Central Heat Pump Water Heater Controls Optimization

Final Report

ET24SWE0030

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Executive Summary

This report documents the results of optimizing load shift controls for two multifamily central heat pump water heater systems. When done properly, load shift controls on these systems can save money, carbon emissions, and total system benefits without sacrificing equipment wear-and-tear or occupant experience.

Domestic water heating accounts for approximately 32 percent of site energy consumption in multifamily buildings across the United States. It has become the focus of many energy efficiency and decarbonization efforts due to this large energy footprint and the increasing availability of emerging technologies. In multifamily buildings, hot water is often supplied with a central system design that consolidates the heat source to a single point with recirculation through the building's plumbing and residences. There are approximately 58,000 buildings in California with central water heating systems — serving approximately 1.9 million housing units — with additional central systems in the commercial building stock. While these systems have historically been almost exclusively natural gas-fired, central heat pump water heater systems are now becoming more widely available. Central heat pump water heaters have the potential to drastically reduce greenhouse gas emissions and provide total system benefits, especially with optimized control sequences and load shifting.

This is a follow-up study to a previous CalNEXT project, ET22SWE0017, that evaluated the performance of a central heat pump water heating design in two multifamily buildings. The previous study added instrumentation to new central heat pump water heater systems that were installed in two low-income, high-rise multifamily buildings in San Francisco with 120 and 135 studio residences, respectively. The previous study found that these central heat pump water heater systems in a swing tank configuration operated with daily coefficients of performance between 2.3 and 3.1, reduced energy consumption by about 68 percent, and reduced greenhouse gas emissions by 85 percent when compared to a code-compliant natural gas baseline alternative.

However, the cost benefits of initial load shift testing were minimal and difficult to confirm due to negligible impacts on peak demand, demand charges, and bounce-back energy consumption increase after the shed period. The first study looked at control strategies that were designed solely to shift energy out of the on-peak and partial-peak utility time periods. This follow-up study added control strategies that also reduce maximum electrical demand to lower demand charges and increase cost benefits. This report presents the results of these additional load shift strategies for improvement of emissions, total system benefits, and energy costs. This optimization is crucial for cost parity of electrified hot water systems, equitable adoption, maximized emissions reduction, maximized total system benefits, and minimized grid impact of new electrical loads.

The team tested several different load shift control sequences at each site, with different schedules designed to align with the buildings' time-of-use energy rates. The tested controls included staging of the heat pumps during the shed period as well as lockout of the electric resistance swing tanks. The team observed no negative impact on hot water delivery or reliability for occupants resulting from the interventions.

The tested load shifting strategies and schedules were very successful. Electrical demand, energy, greenhouse gas, and cost benefits were substantial, with impacts varying depending on the metric used for evaluation. Unfortunately, no single control strategy appeared to maximize all three

measurements of benefit simultaneously — maximized impacts of different metrics are not mutually assured. One tested strategy may maximize customer cost impacts while a different strategy may maximize greenhouse gas emissions reduction. The maximum observed impacts for the different tested control strategies and schedules are shown in the following table.

Table 1: Observed Impacts of Tested Load Shift Control Strategies

Metric	Site 1 Maximum Impact	Site 2 Maximum Impact
Customer hot water energy cost reduction	19%	10%
Greenhouse gas emissions reduction	8%	12%
Total system benefit improvement	15%	24%

While these observed savings are unique to the conditions and systems at the individual sites, the team can make certain conclusions and recommendations for future study, technology transfer to programs, and enhancing existing manufacturer offerings:

- The selection of appropriate load shift controls is highly dependent on utility rate structures. Initial project testing demonstrated that while certain load shift control strategies could successfully move energy consumption out of peak times, these strategies did not reduce costs for the building owner under a utility rate structure with high demand charges. The follow-up control strategies effectively mitigated these higher costs by specifically addressing demand charge impacts. While this demonstrates the technical feasibility of managing such charges, the project team feels that the need to intricately navigate demand charges introduces an unnecessary layer of operational complexity that is counterproductive to expanding load shifting as a resource and leveraging load shift capable buildings. Ideally, such buildings would operate under rate structures based on variable energy charges, like real-time pricing or time-of-use rates with minimal demand charges. If necessary, utilities could provide staggered pricing schedules to limit peaks on a particular feeder. Until such changes are made to utility rate structures, two standardized controls approaches could be developed and deployed for load shift capable central heat pump water heaters – one to shift energy and one to simultaneously shift energy and reduce peak electrical demand.
- Standardized controls and commissioning test procedures will reduce the labor burden of setting up load shifting, allow standardized program metrics to be captured from sites, and increase the reliability of load shifting central heat pump water heaters. Northwest Energy Efficiency Alliance developed a load shift commissioning test that can be further developed and used in California programs (Spielman 2025).
- Manual programming of load shift sequences and schedules is currently available on some central heat pump water heating systems and can be effective. However, manufacturers should be incentivized to include standard controls adjustment for (1) the control temperature sensor location referenced for turning heat pumps on and off, (2) the temperatures at the sensor location used for turning heat pumps on and off, (3) supply and heat pump temperature

setpoints, and (4) a staging command for each heating device including primary heat pumps and each temperature maintenance heater. Standard controls should be updated to accept a matrix of values from each EcoPort request. In addition to accepting the mode - Normal, Shed, Load Up, Advanced Load Up, Critical Peak Event, and Grid Emergency - standard controls should accept values for each of the controls adjustments listed above. Additionally, controls should be capable of automatically adjusting the EcoPort mode based on either a (1) pre-programmed schedule or (2) a signal from an EcoPort universal communication module.

- Once standard controls are included, programmed on a particular site, and a commissioning test has recorded site specific metrics, EcoPort communication modules can reference real-time pricing published by utilities to automate the adjustment of EcoPort modes and fully realize the load shifting resource. Algorithms used to convert real-time price signals to EcoPort modes have been developed and tested (Woo-Shem 2025). Those algorithms could be loaded onto EcoPort communication modules so they can read the real-time pricing and adjust CHPWH operation. This approach can also support security and site-specific customization.
- There is a misalignment between the metrics for measuring load shift effectiveness: customer energy cost, greenhouse gas emissions, and total system benefit. These metrics could potentially be brought into better alignment with rate reform, electrification-specific rate schedules, or real-time pricing.
- Monitoring and visibility into system performance should be made available to maintenance contractors. There is a stark need for maintenance contractors to have more visibility into system operation for diagnostics, preventative maintenance, and sustaining benefits over the life of the hot water system.
- Temperature maintenance and recirculation loads due to distribution system losses are highly impactful. Even small failures in these systems can have negative impacts on the central heat pump water heater system and lead to performance penalties. Monitoring, maintaining, and managing the distribution system and temperature maintenance loads are paramount and warrants more attention from the hot water industry.
- In swing tank central heat pump water heater system configurations, small failures in recirculation management can lead to significant electric resistance usage and negatively impact system efficiency. These issues can be partially mitigated with return-to-primary configurations. However, return-to-primary systems are currently uncommon and the industry needs sizing tools and demonstrations. A key stumbling block to return-to-primary options is the Underwriters Laboratories 60335-2-40 limitations on R-290 refrigerant that are referenced in California's mechanical code (Spielman, McKinney and Frankel 2024) (Stewart, et al. 2023). California can support return-to-primary systems, domestic manufacturing, and remove a huge market barrier to many different efficient applications of heat pumps – including water heaters - by updating its mechanical code with a proposal similar to the Washington State 24-GP1-113 which allows for International Electrotechnical Commission equipment certification (Washington State Building Code Council 2024).

Abbreviations and Acronyms

Acronym	Meaning
A	Amps
ACC	Avoided cost calculator
AWHI	Advanced Water Heating Initiative
AWHS	Advanced Water Heating Specification
CA	California
CASE	Codes and Standards Enhancement
CEC	California Energy Commission
CHPWH	Central heat pump water heater
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Coefficient of performance
CT	Current transducer
CTA	Consumer Technology Association
CZ	[California] climate zone
DAC	Disadvantaged community
DHW	Domestic hot water
EPIC	Electric Program Investment Charge
ER	Electric resistance
GHG	Greenhouse gas
gpm	Gallons per minute
GWP	Global warming potential

Acronym	Meaning
HPWH	Heat pump water heater
HX	Heat exchanger
IOU	Investor-owned utility
IPMVP	International Performance Measurement and Verification Protocol
kWh	Kilowatt-hour
M&V	Measurement and verification
MXV	Mixing valve
NEEA	Northwest Energy Efficiency Alliance
NOAA	National Oceanic and Atmospheric Administration
OAT	Outside air temperature
P	Power
PG&E	Pacific Gas and Electric
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SGIP	Self-Generation Incentive Program
SRO	Single room occupancy
T	Temperature
TH	Thermistor
TOU	Time-of-use
TSB	Total system benefit
WH	Water heater

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Introduction

In recent years central heat pump water heaters (CHPWHs) have become a high-priority solution for the energy-efficient decarbonization of domestic hot water (DHW). Central DHW systems often have energy-intensive usage profiles, high losses, high-emission gas-fired heat sources, and are found in a broad swath of the market, from multifamily buildings to offices and education facilities. High-efficiency, electrified CHPWH replacement systems come in a variety of configurations, all of which are well-suited for reducing emissions and improving the efficiency of large, centralized hot water loads in both retrofit and new construction applications.

However, further research is necessary to minimize grid impact, maximize benefits, and reduce the energy costs associated with the electrification of this substantial end use. One primary path to achieving this goal is the optimization of CHPWH system controls and load shifting. Controls optimization is essential to overcoming some of the remaining barriers to widespread market adoption and realizing maximum benefits. Refined control strategies, installer training, commissioning programs, case studies, guidelines, and standards are needed.

To that end, this study evaluates various novel load shifting strategies at two multifamily buildings with CHPWH systems. Two low-income senior living buildings in San Francisco were retrofitted with custom-engineered CHPWH systems using carbon dioxide (CO_2) as a refrigerant in 2022, presenting an opportunity to study the emerging technology in situ. This study is a follow up to ET22SWE0017, which evaluated the performance of the technology but identified room for improvement (Valmiki, et al. 2023). The project team returned to further collaborating with the building owners, subject matter experts, and the equipment manufacturer to implement control strategies aimed at reducing costs, greenhouse gas (GHG) emissions, electric demand, and electric consumption during the on-peak and partial-peak periods of time-of-use (TOU) utility rate schedules.

Background

More comprehensive technology and market background is documented in the preceding study, ET22SWE0017, but is paraphrased here. For more detail, refer to that report, which can be considered the first phase and companion piece to this project.

DHW has one of the largest energy footprints of all residential end uses in the United States. According to the Energy Information Administration, DHW accounts for about 32 percent of site energy consumption in multifamily buildings with five or more units across the country (U.S. EIA 2018a). Thus, this high-impact end use has become a major focus of the energy efficiency industry's efforts to achieve energy savings, decarbonization, and GHG emissions reduction goals.

Hot water demand in multifamily buildings is often satisfied by one or more centralized systems, as opposed to distributed water heaters in every unit. Central hot water system designs vary, but at minimum comprise a primary heat source (typically gas-fired), hot water storage (in pressurized tanks), and a distribution plumbing network (often with recirculation). The new CHPWH technology uses one or more heat pumps as the primary heat source instead of the typical gas-fired burner.

In one common CHPWH configuration, recognized as a qualified piping configuration in NEEA's Advanced Water Heating Specification (AWHS) (Northwest Energy Efficiency Alliance 2024). There is also an electric resistance (ER) storage tank that provides additional heat, especially during low load hours when it is inefficient or prohibitive to use the heat pump water heaters without short cycling or failures. This ER tank is colloquially called a "swing tank" or the "temperature maintenance" system, since it runs most often to keep the recirculation flow at setpoint when there is no actual hot water draw load. Figure 1 shows a simplified depiction of a CHPWH system configured with a swing tank for temperature maintenance. This configuration is representative of the CHPWHs installed at the two host sites. More detailed plumbing diagrams and operating conditions are described below.

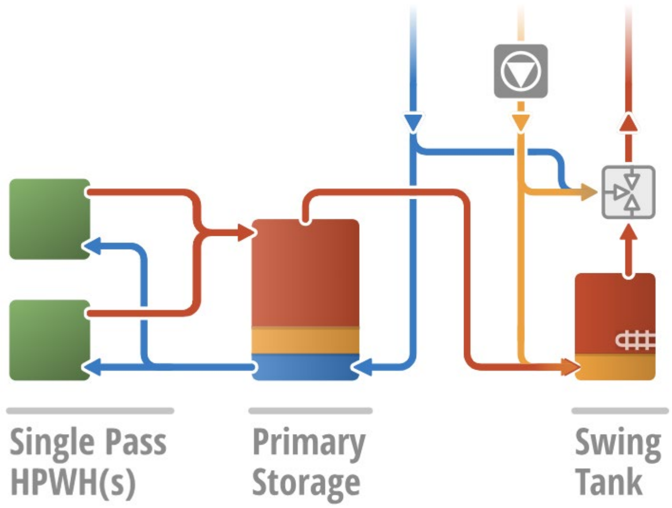

Figure 1: Single-pass CHPWH with in-series ER swing tank (Ecotope 2020).

The potential existing market size for CHPWH retrofits was quantified in ET22SWE0017. By combining data from various sources, including census data, DHW market characterization studies, and typical hot water energy use in the literature, it was estimated that there are about 1.9 million California residences using hot water delivered from central DHW systems (Valmiki, et al. 2023). These residences exist in about 58,000 buildings with about two-thirds of them in mid-rise and high-rise buildings. Virtually all of these systems are directly fueled by natural gas, with a total on-site energy consumption of about 480 million therms per year. Furthermore, a new construction growth rate of 1.2 percent is expected for the multifamily sector (Pande, et al. 2022) (Goyal, et al. 2022); new construction also presents an opportunity for CHPWH implementation. Additionally, central DHW systems in nonresidential buildings consume an estimated 243 million therms — about 50 percent that of the multifamily sector — albeit with very different load profiles (Valmiki, et al. 2023).

According to the 2021 US Census American Community Survey, in California, about 90 percent of apartments in buildings with three or more dwellings are occupied by renters (United States Census Bureau 2021). This compares to less than 45 percent of the total residential population. Thus, a focus on end uses and energy systems such as central hot water in multifamily buildings can benefit these underserved communities, especially when such measures impact whole buildings, reduce on-site natural gas consumption and emissions, and connect the incentive structure to both renters and building owners.

Previous CHPWH Research

Past studies of CHPWH systems in multifamily buildings have shown coefficients of performance (COPs) between 2.1 and 3.3 with installed costs of $1,110 to $3,540 per residence (Heller and Oram 2015) (Hoeschele and Weitzel 2017) (Banks, Grist and Heller 2020) (Banks, Spielman and Heller 2022) (Gartman and Armstrong 2020). Additionally, the Advanced Water Heating Specification (AWHS) has established four efficiency tiers for CHPWH products for use in qualified products lists and programs (NEEA 2022) (Northwest Energy Efficiency Alliance 2024). Past published case studies have demonstrated systems achieving efficiencies in the higher Tiers 3 and 4 of the standards.

The previous study of the CHPWH systems at these two sites showed performance within the AWHS Tier 3 efficiency range. The sites operated with daily COPs ranging from 2.3 and 3.1, as seen in Figure 2 (Valmiki, et al. 2023).

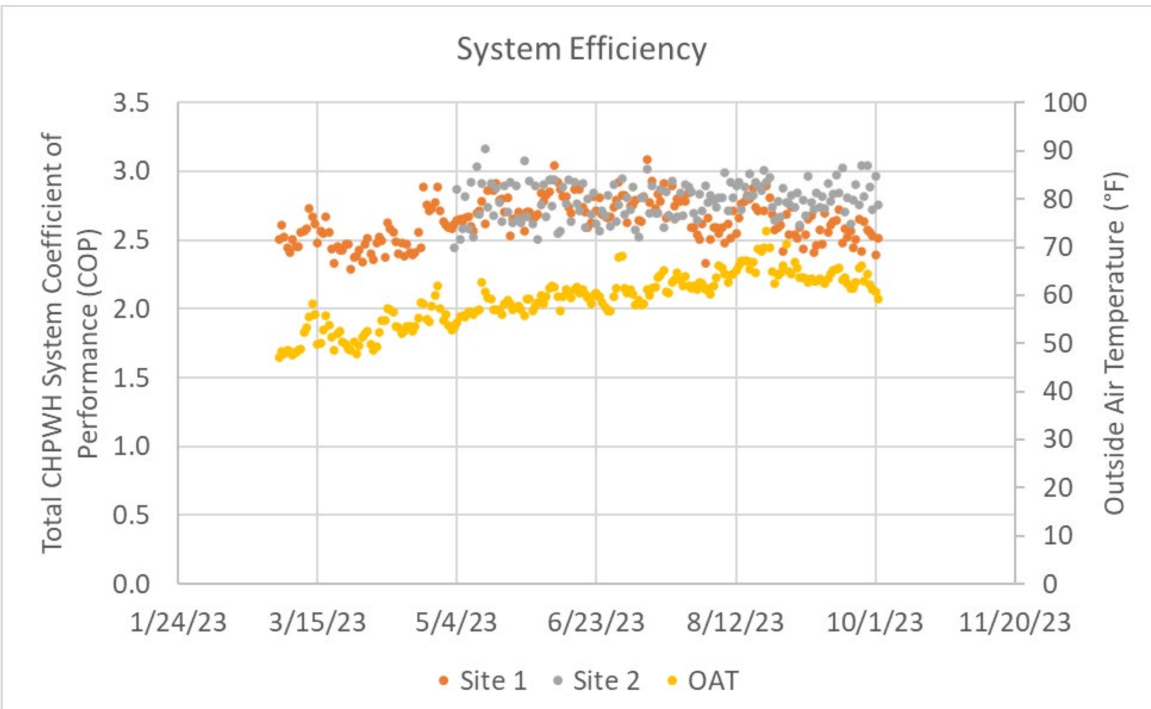

Figure 2: System COP for the host sites observed in ET22SWE0017.

When compared to a code baseline natural gas central DHW alternative, the CHPWHs installed at the two sites reduced energy consumption by 68 to 69 percent and GHG emissions by 90 percent, as seen in Table 2.

Table 2: Energy, GHG, and Cost Impacts at the Two Host Sites Observed in ET22SWE0017

	Site 1	Site 2
Monitoring length (days)	214	153
Baseline energy (therms)	6,175	6,833
CHPWH energy (kWh)	57,212	61,773
Energy savings (kBtu)	422,145 (68%)	472,348 (69%)
GHG emissions savings (tons CO_2e)	30.5 (90%)	33.6 (90%)
Customer utility cost increase over summer-biased test period	223% (183% with CARE* discount)	176% (142% with CARE discount)

*California Alternate Rates for Energy

However, the customer utility costs increased substantially over a natural gas baseline during the observed summer-biased monitoring period. This is largely due to the impacts of demand charges during partial-peak and on-peak TOU rate schedules, which the manufacturer's original standard controls were not capable of addressing. It should be noted that this monitoring period was almost entirely in summer months, when demand charges are most influential. Over the course of an entire year, the utility cost differential between a gas baseline and the CHPWH measure would have been much less pronounced, but an increase, nonetheless.[1]

Mitigating the energy cost impact of DHW electrification is critical to CHPWH adoption and equity for multifamily building owners and occupants. To address this cost issue, load shifting optimization is necessary (Farnsworth, Lazar and Shipley 2019). Such cost minimization would also inherently have positive impacts on the grid load, GHG emissions, and total system benefit (TSB) of the technology.[2]

In general, the load shifting of a CHPWH system is performed by employing "load up" and "shed" programming. During load up mode, additional heat is stored in the tanks in preparation for shed mode, where that stored heat is then used to coast through the high-emission, high-cost period for as long as possible without impacting hot water supply. In previous work, Ecotope has proposed, modeled, and performed initial testing of load up and shed modes based on adjustment of three operating parameters (Spielman 2022) (Spielman and Johnson 2023):

[1] Annualization of costs was not feasible with the data from ET22SWE0017.

[2] TSB is a holistic metric for energy efficiency and load management programs derived by California regulators that reflects the benefits to the grid, infrastructure, environment, utilities, and ratepayers represented by a dollar value. It incorporates factors such as greenhouse gas emissions, refrigerant usage, transmission and distribution, and electrical generation costs (California Public Utilities Commission 2024). This metric can also be thought of as representing total avoided costs.

1. Thermistor locations in the storage volume that are used to trigger calls for primary heat: by selecting locations that are further towards the top or bottom of the volume, total thermal storage can be maximized or discharged more fully.
2. Hot water temperature setpoint: this can be raised to increase thermal storage across the stratified volume during the load up mode.
3. Heat pump capacity: in the case of the system under study, the heat pumps can be ramped up to generate more heat during the finite load up period in a shorter amount of time.

Beyond these possible control parameters for tuning load shifting, adding staging of multiple heat pumps or locking out electric resistance backup or swing tanks could potentially cap peak demand during on-peak or partial-peak times. This could be especially beneficial for buildings with demand charges in their electric tariffs.

The CHPWH industry has prepared for external signaling that can trigger such programmed load shifting modes or settings. The Advanced Water Heating Initiative (AWHI) grid connectivity working group has coordinated with stakeholders to establish the Consumer Technology Association (CTA) 2045 technical specification (brand name EcoPort) for products certified by the OpenADR Alliance. This device-to-device communication port allows for such external triggering of load shifting. A service provider, utility, or program administrator can use CTA 2045 for load management of these distributed resources via standard communication protocols, e.g., via Wi-Fi, Zigbee, Bluetooth, FM radio, and others. This new CTA 2045 interface technology is being integrated into many HPWH and CHPWH products.

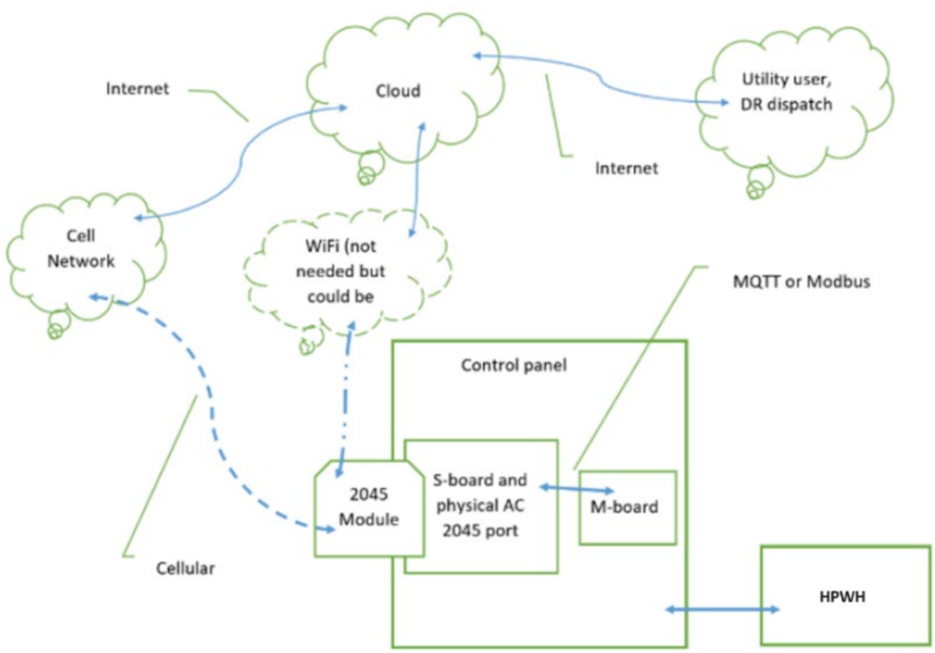

Figure 3: Sample CHPWH communication diagram using a CTA 2045 module (Spielman 2022).

The project team tested some load shifting capabilities as part of ET22SWE0017 using an installed CTA 2045 module and manually programmed load shift modes. The test included a four hour load up period between 12 p.m. and 4 p.m. (off and partial-peak TOU periods) and a shed between 4 p.m. and 9 p.m. (on-peak TOU period). The project team tested two different load shift sequences of operation; the results of one of the sequences at Site 1, compared to a normal operation day, are shown in Figure 4.

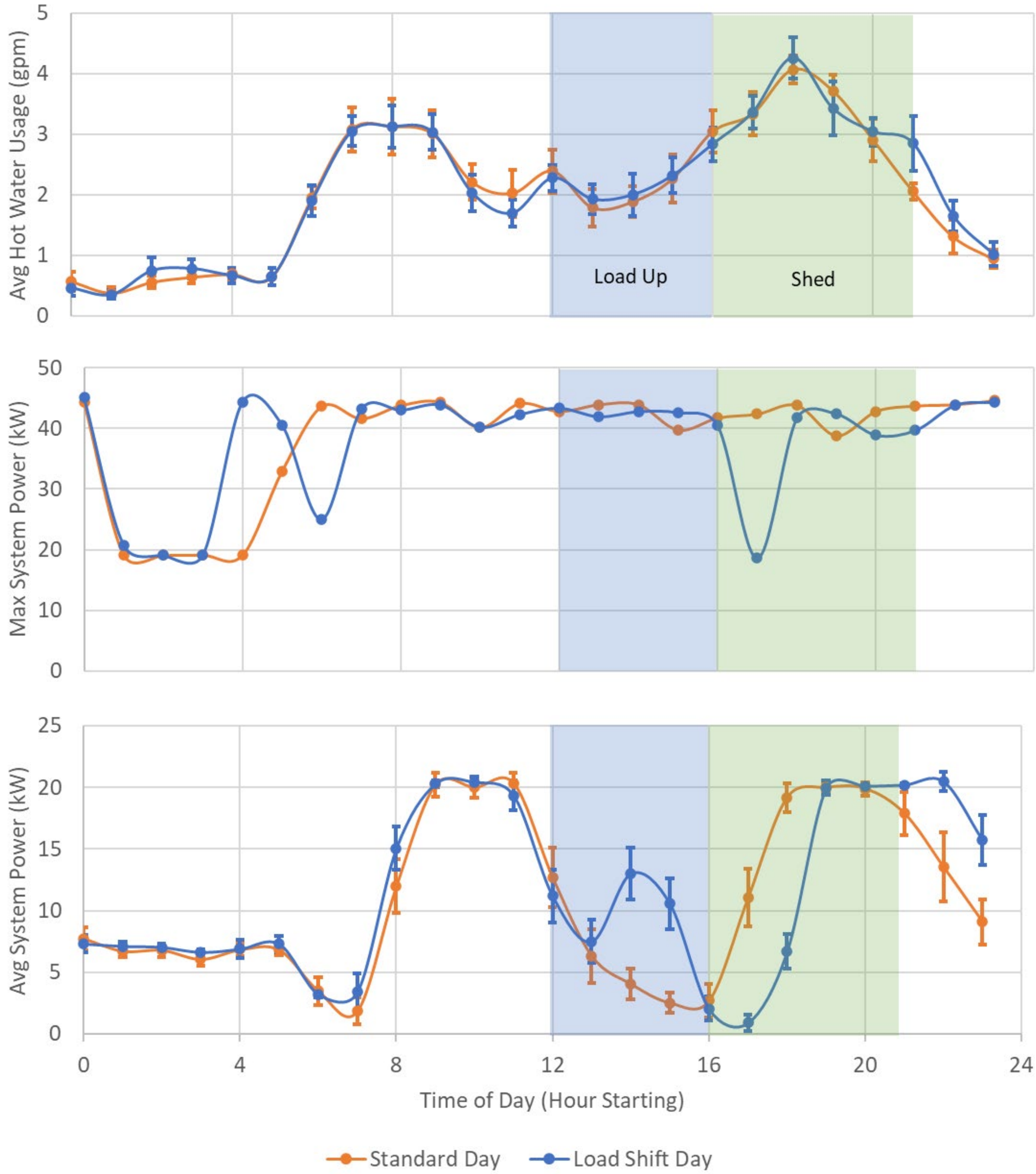

Figure 4: Site 1 load shift performance (Valmiki, et al. 2023).

The consistent water usage confirms that the normal day and load shift day can be reasonably compared. The comparison clearly shows that there is a distinct increase in energy consumption during the load up period, a clear decrease during the shed period, a bounce-back period after the shed, and no change in the peak electrical demand during either the load up or shed periods.

Table 3 compares the energy consumption during load up and shed periods. Usage during the load up period increased by 40 to 65 percent and decreased during the shed period by 32 to 63 percent, demonstrating successful load shift abilities.

Table 3: Magnitude of Load Up and Shed Effects

Time of Day (Hour)	Standard Operation Day Energy (kWh)	Load Shift Day Energy (kWh)	Difference (kWh)
Site 1 Sequence of Operation 1			
Load up (12–16)	25.6	42.3	−16.7 (−65%)
Shed (16–21)	72.9	49.7	23.1 (32%)
Site 1 Sequence of Operation 2			
Load up (12–16)	36.1	50.5	−14.4 (−40%)
Shed (16–21)	58.3	23.8	34.5 (59%)
Site 2 Sequence of Operation 2			
Load up (12–16)	52.0	73.6	−21.5 (−41%)
Shed (16–21)	97.9	35.9	62.0 (63%)

While the tests were successful in shifting energy consumption out of the on-peak period, peak electrical demand was not reduced and it was not clear how the overall daily energy consumption was impacted, including the bounce-back period during recovery after the shed due to the day-on/day-off test strategy. The team concluded that, although the system was doing what was asked and energy was indeed shifted out of the on-peak period, customer energy costs were not significantly reduced, primarily due to the dominance of demand charges and the net overall increase in total daily energy usage. The team acknowledged that there was ample room to further optimize controls based on load patterns, CHPWH capabilities, TOU pricing, and GHG reduction. This motivated the follow-up study presented here.

Objectives

The study objectives were to:

1. Install measurement and verification instrumentation at two multifamily building host sites with CHPWH systems
2. Modify equipment to enable HPWH staging and swing tank lockout to allow new load shifting strategies that can improve energy costs, GHG emissions reduction, and TSB
3. Implement several load shifting control sequences of operation at both sites with a week-on/week-off strategy
4. Assess the impacts of load shifting strategies on operation, energy costs, energy consumption, peak electrical demand, GHG emissions, and TSB
5. Develop conclusions and recommendations for manufacturers, designers, utilities, and program administrators regarding the adoption of beneficial load shifting strategies

Host Sites

The host sites are two multifamily buildings for low-income senior citizens located in a disadvantaged community (DAC) designated area in downtown San Francisco, as described in Table 4. Both buildings primarily consist of studio residences, with common spaces on the ground and basement levels.

Table 4. Host Sites

	Site 1	Site 2
Year built	1914	1926
Number of residences	119 (118 studios and 1 one-bedroom)	133 (131 studios and 2 two-bedrooms)
End uses per residence	Three (kitchenette sink, bathroom sink, shower/tub)	
Number of residences	120	135
Floor area (square feet)	51,250	50,538
Stories	7	10
California climate zone	3	3

Both buildings have recirculating central DHW systems. In 2022, the recirculation and distribution piping systems were rebalanced, correcting excessive recirculation rates, shower crossover, and losses in preparation for the CHPWH retrofits. Both gas-fired systems were replaced with custom-engineered, site-built CHPWH systems in 2022.

Figure 5: Swing tank and storage tank array, mixing valve, and rooftop HPWHs.

The CHPWH systems have a similar design at each site, comprising two CO_2 heat pumps, storage tank arrays, recirculation pumps, electronic mixing valves, central control systems with telemetry, and an ER swing tank. Each HPWH has a dedicated plate and frame heat exchanger (HX) that isolates the HPWH water loop from the potable DHW plumbing. Table 5 outlines some of the CHPWH system characteristics.

Table 5. Host Site CHPWH Systems

	Site 1	Site 2
Number of HPWH units	2	2
Per-unit HPWH rated capacity (Btu/h)	136,000	136,000
Per-unit HPWH rated power (kW)	9.73	9.73
HPWH rated COP (DOE CFR* 431 standard conditions)	4.11	4.11
Storage tank quantity, excluding swing tank	8	11
Storage capacity, excluding swing tank (gal)	1,550	2,150
Swing tank capacity (gal/power (kW))	200/18	200/18

*US Department of Energy Code of Federal Regulations

Figure 6 and Figure 7 show plumbing diagrams of each site along with selected measurement and verification (M&V) datapoint locations. The storage tanks were plumbed in a combination series and parallel arrangement. Sets of two or three tanks were arranged in parallel, with several of these sets plumbed in series. In these plumbing diagrams, WH stands for ER water heater (i.e., swing tank), T and TH for temperature measurement, P for power measurement, ST for storage tank, HX for heat exchanger, and CT for current transducer.

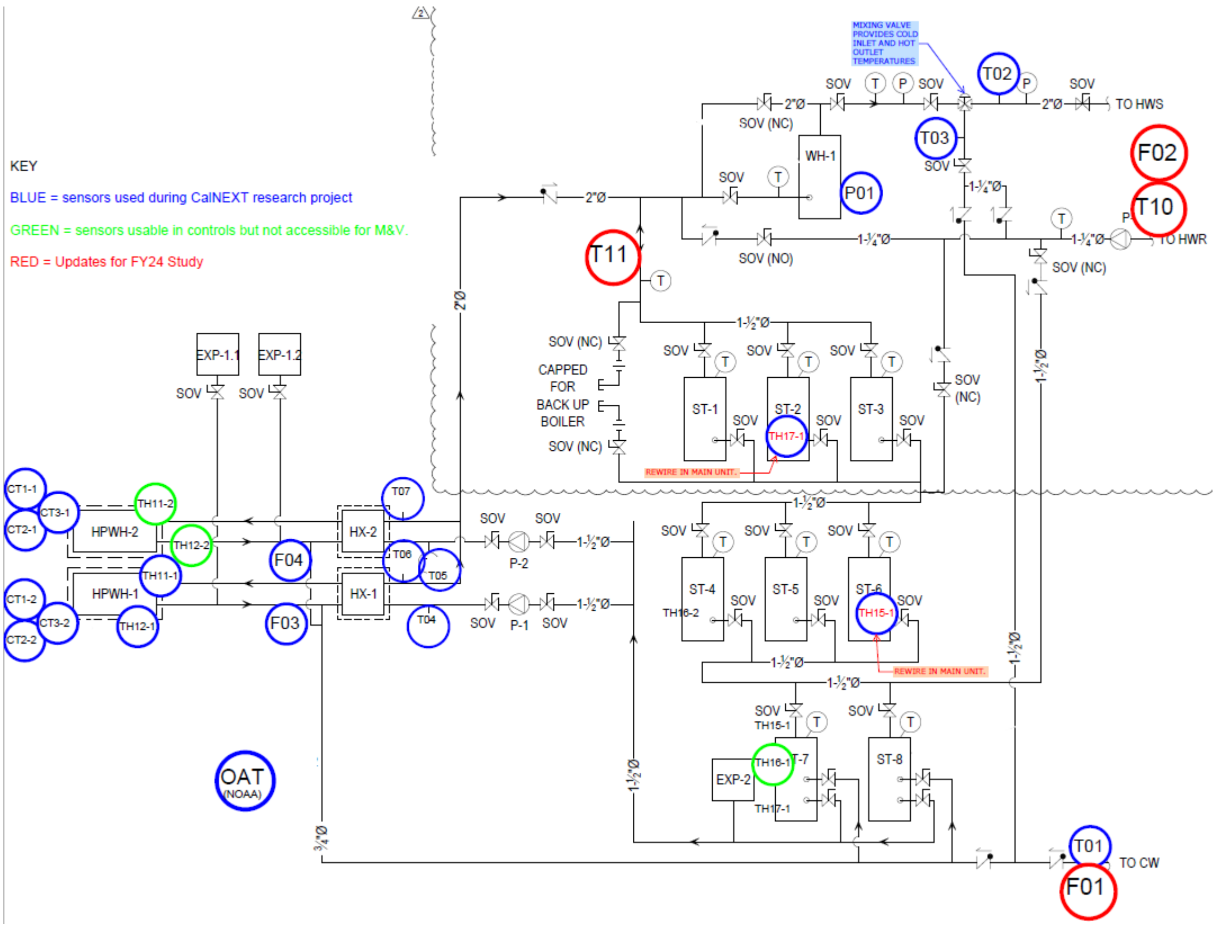

Figure 6: Site 1 plumbing line diagram and M&V datapoints.

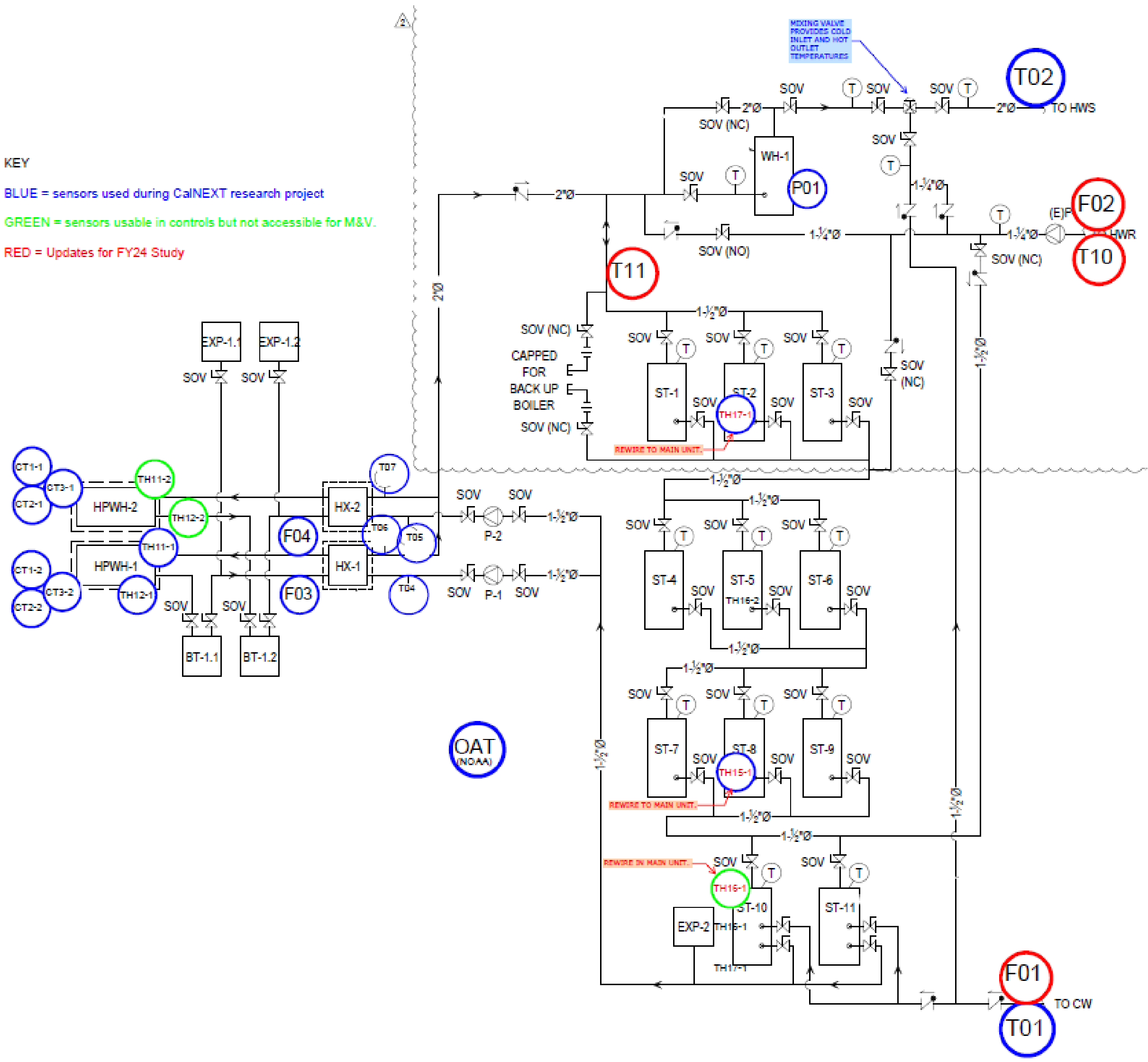

Figure 7: Site 2 plumbing line diagram and M&V datapoints.

Methodology and Approach

Measurement Plan and Instrumentation Installation

The project team developed a measurement plan to gather data sufficient for assessment of the installed CHPWH systems based on the International Performance Measurement and Verification Protocol (IPMVP) Option B (retrofit isolation — all parameter measurement). The selected datapoints consisted of various power, temperature, and flow measurements, as identified in Figure 6 and Figure 7 on a one-minute interval. All data was accessible remotely, allowing the team to monitor real-time conditions and observe system performance and response to load shift test signals as the project progressed. The measurement points are listed in Table 6. Local outside air temperature (OAT) was collected from National Oceanic and Atmospheric Administration (NOAA) data for the

Oakland International Airport weather station KOAK. Changes from the datapoints used in the study ET22SWE0017 include relocation of the tank storage thermistors for improved controllability across the storage volume and the addition of a flowmeter on the recirculation return pipe.

Table 6: Measurement Points

Point Description	Site 1 Tags	Site 2 Tags
Incoming city water temp (°F)	T01	T01
Mixing valve water temperatures (°F)	T03, T11	T01, T10, T11
Supply water temperature (°F)	T02	T02
Recirculation return temperature (°F)	T10	T10
Tank temperatures (°F)	TH16-1 (11% height) TH15-1 (30% height) TH17-1 (69% height) T11 (100% height)	TH16-1 (14% height) TH15-1 (22% height) TH17-1 (78% height) T11 (100% height)
Secondary temperatures in/out HX-1 and HX-2 (°F)	T04, T05, T06, T07	T04, T05, T06, T07
Inlet and outlet water temperatures at HPWHs (°F)	TH11-1 and TH12-1 (HPWH 1) TH11-2 and TH12-2 (HPWH 2)	TH11-1 & TH12-1 (HPWH 1) TH11-2 & TH12-2 (HPWH 2)
Incoming city water flow (gpm)	F01	F01
Primary loop flow (gpm)	F03 (HPWH 1), F04 (HPWH 2)	F03 (HPWH 1), F04 (HPWH 2)
Recirculation flow (gpm)	F02	F02
HPWH current (A)	CT1-1, CT2-1, CT3-1 (HPWH 1) CT1-2, CT2-2, CT3-2 (HPWH 2)	CT1-1, CT2-1, CT3-1 (HPWH 1) CT1-2, CT2-2, CT3-2 (HPWH 2)
Swing tank power (kW)	P01	P01
OAT (°F)	NOOA hourly data for KOAK weather station	

The three tank temperature thermistors used for load shift control points represent different points along the total volume height, as shown in Figure 8. The calls for heat, which would turn the heat pumps on or off, are programmed based on these three locations along with assigned cut-in or cut-out temperatures.

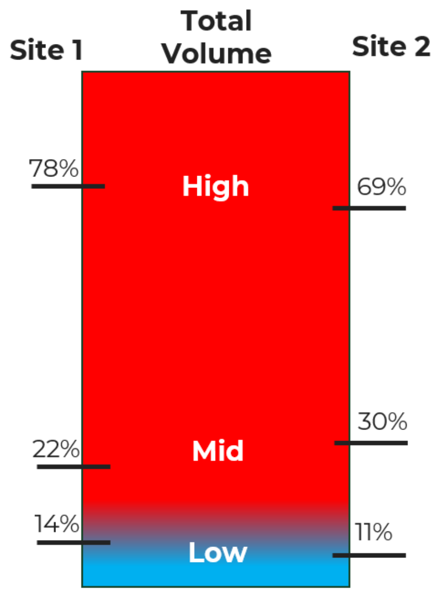

Figure 8: Storage volume thermistor locations.

M&V instrumentation was added to each host site the week of August 12, 2024. The images in Figure 9 illustrate some of the temporary sensors installed by the research team.

Figure 9: Swing tank power meter (P01), city water flowmeter (F01), and recirculation flowmeter (F02).

The project team took two approaches to COP calculation, which theoretically should be equivalent. Both approaches are based on monitored field data, The first method follows the boundary method, as outlined in the (AWHS version 8.1) (Northwest Energy Efficiency Alliance 2024).

Boundary Method:

$$COP_{Sys} = \frac{Primary\ Load\ +\ Recirc\ Load}{Total\ Electric\ Use}$$

$$= \frac{500 * Flow_{CW} * (Temp_{OutMXV} - Temp_{CW}) + 500 * Flow_{RecircReturn} * (Temp_{OutMXV} - Temp_{RecircReturn})}{Power_{HPWH1} + Power_{HPWH2} + Power_{SwingTank}}$$

where COP_{sys} is the total system efficiency, *Flow* is the flowrate in gallons per minute (gpm), *CW* denotes city make-up water, and *MXV* denotes the mixing valve.

The second method, recognized as the equipment method in AWHS version 8.1, has been used on several other monitored sites and provides a similar level of accuracy while relying on fewer datapoints from fallible instrumentation.

Equipment Method:

$$COP_{Sys} = COP_{HPWH} * \frac{Electric\ Use_{HPWH}}{Total\ Electric\ Use} + COP_{resistance} * \frac{Electric\ Use_{Resistance}}{Total\ Electric\ Use}$$

where COP_{HPWH} is calculated using power into the HPWH, flow through the HPWH, and inlet and outlet temperatures of the HPWH flow. The ER swing tank COP is assumed to be 1.

Load Shift Controls Design and Test Plan

The project team designed new control sequences for load up and shed with consultation from the HPWH manufacturer to ensure feasibility. The new sequences are designed to maximize the heat stored during load up, draw down to a minimum during shed without impacting hot water delivery, avoid over cycling the HPWHs, and reduce peak electrical demand during partial-peak and on-peak times. The team worked with the manufacturer to implement these changes on-site during the week of August 12, 2024. The native control logic of the HPWH system did not include staging sequences so custom programming from the manufacturer was required. Similar to ET22SWE0017, the schedules were developed based on the utility TOU schedule and rates of the host sites, which have partial-peak rates from 2 p.m. to 4 p.m. and 9 p.m. to 11 p.m., and on-peak rates from 4 p.m. to 9 pm. during the summer months (Pacific Gas and Electric (PG&E) rate schedule B-19). Both sites are subject to energy and demand charges.

Table 7 lists the control parameters for each programmed mode that can be called with EcoPort module requests: normal, shed, critical peak, load up, and advanced load up. For each mode, on/off thermistor locations and setpoints are defined. For instance, when Site 1 is in normal mode, the system will call for heat from the HPWH whenever the temperature at the high location (69 percent height) is less than 120°F and will stop calling for heat when the temperature at middle location (30 percent height) reaches 140°F. For the purposes of this study, the load shifting relied primarily on normal, shed, critical peak, and load up modes. Critical peak was a custom shed mode that included HPWH staging and swing tank lock out, added specifically to enable peak electric demand reduction for cost, GHG, and TSB savings beyond the less aggressive shed mode.

Table 7: Load Shift Controls and EcoPort Request Modes

HPWH	Control Point	Normal Mode	Shed Mode	Critical Peak Mode	Load Up Mode	Advanced Load Up Mode
1	On thermistor	High	High	High	Low	Low
	Off thermistor	Mid	High	High	Low	Low
	Thermodifferential	20°F	30°F	30°F	10°F	10°F
	Off setpoint	140°F	140°F	140°F	125°F	125°F
2	On thermistor	High	High	Mid	Low	Low
	Off thermistor	Mid	High	Mid	Low	Low
	Thermodifferential	20°F	30°F	15°F	10°F	10°F
	Off setpoint	140°F	140°F	130°F	125°F	125°F
Swing tank		Enabled	Enabled	Disabled	Enabled	Enabled
HPWH capacity setting		40 kW	40 kW	40 kW	40 kW	60 kW
HPWH outlet temperature		165°F				
HX outlet temperature		150°F				
MXV target supply temperature		Site 1: 126°F		Site 2: 122°F		

The team developed load shift schedules as shown in Table 8. This test plan allows for comparison between several different load shift approaches and the normal operation baseline. Each schedule was designed to explore load up and shed potential aligned to PG&E's TOU pricing, which also tends to coincide with a typical peak hot water draw period for a multifamily residential building. In general, the schedules proceed from least aggressive to most aggressive. Schedules 1 and 2 target maximum energy shift out of the peak period without HPWH staging or swing tank lockout, similar to the load shifting first tested in ET22SWE0017. Subsequent schedules include HPWH staging and swing tank lockout which were hypothesized to enhance customer cost benefits by reducing demand charges.

Table 8: Load shift test schedules.

	Mode per hour of day														*Part Peak*		*Peak*					*Part Peak*		
Schedule	***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***
Baseline	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Schedule 1	N	N	N	N	N	N	N	N	LU	LU	LU	LU	LU	LU	LU	LU	S	S	S	S	S	N	N	N
Schedule 2	N	N	N	N	N	N	N	N	N	N	N	N	LU	LU	LU	LU	S	S	S	S	S	N	N	N
Schedule 3	N	N	N	N	N	N	N	N	N	N	LU	LU	LU	LU	LU	LU	CP	CP	CP	CP	CP	N	N	N
Schedule 4	N	N	N	N	N	N	N	N	N	N	N	N	LU	LU	LU	LU	CP	CP	CP	CP	CP	N	N	N
Schedule 5	N	N	N	N	N	N	N	N	LU	LU	LU	LU	LU	LU	CP	CP	CP	CP	CP	CP	CP	N	N	N
Schedule 6	N	N	N	N	N	N	N	N	LU	LU	LU	LU	LU	LU	CP	CP	CP	CP	CP	CP	CP	CP	CP	N
Schedule 7	N	N	N	N	N	N	N	N	N	N	LU	LU	LU	LU	CP	CP	CP	CP	CP	CP	CP	CP	CP	N

Normal	Load Up	Critical Peak	Shed

The team tested the individual schedules over each calendar week of the study timeline. One-week intervals were selected so that each schedule could be observed over the full range of load profiles that the building might experience across different weekdays. The one-week interval also allowed the team to do a full comparison of total energy consumption between the different load shift strategies, including any bounce-back effect during hot water recovery after the shed periods; this was not possible in the preceding project, which used daily intervals to vary schedules rather than weekly.

Findings

The two sites were observed to have hot water loads of 19.2 and 31.2 gallons per day per residence, respectively. Comparing the hot water draw profile of normal operating days to that of load shift days can confirm a fair basis for evaluating load shifting. If the hot water draw profile is consistent between normal and load shift days, any load shift benefits are not coming at the expense, or as a result of, changed hot water usage behavior.

Another valuable basis for comparison between normal and load shift days is the amount of time the system spends delivering supply temperatures below the desired setpoint. The amount of time hot water is delivered to occupants below setpoint is a measure of the system's effectiveness at supplying hot water at temperatures desired by the building staff.

Figure 10 and Figure 11 show the consistency between average load profiles of normal and load shift days over the study timeline as well as the amount of time spent with delivered supply hot water below the target setpoint for the typical normal operation and load shift day.

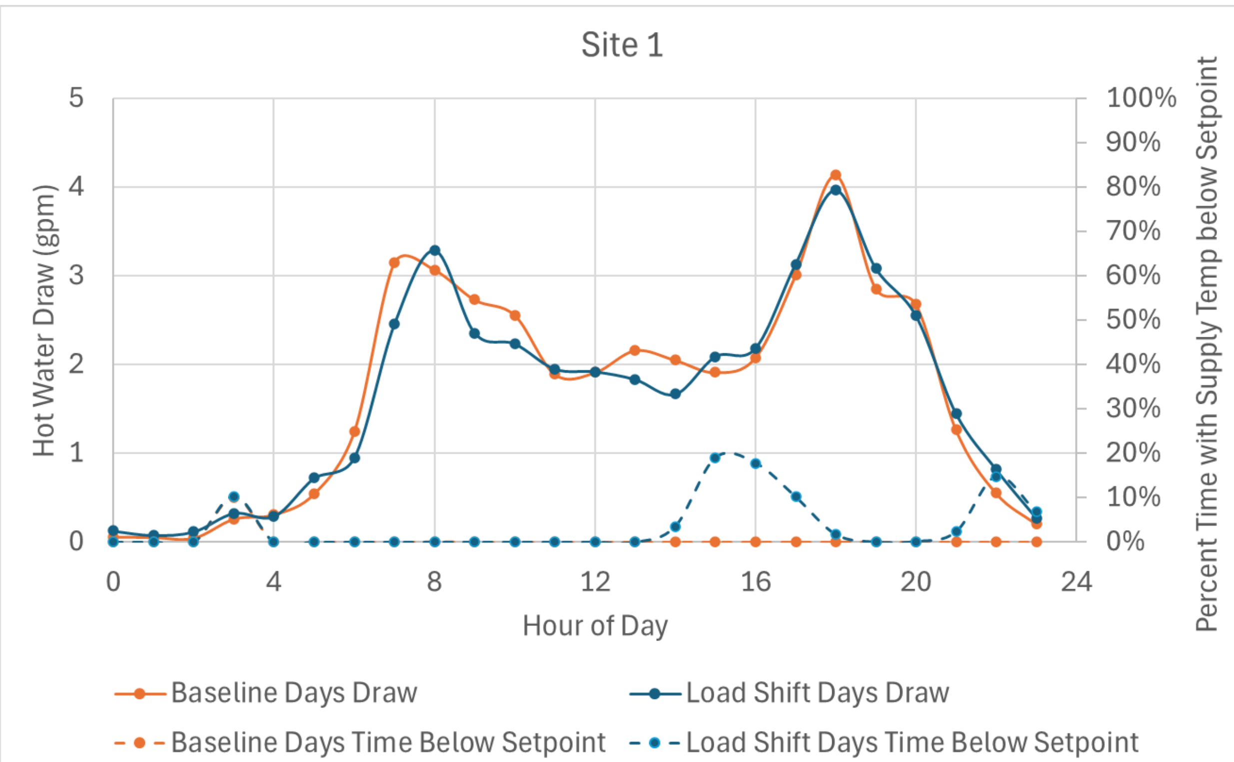

Figure 10: Site 1 hot water draw profiles for typical baseline and load shift days.

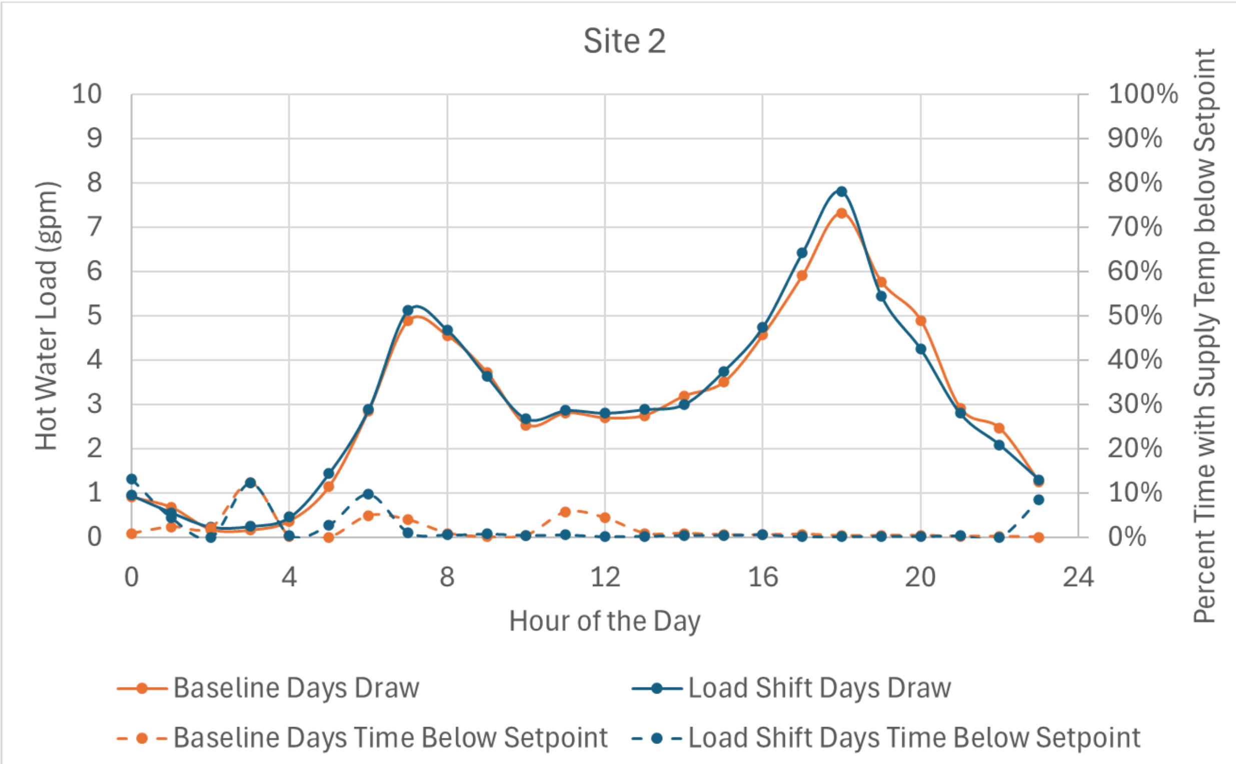

Figure 11: Site 2 hot water draw profiles for typical baseline and load shift days.

If load shifting controls result in excessively low supply temperatures, there could be negative reactions by building occupants or an unintended increase in hot water usage by volume. The load shift controls deployed in the first phase of the study did not pose a risk of low supply temperatures; the swing tank was free to operate during periods of low DHW usage and in the unlikely event that temperatures from the primary storage tank dropped below the setpoint, the swing tank would have been able to provide the necessary trim heating to maintain supply temperature. However, with the swing tank locked out during critical peak operation, there is a potential risk of supply water temperatures dropping if insufficient hot water is drawn from the primary storage, even if the primary storage tanks contain adequate water.

While Site 1 did appear to have an increase in time with supply temperatures below the desired setpoint during some of the load shift hours, Site 2 did not show any such effect. That said, there were no complaints from staff or occupants regarding hot water temperatures at Site 1 and, as seen in Figure 10, there was no apparent increase in hot water usage that would have coincided with the hours at which supply temperatures were not meeting the setpoint. Therefore, the small increase in time with supply temperatures under target can be considered an acceptable cost for the load shift measure that went unnoticed or without compensatory behavior by the residents.

However, some data over the study timeline had to be excluded from the load shift evaluation. At both sites, there were complicating issues related to the temperature maintenance, recirculation load, and distribution system losses that precluded fair comparisons with the baseline, normal operation weeks. At Site 1, there was an issue with the swing tank: the fuses for the three electric resistance elements failed on several occasions for reasons that could not be identified by the building's hot water maintenance contractor. When these fuse failures resulted in only one of the three elements remaining operational, the amount of time spent below the hot water supply setpoint was clearly affected, as seen in Figure 12. The project team had to exclude this section of data from the evaluation of load shifting since it represented a timeframe in which the system was malfunctioning and did not allow for fair comparison to the baseline weeks which had no such issues.

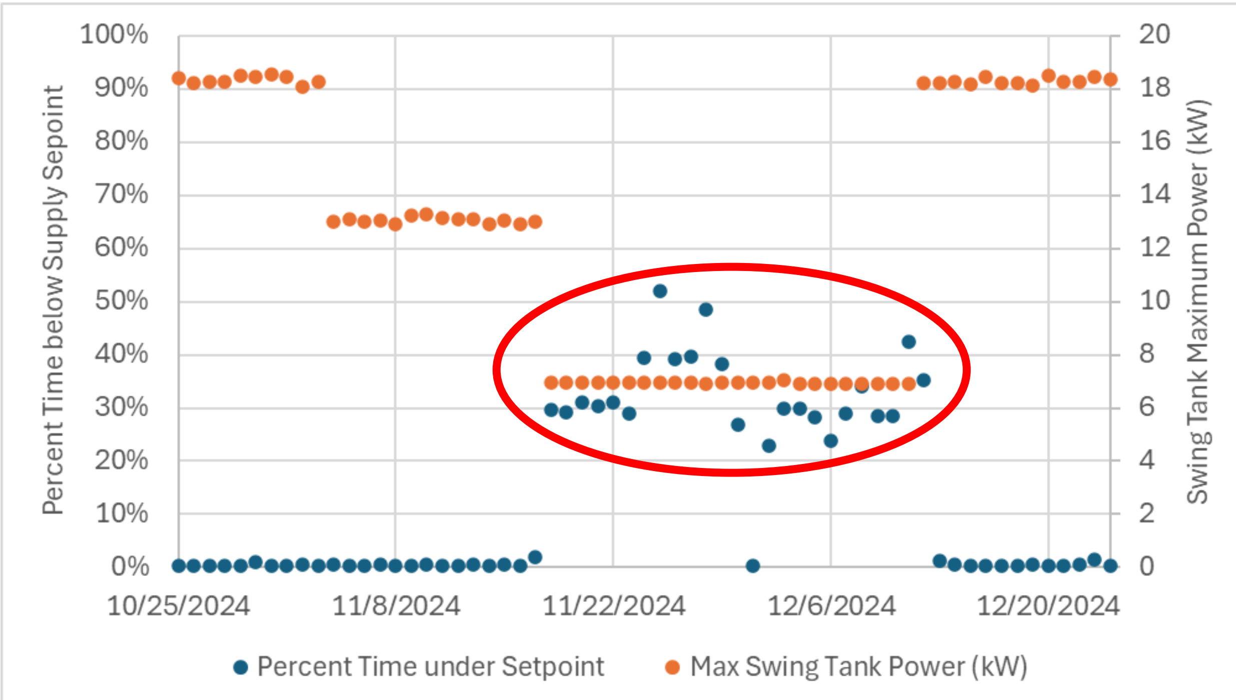

Figure 12: Site 1 swing tank issues.

At Site 2, the distribution system developed an issue during the study timeline as denoted by the red line in Figure 13. There was an increase in make-up water temperature, increased swing tank usage, decrease in return water temperature, and decrease in system COP from some event that occurred about halfway through the study timeline. Unfortunately, the root cause of the issue could not be identified and, again, the change in system operation prevented fair comparison to baseline weeks. The data from after this event had to be excluded. The team suspects there was a failure at a check valve or a crossover event that occurred, but this could not be confirmed.

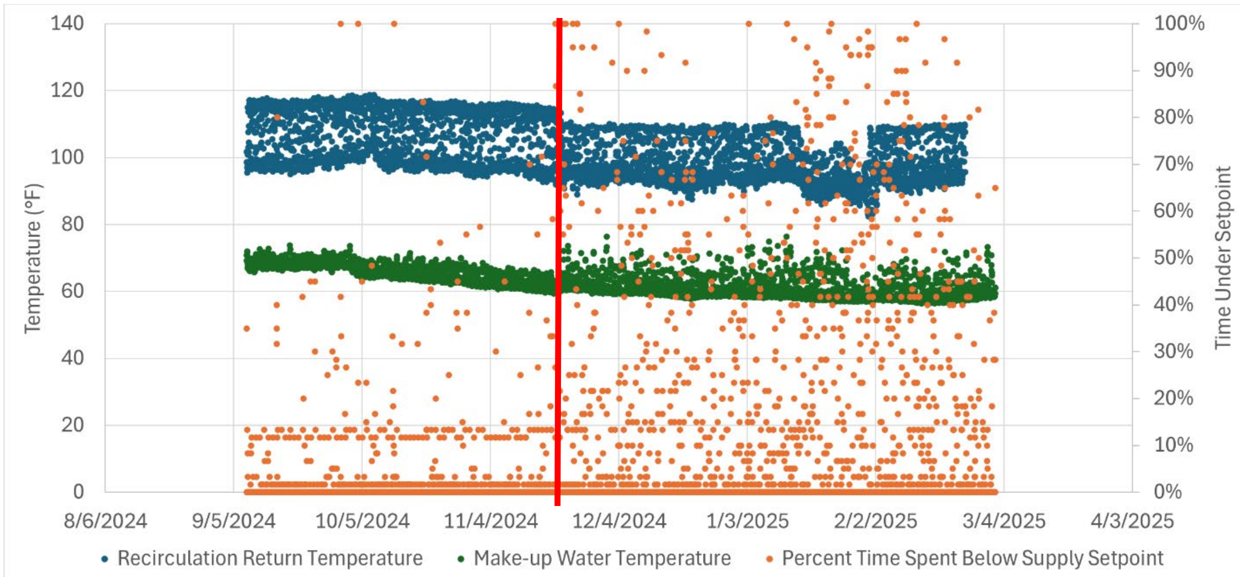

Figure 13: Site 2 distribution system issues.

These issues at both sites demonstrate the high sensitivity of CHPWH system performance and reliability to recirculation loads, temperature maintenance, and distribution system function. Even small failures or changes to those systems can have large impacts on CHPWH performance, reliability, and benefits. This is especially relevant to systems that are of swing tank configuration; return-to-primary CHPWHs would likely not have such negative responses to these events.

Other than these issues, both sites continued to operate as expected and as observed in the previous study, ET22SWE0017. Site 1 continued to have a high recirculation load but otherwise operated well, with daily COPs between 2.0 and 2.7 and an overall swing tank energy usage of about 45 percent. Site 1 had a lower COP and higher swing tank energy fraction than expected due to ongoing high recirculation losses and low recirculation temperatures that have persisted since 2022.

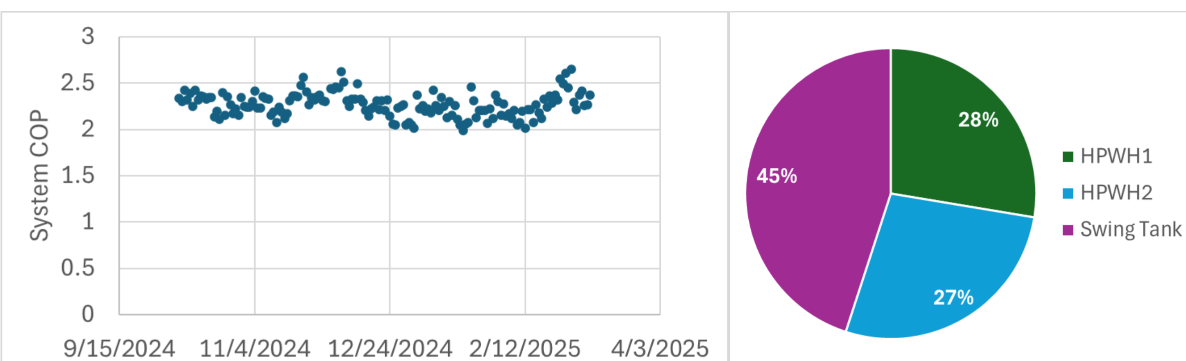

Figure 14: Site 1 daily COP and energy pie

Site 2 had daily COPs between 2.7 and 3.3. The overall average COP was 3.0 before the observed distribution system event and 2.7 afterward. The overall swing tank energy fraction was only 10 percent, about what would be expected for a well-functioning CHPWH system.

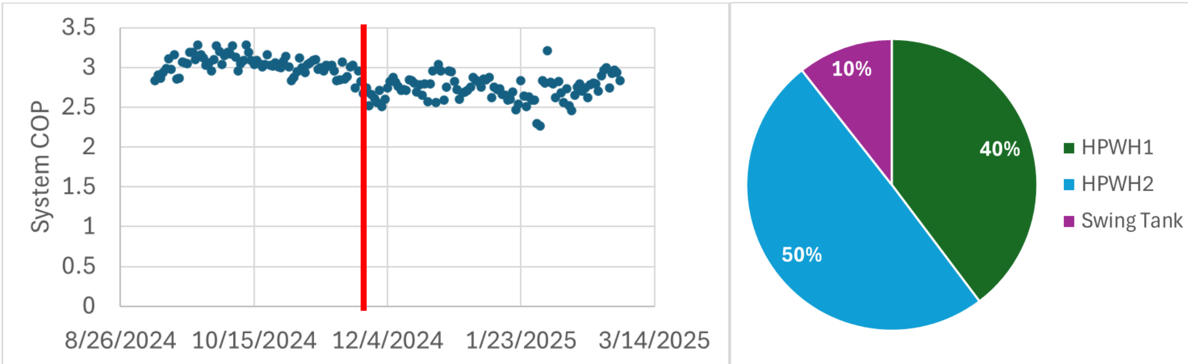

Figure 15: Site 2 daily COP and energy pie

Comparing equipment energy consumption over the average day is a useful means of visualizing impacts of load shifting controls. For examples of this, Figure 16 shows the energy consumption of each heat source in the system (heat pumps and swing tank) over the average day in baseline operation, Schedule 1 (without staging or lockout), Schedule 2 (least aggressive with staging and lockout), and Schedule 7 (most aggressive with staging and lockout). The plots clearly show additional runtime of the HPWHs during the load up hours and effective reliance on only a single heat pump for the entire shed period due to staging and swing tank lockout.

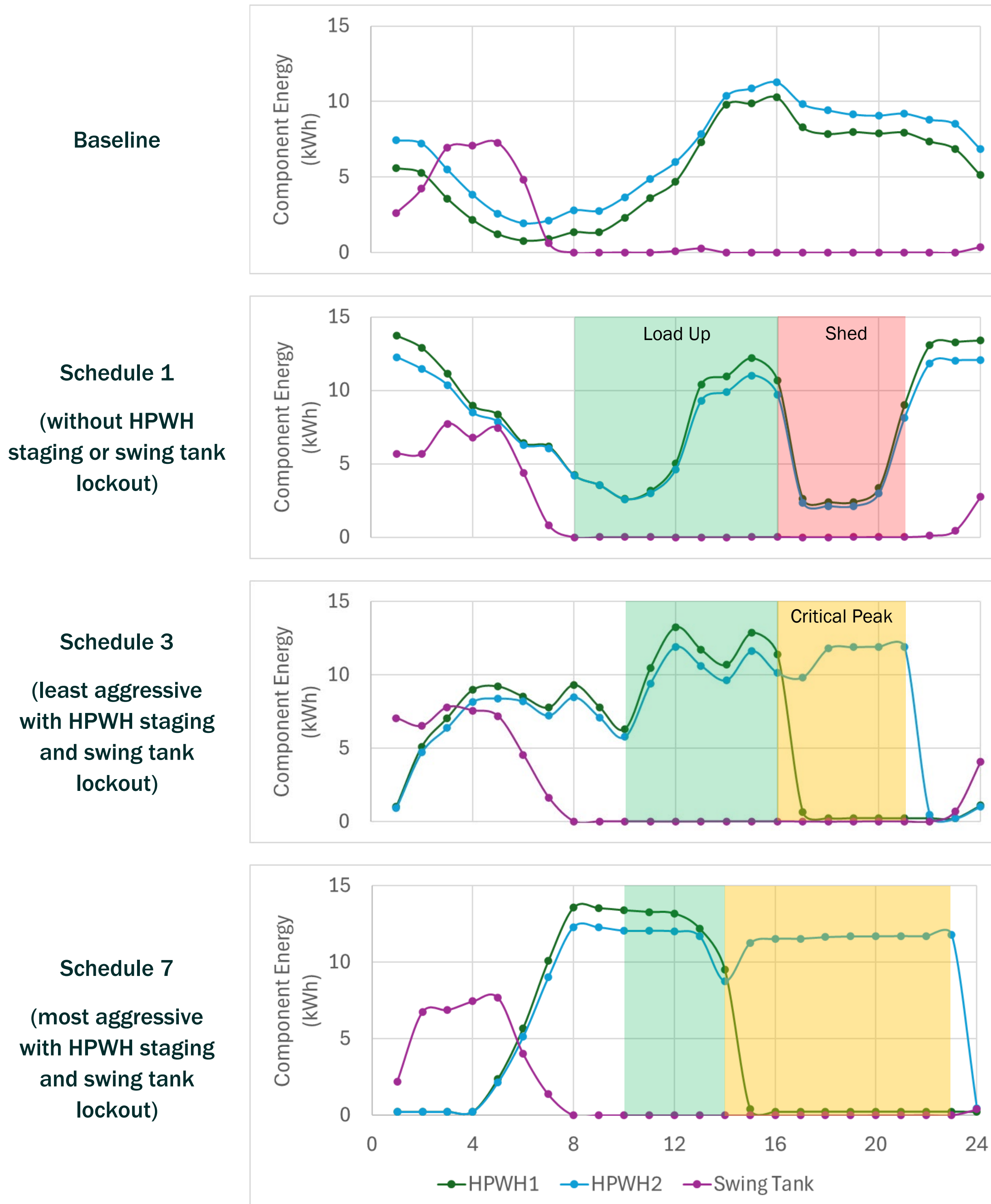

Figure 16: Site 2 HPWH and swing tank energy consumption across average Baseline, Schedule 1, Schedule 2, and Schedule 7 (least to most aggressive).

Combined with utility rate schedules, hourly GHG factors, and hourly TSB factors, these representative days for each site and each test schedule allow for calculation of load shift impacts over a calendar year. Table 9 and Table 10 show the results of load shift testing for each test schedule at each site, compared to their normal, baseline CHPWH operation. At Site 1, the most aggressive load shift, Schedule 7, achieved up to 24 percent of shifted peak and partial-peak energy, 65 percent peak demand reduction, 16 percent annual energy cost savings, 5 percent GHG reduction, and 4 percent improvement in TSB. It is important to note that each metric may be maximized by a different strategy and schedule.

Table 9: Site 1 Load Shift Impacts[3]

Load Shift Schedule	On-Peak Energy Shift (kWh/day)	On-Peak and Part-Peak Energy Shift (kWh/day)	Net Daily Energy Savings (kWh/day)	On-Peak Demand Reduction (kW)	Utility Cost Savings ($/yr)	GHG Impacts (tons CO_2e/yr)	TSB Impacts ($/yr)
1	39.5 (58%)	-1.0 (-1%)	-37.5 (-13%)	4.9 (11%)	$2,428 (5 %)	-0.36 (-4%)	$1,539 (15%)
2	37.0 (55%)	-2.2 (-2%)	-50.8 (-18%)	-0.7 (-2%)	-$1,754 (-3%)	-0.90 (-10%)	$728 (7%)
3	23.7 (35%)	22.6 (21%)	-18.9 (-7%)	12.9 (29%)	$2,884 (6%)	0.71 (8%)	$867 (9%)
4	22.9 (34%)	22.3 (20%)	-21.4 (-8%)	14.6 (33%)	$3,335 (7%)	0.74 (8%)	$755 (7%)
5	10.3 (15%)	27.5 (25%)	-27.9 (-10%)	29.1 (65%)	$9,713 (19%)	0.09 (1%)	$162 (2%)
6	10.3 (15%)	28.3 (26%)	-15.9 (-6%)	29.2 (65%)	$8,558 (17%)	0.14 (1%)	$314 (3%)
7	9.5 (14%)	26.0 (24%)	-9.3 (-3%)	29.0 (65%)	$7,860 (16%)	0.47 (5%)	$360 (4%)

[3] Positive values indicate reduction and savings; negative values indicate increases and penalties.

Not all planned schedules could be tested at Site 2 due to the compromising event in the distribution system that occurred part-way through the study. Several load shift schedules were tested prior to this event. The most aggressive load shift, Schedule 7, achieved up to 33 percent of shifted peak and partial-peak energy, 52 percent peak demand reduction, 10 percent annual energy cost savings, 12 percent GHG reduction, and 13 percent improvement in TSB.

Table 10: Site 2 Load Shift Impacts[4]

Schedule	On-Peak Energy Shift (kWh)	On-Peak and Part-Peak Energy Shift (kWh)	Net Daily Energy Savings (kWh)	On-Peak Demand Reduction (kW)	Utility Cost Savings ($/yr)	GHG Impacts (tons CO_2e/yr)	TSB Impacts ($/yr)
1	53.6 (62%)	68.8 (43%)	-21.9 (-7%)	-8.9 (-32%)	-$1,781 (-4%)	0.25 (2%)	$3,029 (24%)
3	27.7 (32%)	53.6 (33%)	-54.1 (-17%)	14.9 (53%)	$2,578 (5%)	-0.40 (-4%)	$1,013 (8%)
4	36.4 (42%)	68.0 (42%)	-7.7 (-2%)	14.9 (53%)	$4,759 (10%)	0.50 (%5)	$2,284 (18%)
6	27.0 (31%)	52.6 (33%)	-20.0 (-6%)	14.8 (53%)	$4,222 (9%)	1.19 (11%)	$1,708 (14%)
7	27.2 (31%)	53.6 (33%)	-24.9 (-8%)	14.5 (52%)	$4,819 (10%)	1.35 (12%)	$1,680 (13%)

While these results were very successful, the team expects even more benefits could likely be realized in further iterations with more aggressive and further optimized control sequences.

[4] Negative values indicate reduction and savings; positive values indicate increases and penalties.

Discussion and Recommendations

The tested load shift strategies were very successful at reducing energy costs, reducing GHG emissions, and improving TSB. The load shifting measures demonstrated the ability to reduce customer energy costs by up to 19 percent, reduce GHG emissions by up to 12 percent, and increase TSB by up to 24 percent, although not necessarily all at the same time. The CHPWH systems were able to deliver these impacts without increasing the risk of over cycling the heat pumps or compromising hot water availability.

While load shifting capability is generally considered an eligibility requirement by utility programs for new HPWH systems, it is not consistently applied or commissioned in the field. Even if an installed system is capable of load shifting, there is little supporting evidence that it is being implemented successfully as standard practice. This study demonstrates the benefits of load shifting in CHPWH systems and serves as a precedent and motivation for future implementation. Even simple tuning of load shift settings to match TOU rate periods is sufficient to deliver value to the building owner, ratepayers, the environment, and utilities.

There are some key topics worth discussion:

- In swing tank CHPWH configurations, small failures in recirculation management can lead to significant electric resistance usage and negatively impact system efficiency and COP. Therefore, monitoring, management, remediation, and preventative maintenance of the distribution and recirculation systems are very important for realizing maximum CHPWH benefits. These risks can also be reduced with return-to-primary system designs. However, return-to-primary systems are currently uncommon and the industry needs appropriate sizing tools and demonstrations. A key stumbling block to advancing return-to-primary options is Underwriters Laboratories (UL) 60335-2-40, which restricts the use of R-290 (propane) refrigerant severely, even in outdoor, factory-sealed installations. California can address this significant market barrier by updating the California Mechanical Code with a proposal similar to Washington State's 24-GP1-113, which allows International Electrotechnical Commission (IEC) certification as an alternative pathway to UL for certain applications and equipment. Such a mechanical code update would significantly benefit domestic heat pump manufacturing and allow for high performing return-to-primary CHPWH systems – as well as other applications outside hot water.
- The effectiveness of load shifting strategies can vary between sites due to differences in storage volume, load profiles, control settings, building characteristics, and hot water draw patterns. While site-specific tuning can optimize performance, HPWH load shifting is valuable in aggregate, and therefore the focus for market transformation should be on (1) identifying and promoting standardized load shift controls that provide the most significant benefit on average and (2) improving the cost-effectiveness proposition for building owners. The path forward should reduce the need for costly, intensive customization for every installation while still achieving substantial positive impacts.
- Commissioning load shifting controls in CHPWH systems currently requires specialized expertise and can be labor-intensive due to complex programming interfaces on some equipment. This is not a scalable market approach. Manufacturers should be incentivized and

guided to incorporate standardized, easy-to-use load shift control sequences directly into their products. This could be done through updated code requirements like Joint Appendix 13 and industry standards, for instance. This should include standard adjustments for control sensor inputs, temperature setpoints, turn-on/turn-off logic, and staging inputs for each heating source including both primary HPWHs and temperature maintenance heaters. Controls must accept EcoPort requests - Normal, Shed, Load Up, etc. - to trigger pre-defined EcoPort modes, simplifying setup and reducing human error.

- Utility rate structures, particularly those with high demand charges, can counteract the intended benefits of load shifting if not carefully managed, potentially increasing customer energy costs even when other operational goals are met. While the project successfully developed control strategies to mitigate demand charge impacts, this adds complexity. The most effective long-term solution involves utility rate reform towards structures that better support load-flexible buildings, such as energy-based real-time pricing or time-of-use rates with minimal demand charges. These could be specific to electrified buildings or include submetering of large electrification retrofit systems, perhaps. Utilities could also explore options like staggered pricing schedules for specific feeders if snapback after aggregated load shedding is a concern.
- While manual programming of load shift schedules is currently feasible, a more advanced and scalable approach involves automated adjustments. Future systems should leverage the standardized controls built into CHPWHs, allowing EcoPort universal communication modules (UCMs) to automate mode adjustments. These UCMs can be programmed with algorithms like those developed at Berkeley Lab to interpret real-time pricing and select the appropriate pre-programmed EcoPort mode (Woo-Shem 2025). This approach combines simple, reliable onboard controls with sophisticated external logic for optimization. It supports security and site-specific customization by storing the control logic on the UCM rather than in the cloud.
- Different metrics for evaluating load shift success - customer energy cost, system operational efficiency, GHG emissions, and TSB - may not always align under current conditions. Continued efforts towards utility rate structures or real-time pricing that better reflect overall system benefits and GHG emissions can help align these metrics.
- Effective load shifting and energy savings require smartly designed monitoring and automated alarming to ensure continued performance. Providing maintenance contractors with enhanced visibility into system operation through robust training, onsite documentation, online technical support, and accessible monitoring platforms is essential for diagnostics, preventative maintenance, and ensuring long-term performance.
- Observations from the study indicate that shorter "load up" periods such as one to two hours were generally sufficient to prepare for extended "shed" periods. Additional research, self-learning control algorithms, and load shift commissioning tests can be used to understand how to best minimize pre-emptive energy use while ensuring adequate stored hot water.

Recommendations for future work include:

- **Automated Load Shifting:** Scale and test real-time pricing-driven load shifting by having EcoPort UCMs, loaded with appropriate algorithms, adjust standardized EcoPort modes of CHPWHs in multifamily applications. Provide a standard commissioning test on all sites. Monitor the systems and analyze the aggregate as well as individual performance. Compare actual performance to commissioning test performance.
- **Continued Load Shift Testing:** Continue testing and demonstrating load shift strategies across a wider variety of sites and applications, CHPWH products, storage volumes, and temperature maintenance designs such as return-to-primary configurations. Use these individual studies to understand different hot water applications other than multifamily and CHPWH system designs.
- **Standards Development:** Continue the development of standard load shifting control requirements and recommendations[5]. Include these protocols, which adjust controls based on EcoPort requests, into relevant standards, such as JA13, to ensure reliable and consistent load shifting capabilities in the market. Define requirements for manufacturer controller inputs to be load shift compliant and incentivize only manufacturers who comply.
- **Refine Sizing & Modeling Tools:** Create a free online web tool for sizing return-to-primary systems. Current tools only support swing tank designs which, along with code barriers around R-290, have resulted in more swing tank configuration CHPWH deployments. Use empirical results from this and other studies to refine and validate CHPWH sizing tools and load shift modeling software.
- **Recirculation and Distribution System Performance:** Characterize the state of distribution systems in the existing building stock and current maintenance practices. Identify monitoring solutions, remediation guidelines, maintenance practices, and program pathways that can support the minimization of distribution system losses and degradation. This will save energy in and of itself regardless of hot water system type but is also important for the sustained realization of full CHPWH system benefits.

[5] The California TECH incentive program shows standard control requirements on the simulation webpage - https://ecosizer.ecotope.com/sizer/annualsim/. These controls are validated by research funded by CalNEXT, BPA, and NEEA.

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