Grid-interactive Load Flexibility Control of Multifamily Heat Pump Water Heater Systems

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ABSTRACT

Achieving grid-interactive load controls is critical to the success of building electrification for significantly reducing greenhouse gas (GHG) emissions and energy use during peak grid conditions. This study presents a comprehensive analysis of 2022-2024 data from the first field demonstration of load flexibility controls for central heat pump water heater (HPWH) systems in response to time-varying electricity price signals obtained from Lawrance Berkeley National Laboratory's CalFlexHub. The project team uses an advanced system integration and control solution, the LOCUS (Load Optimization Control Using Storage) technology, to achieve this goal. The LOCUS technology enables plug-and-play integration of HPWH and storage equipment and intelligent controls of system operation to optimize performance according to electricity rates and hot water demand.

Three California multifamily sites serving low-income communities were included in this study of the LOCUS technology. This These HPWH systems at the three multifamily sites represent diverse central HPWH system designs, which provides an opportunity to investigate how system performance is affected by key design parameters such as HPWH type, heating capacity, storage size, and recirculation controls, which will inform future HPWH system design practices. One site, in Santa Rosa, CA, is covered in detail in this paper after approximately one year of post-retrofit data collection. This year of field testing shows that LOCUS technology enables HPWH systems to avoid energy use during high-price periods and reduce operational costs by up to 75% without impacting hot water delivery.

Introduction

Rapid changes in the grid supply and demand characteristics have caused the wholesale price and carbon intensity of electricity in California to vary substantially throughout the day and year (CAISO 2023). This price variation will continue to increase over time as more solar and other renewables enter the grid and appliances become electrified. In general, electricity production costs are currently substantially cheaper during the middle of the day when solar production is highest, and most expensive during the evening peak when production falls and demand increases. This additional strain on the grid encourages demand-side strategies to smooth out demand if we are to meet climate goals set by the state (Lawrence Berkeley National Laboratory 2020).[1]

One of the technologies increasing grid load is the rapid addition of heat pump water heaters (HPWHs). Unlike electric space heating, which primarily increases winter grid load, HPWHs also add summer grid load and hot water demand schedules align closely with morning

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[1] SB 100 was passed in September of 2018, which sets a goal of phasing out all fossil fuels from the state's electricity sector by 2045.

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and evening grid peaks (Murphy, et al. 2021). This presents an opportunity to utilize thermal load shifting technologies to shift hot water production to off-peak hours as a means of reducing expensive and carbon-intensive electricity production to meet this added demand (Delforge P., Vukovich J. 2018). Previous studies (Brooks, et al. 2021; Advanced Water Heating Initiative 2024) have demonstrated the potential benefit for HPWH load shifting and challenges associated with existing technologies.

Project Background

This research project (EPC-20-004), conducted under the California Energy Commission's (CEC) Electric Program Investment Charge (EPIC) program,[2] aims to test and demonstrate an advanced HPWH load control system that does the following:

1. **Responds** to hourly or sub-hourly price and demand response signals to minimize cost and grid impacts,
2. **Optimizes** energy use based on building owner/occupant preferences, and
3. **Provides** reliable and cost-effective load flexibility as a grid resource.

Under the grant EPC-20-004, the thermal load-shifting technology developed by ZYD Energy known as Load Optimization Control Using Storage (LOCUS) has been tested in the field at three different sites and evaluated by the California Energy Commission EPIC grant team.[3] This project began in early 2021 and is slated for completion by early 2025.

LOCUS Technology Overview

This project uses LOCUS technology developed by ZYD Energy to retrofit central HPWH systems and demonstrate load flexibility controls. The core of the LOCUS technology is a flow router which uses strategically arranged pipes, electric valves, and circulation pumps to establish versatile and dynamic flow paths between water heaters and storage tanks. The flow router is coupled with an advanced controller, which controls the electric valves and circulation pumps in the flow router. Using intelligent algorithms, the controller aims to optimize overall system performance according to hot water demand forecast and grid control signals. With LOCUS technology, integration of water heaters and storage tanks is achieved by simply connecting each piece of equipment directly to the flow router. A system-level control coordinates water heating operation and storage tank utilization to manage electric load and improve system efficiency. (see Fig. 1).

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[2] This program is designed to fund and invest in scientific and technological research to accelerate the transformation of the electricity sector to meet the state's energy and climate goals.

[3] The team consists of individuals noted as co-authors in this paper.

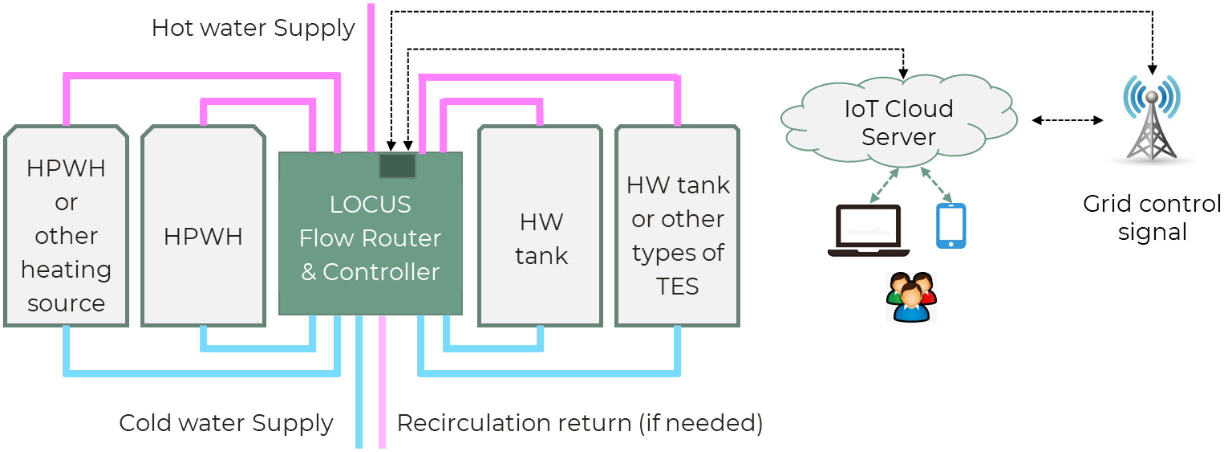

Figure 1. A simplified diagram of the grid-connected LOCUS flow router and controller.

LOCUS system-level control is achieved by managing system operation using a sequence of operational modes, each of which defines a specific way to use water heaters and storage tanks in the system. By creating multiple operational modes, LOCUS technology makes the system operation adjustable for flexible load controls. The sequence of operational modes is determined by optimization algorithms according to site-specific hot water demand forecast and electricity price and/or carbon intensity (depending on the optimization goal), which are real-time inputs to the system. Algorithm inputs also include other variables like heating capacity, storage volume, cold water supply temperature, etc., and an array of sensors is used to assess real-time operational status and adjust operation mode sequence accordingly. Because LOCUS system-level control is based on flow management without imposing any requirements on the HPWH's internal controls, LOCUS control is potentially applicable to all HPWHs systems. LOCUS optimization algorithms use high-level system configuration parameters, such as total heat pump heating capacity, total electric resistance heating capacity, and total storage capacity, to create optimal heating schedules specific to each system. To further optimize system operation, LOCUS technology implements flow management procedures based on the HPWH's performance characteristics. For example, for hybrid HPWHs, water flows for charging storage are adjusted to either avoid or trigger electric resistance heating according to the optimal heating schedule.

A simplified schematic of the different operational modes is shown in Fig. 2. While there are numerous possible operational modes depending on the configuration and complexity of the HPWH system, the primary function of the LOCUS is to charge and discharge storage tanks with regards to price optimality. For instance, this could mean midday peak charging when solar production in the grid is high and electricity is cheap and clean, and discharging while avoiding water heater operation during evening peak times when dirtier, more expensive, electricity is present. Note also that the LOCUS can be easily fully separated from the main system and operate in "bypass" mode. In this way, the system is not affected by LOCUS equipment failures, maintenance, or changes made to the algorithm requiring the system to be temporarily taken offline.

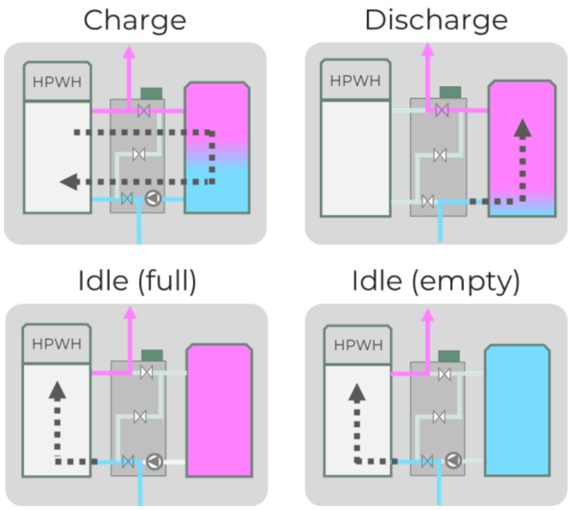

Figure: 2. A simplified diagram showing charge and discharge modes for a basic LOCUS-controlled system.

Description of Project Sites

Three separate all-electric multi-family developments in California (hereafter referred to by their location: Gilroy, Eureka, and Santa Rosa) were chosen for retrofits under this project. All three are diverse in their HPWH configuration and therefore provide an opportunity to study the LOCUS technology under a wide range of conditions (see Table 1).

Table 1. Summary of buildings used in study.

Site	Monterey Gateway	Bayview Heights	Santa Rosa Veterans Housing
Location	Gilroy, CA	Eureka, CA	Santa Rosa, CA
Owner	Danco Communities	Danco Communities	Community Housing of Santa Rosa
CA CZ	4	1	2
Year Built	2019	2019	2019
Number of Stories	4	3	1
Number of Units	60 1BR, 15 2BR	50 Studio	14 tiny homes
Number of Occupants	83	50	14
Resident Type	Very low-income seniors, half special needs seniors	Formerly homeless, formerly homeless veterans	Formerly homeless senior veterans
Baseline DHW System	One central Colmac with recirculation	12 distributed Rheem HPWH systems, each serving 3-6 dwelling units, with recirculation	Two Sanden SanCO2 HPWH systems, each serving 7 tiny homes, no recirculation

Site	Monterey Gateway	Bayview Heights	Santa Rosa Veterans Housing
Baseline Hot Water Storage Tank(s) Volume (Gallons)	415	145	83
Compressor Heating Capacity (kBTUh)	276.7	4.2	15.4
Resistance Element Heating Capacity (kW)	27	3.8	N/A
Spec Sheet Compressor COP	4.0	3.7	3.84
Hot Water Distribution	Continuous recirculation	Recirculation controlled by aquastat	Trunk and branch with no recirculation
System Location	HPWHs on roof, tank and electric resistance water heater are in mechanical room	Inside a mechanical room, vented to and from interior lounges	Outside

Building characteristics for the three sites chosen for the study.

Study Design and Timeline

The goal of this study is to demonstrate load flexibility and commenced as follows:

1. Prior to the retrofit, each site in this study was instrumented extensively to measure temperature, flow, and power. A baseline period of at least a year was established for each site, and data was collected and evaluated.
2. Each HPWH system was retrofitted, where additional storage was added, and the LOCUS control module and flow routers were installed.
3. A year of LOCUS control optimization testing took place, where various CalFlexHub price signals were tested and the performance of the load shifting was evaluated.

Site Baseline Characteristics

Baseline data was collected at Santa Rosa for a year prior to retrofit from March 2022 until May 2023. This baseline data was used both a) to evaluate the performance of the LOCUS system, b) determine the necessary additional storage for retrofit, and c) as baseline data for training the LOCUS demand pattern algorithms and optimization.

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There is no recirculation at Santa Rosa, so makeup water temperatures reflect municipal water supply temperatures (peaking at 80°F from June-September and 60°F from Dec-March). This represents a 35% increase in water heating demand per gallon of makeup water from winter to summer. The units are located outside; average daily temperatures vary from 35°F to 94°F throughout the year and instantaneous temperatures range from as low as 8°F to as high as 112°F. This impacts both seasonal thermal losses and vapor cycle COPs throughout the year. However, compared to many other types of HPWHs, the SanCO2 systems provide more stable operating COPs for a wide range of temperatures and can operate at 4.5kW of heat capacity without a decrease in heat output down to 4°F. Field data from this study supports this rating; average output heat capacity over the baseline period was measured at 4.4kW for both east and west systems. Vapor compression cycle COPs[4] average 4.0 (east) and 4.1 (west) and show only a 6% decrease from summer to winter as lower air temperatures are offset to some degree by greater heat exchanger effectiveness resulting from colder incoming water temperatures. Total system efficiency averages 3.5 (east) and 3.6 (west) and represents an average of 12.5% thermal losses. This varies from day to day driven primarily by the amount of hot water demand; greater hot water demand results in lower thermal losses as a fraction of the total. Average daily electricity usage is 10.7kWh (east) and 5.7 kWh (west).

Increased seasonal demand due to colder incoming water temperatures (i.e., variable seasonal mixing at the tap to achieve a desired water temperatures) is likely present but daily behavioral variance is far greater than any measured seasonal variation in hot water demand (either in gallons or BTU). Despite being physically identical and having the same number of occupants, each side (east and west) of the Santa Rosa site has unique hot water demand characteristics in terms of both magnitude and time of use. Fig. 3 shows daily hot water demand and average demand profiles over the year-long baseline period. Average demand for each system is 178 gallons per day (GPD) and 102 GPD (east and west, respectively) and both systems are dual-peaking (morning and evening) with peak hot water demand occurring at approximately 8:00AM and 6:00PM.

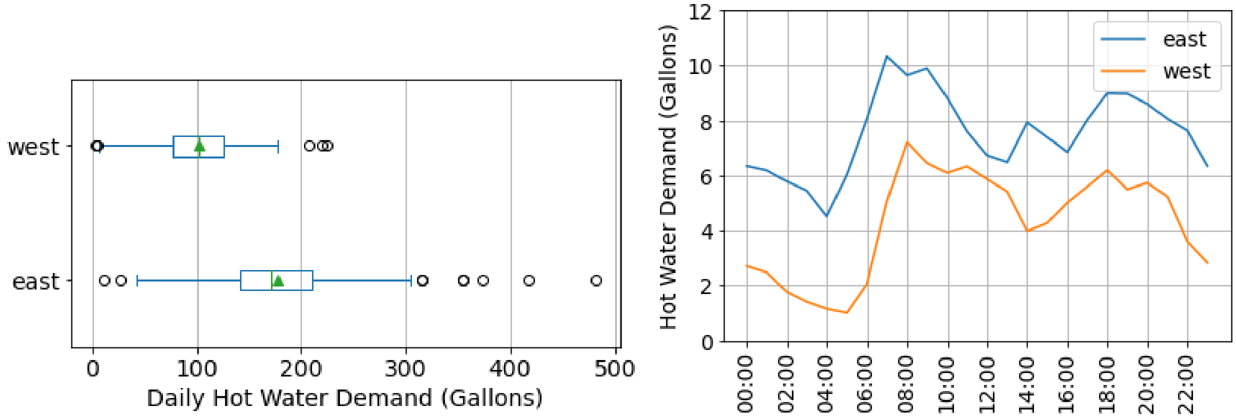

Figure 3. Average gallons of hot water demand per day over the baseline period for east and west systems (left) and average hot water demand profiles (right).

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[4] Referenced from COP curves, excludes thermal losses.

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Daily hot water demand is quite normally distributed, though high-flow events are certainly present particularly at the higher-demanding east system with a max flow of 481 GPD. Each system at Santa Rosa services seven single-occupant units and the variance from day to day (%RSD = 37% and 35% east and west, respectively) is less than typical unitary systems but far greater than much larger central systems such as the larger Gilroy site described in the previous section of this paper.

Demand relative to the heating capacity (approximately 4.5kW) of the system is somewhat low; the system can supply a continuous 15.4kBTU per hour. Hourly demand during the baseline period exceeds this 15kBTU amount only 8% (east) and 3% (west) of the time. For reference, this represents approximately 20 gallons of makeup water (varies with environmental temperatures) and represents only 25% of the pre-retrofit storage tank volume. This adequacy of hot water delivery is confirmed both qualitatively and quantitatively. Surveys from residents suggest that hot water delivery is sufficient and less than 0.1% of hot water demand was not met at both systems during the entire baseline period based on measured temperatures. This results in a well-performing system with ample opportunity for load shifting. Finally, since recirculation is not present, it is not a variable load to consider and does not create potential tank stratification issues that would otherwise impact the ability of the system to either adequately estimate hot water demand or deliver hot water.

CalFlexHub Price Schedules

As previously noted, the LOCUS controller requires a signal to optimize against (i.e., electricity price). The signals chosen to evaluate the LOCUS for this study are price schedules developed by Lawrence Berkeley National Lab's (LBL) California Load Flexibility Research and Development Hub (CalFlexHub or CFH)[5]. Fig. 4 shows the price signals tested in this study, which represent a variety of typical seasonal price schedules. Actual utility rate schedules were not used as price schedules in this study but were closely monitored to ensure that water heating costs did not increase.

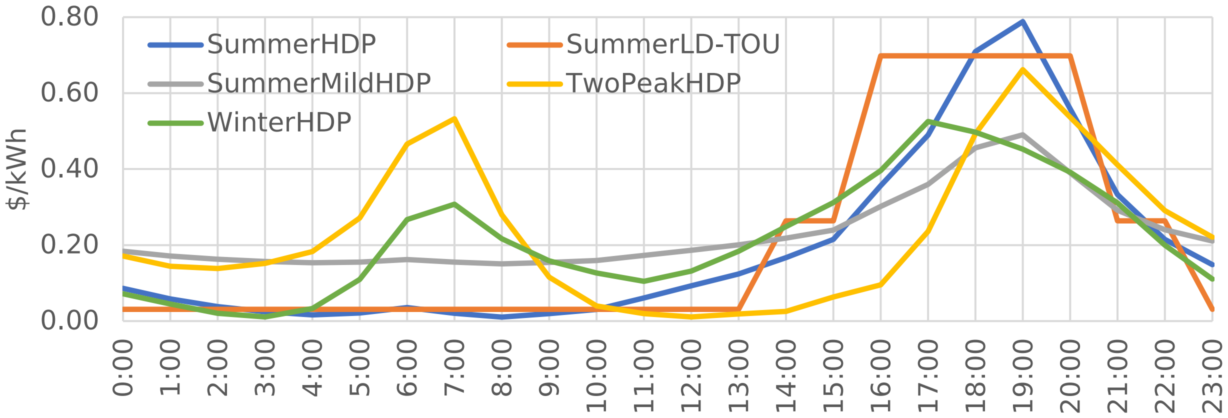

Figure 4. CalFlexHub rates chosen for this study in $/kWh which vary hourly.

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[5] The California Load Flexibility Research and Development Hub (CalFlexHub) is the innovation hub supporting the scaled adoption of affordable, equitable, and reliable load flexible technologies. CalFlexHub seeks to advance the capability of smart building technologies to provide flexible energy load for the State of California and beyond (LBNL 2024).

Site Retrofit

The retrofit was undertaken in May 2023 with minimal impact to residents and included adding the LOCUS control manifold and an additional 80-gallon storage tank to increase thermal storage capacity from 83 gallons to 163 gallons. This secondary tank size was chosen based on Ecotope's Ecosizer tool (Ecotope 2020) and custom load shapes from baseline data collection. After retrofit, a period of three weeks allowed the system to function without explicit LOCUS control based on optimization to evaluate performance and identify any potential issues that may need correcting prior to thermal load shifting experimentation.

Figure 5. A photo of one of the LOCUS retrofits at Santa Rosa (left) and a close-up of the internal manifold of the LOCUS (right). The tank on the right side of the photo is the primary storage tank, and the tank on the left side is the added storage. Note that this photo was taken before pipes were insulated.

Testing and Analysis

After retrofitting each site with LOCUS controllers and added storage, each of the CalFlexHub price schedules were applied during a test period of 3-8 weeks each over the next year with performance monitoring. The algorithm was allowed to optimize against a given schedule over the course of the study period and normalized costs were calculated to compare to baseline performance. Water flows, electric energy/power, system temperatures, and vapor cycle and total system COPs were closely monitored on a weekly basis to identify problems and learn from system performance. Results were evaluated on an ongoing basis, and while several metrics were considered, the primary metric used to evaluate demand-normalized costs ($/kBTU).[6]

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[6] $/kBTU is defined where $ is the total cost during the period of evaluation based on the CalFlexHub price schedule that was being optimized against, and kBTU are calculated hot water demand based on cold water makeup and hot water delivery temperatures. By normalizing costs per unit of energy demanded hot water users, seasonal and behavioral variation is compared on a level basis.

Study Results

As of the publication of this paper, some tests are still being completed and complete analysis for all tests at all sites will be included in the final project deliverables in 2025. The following results are specific to post-retrofit testing done over a year period at Santa Rosa, which show success in reducing costs without impacting hot water delivery or otherwise negatively impacting residents. At a high level, the efficacy of the LOCUS' ability to shift load is affected by the following factors:[7]

Heating capacity of compressor: The recovery rate of the compressor relative to demand is an important variable not only in baseline operation but perhaps even more important for shifting load. This is particularly important in hybrid systems where avoiding resistance backup is crucial to reducing demand. How rapidly and inexpensively the LOCUS system can react to changes in hot water demand or grid price signals is dictated primarily by the capacity of the compressor to meet that demand. As noted in the site baseline characteristics section of this paper, the heating capacity of the Sanden system is sufficient for this purpose.

Seasonal variation: Colder incoming water temperatures and cooler ambient air temperatures affect system performance negatively. While this is noted to be less true for systems like the Sanden SanCO2 systems in this study, where the vapor compression cycle COP curve is more stable over wide range of temperatures, winter temperatures do still increase demand (greater mixing of hot water at the tap, higher dT for the HPWH, and greater thermal losses). Decreases in performance and increases in demand in the winter make it more challenging to effectively shift load. This was previously noted to be of minor impact during the baseline period and was not seen to be a primary challenge at Santa Rosa post-retrofit despite the outdoor location of the system.

Hot water demand variance: Success of daily load shifting depends on the LOCUS controller's ability to predict hot water demand. Outlier days, particularly those with large unforeseen peak demands, can provide performance challenges. That said, in many cases the benefits of additional storage added in the retrofit helped smooth out these large demands more than would have been present under baseline conditions. This challenge is most present in smaller systems with fewer occupants, where one person's hot water consumption has a greater impact on the system whole. At Santa Rosa this was noted to occasionally be a problem when apparent coincident demand aligns with peak hours or just preceding peak hours. Some examples are discussed in detail in the "Load Flexibility Scenarios" of this document. Day-to-day variance in hot water demand was noted to be a much larger challenge than seasonal fluctuations for the LOCUS system, and in particular, large flow events preceding or during high-price periods proved to be challenging to react to or anticipate. Some examples of this are discussed in the "Load Flexibility Scenarios" section of this document.

Rate schedule characteristics: Dual-peak (morning and evening) rate schedules like those commonly present in winter further compound the seasonal variation noted above. Shorter windows of time within which to shift load exacerbate winter (and to a lesser extent shoulder) season challenges of greater demand and lowered HPWH performance.

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[7] Many of these factors impacting load shifting are not specific to the LOCUS system but are present in MF central HPWH systems and worth mentioning as they are greatly impactful to the results of this study.

Recirculation servicing: The presence of recirculation and how well/often it operates induces performance challenges (additional hot water load) and load-shifting complications (recirculation tends to destratify tanks making hot water transfer by the LOCUS a challenge). This challenge is not present at Santa Rosa.

Table 3 shows aggregate results from two key tests: a summer price schedule (SummerLD-TOU) and a dual-peak winter-like profile (WinterHDP). In both testing periods storage proved adequate particularly on the west side where hot water demand is lower. Worth noting is that hot water delivery temperatures improved under both tests compared to baseline due to greater storage, though even under baseline conditions hot water delivery temperatures were already sufficient >99.8% of the time. The actual cost of electricity to residents was not impacted by testing.[8]

Table 3. Summary of testing results at Santa Rosa

	Baseline		SummerLD-TOU		WinterHDP	
System	East	West	East	West	East	West
Time Period	3/20/22 - 5/18/23		10/4/23 - 10/31/23		1/16/24 – 3/22/24	
Daily Avg HW Demand (Gal)	175.8	100.8	162.5	67.2	135.8	116.0
Daily Avg HW Demand (BTU)	122,275	64,468	99,059	38,771	94,334	68,155
Average Ambient Air Temp. (°F)	53.8	53.6	64.6	64.2	52.2	53.9
Avg HPWH Makeup Temp. (°F)	67.3	62.1	70.7	70.1	56.6	60.7
Estimated Vapor Cycle COP	4.0	4.1	4.4	4.2	3.9	3.9
Daily HPWH Energy (kWh)	10.7	5.7	7.6	3.5	8.3	6.7
Total System Efficiency	3.5	3.6	3.9	3.4	3.5	3.4
Reduction in CFH Costs ($/kBTU normalized)	-	-	71.2%	75.0%	37.0%	64.2%
Hot Water Demand Not Met (%)	0.18%	0.11%	0.00%	0.05%	0.09%	0.08%

Summary results from two tests performed at Santa Rosa with baseline for comparison. Vapor cycle COP is estimated from COP curves and measured temperatures during operation of the compressor. Cost reductions are normalized to hot water demand (kBTU). Hot water demand not met is determined as the percentage of flows below 110°F.

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[8] We did not optimize around utility rate schedules, but relative congruence with the CalFlexHub rates we *were* optimizing for ensured that residents did not incur additional costs as a result of these interventions.

Summer Results (SummerLD-TOU)

All tested variations of summer price schedules showed improvement compared to baseline even for days with large hot water demands. This is primarily due to the long period of time in the morning/early afternoon available for charging, and the ample storage (163 gallons) available to the LOCUS. Fig. 6 shows the average HPWH power under baseline conditions and during optimization for rate SummerLD-TOU for both systems over the course of four weeks of testing. Note the early charging midday, which dropped to almost nothing during the entirety of the highest peak rate. The LOCUS system, rather than charging right away at midnight, waited until later in the morning, when rates are still low, to charge. This minimizes thermal loss but still achieves optimal charge/discharge operational patterns and is an improvement from earlier rounds of testing against this price schedule.

Due to ample storage and high heat pump heating capacity, compressor usage was avoided altogether during the most expensive time period (4-9PM) during 75% (west) and 77% (east) of days. The days where compressor usage was necessary during the peak hours have little correlation with total demand, but are largely a function of large, unexpected peak or just-prior-to-peak hot water demand events that were not predicted by the LOCUS. Some examples of this are shown in the "Load Flexibility Scenarios" of this document. Total reductions in cost compared to a baseline counterfactual are 71% (west) and 75% (east) over the entirety of this testing period. An upper limit for optimization under this price schedule is 85% based on baseline demand profiles at Santa Rosa, which would represent no heat pump operation between the hours of 2PM-10PM.

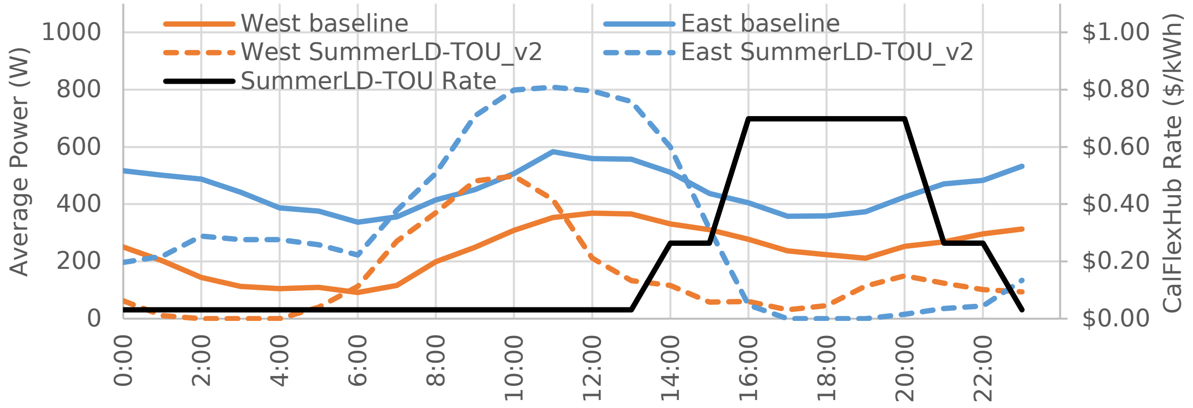

Figure 6. Average HPWH demand for both systems under baseline and optimized summer rate test conditions. Testing occurred for four weeks in October 2023 and is a second iteration of testing against this price signal.

Winter Results (SummerLD-TOU)

The winter schedule tested was more challenging to optimize due to the morning peak. This leaves less time for the LOCUS to charge secondary storage or recover in the middle of the day if large demands are experienced or anticipated by the LOCUS. The east system, which has 38% greater daily and peak hot water demand on average compared to the west system during this time period, experienced this most acutely. Cost reductions (on a normalized basis) were only 37% on the east system compared to 64% on the west system. Fig. 7 shows the average HPWH power under baseline conditions and during optimization for both systems over the course of six weeks of testing against price schedule WinterHDP. Note the early charging between midnight and 5AM before morning peak. Higher-demand days induce compressor operation midday when rates are moderately high, though charging often ceases as the evening peak pricing ramps up. This often resulted (particularly on the east system) in charging happening during a more expensive time period when it could have otherwise been avoided by charging further into the evening peak ramp-up. This balance between charging during moderately expensive times to avoid possible depletion of storage during more expensive times later in the day provides an optimization challenge for the LOCUS. Ultimately, no two days are identical from a hot water demand standpoint, and the LOCUS will not succeed in balancing risk and reward perfectly every time. Future improvements to the LOCUS algorithm involve improvements to this risk calculation with the intent of increasing midday charging to limit the number of days where peak charging becomes a necessary outcome of underestimating peak hot water demand.

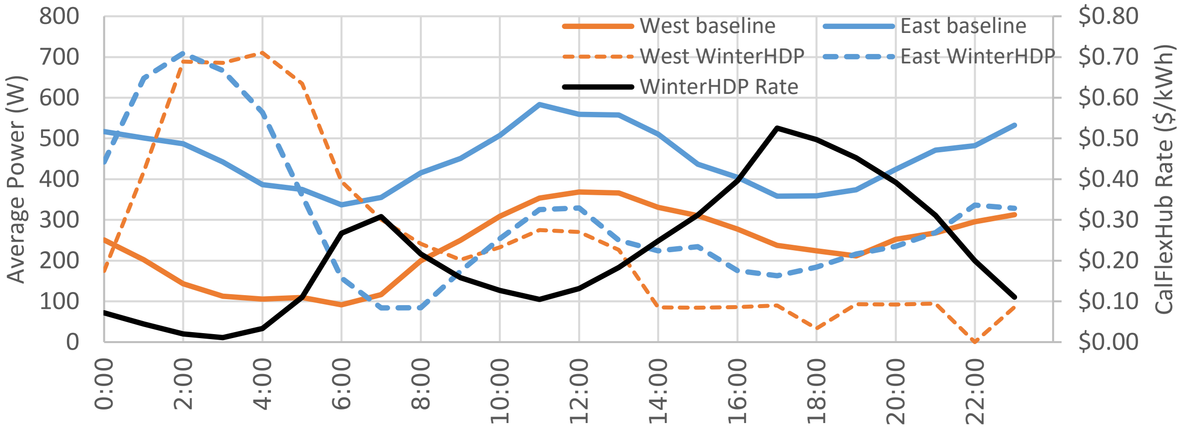

Figure 7. Average HPWH demand for the east and west systems under baseline and optimized winter rate test conditions. Testing occurred for six weeks in January and February 2024.

Load Flexibility Scenarios

Figs. 7–10 present specific load flexibility control scenarios to illustrate load control issues and challenges described in the previous section. Each scenario provides high-level system operational dynamics over a two-day period. The green bars represent hourly hot water consumption. Note that the maximum hot water volume is approximately 120 gallons in these scenarios, representing the system's useful volume rather than the physical volume of 166 gallons.

Fig. 7 shows the LOCUS controller creating and implementing flexible heating schedules to shift peak electricity consumption. Average hot water demand was present during the first day, but the second day had twice the hot water demand compared to the preceding day. In response, the LOCUS controller activated HPWH operation three times. The third time the HPWH was activated by the LOCUS, electricity prices had already begun to increase but this operation ensured adequate storage to shift peak load during the most expensive hours (4-9PM). Note finally that, despite significant draws during late peak hours, the system had enough storage to avoid HPWH operation until after 11:30PM, when prices were again at their lowest. This scenario highlights the control algorithms' adaptability in response to time-varying electricity prices and varying daily demand loads.

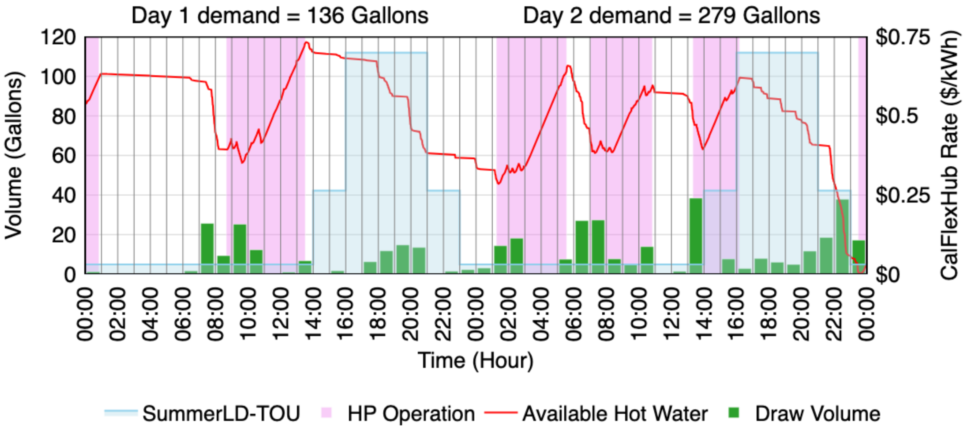

Figure 7. Load flexibility control scenario 1 (SummerLD-TOU rate).

Fig. 8 shows both the adaptive nature of the heating schedule created by the LOCUS controller, and the inevitable effects of excessive hot water demand. The second day had extraordinarily high demand (403 gallons) throughout the day and the compressor was on for more than 19 hours to meet this demand. The LOCUS controller could not avoid peak electricity use because the system lacked adequate heating capacity and storage for such abnormally high demand. High-demand days like this are uncommon (this day falls in the 99th percentile of daily flows for this system), but they affect the overall outcome of load flexibility controls.

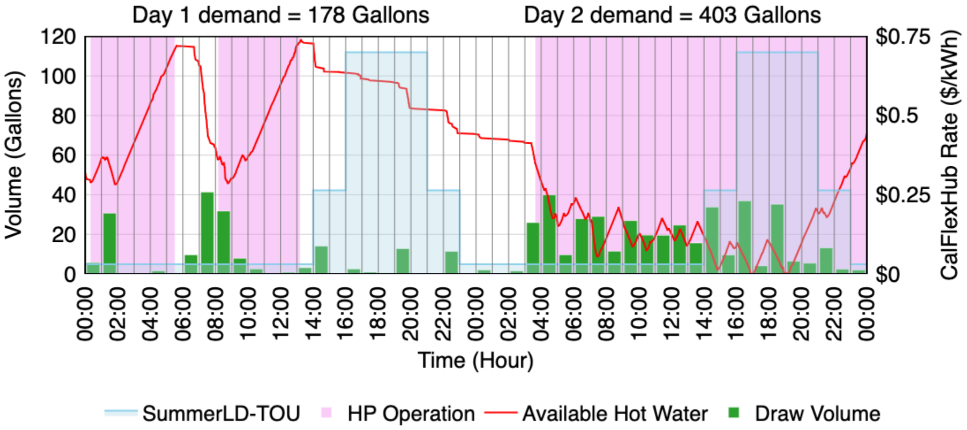

Figure 8: Load flexibility control scenario 2 (SummerLD-TOU rate).

Fig. 9 illustrates the impact of hot water demand uncertainties on price-based optimization in a dual-peak electricity price schedule. On both days, the control algorithms implemented a water heating schedule aiming for utilization of the two low-price periods, 1-5AM and 9AM-1PM. While this load control strategy was mostly successful, it was unable to shift all peak load between 4 PM and 10 PM on the first day because of hot water demand that exceeded LOCUS predictions, especially during the peak. If the heating operation before the afternoon peak hours had extended to hours with slightly higher electricity prices (between 1 PM and 4 PM), the system may have had more stored hot water to avoid peak electricity use. This risk/reward tradeoff is clearly dependent on the LOCUS system to anticipate hot water demand and can fail when abnormal water draw schedules arise.

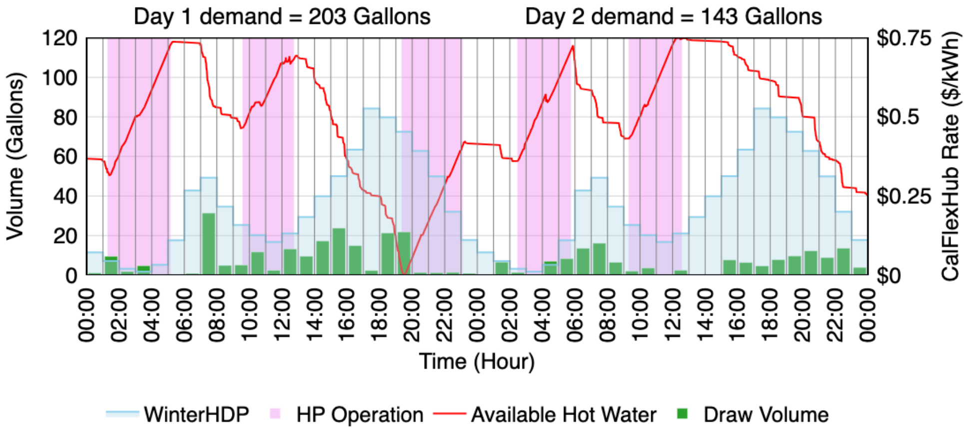

Figure 9: Load flexibility control scenario 3 (WinterHDP rate).

Fig. 10 presents the outcome of the control algorithms modified for increased flexibility to correct the issues observed in Fig. 9. Both days exhibited high demand, causing the controller to allow some higher price heating operations prior to evening peak. This adjustment enabled shifting from the highest-priced hours even hot water demand was high before and during the peak. The algorithm's adaptability lies in recognizing the benefit of using moderate and even high-priced hours to prepare for peak loads. However, there is still room for improvement; for instance, on the second day, starting the midday heating earlier would have increased storage capacity right before the peak, allowing for more effective load shifting toward lower-priced periods.

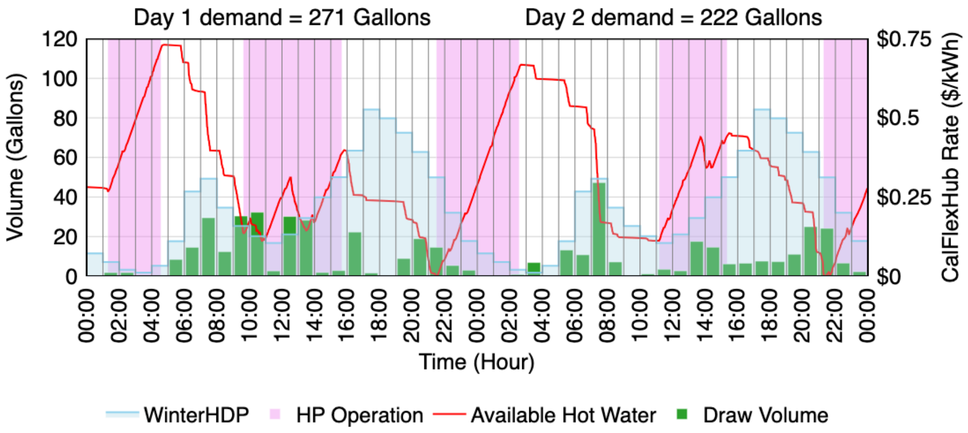

Figure 10: Load flexibility control scenario 4 (WinterHDP rate).

Discussion and Conclusion

The study conducted the first field demonstration of load flexibility controls based on time-varying electricity price issued by CalFlexHub. Final findings from this study will be available in the final EPC-20-004 report, but substantial learnings have already been made to date through studying performance over a year-long period at Santa Rosa. In general, we can conclude that the LOCUS system performed its function of load shifting effectively with negligible impact to residents and in some cases improved performance. Summer rate schedules showed the greatest promise, where peak/off-peak rates have the biggest gap and there is ample time each day to charge before evening peak. While two-peak schedules are more of a challenge, overall costs were also reduced in these cases by up to 65%, and improvements to the algorithm show promise in further increasing optimization in two-peak scenarios. The effectiveness of the system overall met and, in some cases, exceeded expectations set by optimization simulations run prior to retro-commissioning.

Load flexibility controls based on time-varying electricity prices were achieved by creating and implementing operation schedules optimized for energy cost. Successful load controls require the operation schedule to be optimized according to both electricity price and hot water demand forecasts. A fixed load control schedule solely based on electricity price may work for some hot water demand conditions but will not be effective for others.

LOCUS system used a holistic optimization approach, considering hot water demand forecast algorithms, in conjunction with heating and storage capacities of the HPWH system, to create heating and storage utilization schedules. The operation schedule is further adjusted in response to real-time hot water demand and storage utilization assessed through performance monitoring. This adaptive optimization enables the LOCUS system to successfully shift electricity consumption from high-price periods to low-price ones for most scenarios.

Nonetheless, field performance evaluation observed some unsuccessful or only partially successful load control scenarios. Occupancy pattern changes, vacancies, downstream changes in hot water end uses, and normal random variation can have unanticipated impacts on the timing of charging/discharging. The impact of variable flows is particularly felt in smaller systems, where a change in behavior of one person is felt proportionally more. For example, at the Eureka site, each system services 3-6 units each. Compared to Gilroy, where the system services 75 units, an individual's decision to demand hot water (i.e., someone takes a bath at 4PM) makes a much larger difference.

Some of the less successful test days were due to extraordinarily large hot water demand, which exceeded the HPWH system's load shifting capacity determined by its storage capacity and heating rate. Other scenarios were caused by hot water demand uncertainties greatly diverging from the control algorithms' forecast. One approach used to improve load control performance during these scenarios involves extending heating operation beyond hours with low electricity prices to increased storage prior to high-price hours. However, this approach led to increased electricity use during hours with moderately high prices, reducing the cost-optimization effectiveness when hot water demand was less than expected. Further refinement to control algorithms is needed to provide enhance capability in handling hot water demand uncertainties.

Several additional challenges have been identified over the course of study. System performance issues are documented to some degree in the baseline performance section of this document. Overall, systems that already struggle to meet demand will make load shifting challenging. Adding storage and intelligent controls help, but cannot fully overcome issues such as:

- Undersized compressors, leading to long recovery times.
- High thermal losses incurred by over-active recirculation or other site-specific conditions.
- Tank de-stratification caused by over-active recirculation.

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Another challenge in implementing the LOCUS system is the process of retro-commissioning. The LOCUS is flexible in its application and can be installed in most HPWH systems, but each system is unique and proper retro-commissioning depends on careful attention to plans. This has, during our study, necessitated very detailed plans and instructions as well as guidance for the plumbers doing the retro-commissioning. This impacted timelines and quality of work.

Proper evaluation is a challenge for this system and all load-shifting technologies and there is currently no standard for evaluation. Pre/post-retrofit performance, particularly for hybrid (backup resistance) systems, is challenging to evaluate on a level basis. Seasonality impacts vapor compression cycle performance and no two days are identical from a hot water demand standpoint. Normalizing on a per-hot-water-energy-demand-basis (i.e., $/kBTU) helps, particularly for non-hybrid systems, but this is not perfect. No two daily flow patterns will be the same, and the non-linearities present in COP curves combined with algorithmic control of demand separate from the LOCUS (i.e., onboard controls in the primary HPWH) can create strange edge cases.

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