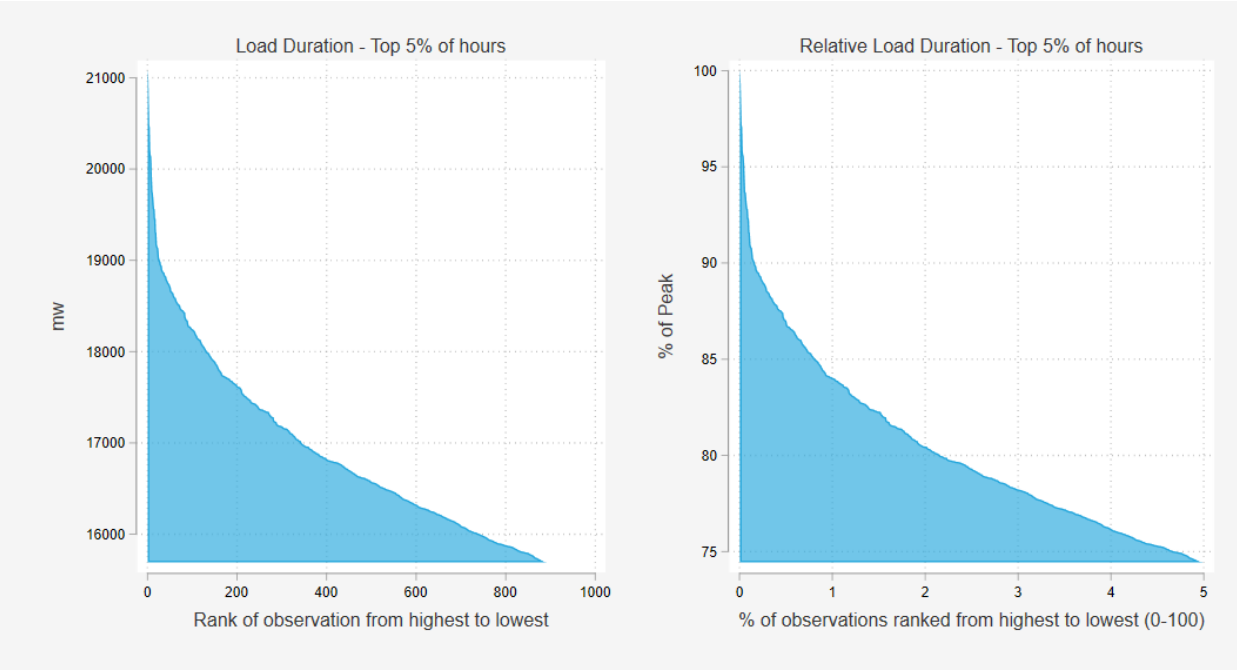


Figure 4 illustrates a fundamental aspect of power system planning – that a significant share of system capacity is built to meet demand on very small number of hours. Load duration curves sort electricity demand from highest to lowest and are a good way to visualize how the concentrated peak demand is across all hours. For PG&E roughly 16% of generation capacity is needed to meet demand on the top 1% of hours.

FIGURE 4: PG&E LOAD DURATION (CONCENTRATION OF DEMAND ON TOP HOURS)



Traditionally, load control technologies and programs were aimed at lowering system peak demand. However, as renewables continue to change system loads, any solutions that provides the grid with additional flexibility to respond to ramping throughout the day is desirable. In some circumstances, the prevalence of renewables on California's grid can result in over-generation, when system supply outweighs system demand. Since renewables produce whenever the weather conditions are right, over-generation is more likely to occur when demand is traditionally low, such as weekends and milder months of the year, when the demand from heating and cooling is lower.

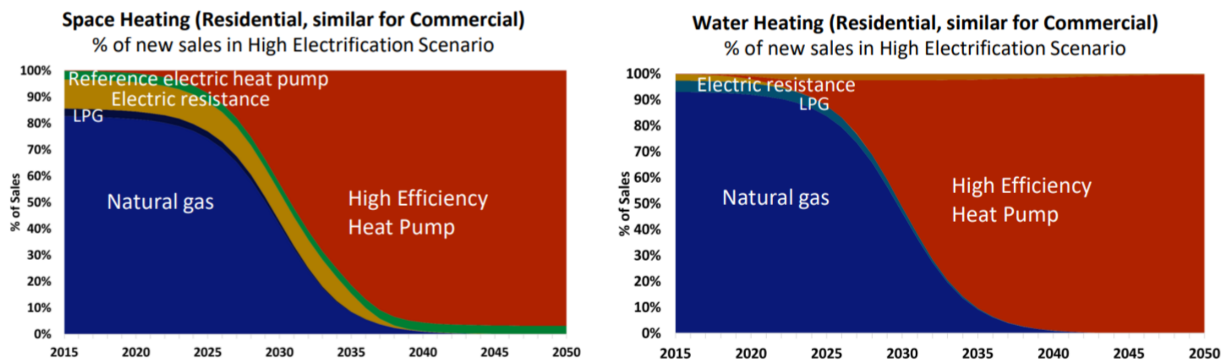
Water heaters are a good candidate for this flexible load response, since water heating is not as seasonal as space heating and cooling, and still accounts for a relatively significant portion of residential energy consumption. Aside from behavioral changes, homeowners traditionally had little control over the temperature settings of their water heaters, how often they run, or what energy source is used to heat the water. However, homeowners today have gained control over many home appliances through Wi-Fi connectivity, and water heaters are no exception. Advances in water heater technology and controllers have provided homeowners the ability to modify the operation of their water heaters to suit their needs and goals, and therefore, respond to demand-side interventions.

DE-CARBONIZATION AND ELECTRICIFICATION OF WATER HEATERS

California has established de-carbonization targets to reduce the impacts of climate change. The mandate is to achieve a required 40 percent reduction in greenhouse gas (GHGs) emissions by 2030, and an 80 percent reduction in GHGs by 2050, relative to 1990 levels. The electrification of water heating plays a critical role in de-carbonizing California.

To attain green house reduction goals, water heaters in California will need to shift from natural gas to highly efficient heat pump water heaters. Figure 5 shows the pace of the transition as estimated by a California Energy Commission Report on deep decarbonization. Currently, nearly all hot water in California is heated by natural gas, with a small percentage of less efficient electric resistance heating. If California engages in the projected level of decarbonization, water heater electric demand will grow over time.

FIGURE 5: CHANGE IN HEATING AND WATER HEATING NEEDED TO MEET DE-CARBONIZATION TARGETS



Source: [Deep Decarbonization in a High Renewables Future (CEC EPIC-14-069)]

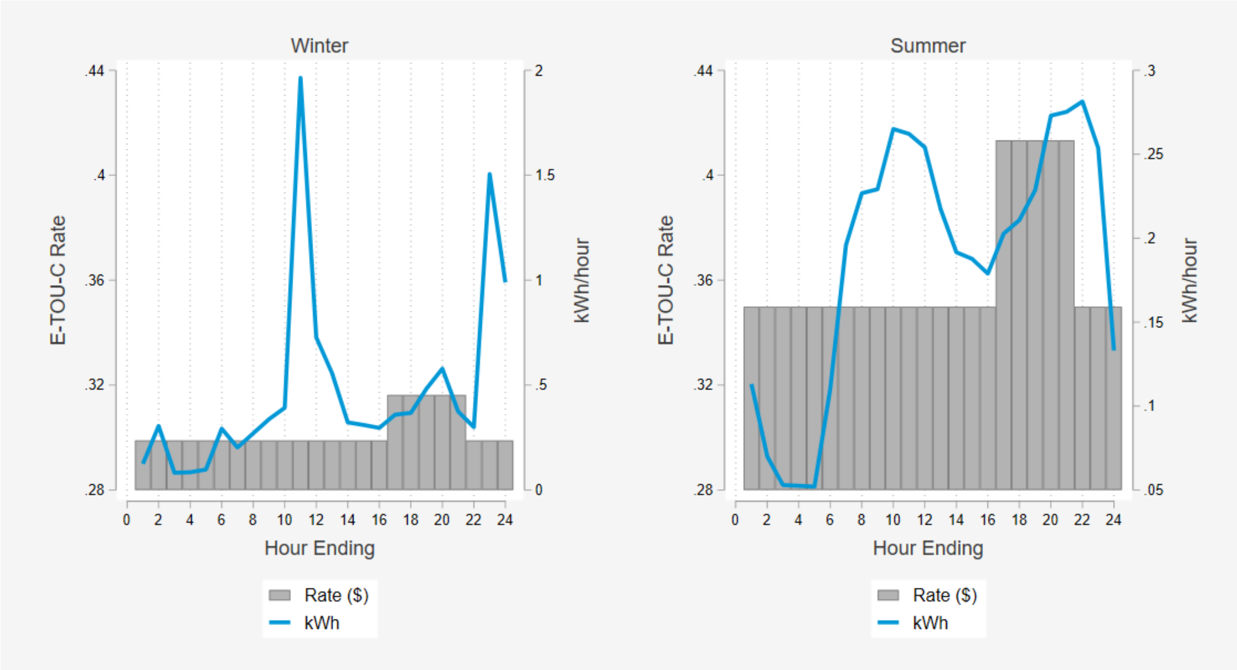
Heat pump water heaters are more efficient than current alternatives and can be scheduled to store heat when renewable production is high. Moreover, when existing electric water heaters are paired with smart controllers, they also can deliver flexible demand to help meet the electric grid's operation and planning needs.

IMPLEMENTATION OF DEFAULT TOU FOR RESIDENTIAL CUSTOMERS

Starting in 2021, PG&E will begin defaulting customers onto a time-of-use rate (E-TOU-C) with a peak period from 4-9 pm on all days, including weekends. The rate transition is designed to factor in when customers consume power in addition to how much they consume in determining their bill; leading to a closer alignment between the prices customers face and the cost of supplying power.

Importantly, water heater loads are dual peaking, reflecting activity in the morning and the evening hours. The second, evening peak, tends to align with the TOU peak period and with peak system loads. Figure 6 compares the water heating load of program participants on baseline days - when no intervention is in place - against the E-TOU-C rate structure. A key driver of the WatterSaver Beta test was the ability to shift loads from peak periods and, thus, reduce system demand and lower customer bills.

FIGURE 6: WATER HEATER LOADS AND THE E-TOU-C RATE

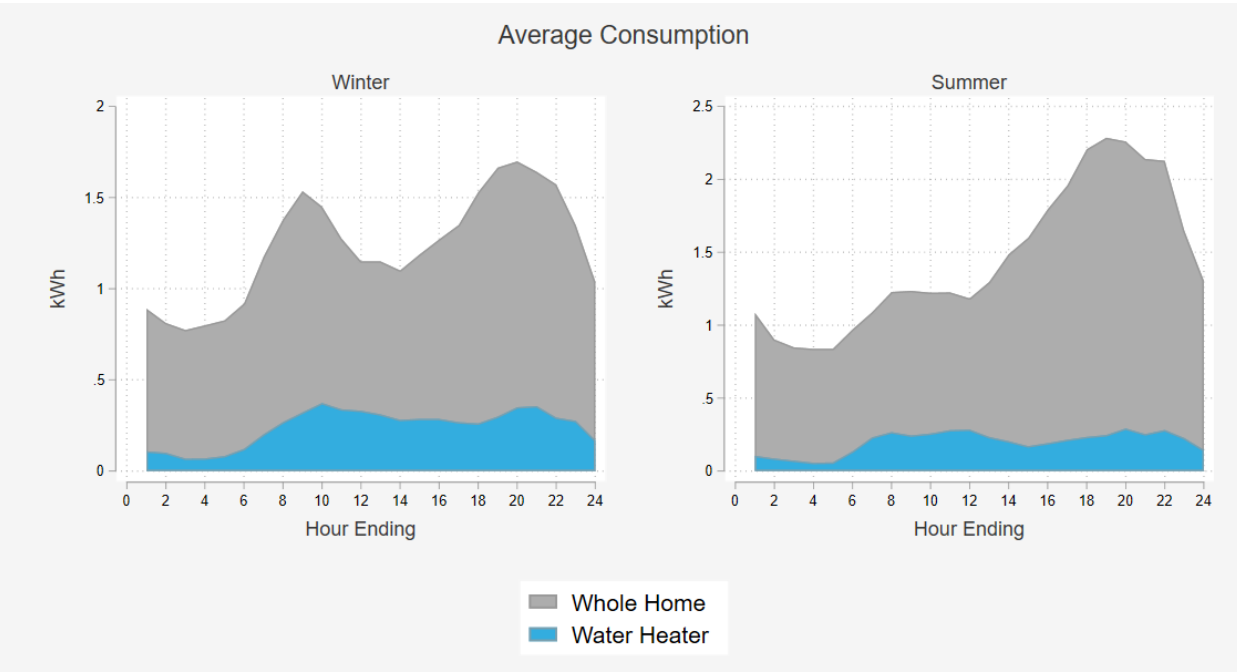


WATER HEATER SHARE OF HOUSEHOLD ENERGY USE

For homes with electric water heaters, they have historically accounted for substantial share of energy use. Typical electric resistance water heaters in California use 25% of household energy,[4] or approximately 1,800 kWh in annual consumption, with a small amount of variation by climate zone. After HVAC systems, water heaters are the third highest source of energy usage in the home.[5] Figure 7 shows the hourly whole building and electric water heater use for the average baseline day across participants in both WatterSaver beta test programs for the same time period. Water heating loads mirror the morning and evening peaks of PG&E's system demand. However for water heaters, the two peaks are relatively similar in magnitude. Water heater usage spikes while residents are active at home, and drops in the middle of the day and at night when people are at work or asleep.

[4] https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf
[5] https://www.eia.gov/tools/faqs/faq.php?id=96&t=3

FIGURE 7: AVERAGE WATER HEAT CONSUMPTION ACROSS WATERSAVER PARTICIPANTS



EMERGING TECHNOLOGY/PRODUCT

PG&E's WatterSaver beta test relies on using the thermal storage capacity of water heaters to enable customers to shift loads and reduce peaks in order to manage their bill given the upcoming default TOU rates. While water heater load control has been available for decades, three recent technology developments made the technology assessment unique:

- **Built-in data collection and two way communication of water heater energy use, temperature settings, and lower and upper tank temperature**. Water heaters and water heater load controllers are now embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet. Increasingly, water heater and control device manufacturers have application programming interfaces (API's) which allow authorized users to access granular data and to automate load management and analysis.
- **High efficiency heat pump water heater technology**. The most common type of water heater is a storage, or tank, water heater. These appliances store water at a certain temperature to provide on-demand hot water in the home. If the water is used up or the temperatures begin to drop, the water heater uses energy to refill and reheat the tank. The vast majority of water heaters currently rely on natural gas or electric resistance coils, both of which are less efficient than heat pump technology. A heat pump water heater works by moving heat from the surrounding air into the tank to heat water instead of generating its own heat, like traditional electric resistance water heaters. They run more often but use less energy than

traditional electric resistance water heaters. Most heat pump technology is, in fact, hybrid technology. They rely mainly on the heat pump for heating water (or air) but typically have an auxiliary electric resistance heating coil, to allow the unit to produce heat more quickly, if needed. Thus, for most units, the energy savings are a function of the share of the time the unit operates using the heat pump versus the electric resistance element. Some water heaters are also WiFi-enabled, or compatible with internet-connectivity devices that provide homeowners with the ability to monitor and control heat pump operations.

- **Aggregation of residential flexible loads into virtual batteries**. The ability to communicate across thousands of devices and customize signals to each allows the development of platforms that aggregate flexible loads and packages them into virtual batteries. The technology allows utilities and aggregators to specify the magnitude, speed, and duration of load changes.

As part of the beta test, PG&E used the ability to set temperatures and operating modes to operate the water heaters like a battery, heating the water to warmer than traditionally necessary temperatures during off-peak hours, and storing this energy as heat until the consumer needs the warm water. PG&E's WatterSaver beta test started in 2019 and comes in two versions of implementation, the addition of Packetized Energy controllers to existing electric resistance water heaters or a complete device replacement with smart hybrid heat pump water heaters. Additional details on each technology are provided in the Smart Water Heater Control Devices and Smart Hybrid Heat Pump Water Heaters sections below.

Water heater loads are flexible enough that they can be used to deliver fast response services such as frequency regulating, operating reserves, and load following. They also can be employed to provide wholesale energy arbitrage – by charging when prices are low and reducing demand when prices are high. In addition, they can be use to reduce peak demand and, thus, reduce generation, transmission, and/or distribution infrastructure capital costs.

The WatterSaver Beta test, however, focused specifically on the ability of water heaters to help customers shift energy use away from the 4-9 pm TOU peak period. It did not assess fast response grid services that can be delivered via flexible water heater loads. Much of the effort was around the development of algorithms that delivered reductions that could be sustained across all five peak hours while meeting customer's hot water needs.

SMART CONTROL DEVICES

EMERGING TECHNOLOGY OVERVIEW

The Packetized heat pump water heater controllers are devices installed on customers' existing water heaters. These devices enable users to monitor and control water temperature setpoints. The controllers operate in storage mode by pre-heating water temperature by roughly 3°F above the setpoint before the peak demand window of 4-9 PM. By doing so, the water heater does not have to use energy to heat the water throughout the peak period. Unlike most load control devices, the platform delivers custom instructions to each device, each of which can request to draw power to ensure water is delivered at the temperature set by the customer.

The Packetized controller is Wi-Fi enabled. It includes a mobile app that gives users control over their water heating, allowing them to customize temperature, add vacation settings, set it on energy savings mode, and monitor the system while at home or away. Based on the agreement with the beta test participants, PG&E can access the device data and modify settings to enable testing and use the water heater as a thermal storage unit.

Unlike traditional water heating load control, the devices record energy use and upper and lower tank temperatures in five minute-intervals. The loads are aggregated and displayed in near real-time portals displaying energy usage and operation settings. Utilities, such as PG&E, have the ability to access the individual device data and to modify the fleet operation settings via an Application Programmable Interface (API). APIs provide the ability to better automate processes and to develop automated applications..

The Packetized Energy platform is designed to aggregate connected devices in homes and small businesses, at the edge of the power grid, and convert them into smart and flexible energy resources. Unlike traditional load control, utilities can specify the amount (MW) and timing of resources needed. In addition, the platform is capable of using water heater loads to deliver fast-response ancillary services needed to operate a stable grid (though this function was not tested in the beta test).

Packetized handled all aspects of the algorithm development and automated the implementation of the research design (which was verified by DSA). They provide the service on a per device fee and provided access to their API which allows PG&E to automate the analysis. The customer recruitment and installation of energy efficiency measures and water heater controllers was performed by a distinct energy efficiency program management firm.

METHODOLOGY

EVALUATION DESIGN

Since the controllers were installed on the customer's existing water heaters, operating the water heaters without the use of the controller provides the baseline for the analysis. Customers were assigned to one of four experimental groups based on their enrollment date. The evaluation employed an alternating treatment design, where the groups were rotated between the two experimental load shifting algorithms and the baseline mode on a daily basis.

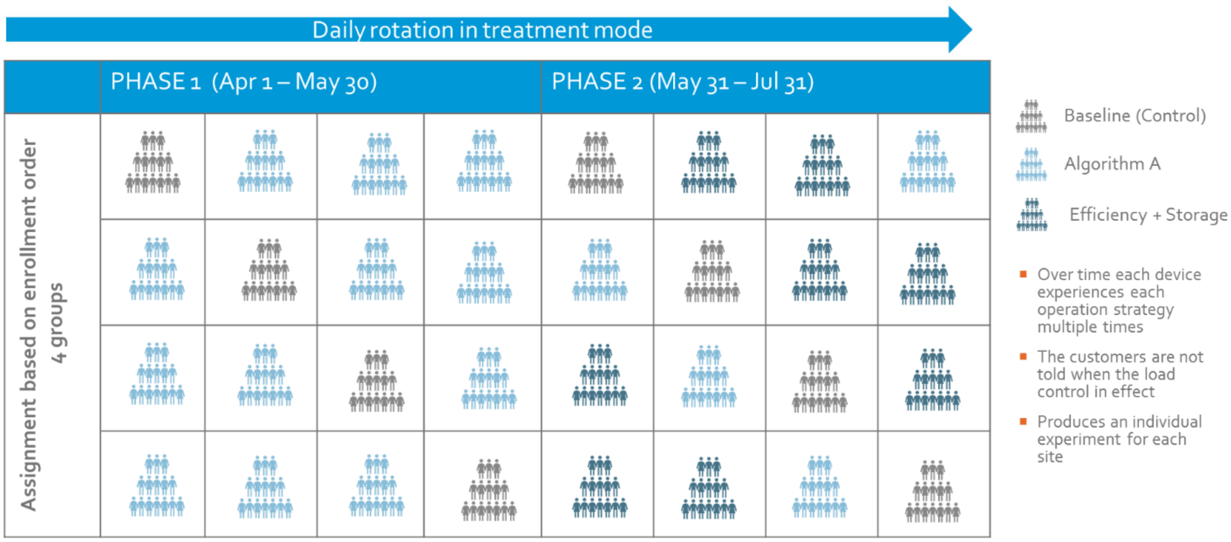
This experimental design allows for very robust estimation of impacts. For any given day, there are "treatment" and "control" customers with similar weather patterns, rates, and end-uses. Because customers do not know which mode they are on each day, on average, they experience similar conditions and behave in the same way under each treatment mode. Therefore, the energy use of each customer can be directly observed and compared under the baseline and storage operating protocols, essentially producing an individual experiment for each site.

Participants were assigned to four experimental groups based on their enrollment order. Each group was rotated daily between three different operation strategies:

- **Baseline (Control).** The devices operate without interference, based on user preferences.
- **Algorithm A**. Allows the water heater to draw more power in advance of the peak and limits energy use during the 4-9 PM window.
- **Algorithm B**. Similar to Algorithm A, but is specifically tailored to deliver steady reductions from 4-9 PM.

Figure 8 shows the alternative treatment design over two testing phases. Phase 1 only operated in two of the modes, baseline and Algorithm A. During the initial phase, Packetized Energy modified the algorithm to optimize operations. Phase 2 was the side-by-side testing phase, where devices were rotated through the baseline day and two competing algorithms (the finalists). Each phase ran for two months. The only drawback of the approach was that the effect of thermal storage operation lingered onto the overnight hours of baseline days.

FIGURE 8: ALTERNATIVE TREATMENT DESIGN

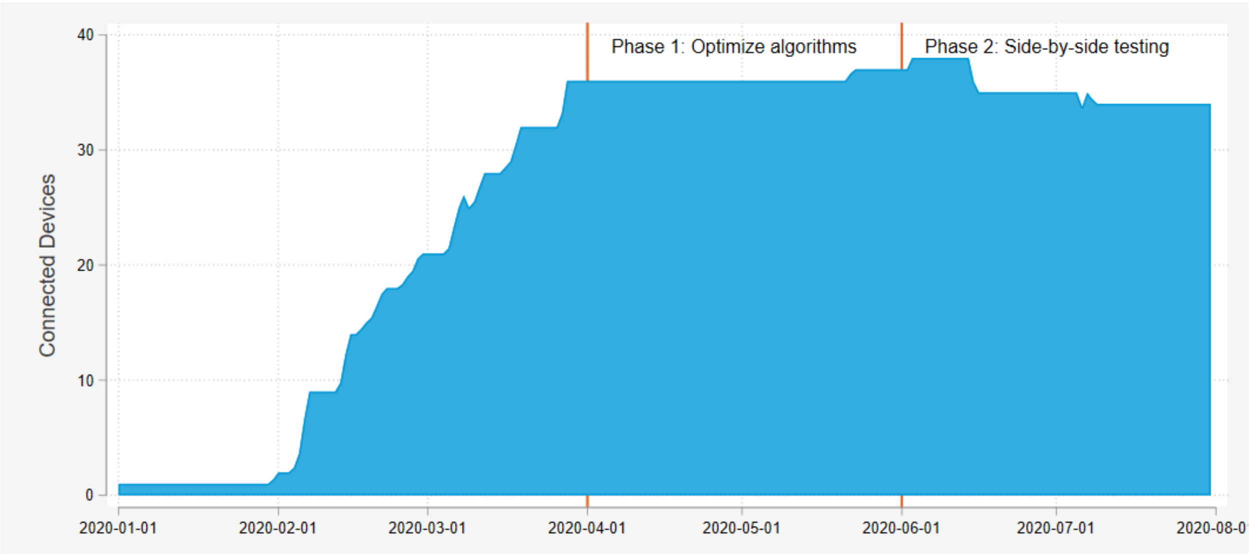


DATA SOURCES AND INPUTS

The Packetized smart water heater control devices record load, temperature, and operations data in five-minute intervals. The data was adjusted for daylight savings time, and then merged with (1) a list that mapped each participant to one of the four groups described above; (2) the weekly schedule of treatment types; and (3) temperature data obtained from the nearest weather station with data. In addition PG&E supplied DSA with customer characteristic data (e.g., prior rate, solar status, zip code) and whole building interval data.

While the experiment modified the upper tank water heater settings, participants could set the water output to their preferred temperature. A total of 38 devices were installed and 33 were connected throughout the Phase II side-by-side testing, which was used for the final analysis. Figure 9 shows the count of connected devices throughout the two phases. There was some attrition in connected devices after the beginning of Phase 2, mainly due to customers moving homes, resulting in disconnected devices.

FIGURE 9: CONNECTED DEVICES THROUGHOUT THE EVALUATION PERIOD



MODEL

The energy impact for each of the two strategies was analyzed using a panel regression with fixed effects, time effects, and clustered standard errors. Separate models were implemented to estimate the change in daily energy use and the change in peak (4-9 pm) energy demand. The following model was used to estimate the impacts on daily energy usage:

$$Consumption_{i,t} = \beta_0 + \sum_{m=1}^{2} \beta_m * Mode_{m,i,t} + u_t + v_i + \varepsilon_{i,t}$$

Where the beta terms represent a regression coefficient, or array of coefficients, and:

- **$Consumption_{i,t}$** = the daily water heater usage for participant i on date t, measured in kWh
- **β_0** = The model intercept
- **Mode** = An indicator variable for the operating mode for participant i on day t, with three possible values: mode 0 = baseline (electric resistance), mode 1 = Algorithm A, mode 2 = Algorithm B
- **U_t =** Time effects designed to capture unique effects of the date that are common across all sites
- **V_i =** Fixed customer effects designed to capture unique customer effects that are time invariant
- **$\varepsilon_{i,t}$ =** The error or residuals

The model specification for peak demand impacts was the same, except for the outcome variable:

$$Demand_{i,t} = \beta_0 + \sum_{m=1}^{2} \beta_m * Mode_{m,i,t} + u_t + v_i + \varepsilon_{i,t}$$

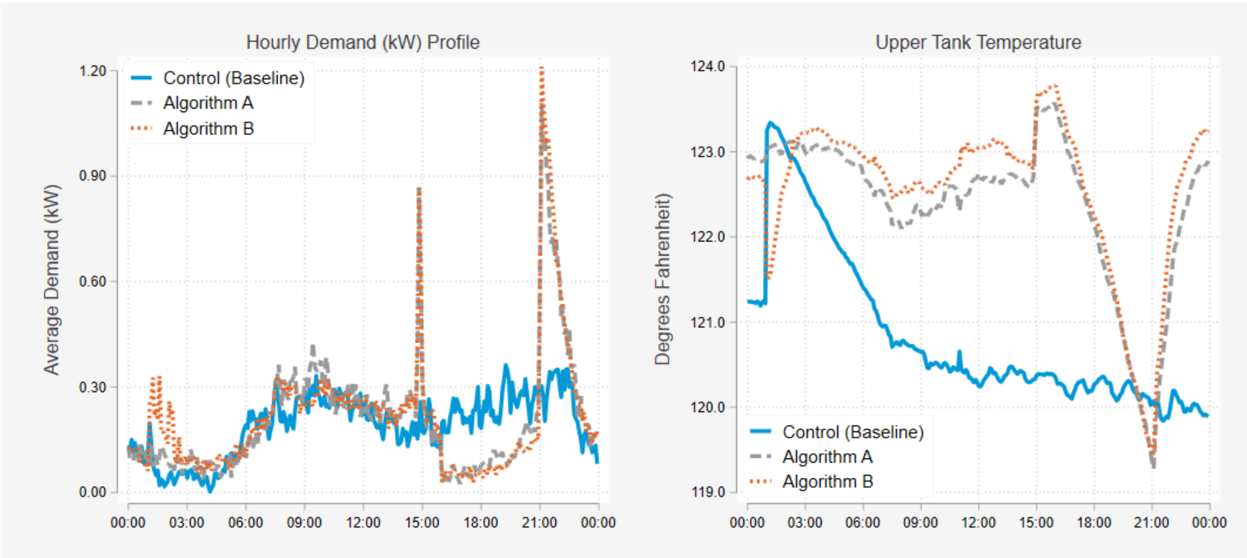
- **Demand$_{i,t}$** = the average peak period (4-9 pm) water heater demand for participant i on date t, measured in kW

RESULTS

The results of the analysis showed peak demand savings resulting from both algorithms. These results are distinctly visible in visual analyses and were statistically significant in the regression analysis.

Figure 10 shows the average demand and temperature settings for the 33 devices included in the final analysis without any modeling. The left panel shows the hourly load shape and the right panel shows the upper tank temperature under each operating strategy. Without the storage option, electric water heaters have a distinct morning and evening peak (blue line). Both storage algorithms follow similar patterns, with a spike in demand before and after the 4-9 PM window, and significantly reduced usage during the peak window. This decrease in usage comes from a sharp drop in the upper temperature tank during the peak period, which is clearly visible in the right panel. The impact of operating the devices in storage mode lingers into the overnight hours of next day. This is observed in the upper tank temperature, which starts at roughly 3 degrees higher than normal. As a result, we analyzed the period from 9 am to midnight when assessing energy consumption impacts.

FIGURE 10: AVERAGE DEMAND AND WATER TEMPERATURE SET POINTS BY OPERATING STRATEGY



The regression analysis shows that the peak demand impacts of both operational strategies were statistically significant at the 95% confidence level. Figure 11 shows the estimated effect for both algorithms compared to the baseline (control) for daily use (kWh) and peak demand (kW). Baseline is shown in blue, with the estimated impacts intervals for the Algorithm A and Algorithm B are shown in orange and gray, respectively.

When operating under Algorithm A, the devices reduced peak demand by 61.6% ± 21.1% (95% confidence), saving 0.151 kW ±0.052 (95% confidence) on average. With Algorithm B, the devices reduced peak demand by 67.6% ± 20.2% (95% confidence), saving 0.166 kW ±0.050 (95% confidence) on average.

FIGURE 11: SMART CONTROLLER ENERGY AND PEAK DEMAND IMPACTS SUMMARY

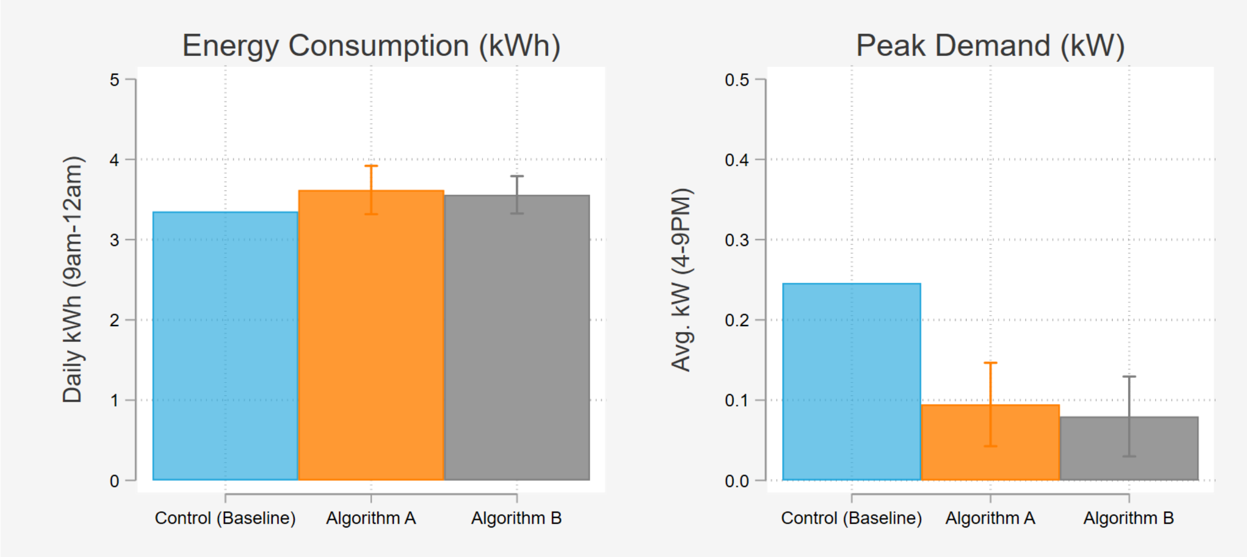
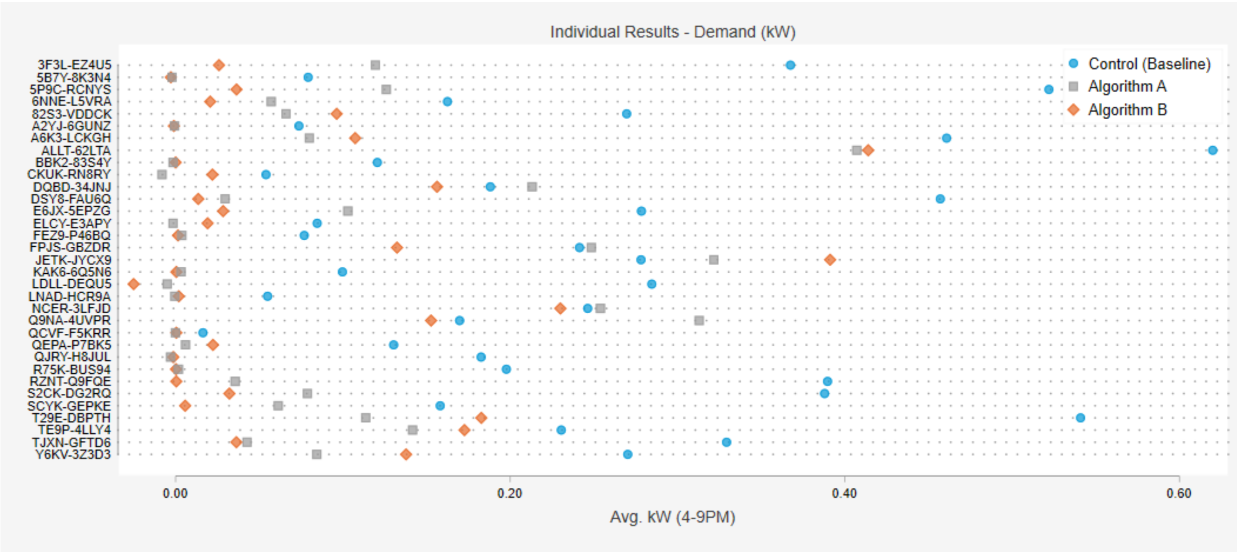


TABLE 3: SMART CONTROLLER ENERGY AND PEAK DEMAND IMPACTS

Metric	Intervention	Baseline	Energy Use	Impact	Std. Error	t	% Impact
Avg. kW (4-9PM)	Algorithm A	0.246	0.095	-0.151	0.027	-5.71	-61.6%
	Algorithm B	0.246	0.080	-0.166	0.025	-6.55	-67.6%
Daily kWh (9am-12am)	Algorithm A	3.351	3.618	0.267	0.153	1.74	8.0%
	Algorithm B	3.351	3.558	0.207	0.119	1.74	6.2%

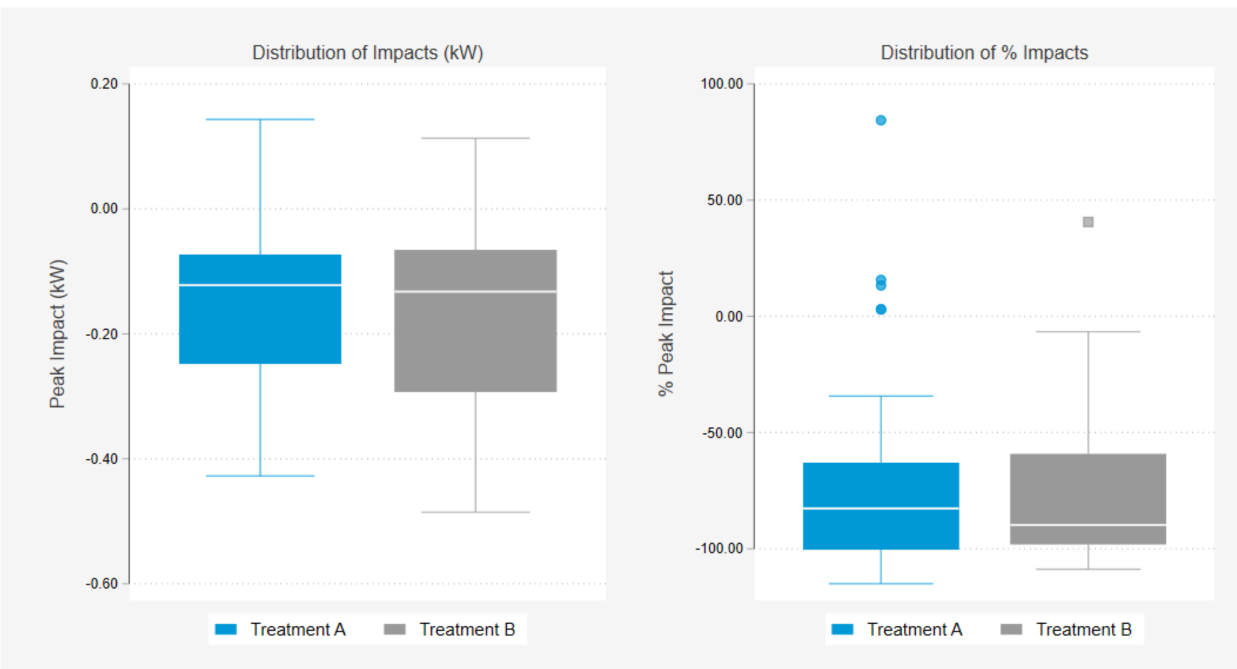
These impacts were also estimated for individual water heaters. Figure 12 shows the estimated average peak demand for each individual under each operational strategy. The blue dots represent the peak demand under control mode, while gray and orange show the estimated average peak demand for each of the algorithms. Peak demand under each of the storage modes was consistently less than the baseline for nearly all sites.

FIGURE 12: INDIVIDUAL PARTICIPANT RESULTS



Overall, both algorithms performed well and customer-level impacts were visible across both strategies. However, Algorithm B led to larger, more consistent reductions in water heater peak demand (68% versus 62%). Figure 13 shows the distribution of kW and percent impacts for both treatments.

FIGURE 13: DISTRIBUTION OF CUSTOMER-LEVEL IMPACTS ACROSS BOTH OPERATING STRATEGIES



SMART HYBRID HEAT PUMP WATER HEATERS

EMERGING TECHNOLOGY OVERVIEW

The hybrid heat pump water heaters work by pre-heating the stored water and minimizing peak period energy use by drawing on pre-heated water to deliver water in the peak period without additional heating.

The hybrid heat pump water heater is WiFi enabled. It includes a mobile app that gives users control over water systems, allowing them to customize temperature, add vacation settings, set it on energy savings mode, and monitor the system while at home or away. Based on the agreement with the beta test participants, PG&E can access the device data and modify settings to enable testing and use the water heater as a thermal storage unit.

The hybrid heat pump water heater can be remotely instructed to change water heater settings and operate in various modes, including:

- **Energy Saver** – This is the default mode. By design, the water heater relies primarily, but not exclusively on the heat pump to heat the water.
- **Heat Pump** – In this mode, the water heater only uses the heat pump for heating.
- **High Demand** – The water heater still relies on the heat pump to heat the water, but it uses the electric resistance heating element more quickly if demand is high.
- **Electric** – The water heater operates as most water heaters do, relying on a less efficient but faster electric resistance element to heat the water.
- **Vacation** – Under this mode, the water heater minimizes energy use and allows the water temperature to cool.

There are three main advantages with smart hybrid heat pump water heaters. In addition to providing storage capabilities, they reduce energy use across all hours due to underlying heat pump technology. Second, the communications technology is built-in and does not require retro-fitting an existing water heater. Third, the water heater vendor currently does not charge additional fees for access to their API and load management portal. The main drawback is that the algorithms to manage the water heater are not as well developed and not all aspects to the load management were fully automated.

For the beta test, the water manufacturer supplied the water heaters, provided access to their online device management portal, and provided weekly deliveries of the end-use data. A distinct energy efficiency progam management firm recruited the participants, coordinated the installation of energy efficiency measures and water heaters, and implemented the algorithm development. They were unable to automate the alternating research design, and, as a result, manually changed the device settings on a weekly basis to rotate across the treatment modes.

METHODOLOGY

In the evaluation of the hybrid heat pump water heater installations, the key evaluation challenges were addressed by using an experimental design that takes explicit advantage of the ability of the smart heat pump water heaters to operate in different modes at different times.

EVALUATION DESIGN

By design, each hybrid heat pump water heater was rotated weekly between three different operation protocols:

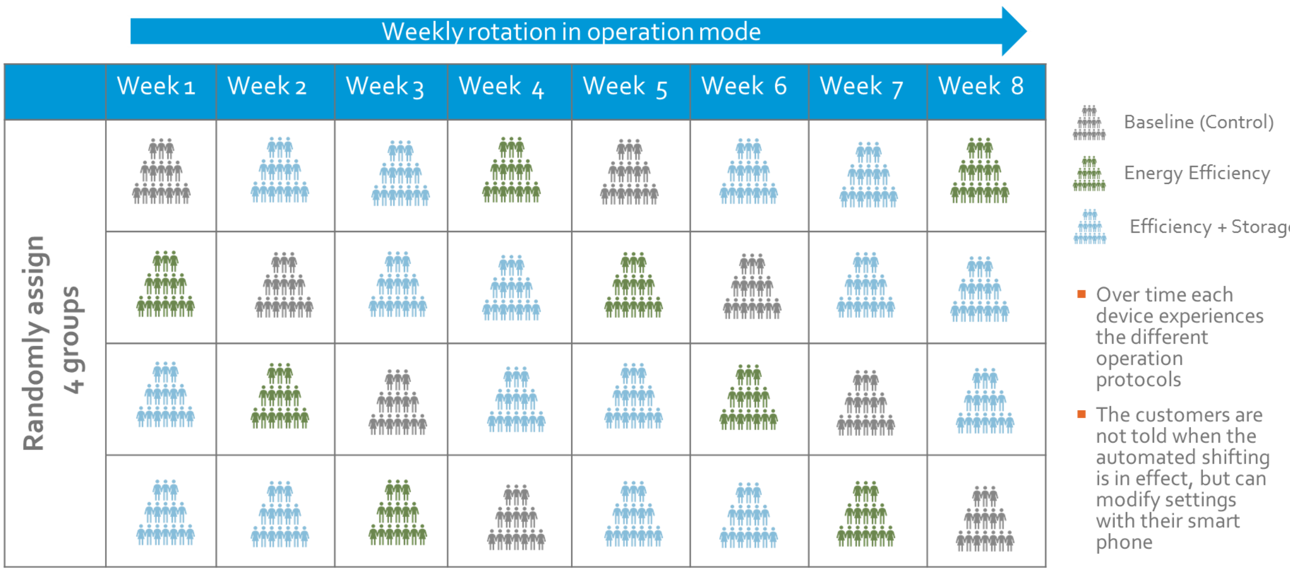
- **Control.** The water heater is set to operate on electric resistance mode, with the water temperature set to 120°F for all hours. This protocol mimics the energy use of a traditional electric water heater, with efficient insulation. It produces a baseline of energy use absent a hybrid HPWH.
- **Efficiency only.** The water heater is set to operate on Energy Saver mode (the default), and the water temperature is set to 120°F. The settings mimic the use of the water heater without storage operations. They also reflect the way hybrid heat pump water heaters typically operate, relying mostly on the heat pump for heating the water, but allowing the use of electric resistance heating element, if needed.
- **Efficiency with storage**. The water heater is set to operate on Energy Saver mode (the default), and the water temperature is set to 120°F. However, during the three hours preceding the peak period (1 pm to 4 pm), the water heater temperature settings are increased to 140°F, and the water heater is only allowed to operate using the heat pump (to avoid a spike in energy use). The customer still receives water at 120°F by mixing the hotter water with colder water. The approach effectively stores convert energy into hot water and reduces the use of energy during the 4 pm to 9 pm peak period.

While the experiment set the water heater settings, participants can override the default modes through their mobile devices and change the water heating set-points or other settings.

All participants are assigned to one of four groups based on their order of enrollment, and each group is rotated between the control, efficiency only, and efficiency with storage operating protocols. The research design enables us to compare energy use as a function of the operating protocols at any point in time. The alternating treatment design also produces a localized experiment. The energy use of each customer can be directly observed and compared under the control, efficiency only, and efficiency with storage operating protocols. The alternating treatment design ensures that aside from the control of the water heaters, customers have similar weather patterns, rates, and end-uses. Because customers are not told which operation protocol is in place in a given week, they behave and consume power in a similar fashion, on average.

Figure 14 shows the operations schedule implemented for the analysis data range.

FIGURE 14: RESEARCH DESIGN FOR SMART HYDRID HEAT PUMP WATER HEATERS



To date, there have been four distinct phases to the beta test. The first phase (pre-August 12th, 2019) was early trouble-shooting, with a limited number of devices. It involved accessing the online portal, understanding the data available, ensuring the devices were set to Pacific daylight time, and testing the ability to instruct the devices to follow operating protocols. In the second phase (8/12/2019 to 10/13/2019), devices were programmed to rotated only between the energy efficiency only and energy efficiency with storage protocols. During that phase, the ability to produce a traditional electric water heater baseline by operating the device in electric resistance mode became evident. On October 14th, the control (baseline) protocols were introduced. Since then, participants have rotated between the control, efficiency only, and efficiency plus battery storage protocols. Finally, the enrollment in the beta test ramped up starting in mid-February.

Because of manual operations, the implementation had two notable shortcomings:

- The operating algorithm was not adjusted for daylight savings time. As a result, before March 8, 2020, devices were set to shift load away from the 4-9 pm peak preiod. After daylight savings time, the devices were shifting load away from the 5-10 pm period.
- When operating in efficiency plus storage mode, the upper tank pre-heating was to be restricted to use the high-effiency heat pump. In practice, after the ramp up in enrollments, a large share of water heaters used less efficient electric resistance coils to pre-heat the water heater temperatures.

As a result, the analysis focuses on the period from 3/8/2020 to 6/19/2020, when the experiment ended. Because the goal was to understand the technology, we analyzed the 5-10 pm period as a "pseudo" peak, despite the misalignment due to daylight savings.

Data Sources and Inputs

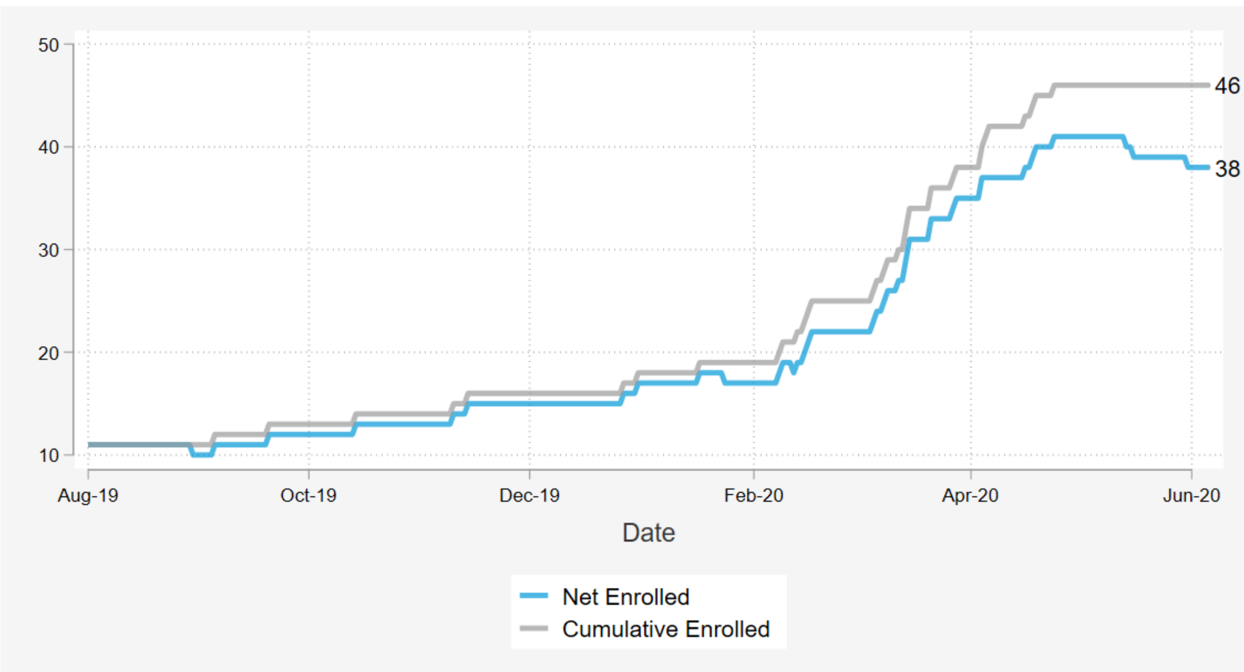
The hybrid heat pump water heaters record energy consumption, temperature set points, and other variables such as upper and lower tank temperatures, operation mode, and whether the heat pump or electric heating element is being used.

The data is recorded based on state-changes. That is, a data point is recorded whenever the settings, energy usage, or temperature values change. The data was converted to 5-minute interval data, adjusted for daylight savings time, and then merged with (1) a list that mapped each participant to one of the four groups described above; (2) the weekly schedule of treatment types shown in Figure 14; and (3) temperature data obtained from the nearest weather station with data.

In the interim reporting phase, 14 participants were enrolled and the analysis was conducted on eight devices. The five devices that were removed from the analysis during this phase either had disconnected from Wi-Fi or were not adhering to the operations protocols.

After the interim analysis, PG&E enrolled additional beta test participants in order to expand on the results of the interim analysis and be able to draw valid statistical conclusions regarding the findings. The final analysis only used data after March 8th because it included enough participants and the peak period window settings for the water heaters had not adjusted for daylight savings. Some attrition from devices disconnecting or participants opting out continued throughout this period. Figure 15 shows the cumulative enrollment of participants, as well as the net enrollment for each day as various participants joined and exited the program.

FIGURE 15: ENROLLMENT COUNTS



After the data from before daylight savings was removed, there were 42 remaining eligible participants. Of these, 33 participants were included in the final analysis. Participants were excluded for not having enough data or improper implementation of operations protocols. Since the analysis only used dates after daylight savings occurred, the effective peak period window used in the final analysis was from 5-10 PM. Additional details on the data cleaning and participant exclusion process are provided in Appendix A: Hybrid Heat Pump Water Heater Data Cleaning.

MODEL

The data was analyzed using a panel regression with fixed effects, time effects, and clustered standard errors. Separate models were implemented to estimate the change in daily energy use and the change in "pseudo" peak (5-10 pm) energy demand. The following model was used to estimate the impacts on daily energy usage:

$$Consumption_{i,t} = \beta_0 + \sum_{m=1}^{2} \beta_m * Mode_{m,i,t} + u_t + v_i + \varepsilon_{i,t}$$

Where the beta terms represent a regression coefficient, or array of coefficients, and:

- **Consumption$_{i,t}$** = the daily water heater usage for participant i on date t, measured in kWh
- **β_0** = The model intercept
- **Mode** = An indicator variable for the operating mode for participant i on day t, with three possible values: mode 0 = baseline (electric resistance), mode 1 = energy efficiency only, mode 2 = energy efficiency plus storage
- **U_t =** Time effects designed to capture unique effects of the date that are common across all sites
- **V_i =** Fixed customer effects designed to capture unique customer effects that are time invariant
- **$\varepsilon_{i,t}$ =** The error or residuals

The model specification for peak demand impacts was the same, except for the outcome variable:

$$Demand_{i,t} = \beta_0 + \sum_{m=1}^{2} \beta_1 * Mode_{m,i,t} + u_t + v_i + \varepsilon_{i,t}$$

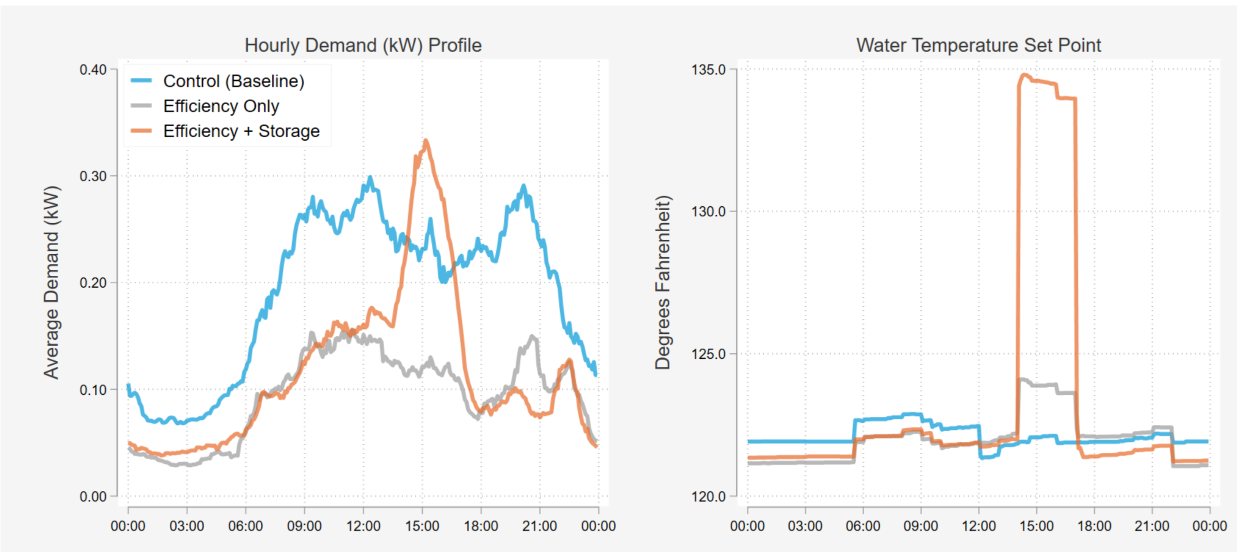
- **Demand$_{,i,t}$** = the peak period average demand for participant i on date t, measured in kW

RESULTS

The results of the analysis showed daily consumption and peak demand savings resulting from "efficiency" mode, which represents the replacement of the water heater with a more efficient, smart heat pump water heater. There were also incremental peak demand savings resulting from "efficiency plus storage" mode, where the new water heater operated in storage mode. Efficiency with storage mode operations had higher average daily use than efficiency only mode, however both efficiency modes show significantly lower average use relative to the electric resistance (control) mode.

Figure 16 shows the average demand and temperature settings for the 33 devices included in the final analysis. The left panel shows the hourly load shape and the right panel shows the temperature set points under each operating protocol. Without the storage option, electric water heaters have a distinct evening peak between 6 pm and 9 pm, coinciding with PG&E peak conditions (blue line). The largest change in energy use is due to the higher efficiency of the hybrid heat pump water heater. With storage, the temperature setting spikes in the 3 hours preceding the 5 to 10 p.m. peak period, indicating the storage protocol is implemented as planned. The effect of storage operations on energy demand can also be seen by comparing the hourly load profiles for efficiency only and efficiency plus storage. The efficiency plus storage shows a distinct increase in energy demand before the peak period - evidence of pre-heating – and lower energy demand during the peak period. As noted earlier, the pre-peak spike is large due to the fact that water heaters were not restricted to pre-heat with the high-efficiency heat pump only, due to manual error. Thus, the 2-5 pm energy use was higher than it would have been if the operating protocol had been implemented correctly.[6]

FIGURE 16: AVERAGE DEMAND AND WATER TEMPERATURE SET POINTS BY OPERATING MODE



The regression analysis shows that the energy and peak demand impacts of both efficiency only and efficiency-with-storage modes were statistically significant at the 95% confidence level. Figure 17 shows the estimated effect for efficiency-only and efficiency-with-storage operating protocols when compared to the baseline (control), as well as the 95% confidence interval. The baseline daily use (kWh) and peak demand (kW) are shown in blue, with the estimated impacts and confidence intervals for the efficiency only and efficiency with storage are shown in orange and gray, respectively. Because the operating mode was rotated weekly, rather than daily, we did not have enough iterations to estimate individual site results with precision.

[6] Appendix A visually shows the results for November 2, 2019 to March 7, 2020, when the pilot had fewer devices, but the correct peak hours were targeted, and pre-heating did not rely on the less efficiency electric resistance element. Although the sample is smaller, the spike in use in the pre-heating hours is noticeably smaller.

FIGURE 17: AVERAGE EFFECT SIZE BY OPERATING MODE AND SAVINGS PERIOD

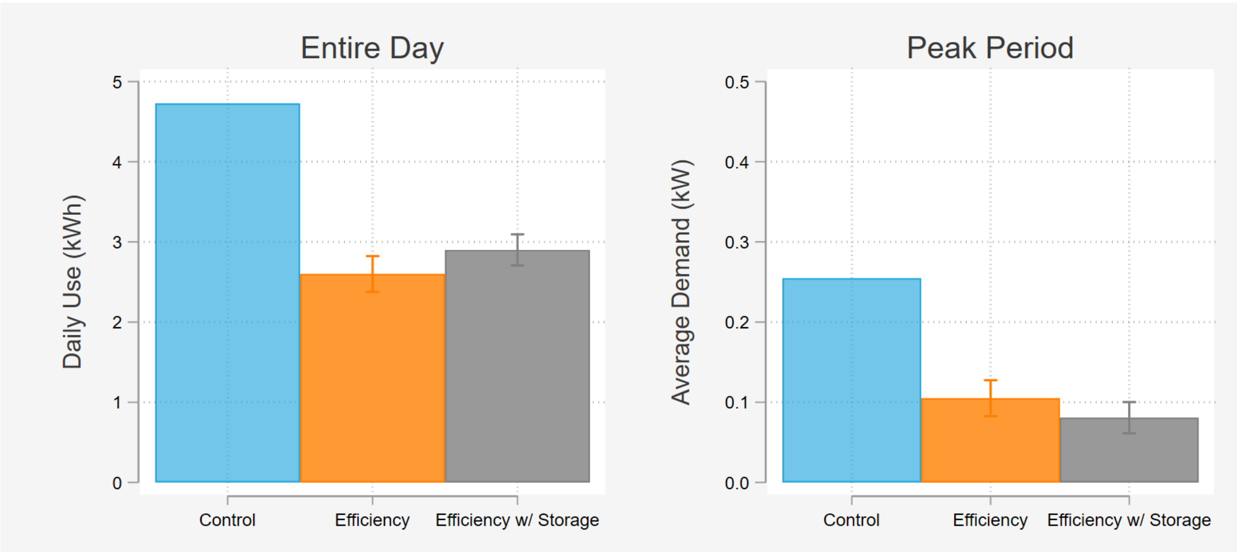


Table 4 shows the effect of each operating protocol on average daily energy usage. The evidence of a reduction in daily usage is conclusive. When placed in efficiency-only mode, the hybrid heat pump water heaters reduced daily energy use by 52.8% ± 4.9% (95% confidence), saving 2.59 kWh per day, or 947 kWh of annual savings. When placed in efficiency-with-storage mode, the hybrid heat pump water heaters reduced daily energy use by 44.5% ± 4.2% (95% confidence), saving 2.19 kWh per day or 798 kWh annually. The evidence of peak demand reduction is also conclusive. When placed in efficiency-only mode, the hybrid heat pump water heaters reduced peak demand (5-10 pm) by 58.8% ± 8.0% (95% confidence), or 0.15 kW on average. When placed in efficiency-with-storage mode, the hybrid heat pump water heaters reduced peak demand by 68.3% ± 6.2% (95% confidence), or 0.174 kW on average.

TABLE 4: SMART HYDRID WATER HEATER ENERGY AND DEMAND IMPACTS

Metric	Intervention	Baseline	Energy Use	Impact	Std. Error	t	% Impact
Avg. kW (4-9PM)	Efficiency	0.255	0.105	-0.150	0.011	-13.10	-58.8%
	Efficiency + Storage	0.255	0.081	-0.174	0.010	-17.49	-68.3%
Daily kWh	Efficiency	4.907	2.315	-2.592	0.122	-21.27	-52.8%
	Efficiency + Storage	4.907	2.721	-2.186	0.106	-20.64	-44.5%

CONCLUSION & RECOMMENDATIONS

There is strong evidence that both interventions led to reductions in peak demand. For the water heater replacement intervention, the higher efficiency of hybrid heat pump water heaters also led to reductions in overall energy use. Table 5 summarizes the key findings for the water heater control devices, while Table 6 highlights the key findings on each of the four main research questions for the water heater replacement intervention.

TABLE 5: KEY FINDINGS SUMMARY – SMART DEVICES

Research Question	Findings
Did the technology work?	Yes. The technology enabled heat pump water heaters to control water heater operations and recorded granular information about water heater energy use, temperature setting, operation modes. The process for dispatching and monitoring electric water heaters control was fully automated, and allowed testing of multiple algorithms. The algorithms clearly reduced peak demand over all five hours in the 4-9 pm window while avoiding increases in total daily energy use. The effect of the impacts was consistently observable for nearly all devices.
What are the peak demand reductions resulting from the installation of smart water heater control devices?	When operating under Algorithm A, the control devices reduced peak demand by 62% ± 21% (95% confidence), saving 0.15 kW ±0.05 (95% confidence) on average. When operating under Algorithm B, the control devices reduced peak demand by 68% ± 20% (95% confidence), saving 0.17 kW ±0.05 on average.
Does overall energy use change due to using water heaters for storage and load shifting?	While the timing of energy use changed, there the storage and shifting operation did not lead to a increase in energy use. The results are nuanced because the treatment effect lingers. On baseline days, between 12 am and 9 am, the water heaters benefit from storage – in the form of higher tank temperatures – from the prior day when a storage algorithm was in place.

	For Algorithm A, the control devices increased overall usage by 8.0% ± 9.0% (95% confidence), and under Algorithm B, the control devices increase overall energy use by 6.2% ± 6.9% (95% confidence). Neither change in energy use was statistically significant. However, there is a noteciable spike in water heating activity immediately before and after the peak period.
How well do the algorithms perform?	Both algorithms resulted in statistically significant peak demand savings overall and at the customer level. Algorithm B delivered slightly more peak demand savings overall, more consistent reduction for individual sites.

TABLE 6: KEY FINDINGS SUMMARY – SMART HYBRYID HEAT PUMP WATER HEATERS

Research Question	Findings
Did the technology work?	Partially. The technology provides the ability to schedule how heat pump water heaters operate. They also provide granular information about water heater energy use, temperature setting, operation modes, and use of the heat pump versus the electric resistance element. The process for automating the dispatch of water heaters was not fully automated and required manual scheduling, which generated implementation challenges. While the devices can be managed, the algorithms to manage the devices need additional refinement to deliver larger peak demand reductions and avoid increases in energy use.
What are the energy savings resulting from the installation of hybrid heat pump water heaters?	When placed in efficiency-only mode, the hybrid heat pump water heaters reduced daily energy use by 53% ± 4.7% (95% confidence), saving 2.59 kWh per day, or 947 kWh of annual savings. When placed in efficiency-plus-storage mode, the hybrid heat pump water heaters reduced daily energy use by 45% ± 4.8% (95% confidence), saving 2.19 kWh per day or 798 kWh annually.

	The effiency-plus-storage mode led to higher energy use than the effiency only mode, although that was largely due to poor implementation of the control algorithm. Further refinement of the dispatch algorithms and better implementation is likely to deliver the peak demand reductions without increases in energy use.
What are the peak demand reductions resulting from the installation of hybrid heat pump water heaters?	When placed in efficiency-only mode, the hybrid heat pump water heaters reduced peak demand (5-10 pm) by 59% ± 8.8% (95% confidence), or 0.150 kW on average. When placed in efficiency-plus-storage mode, the hybrid heat pump water heaters reduced peak demand by 68% ± 7.7% (95% confidence), or 0.174 kW on average.
Do storage operations lead to incremental peak demand reduction?	Storage operations did lead to statistically significant incremental peak demand reduction. Storage operations resulted in an average 0.02 kW in additional peak demand savings compared to efficiency only operations. While the impact of storage is statistically significant, it is small in comparison to the peak demand reduction to the effiency of the smart hybrid heat pump water heater.

The beta test also yielded several findings and recommendations for next steps before program implementation. Table 7 summarizes these general recommendations for both intervention bundles

TABLE 7: RECOMMENDATIONS SUMMARY

Recommendation	Explanations
Further refine the smart hybrid heat pump water heater algorithm	The smart hybrid heat pump water heater requires further refinement and automation. Because of manual updating of operating protocols, the testing of algorithms was limited, and the algorithms that were tested were not fully implemented as designed. We recommend several additional test of multiple operation algorithms to identify ones that more

	successfully shifts loads while limiting increase in energy use.
Conduct early, automated assessments of proper storage operations through smart water heaters	During the initial beta test phase, several (but not all) operating issues were identified and resolved, including failure to adjust the settings to reflect daylight savings time, lack of connectivity for specific sites, and improper implementation of storage operations. Although most of these issues were been resolved after the interim analysis, operational issues arose again as more participants were enrolled, including the failure to adjust for daylight savings. Successful program implementation will require consistent and reliable operations.
Conduct research on how to improve smart water heater connectivity rates	Because storage operations rely on communications via the Wi-Fi enabled device, replacement of the router, resetting of passwords, and customer move-outs, influence the ability to continue operations. The issue is common to other connected devices. However, without pro-active tracking and management of connectivity, the ability to operate the devices remotely decays. Understanding the decay rate is essential for estimating the incremental benefit and cost-effectiveness of storage operations. However, it does not influence the peak demand reductions and energy savings due to the more efficient hybrid HPWH.
Incentivize high penetration of smart hybrid heat pump water heaters to drive down costs	As noted in the study, if California is to meet decarbonization targets, electric water heating will need to shift from natural gas to electricity as a fuel source. Lowering the cost of heat pump waters via mid-stream incentives helps achieve the goal. With high penetration of renewables, California needs the additional load flexibility that built-in smart controllers provide.
Increase the pool of distributors with training to install heat	Roughly 85% of water heaters in PG&E territory rely on natural gas, and the remaining water heaters are

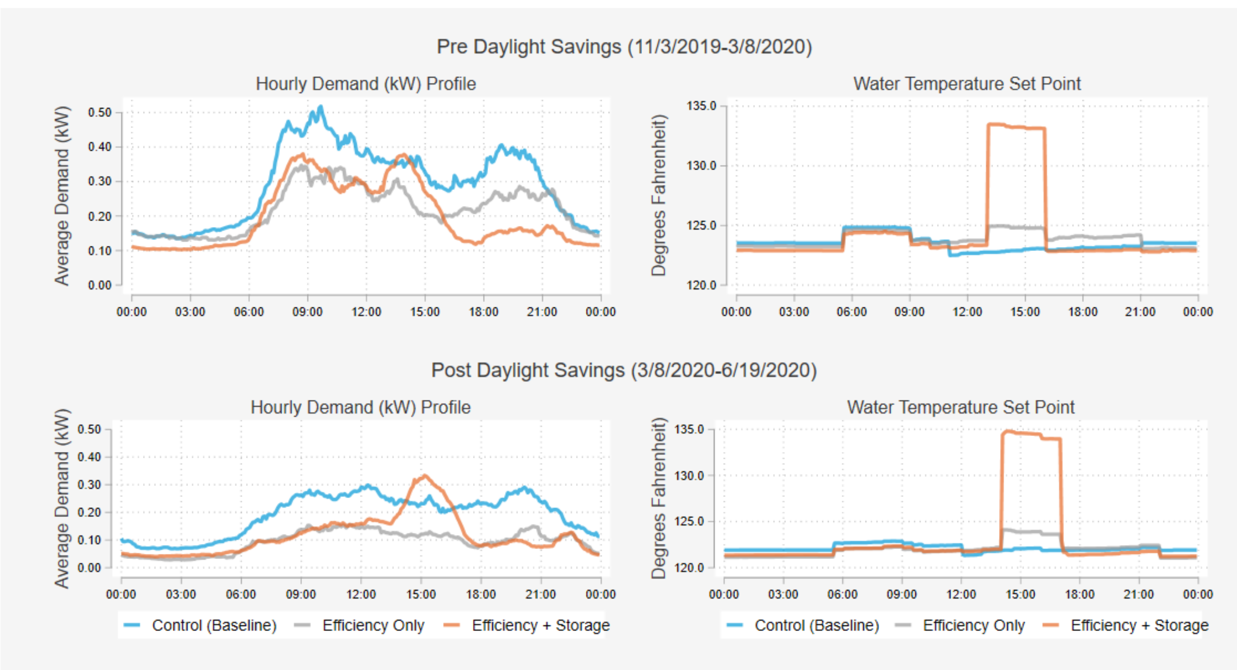
pump water heater and water heater smart controller in PG&E territory	almost exclusively electric resistance water heaters. To successfully expand, training for installers is needed.
Test the impact of incentive levels and distribution channels on uptake	Understanding the relationship between incentive levels, distribution channels (mid-stream vs. partner channels), and uptake is critical to the success of the program. In specific, we recommend implementing pricing trials smart hybrid heat pump water heaters via mid-stream channels, as has been done successfully in the Northeast. The approach requires changing the magnitude of incentives, thus lowering the customer facing price at retail and wholesale outlets in order to quantify the degree to which incentives affect uptake.
Consider fast-response applications of water heater flexible loads	The study focused on one application of water heater thermal storage – the ability to shift loads daily in response to TOU rates. In practice, water heaters can deliver fast-response grid services (i.e., frequency regulation, operating reserves, load following) that are needed.

APPENDIX A: HYBRID HEAT PUMP WATER HEATER DATA CLEANING

In the final phase of the heat pump water heater replacement evaluation, 46 participants were enrolled, but only 33 were included in the analysis. Nine of the enrolled participants were excluded for not having data within the evaluation date range or for not following operations protocols. This appendix provides additional detail on the issues that resulted in the exclusions.

In implementating the evaluation, DSA discovered that the peak period window settings for the water heaters had not adjusted for daylight savings. Although the intended peak period window was 4-9 PM, with a pre-peak window from 2-4 PM, the effective peak window after daylight savings (3/8/2020) was from 5-10 PM, with pre-peak from 3-5 PM. Figure 16 shows the daily loads and temperature settings by mode before and after daylight savings for the same subset of 16 participants. After daylight savings, the pre-heating period shifts back an hour, indicating that the temperature set point settings did not adjust with daylight savings.

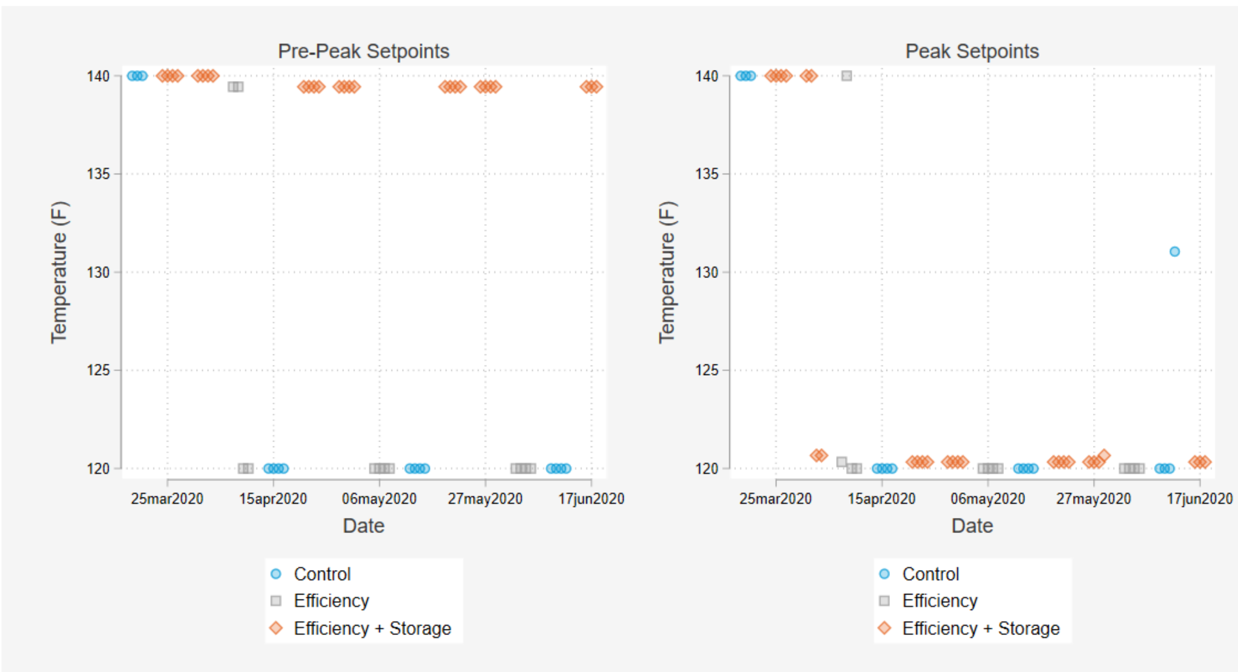
FIGURE 18: AVERAGE DAILY USAGE BEFORE AND AFTER DAYLIGHT SAVINGS



To mitigate this issue, the analysis was only conducted on data from after daylight savings occurred. As a result, three enrolled accounts were dropped from the final analysis.

The remaining nine customers who were removed from the final analysis did not follow operations protocols. There were several checks conducted to identify which customers adhered to the rules of the beta test evaluation framework, including daily and peak load patterns, pre-peak temperature setpoints, and peak temperature setpoints. In the initial investigation, DSA found that most of the issues occurred in the first few weeks of a customer's participation in the program, regardless of their enrollment date. This suggests that there is an "adjustment period" for operations protocols to be implemented. Figure 19shows the pre-peak and peak temperature setpoints for one of these customers, as an example. This customer's temperature was set at 140 F consistently for the first 10 days, and then adjusted to follow the mandated temperature settings.

FIGURE 19: EXAMPLE OF PRE-PEAK AND PEAK TEMPERATURE SETTINGS ISSUES



To account for this "adjustment period", the first two weeks of data for each customer were dropped. This drop removed one customer who had less than 2 weeks of data, leaving 42 customers eligible for the analysis.

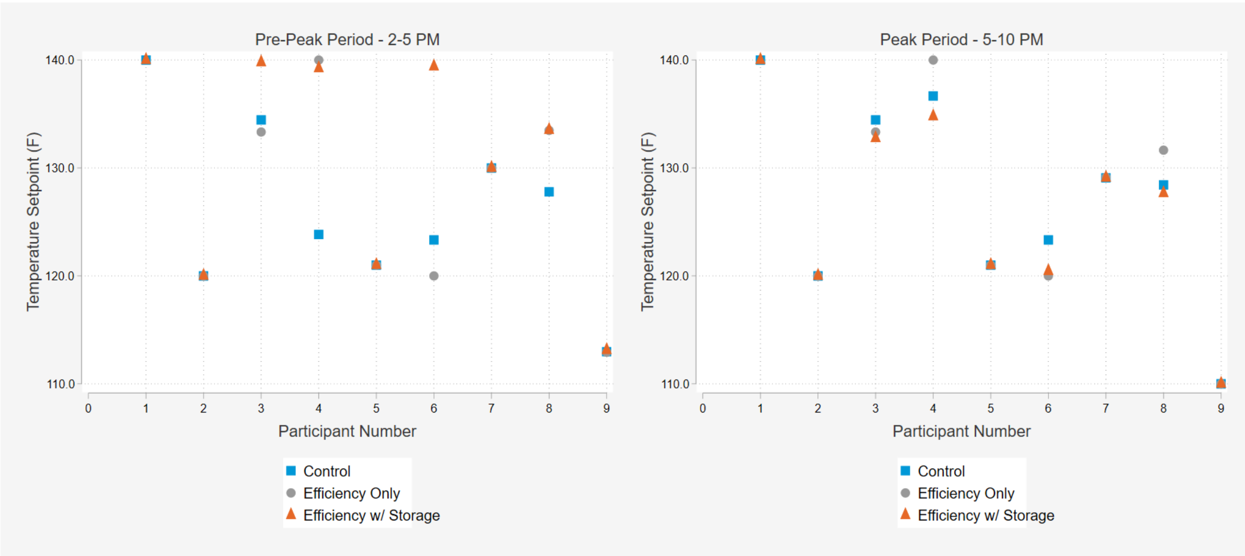
The final step of the investigation was to identify customers who consistently did not follow operations protocols, even after their adjustment period. Customers were flagged if their temperature settings deviated significantly from the target temperatures for each mode or if they had less than 3 weeks of data. Table 8 shows the criteria for each issue and how many customers were flagged under each.

TABLE 8: ISSUE FLAGS

Issue	Issue Criteria	Customers Flagged
Pre-Peak Temperatures	Pre peak temperatures signficantly deviated from target mode temperature	7
Peak Temperatures	Peak temperatures signficantly deviated from target mode temperature	6
Not Enough Data	Less than 3 weeks of data available	2
TOTAL SITES EXCLUDED		**9**

Temperature settings were the primary indicators that a customer was not following the operations protocols. Figure 20 shows the average pre-peak and peak temperature settings by mode for excluded participants. According to the operations protocols, the temperature during the pre-peak window from 2-5 PM should have been set at 120 F for both control and efficiency-only modes and set at 140 F for efficiency-with-storage mode. These deviations could have a significant impact on the model results.

FIGURE 20: TEMPERATURE SETPOINTS FOR EXCLUDED ACCOUNTS



Customers were excluded if they met the criteria of any three of the issues flags, and as a result, nine customers were excluded from the final analysis.

Although the final exclusion rules were designed to keep as many customers in the analysis as possible, the investigation identified another operational issue in the beta test. One important aspect of the beta test program design was for the water heaters to function in heat pump mode only when pre-heating the water in the storage mode. However, large spikes in energy usage in the pre-peak period during the efficiency-with-storage mode indicated that the water heaters may have been using electric resistance heating during this window. Further investigation revealed that this was the case. Of the 42 customers available for the final analysis, only ten customers did not use electric resistance heating at all during the pre-peak window under efficiency-with-storage mode. In general, it appears that customers began the pre-peak mode in resistance and then switched to heat pump mode, however, a handful of customers did use resistance heating significantly throughout this period.