Packaged Central CO_2 Heat Pump Water Heater Multifamily Demonstration

Final Report

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Acknowledgements

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Executive Summary

Central heat pump water heaters are an emerging product class essential to the efficiency and decarbonization of the multifamily and commercial building sectors. Central heat pump water heaters will have a key role in efficiency program portfolios, addressing one of the largest energy-consuming end-uses in the California building stock. Water heating, alone, accounts for around 45 percent of energy usage in multifamily buildings in California (U.S. EIA 2023a). Reliable, cost-effective heat pump water heaters are necessary for the market transformation and greenhouse gas emission reduction of this impactful end-use.

While some configurations of central heat pump water heaters in the early stages of market adoption driven by energy program support are feasible and reliable, there are many questions to be answered and product improvement opportunities. These opportunities include first cost reduction, program design choices, product refinement, and load shift optimization. Central heat pump water heaters are relatively expensive and can have high operating costs and electrical grid implications, as any electrification measure does. The minimization of these barriers is essential to equitable, beneficial adoption. One promising path to reducing costs is through the offering of packaged products that simplify the design, installation, and procurement process while streamlining the overall supply chain.

This report presents the background, methodology, and findings of a field demonstration of packaged, carbon dioxide (CO_2) central heat pump water heaters installed at two neighboring multifamily buildings in Menlo Park, California. The project team added instrumentation to the systems for performance monitoring and implemented load shift controls. Assessment of the energy usage, greenhouse gas impacts, and total system benefit bolster previous findings of similar systems at other sites. The well-commissioned system reduced greenhouse gas emissions by 86 percent and provided total system benefits of 61 percent as compared to a natural gas code baseline alternative, with some room for additional improvement. These installs were among the very first instances of this new product. Since these were among the first, the project team was able to identify some opportunities for improvement which will yield even further benefit to building owners, utility programs, manufacturers, and installers.

At the same time, the installing contractor stated that it was “the simplest water heating system [they] have put in” and “highly would recommend the product.” The simple nature of the packaged product avoids the risk premium pricing of more custom, site-built alternatives and reduces the extended learning curve that installers and contractors face as they facilitate the market transformation towards central heat pump water heater use. The fact that the installing plumber loved the product despite it being a new experience shows that a packaged, simplified product can make it more possible to scale central heat pump water heater adoption more quickly and with fewer supply chain barriers.

Table 1 below lists verified efficiency impacts over a calendar year as compared to an equivalent, code-efficiency natural gas alternative. Results were calculated for several different regimes depending on occupancy level and swing tank temperature setpoint. The full occupancy results are shown in the table, one for Building 1 at a final, reduced swing tank setpoint and one for Building 2 with an elevated swing tank setpoint. The Building 1 average annual coefficient of performance of

2.9 represents the expected system performance; the COP of 2.3 at Building 2 shows an example of the energy penalty that can be expected if a swing tank is set too high. These efficiencies and annual impacts are similar to previous findings at equivalent multifamily central heat pump water heating systems in California.

Table 1: Efficiency and annualized impacts of central heat pump water heaters over gas system baseline.

Building and Regime	Annual Coefficient of Performance[1]	Greenhouse Gas Emissions Reduction	Total Grid System Cost Reduction[2]	Energy Cost Increase
1 (extrapolated full occupancy, low swing tank setpoint)	2.9	86%	61%	88%
2 (actual full occupancy, high swing tank setpoint)	2.3	83%	51%	135%

1 – Rated system coefficient of performance is 3.2.
2 – Also known as Total System Benefit.

One key finding is that central heat pump water heater systems in swing tank configurations may have significant energy penalties in new construction projects while building occupancy is increasing. This energy penalty could also manifest in the retrofits of existing buildings if the building occupancy is also well below the design point with many vacant units. During these low load periods, the system energy consumption can be dominated by the electric resistance swing tank instead of the high-efficiency heat pumps. This can be exacerbated by certain commissioning and design decisions such as high swing tank setpoints and poor recirculation return water balancing. Control measures or the elimination of the swing tank may also help alleviate this transient energy penalty. Future instances of the product will and are incorporating the opportunities for performance improvement that were identified in this study.

Load shift performance was also tested. Building 1 did not yield useful load shift data due to partial building occupancy, high swing tank energy, and low hot water flow impacts on primary storage tank stratification. However, several schedules were tested successfully at Building 2. Tested schedules were effective at shifting energy, up to 52 percent of the energy during peak hours. This load shift capability resulted in about a 4.9 percent greenhouse gas emission reduction and a 15.6 percent improvement in total system benefit. However, the customer operating energy cost benefits of load shifting were less pronounced than a previous study primarily due to rate structures. Since these sites did not have peak demand charges in their rate schedule, the customer energy cost benefits are reduced and do not reflect the greenhouse gas and total system benefits to the grid and society.

Some recommendations for product improvements, further study, program design, and commissioning include the following:

- Inclusion and proper commissioning of a balancing valve on the recirculation return line, a feature that is now being included in more recently produced units. This should be present on any central heat pump water heater system.
- Easily controllable swing tank setpoints set at a minimum, a feature that will be included in future production. This, too, should be present for any central heat pump water heater system with a swing tank.
- Attentive monitoring of transient performance of the system as new construction building occupancy grows, with possible recommissioning after reaching full or steady state occupancy, as needed. Monitoring and fault detection diagnostics features could be of particular use in these situations.
- Development and testing of packaged, skid-mounted solutions without a swing tank or in return-to-primary configuration.
- Programs and utility rates should be designed to reward building owners for the energy efficiency impacts that are being realized with central heat pump water heater systems. The well-commissioned system delivered substantial impacts but at a customer energy cost increase of 88 percent over a natural gas system. Rate structures and programs should be designed to deliver cost savings to the building owner for heat pump water heating with well-functioning load shift controls.

Acronyms

Acronym	Meaning
AWHS	Advanced Water Heating Specification
CHPWH	Central heat pump water heater
CO_2	Carbon dioxide
COP	Coefficient of performance
CTA	Consumer Technology Association
GHG	Greenhouse gas
gpm	Gallons per minute
GWP	Global warming potential
HPWH	Heat pump water heater
IOU	Investor-owned utility
IPMVP	International Performance Measurement and Verification Protocol
kWh	Kilowatt-hour
M&V	Measurement and verification
OAT	Outside air temperature
PG&E	Pacific Gas and Electric
TSB	Total system benefit

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Introduction

This study is an evaluation of packaged central heat pump water heaters (CHPWH) installed at two California multifamily buildings. The air-to-water heat pumps use low-global warming potential (GWP) carbon dioxide (CO_2) as a refrigerant and are factory-built in a packaged system to be delivered to the sites on skids. These water heating systems serve two separate building loops and were installed during the construction of a new multifamily building complex in Menlo Park, California, with start-up in the summer of 2024. With the support of the CalNEXT program, the project team saw this as an opportunity to study the emerging technology in situ.

The project team collaborated with the building owners and heat pump equipment manufacturers to add measurement, data collection capabilities, and load shifting to the system. The project team used this data to quantify system performance, energy efficiency benefits, market potential, and electrical load management capacity. This project adds to the growing body of knowledge on CHPWH product performance and load shifting. This body of knowledge is setting the stage for market transformation and optimized program channels to the benefit of utilities, multifamily and commercial building stakeholders, and the hot water industry.

Background

Domestic hot water has one of the largest energy footprints of all residential end-uses in the United States. According to the Energy Information Administration, domestic water heating accounts for about 32 percent of site energy consumption in multifamily buildings with five or more units across the country (U.S. EIA 2018a). Across the individual California multifamily building responses in the 2020 Residential Energy Consumption Survey, this figure is about 45 percent of total site energy usage (U.S. EIA 2023a). Hot water demand in multifamily buildings is often satisfied by one or more centralized systems, as opposed to distributed water heaters in every unit. There are a wide variety of design choices and conditions in the existing building stock, but these typically include:

- A heat source, historically almost always direct-fired natural gas in California, but also can be electric resistance, steam, or other alternative fuels.
- Hot water storage in one or more pressure-rated vessels, i.e., tanks.
- Continuous pumped recirculation through a distribution piping network that includes one or more loops to maintain hot water supply in proximity to end-uses — e.g., showers and sinks — and branch take-offs to the dwellings.
- Recirculation pump speed or flowrate controls based on load parameters such as occupancy schedules, pressure setpoints, or return temperature.
- Mixing valves that can temper hot water supply with cold water for delivery of hot water at the desired temperature setpoint.

As the project team reported in a previous CalNEXT report, central water heating systems in existing low-, medium-, and high-rise multifamily buildings account for about 1.9 million residences in

California (Valmiki, Sweek, et al. 2023).[1] There are about 12 million residences served by central water heaters nationwide. In this existing building stock, gas central water heaters essentially cover the entire market, with new construction adding to the size at a growth rate of about 1.2 percent per year in California (Pande, et al. 2022). While recent Title 24, Part 6 code language makes CHPWHs in new multifamily buildings more attractive from a compliance standpoint, they are not mandatory, and gas systems still dominate.

The existing nonresidential market size served by central water heaters is more difficult to quantify using publicly available information; the team estimated that the existing opportunity is about 50 percent that of the multifamily market in terms of installed capacity (Valmiki, Sweek, et al. 2023). These nonresidential buildings that commonly have central domestic hot water (DHW) include hospitality, education, and healthcare buildings. However, the overall hot water loads per building are typically much lower, as most DHW usage occurs at home.

Central heat pump water heaters are a promising alternative to the incumbent gas systems. Commercially available CHPWH products are relatively new to the market and adoption is slowly starting to occur through code measures and program support, mainly in new construction. Program support is still very much needed to encourage market transformation. In both retrofit and new construction scenarios, the electrification of central water heating with heat pump technology can save large amounts of energy, reduce greenhouse gas (GHG) emissions, and provide total system benefit[2] (TSB) over just about any baseline alternative such as electric resistance, gas, propane, or steam. Existing literature and similar multifamily field testing suggest that the energy savings are around 68 percent over gas baseline equipment (Valmiki, Sweek, et al. 2023). This would, in turn, avoid around 85 percent of the GHG emissions and 50 percent of total system costs in California in comparison to natural gas alternative central systems (Valmiki, Sweek, et al. 2023). The potential across the entire market is huge, made accessible by economies of scale where replacing a single system can impact tens or hundreds of homes. The potential avoidable GHG emissions through CHPWH installations in California alone could be around 1.7 million tons per year.

Central heat pump water heaters come in various configurations based on the underlying equipment and design choices, including how the temperature in the hot water distribution loop is maintained, what heat pump is selected, how the storage tanks are arranged, and other engineering decisions. For instance, a heat pump could use a low-GWP natural refrigerant such as CO_2 — i.e. R744 — or could use R513A, with implications on operating temperatures and other variables. The system could maintain the temperature in the hot water distribution loop when loads are low with a dedicated electric resistance tank, also known as a “swing tank,” or be arranged in a return-to-primary configuration if the heat pump can serve low load periods of the day. Additionally, the system could be sized to accommodate load shifting or not. These choices, along with other options, are all factors in the engineering specification process and are truly unique across individual installations at the current time. Over time, standardization and emerging best practices are likely to simplify and streamline these decisions. Regardless, these systems are being proven to operate with large

[1] This previous CalNEXT report for ET22SWE0017 includes more comprehensive market and technology details that could be referred to for additional context and background.

[2] TSB is a valuation of benefits of a measure expressed in dollars that captures the impacts on GHG emissions, grid transmission costs, grid distribution costs, generation costs on an hourly basis (CPUC 2023).

energy, emissions, and societal benefits in all cases. Figure 1 and Figure 2 below illustrate a simplified representation of common CHPWH configurations (CEC 2022) (PG&E, SCE, SDG&E 2022).

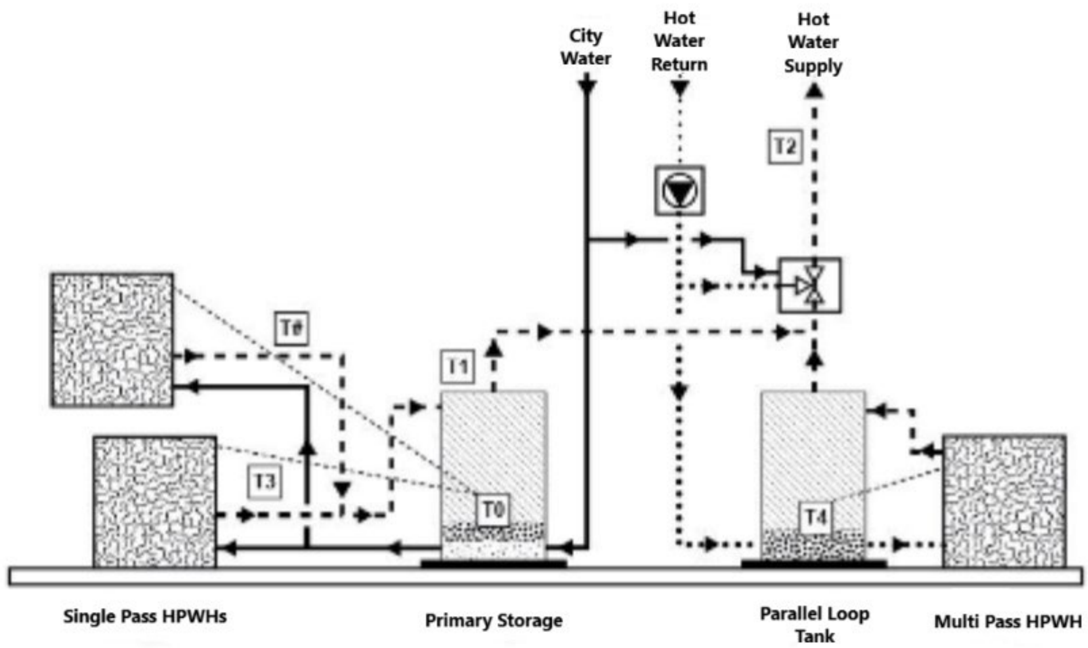

Figure 1: Parallel multi-pass heat pump water heater temperature maintenance configuration.

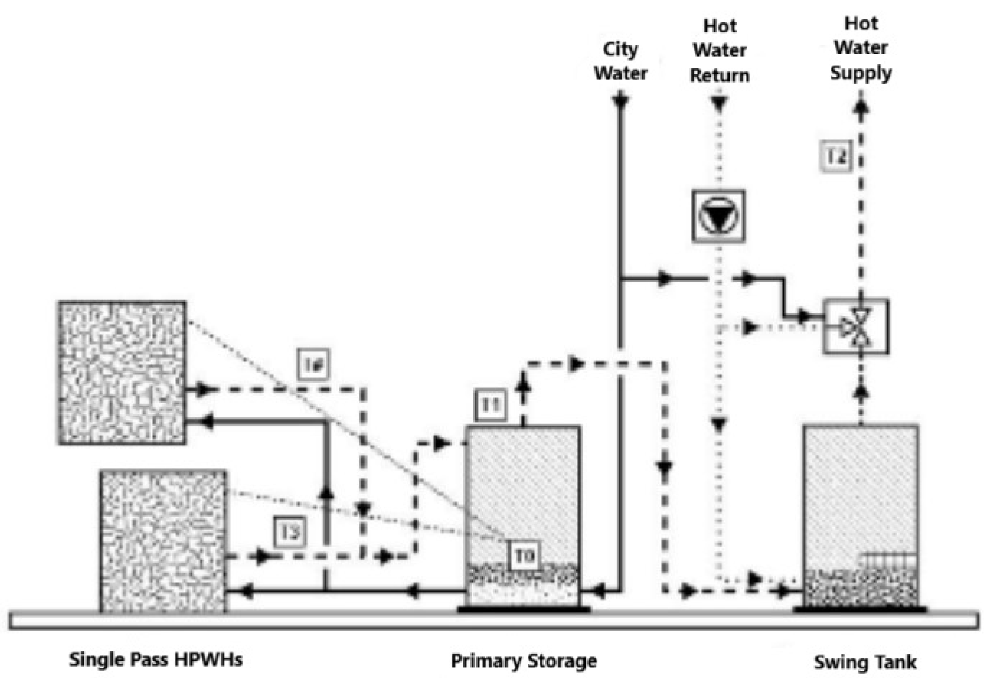

Figure 2: Series electric resistance swing tank temperature maintenance configurations.

However, these benefits and high-tech water heating products do come at a cost premium with installed project costs between $1,500 and $6,300 per residence (Valmiki, Sweek, et al. 2023). For equitable, natural adoption, stakeholders need to find ways to reduce costs. One such way is to offer packaged product lines. Highly custom, labor-intensive site-built systems will have much higher costs than factory-built, packaged skid-based products. As these systems become better understood, it will become easier for manufacturers to offer packaged products optimized for cost and efficiency while still offering enough flexibility in factory options that can satisfy most of the market. An appropriately specified packaged CHPWH can be delivered on a skid with all plumbing, electrical, and control interconnections simplified, offering the installer a nearly plug-and-play installation. Packaged systems will not only cost less but also reduce the number of parties involved in any given project. Simplifying the supply chain to a single, responsible entity — the manufacturer — will also reduce overhead, project complexity, and system maintenance.

These expected benefits have been motivating for manufacturers in product development. However, given the complexity, uncertainties, and emerging nature of this market, there are few packaged solutions available. Only two manufacturers with packaged systems are currently listed on the Advanced Water Heating Specification (AWHS) Qualified Product's List as of 2024 (Northwest Energy Efficiency Alliance 2024). Note that one of these two has since changed and been rebranded with different distribution channels and thermal storage design (Valmiki, Spielman, et al. 2024). More products are expected to come to market as packaged solutions and these should ultimately be an important cost-effective path to market adoption in many, if not most, cases.

Load shifting offers another promising path toward cost reduction, as it can lower operating expenses while also mitigating impacts on the electric grid and infrastructure. Through the informed specification of storage volume, controls parameters, and time-of-use rate schedules, a CHPWH can maximize stored heat during lower-cost times of the day and use it to reduce operation or peak electrical demand during high-cost times.

There are numerous ongoing studies conducting field demonstration and optimization of this necessary feature; for example, previous work by this project team has shown load shifting capacity of up to 60 percent during daily peak time-of-use periods, reduced operating costs by up to 19 percent, and reduced GHG emissions up to 12 percent (Valmiki, Sweek, et al. 2023) (Valmiki, Johnson, et al. 2025). Central heat pump water heaters will add electrical load to the grid and peak period costs are especially impactful on building owner billing; load shifting will eventually have to become a standard, straightforward, reliable feature as this product class matures.

In general, CHPWH adoption barriers include (Opinion Dynamics 2022) (NBI 2023):

- Higher first cost and complexity than similarly sized gas-fired equipment.
- Limited subject matter expertise among design and construction firms.
- Uncertainty surrounding energy cost parity or savings relative to natural gas systems.
- Long lead times and low availability of CHPWH equipment.
- Distribution systems and recirculation losses in existing buildings, which may require remediation for enabling cost-effective CHPWH implementation.
- Site-level electrical infrastructure constraints, e.g., utility service, circuit, or panel limitations.
- Inaccessible installation locations, e.g., pathways for storage tanks in existing buildings.

- Limited physical space for storage tank arrays or heat pump units requiring sufficient ambient air, e.g., external placement.
- Few field demonstrations and case studies.
- Unknown long-term performance, useful life, and lifetime maintenance burden.
- Lack of load up and shed control best practices, testing, and benefits of load shifting.

Objectives

The project team conducted a field demonstration to gather data that helps address these barriers to market transformation and informs recommendations for engaged stakeholders. This study explores uncertainty around packaged system performance, costs, and load shifting capacity. Field demonstrations such as this one are necessary to increase market confidence and gather data for use in future product improvement, program design, and standards development of this emerging product class.

The study's objectives are:

1. Characterize the energy performance of two packaged CO_2 central heat pump installations through comprehensive measurement and verification (M&V).
2. Assess energy, cost, and GHG impacts relative to a natural gas baseline system.
3. Assess the total packaged measure cost compared to historical site-built CHPWH average costs.
4. Implement load shifting controls and assess their performance.
5. Validate past estimates of total potential California market potential.
6. Develop conclusions and recommendations for manufacturers, designers, utilities, and program administrators toward increased market adoption.
7. Survey building developers and contractors on packaged system design and its impacts.

Methodology and Approach

The field demonstration was carried out at two new construction buildings in Menlo Park, California. Each building had four separate CHPWH systems which were among the first of their kind ever produced by the manufacturer. The study conducted measurement, load shifting, and analysis at one system at each building. Comprehensive monitoring at various points in the system collected data on one-minute intervals. The project team used this data to observe performance and analyze impacts of the technology in situ. The following sections describe the test sites, data collection, and analysis fundamentals.

Test Sites

The host sites are two new construction, luxury multifamily buildings located in Menlo Park, California, with 15 percent of the residences designated as affordable housing. Each building has a mix of studio, one-, two-, and three-bedroom apartments with one or two bathrooms. Both buildings were designed with CHPWHs specified in the building plans with separate packaged units for individual recirculation loops, each serving roughly 56 residences. Building construction was completed in the summer of 2024. Building 2 reached full occupancy by March 2025; however, Building 1 remains at roughly 50% occupancy over a year after the start of leasing and over the analysis period. These building profiles are shown in Table 2 below.

Table 2: Host site descriptions.

Building Attributes	Building 1	Building 2
Year built	2024	2024
Number of residences	56 (13 studio, 37 one-bedroom, four two-bedroom, two three-bedroom)	56 (13 studio, 37 one-bedroom, four two-bedroom, two three-bedroom)
Approximate current number of residents (percent occupied)	40 (48%)	80 (95%)
Stories	7	7
California Climate Zone	3	3

Figure 3, Figure 4, and Figure 5 show one of the water heating systems located on the building rooftop. Each system includes two packaged skids with storage tanks, controls, and plumbing located inside the enclosures and heat pump banks mounted on the outside. Additionally, each skid has four heat pumps mounted to the outside, plumbed in parallel for a total of eight heat pumps per system. Combined, the two skids for each hot water system have four storage tanks: three primary storage tanks and one swing tank. Figure 5 shows some of the complex plumbing, tanks, and controls located in the enclosures which were assembled at the factory. In a site-built case, all this assembly would have to occur on site based on custom engineering plans at a higher cost.

Figure 3: Packaged CHPWHs on rooftop.

Figure 4: Heat pump banks mounted on side of packaged unit.

Figure 5: Swing tank and plumbing located inside packaged unit.

Table 3 lists the specifications and components of the packaged system, each comprising two connected packaged skids. The expected efficiency in total system coefficient of performance (COP) for the site’s Climate Zone is about 3.2 based on the AWHS Qualified Products List documentation.

Table 3: Host site CHPWH system.

CHPWH System Details	Per Hot Water System
Number of HPWH units	8
Per-unit HPWH rated capacity (Btu/h)	15,350
Total system HPWH capacity (Btu/h)	122,800
Rated COP	3.2
Storage tank quantity, excluding swing tank	3
Storage capacity, excluding swing tank (gal)	855
Swing tank capacity (gal); power (kW)	120; 9

Figure 6 shows plumbing line diagrams of the installed system, with selected M&V datapoint locations circled in red, which are further identified in Table 4. The three primary storage tanks are plumbed in series with supply and return from the heat pump water heater (HPWH) banks which themselves are plumbed in two parallel banks of four heat pumps. The swing tank is installed in series with the primary storage volume, located between the hot outlet side of the primary storage tanks and the mixing valve. The mixing valve tempers the system hot water to the distribution supply temperature as needed. Initial designs included a balancing valve to direct a small proportion of the return flow to the bottom of the swing tank while sending the remainder directly back to the recirculation supply; however, this component was not included in the final skid design.

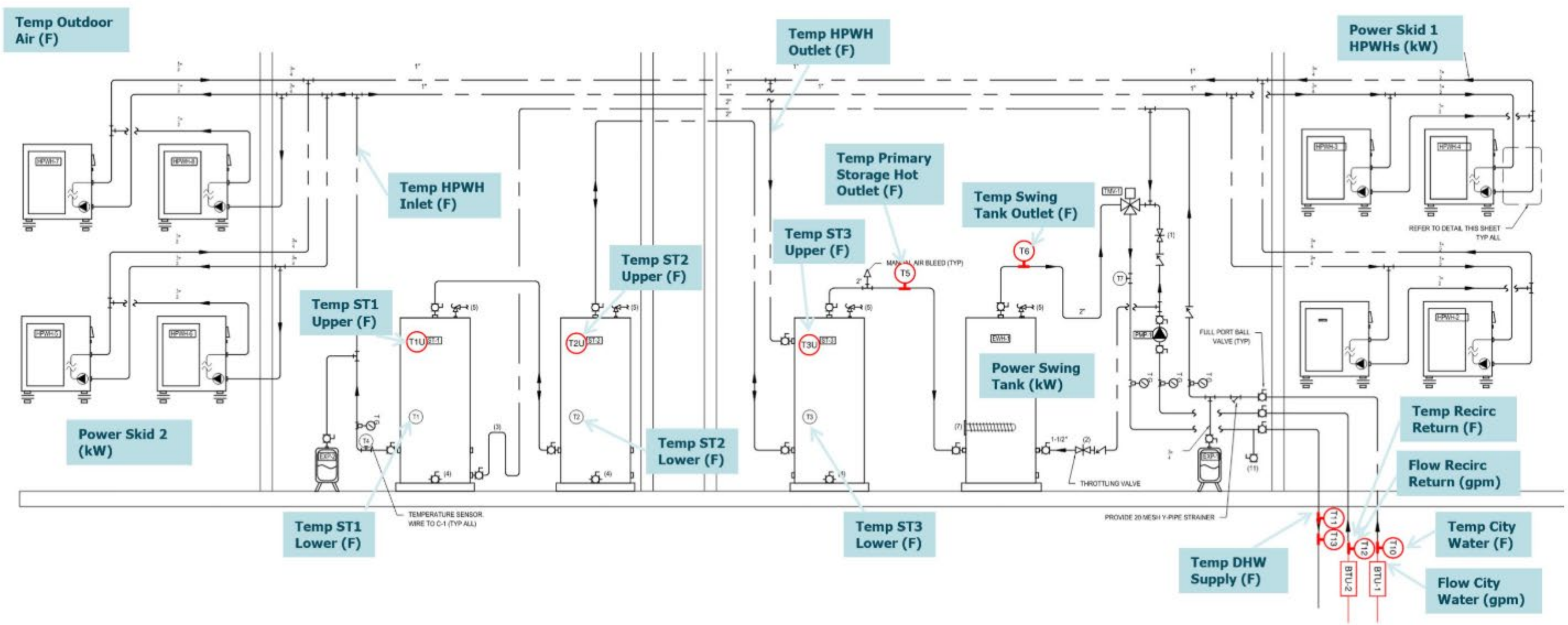

Figure 6: Central heat pump water heater diagram.

The installing plumbing contractor provided a total system installed cost of about $175,000 per skid system which equates to an installed cost of about $3,125 per apartment. This cost per apartment is in line with the range of cost data from other project reporting but 40 percent less than a similar custom site-built system in a retrofit scenario (Valmiki, Sweek, et al. 2023). These units, being of the very fist produced by the manufacturer, are likely to come down in cost as production and adoption ramp up.

M&V Planning and Datapoints

The project team developed a measurement plan that would gather data sufficient for assessment of the installed CHPWH systems based on Option B, otherwise known as retrofit isolation with all parameter measurement, of the International Performance Measurement and Verification Protocol (IPMVP). This measurement plan also follows the approach outlined in the AWHS Appendix H which aligns with IPMVP Option B (Northwest Energy Efficiency Alliance 2024). The selected datapoints consist of various power, temperature, and flow measurements as identified in Table 4 below. The team collected local outside air temperature (OAT) from National Oceanic and Atmospheric Administration (NOAA) weather station data for the nearby San Carlos Airport.

Table 4: Measurement points.

Point Description	Instrument Type	Instrument Model
Incoming city water temperature and flow (°F and gpm)	Btu meter	ONICON SYS-40-150-010-162
Recirculation supply temperature and flow (°F and gpm)	Btu meter	ONICON SYS-40-340-010-161
Storage tank upper and lower temperatures (°F)	Thermistor	Carel NTC
Heat pump water heater inlet temperature (°F)	Thermistor	Carel NTC
Primary storage outlet temperature (°F)	Thermistor	Carel NTC
Swing tank outlet temperature (°F)	Thermistor	Carel NTC
Recirculation return temperature (°F)	Thermistor	Carel NTC
Swing tank power (kW)	Power meter	Dent Powerscout 3
Packaged system power (kW)	Power meter	Dent Powerscout 3
Outdoor air temperature (°F)	NOAA hourly data for San Carlos Airport weather station	

Load Shift Testing

The water heater controls do not come standard with load shift programming, so the project team worked with the manufacturer to add operating modes and setpoints for load shifting capacity. Three operating modes were programmed: normal, load up, and shed. Normal mode represents typical operation that would occur at all hours without any intervention, load up maximizes the stored heat in the volume, and shed allows the storage volume to more fully deplete before the heat pumps turn back on. By loading up during lower-cost times of day, the system can coast without heat pumps turning on during shed mode at higher-cost times of day, thereby lowering operating costs and grid impacts.

The three operating modes are defined by the following setpoints in Table 5, custom-implemented by the project team based on project experience. Note that custom staging of the heat pumps was considered but was not possible at the time with the product control system. However, the system does have some inherent staging that could not be changed. The first bank of four heat pumps turns on when the “on setpoint” is reached, while the second bank of four heat pumps turns on if the sensor reads 6°F below the setpoint. This should inherently limit peak demand under some load conditions. This staging is limited however and, if technically feasible, further staging logic would like have additional benefits from an energy perspective. Load shift testing did not include lock-out controls on the swing tank.

Table 5: Load shift control modes.

Mode	Operation mode	On sensor height	On setpoint	Off sensor height	Off setpoint
1	Normal	40%	121°F	10%	122°F
2	Load up	10%	106°F	10%	122°F
3	Shed	75%	131°F	75%	135°F

The project team tested the load shifting capacity of the system with the schedules shown in Table 6 below. Load shift schedule signals were sent through CTA-2045 remote communication hardware at the beginning of each test week, similar to third-party load management program standard practice.

Table 6: Load shift test schedules.

	Operating Mode per Hour of Day																							
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
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	3	3	3	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	3	3	3	3	3	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	3	3	3	1	1	1

Note: green=normal, orange=load up, blue=shed.

Calculations

The measured data will be used to evaluate the system efficiency defined by the system coefficient of performance (COP_{sys}). The method for calculating efficiency follows the Boundary Method specified in the AWHS (Northwest Energy Efficiency Alliance 2024):

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

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

In this analysis, COP is presented as a daily value. The COP of a full day captures the overall system performance across the natural daily load profile including the cyclical draw down and recharge of the tanks and is therefore a useful minimum interval for representing overall system performance.

Energy usage is also compared to the theoretical consumption of an equivalent natural gas water heater with a code-minimum thermal efficiency of 80 percent. The natural gas usage for the baseline alternative is calculated with the following formula:

$$Natural\ gas\ usage = \frac{Primary\ Load + Recirc\ Load}{0.8}$$

For both electrical and natural gas energy usage, GHG, TSB, and customer energy cost can all be calculated on an hourly interval. The California Energy Commission publishes hourly GHG factors per unit energy while the California Public Utilities Commission publishes hourly factors system cost per unit energy which can be used to calculate TSB (CPUC 2024) (CEC 2025).

Energy costs were calculated for both natural gas and electric CHPWH scenarios on an hourly interval basis using the current PG&E rate schedules that the host site is enrolled in: Electric B-1 and natural gas G-NR1.

Findings

This section includes findings for the monitoring period, annualized impacts, and the instances of load shift testing.

Monitoring Period Performance

Data collection began in May 2024 with data stored on one-minute intervals for each of the points in Table 4. However, there were a few factors that required the separation of the datasets into several different regimes. First, monitoring was not fully, reliably functional until early 2025 due to some measurement equipment failures and extended timeframes that were needed to gain access to the sites for remediation and correction of measurement devices. At that point, hot water loads were still growing at both buildings as occupants continued to move in. The systems' efficiency and performance varied as the buildings' populations grew to an ultimate steady state. Finally, in one of the buildings, the swing tank temperature setpoint was intentionally decreased in cooperation with the project team; this resulted in a new commissioned state and impacted efficiency. Table 7 shows the time periods for each of these regimes. System performance was evaluated during each of these regimes. Winter data was not collected but the range of weather conditions over the monitoring period was sufficient to extrapolate confidently to cold weather extremes for the climate zone.

Table 7: Monitoring period regimes.

Regime	Building 1	Building 2
Monitored period	Feb 1 – Aug 25, 2025	Mar 17 – Aug 25, 2025
Transient occupancy period	n/a	Mar 17 – June 9, 2025
Steady state occupancy period (Estimated percent occupancy at steady state)	Feb 1 – Aug 25, 2025 (50%)	June 10 – Aug 25, 2025 (95%)
Steady state occupancy period at reduced swing tank setpoint	June 10 – Aug 25, 2025	n/a

It should be noted that future swing tank temperatures are likely to be commissioned more easily and at more appropriate temperatures from the start. These were among the first of their kind being installed and findings from this study will result in future improved, initial commissioned state. As such, the lower swing tank setpoints are more representative of expected operation and performance while higher swing tank setpoint regimes show the penalty of incomplete commissioning of that particular aspect of the system.

While the data during the ramp up to steady state occupancy can be useful for studying the impacts of partial loads on the system performance, steady state operation is the better regime for calculation of long-term performance. Under-occupied buildings will see the swing tank handle a larger portion of the temperature maintenance load. This shift will lead to a lower system efficiency and higher energy consumption by the swing tank. Results are presented in the context of these various occupancy and operating time frames.

Figure 7 shows the two regimes over the monitoring period at Building 1, both at steady state occupancy. On June 10, the swing tank setpoint was manually reduced at the recommendation of the project team. An unnecessarily high setpoint in the swing tank was reducing system efficiency. The COP clearly takes a step change higher after this date. This efficiency improvement opportunity from recommissioning would not have occurred without the teams intervention and performance monitoring.

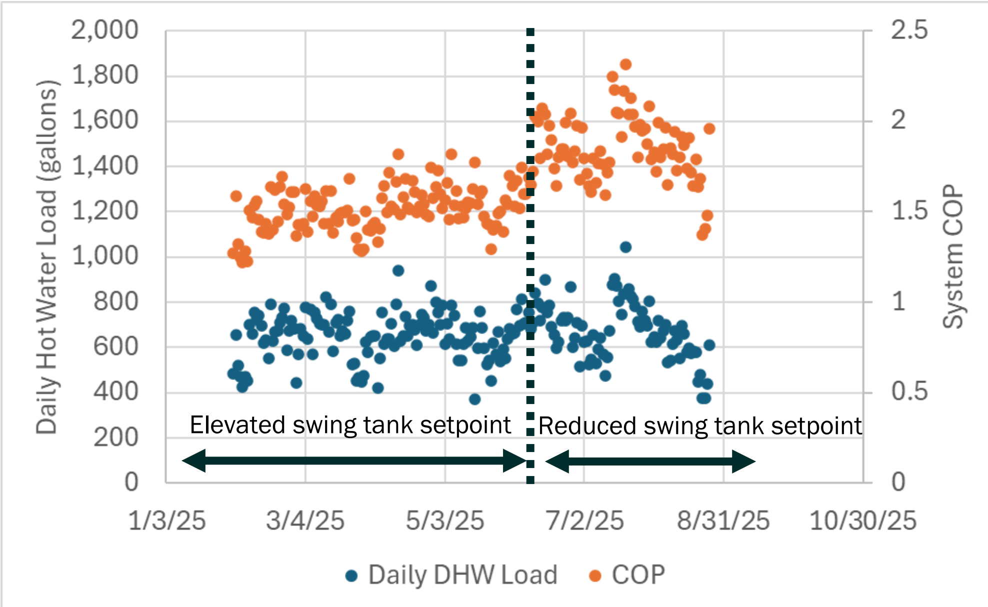

Figure 7: Building 1 measured hot water loads and system efficiency.

Figure 8 shows the two regimes over the monitoring period at Building 2, both at an elevated swing tank temperature setpoint. Both the daily hot water loads and system efficiency clearly plateau after occupancy growth stops.

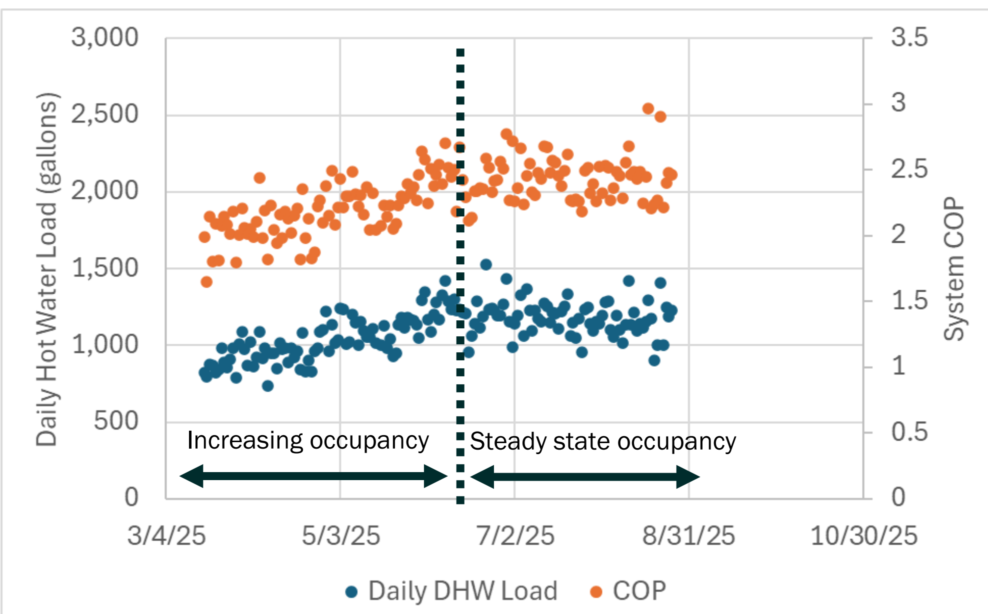

Figure 8: Building 2 measured hot water loads and system efficiency.

Temperatures and recirculation loads in both buildings were very consistent over the measurement period. Table 8 shows the observed temperatures and recirculation loads over the monitoring period. The recirculation loads per apartment are within expectations for a new construction building with a very reasonable seven-degree difference between the recirculation supply and return temperatures. Due to high swing tank temperature setpoints, high recirculation loads relative to total building load, and low occupancy at Building 1, the energy consumption was heavily biased towards the swing tank.

The team made several attempts to work with building staff to lower the swing tank setpoints, but interventions were unsuccessful until the manufacturer visited the site to perform the adjustment, themselves. Two primary factors contributed to the difficulty of this task. First, the adjustment required removing a large panel to access the controls, which necessitated two people. While this design may prevent building staff from using the swing tank setpoint as a “quick fix” for other system issues, it was a major obstacle in getting the system to proper baseline operation and prevented the commissioning agent from validating the setpoint during commissioning. Second, the swing tank controls are rudimentary and low-resolution, as is common with many electric resistance tank heaters, making it difficult for the user to have exact control of the minimum outgoing water temperature. The intended commissioning parameters specified that the swing tank should activate a single element when its on-board sensor drops below 122°F. However, the manufacturer was unable to lower the setpoint to confidently match the intended settings without risking drops in DHW supply temperature due to the controls’ lack of granularity and desire to avoid causing multiple heating elements to fire at once.

The installed systems also did not have balancing valves on the recirculation return system as was intended. AWHS guidelines recommend setting this balancing valve to direct the minimum possible flow back to the swing tank and maintain stable mixing valve operation when the system has no DHW demand. Instead, a single manually-adjusted ball valve on the recirculation return line to the swing tank was installed, but remained fully open, allowing unrestricted return water flow back to the swing tank. These factors resulted in swing tank energy consumption of 46 to 68 percent of total system energy, far exceeding a reasonable target of around 10 to 15 percent. Newer versions of the skidded product now include this balancing valve.

Table 8: System operating conditions.

Building and Regime	Recirculation Load (Watts/apt)	Supply Temp (°F)	Recirculation Return Temp (°F)	HPWH Outlet Temp (°F)	Swing Tank Setpoint[1] (°F)	Swing Tank Energy Fraction
1 (half occupancy, high swing tank setpoint)	53.5	124	117	145	143 (est.)	68%
1 (half occupancy, low swing tank setpoint)	51.7	124	117	145	133 (est.)	62%
2 (full occupancy, high swing tank setpoint)	59.9	124	117	145	143 (est.)	46%

1 – Swing tank temperature is estimated based on observations of the swing tank outlet temperature. Setpoint control knob did not have marked setpoint value to reference.

Emissions, TSB, and energy costs were calculated for the CHPWH systems over the monitoring period and compared to the energy that would be used for a code-minimum natural gas water heater under the same loads. Table 9 lists these results. Greenhouse gas emissions reductions and energy cost impacts were in line with previous findings at other sites. While GHG emissions are far less than those of a natural gas system, customer billing energy costs are far higher for the CHPWH system. This is driven by the difference in per-unit cost between natural gas and electrical energy service under current rate structures. Operating energy costs for the CHPWH system are far greater despite far less energy used.

Table 9: Impacts over the monitoring period.

Building and Regime	Days Monitored	Natural Gas WH GHG (tons)	CHPWH GHG (tons)	GHG Savings (%)	Natural Gas WH Energy Cost ($)	CHPWH Energy Cost ($)	Energy Cost Increase (%)
1 (half occupancy, high swing tank setpoint)	129	4.5	1.0	77%	1,521	5,283	247%
1 (half occupancy, low swing tank setpoint)	77	2.7	0.4	84%	858	2,823	229%
2 (full occupancy, high swing tank setpoint)	77	4.7	0.5	89%	1,492	3,744	151%

Annualized Performance

These monitoring period results were used to extrapolate performance and energy usage over a typical calendar year at the host site location. This annualization process included establishing regressions of the system efficiency and applying them to the hot water load shape for each regime, replicated over the entire calendar year.

Linear regressions for system efficiency of the following form were established based on the measured data:

$$COP_{sys} = a + b * GPD + c * OAT$$

where GPD is the hot water load in gallons per day and OAT is the average daily outside air temperature. Table 10 lists the coefficients for each linear regression. Note that these regressions are specific to these sites and should not be used to represent performance in other contexts. Additionally, the regressions only apply within reasonable bounds such as minimum and maximum weather year temperatures and up to a peak daily load that the building occupants would use.

Table 10: COP regression coefficients.

Building and Regime	a	b	c	R^2
1 (half occupancy, high swing tank setpoint)	0.720987	0.000944	0.005248	0.54
1 (half occupancy, low swing tank setpoint)	0.621315	0.001544	0.005566	0.82
2 (full occupancy, high swing tank setpoint)	0.336679	0.001118	0.012408	0.75

Figure 9 and Figure 10 show the agreement between the measured, daily COP and the regression value as a function of the measured GPD and average daily OAT.

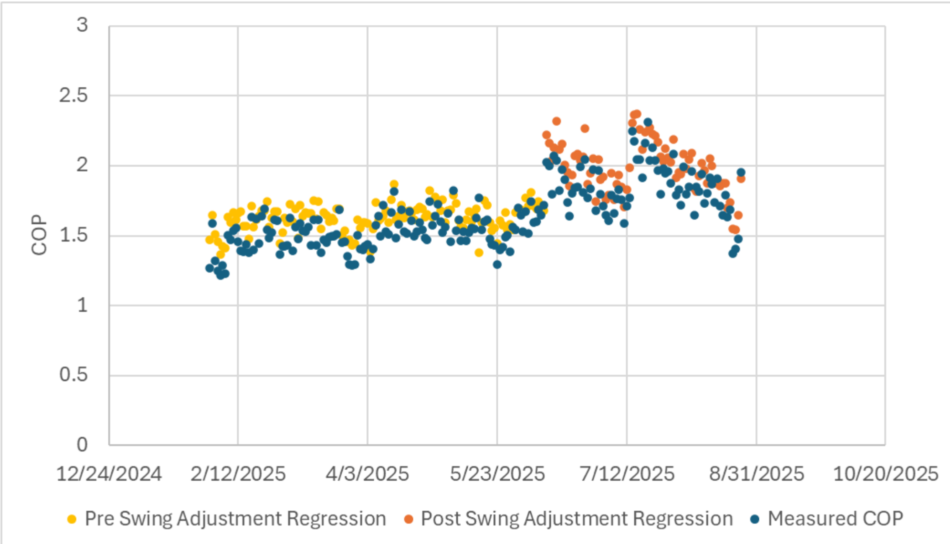

Figure 9: Comparison of measured efficiency and linear regression output for Building 1.

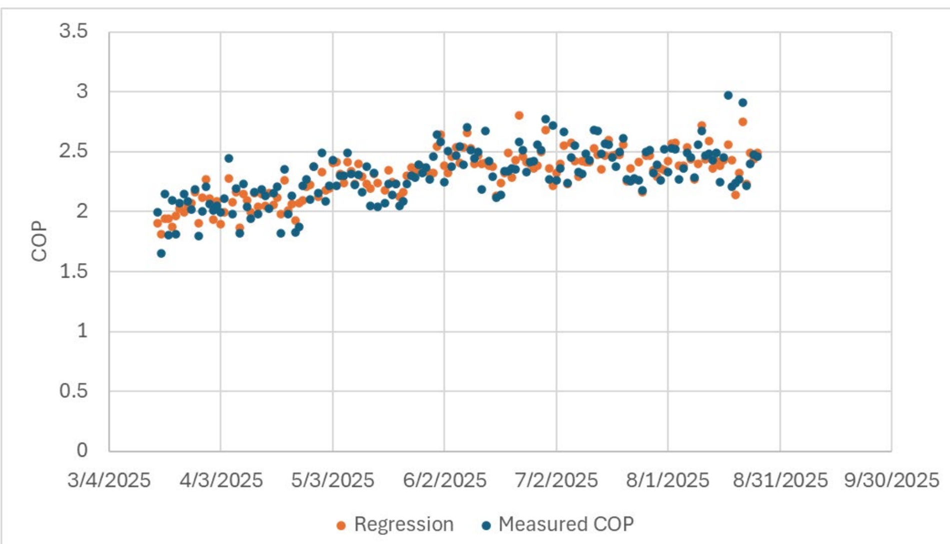

Figure 10: Comparison of measured efficiency and linear regression output for Building 2.

System efficiency was calculated for each day of the typical calendar weather year and measured load shape. This was done for each monitoring period regime as well as an extrapolated, full occupancy scenario at Building 1, defined as 95 percent occupied. Since Building 1 reached steady state around 50 percent occupancy during the monitoring period, an extrapolated full-load COP gives a perspective of how the system should operate in the future when the building is fully occupied. Building 2 was fully occupied after reaching steady state but remained at an elevated swing tank temperature setpoint. Table 11 shows the calculated average annual efficiencies after extrapolation of the measured data and regressions.

Table 11: Average annual system efficiency.

Building and Regime	Average Annual COP
1 (half occupancy, high swing tank setpoint)	1.5
1 (half occupancy, low swing tank setpoint)	1.8
1 (extrapolated full occupancy, low swing tank setpoint)	2.9
2 (full occupancy, high swing tank setpoint)	2.3

As noted earlier, the elevated swing tank setpoint is largely due to these being among the first of their kind. Future installs will likely be commissioned with more appropriate swing tank setpoints. Therefore, the extrapolated full occupancy state at Building 2 with an average annual COP of 2.9 should be considered the representative result. The COP of 2.3 at Building 2 will full occupancy reflects the energy penalty of having an elevated swing tank setpoint.

Figure 11 plots the system COPs on a daily interval over the typical calendar year. Note that if the swing tank temperature setpoint had been reduced at Building 2, the system efficiency would have risen close to that of the extrapolated values for full occupancy of Building 1.

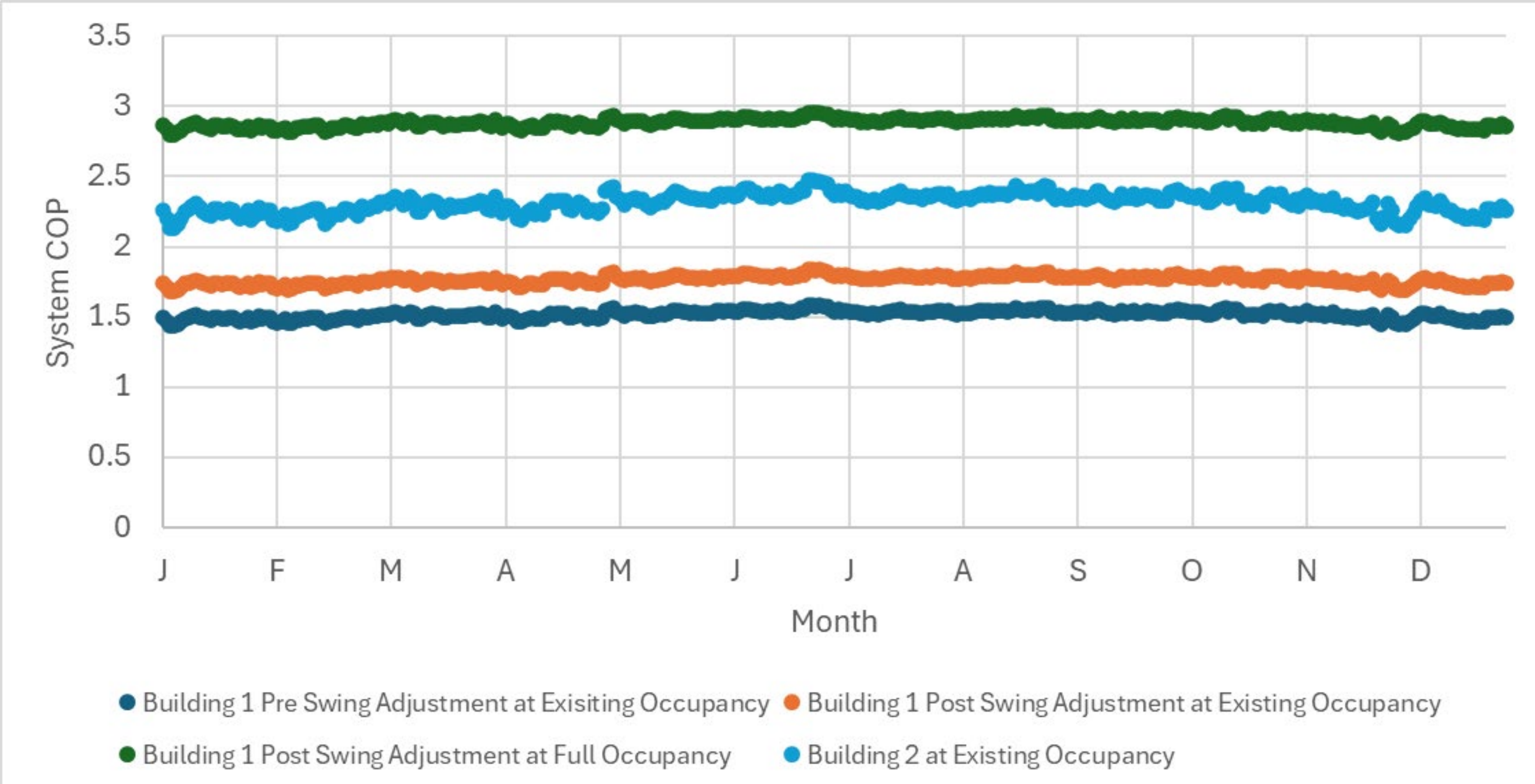

Figure 11: Annualized system efficiency at Buildings 1 and 2.

These annualized system efficiencies were applied to an hourly load profile over the calendar year to calculate estimated energy usage, GHG emissions, TSB, and customer energy costs. Table 12 shows these various annualized results for the whole building. As seen in the progression in Building 1 results from elevated swing tank setpoint to reduced swing tank setpoint to full occupancy, all impact metrics improve at each step.

Table 12: Annualized impacts for the entire building.

Building and Regime	CHPWH Energy (kWh/yr)	Natural Gas WH GHG (tons/yr)	CHPWH GHG (tons/yr)	GHG Savings (%)	TSB over gas baseline ($/yr)	TSB (% improvement over gas baseline)	Natural Gas WH Energy Cost ($/yr)	CHPWH Energy Cost ($/yr)	Energy Cost Increase (%)
1 (half occupancy, high swing tank setpoint)	36,187	12.8	3.3	74%	$1,010	24%	$4,288	$15,353	258%
1 (half occupancy, low swing tank setpoint)	31,107	12.8	2.9	78%	$1,446	34%	$4,288	$13,197	208%
1 (extrapolated full occupancy, low swing tank setpoint)	32,080	21.6	3.0	86%	$4,360	61%	$7,225	$13,595	88%
2 (full occupancy, high swing tank setpoint)	41,558	22.4	3.8	83%	$3,803	51%	$7,508	$17,610	135%

Table 13 shows these same annualized results on a per-occupant basis.

Table 13: Annualized impacts on a per occupant basis.

Building and Regime	CHPWH Energy (kWh/ person-yr)	Natural Gas WH GHG (tons/ person-yr)	CHPWH GHG (tons/ person-yr)	GHG Savings (%)	TSB over gas baseline ($/person-yr)	TSB (% improvement over gas baseline)	Natural Gas WH Energy Cost ($/person-yr)	CHPWH Energy Cost ($/person-yr)
1 (half occupancy, high swing tank setpoint)	905	0.32	0.08	74%	$25	24%	$107	$384
1 (half occupancy, low swing tank setpoint)	778	0.32	0.07	78%	$36	34%	$107	$330
1 (extrapolated full occupancy, low swing tank setpoint)	401	0.27	0.04	86%	$55	61%	$90	$170
2 (full occupancy, high swing tank setpoint)	519	0.28	0.05	83%	$48	51%	$94	$220

Load Shift Performance

The five operating schedules shown in Table 6 – one baseline and four load shift schedules - were tested for as many days as possible over the monitoring period. The team calculated average load shift shapes for Building 2 as seen in Figure 12 through Figure 15.

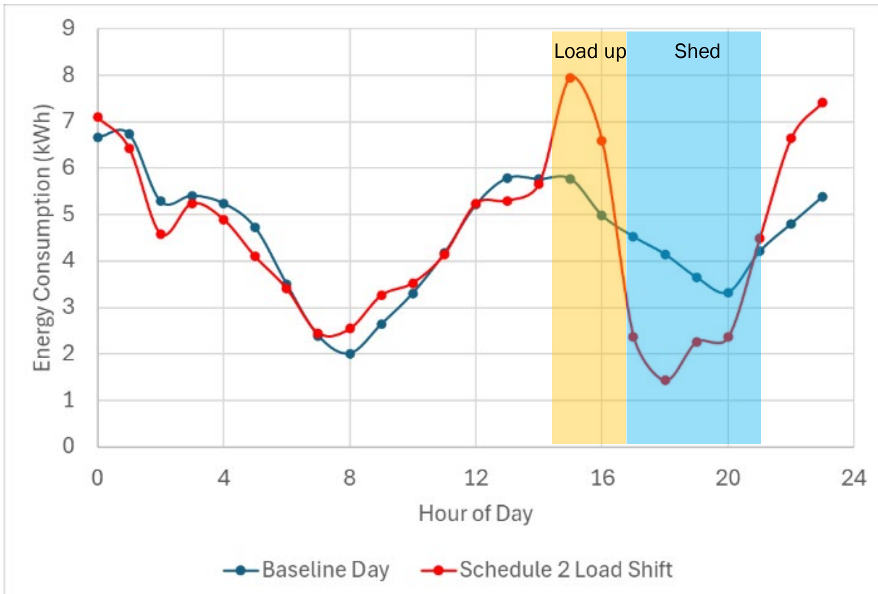

Figure 12: Load shift daily profiles for schedule 2 at Building 2.

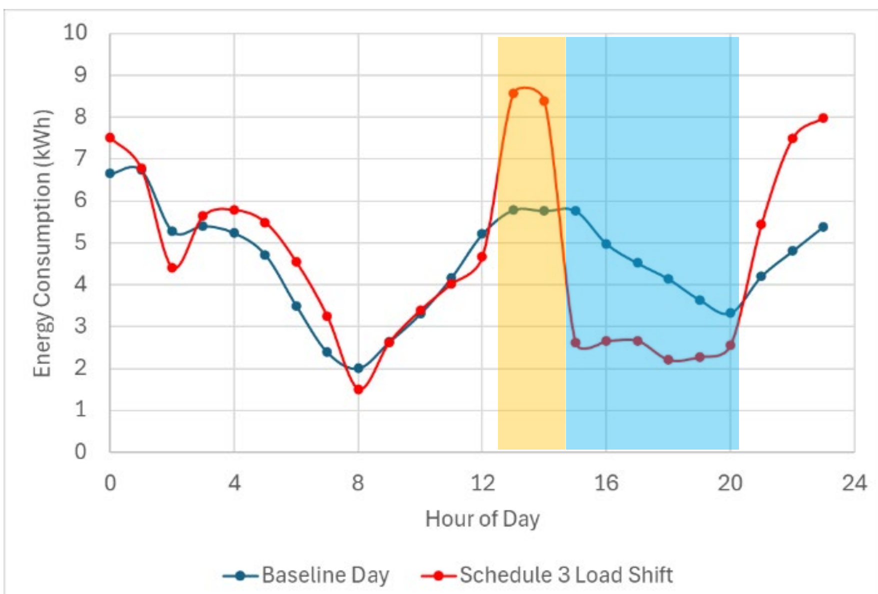

Figure 13: Load shift daily profiles for schedule 3 at Building 2.

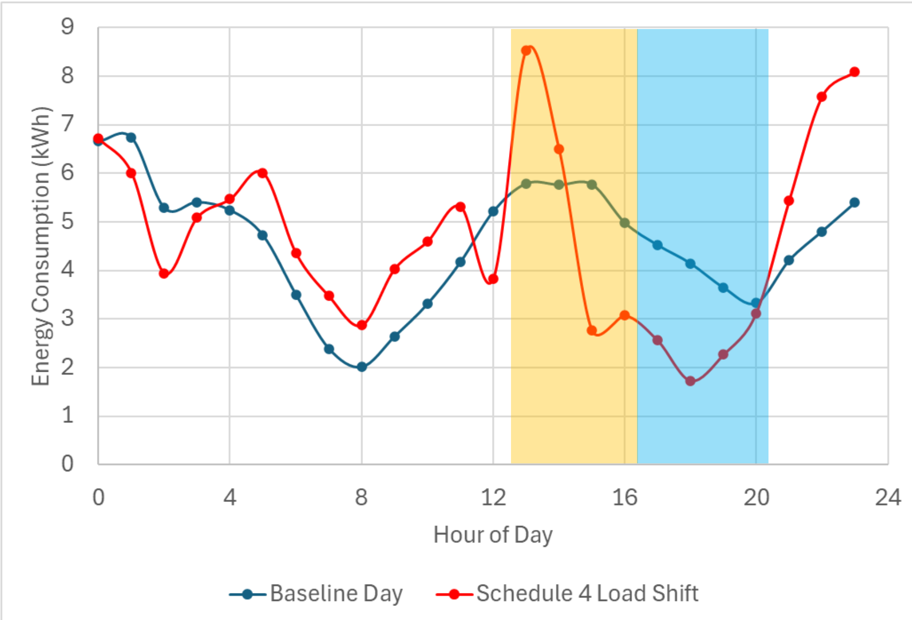

Figure 14: Load shift daily profiles for schedule 4 at Building 2.

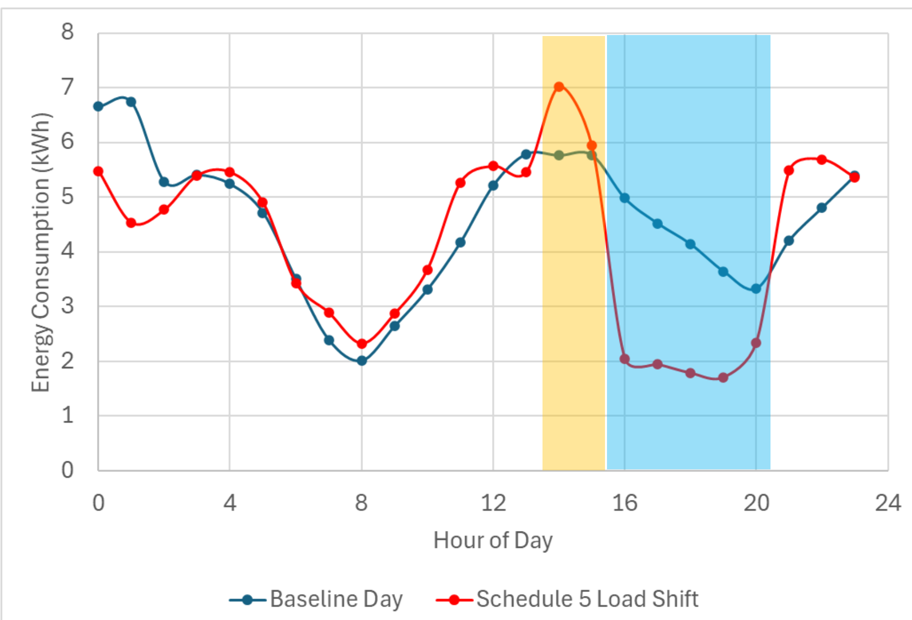

Figure 15: Load shift daily profiles for schedule 5 at Building 2.

Table 14 shows the amount of total system energy that was shifted out of the shed hours for each of the tested schedules and the impacts on energy cost, GHG, and TSB. The most successful shed of 52 percent occurred during the utility's peak hours of 4 PM to 9 PM, corresponding directly with the highest cost time of day. Note that the swing tank controls were not impacted by load shifting; locking out the swing tank could result in additional load shift benefits.

Table 14: Load shift impacts for Building 2.

Load Shift Schedule	Daily Energy Shifted out of Shed Hours	Customer Cost Savings ($/yr)	GHG Savings (ton-CO2e/yr)	TSB Savings ($/yr)
2	6.9 (35%)	$61 (0.3%)	0.13 (3.3%)	$517 (13.6%)
3	10.2 (33%)	$98 (0.6%)	-0.01 (-0.3%)	$513 (13.5%)
4	4.7 (24%)	$103 (0.6%)	0.08 (2.0%)	$578 (15.2%)
5	10.8 (52%)	$106 (0.6%)	0.19 (4.9%)	$593 (15.6%)

Unfortunately, poor cellular signal and outdated communication devices resulted in fewer instances of successful load shift days than anticipated. Despite retroactive improvements to communication protocol, demand response signals were often missed. Load shift testing was attempted at Building 1 as well. However, the lower occupancy and hot water loads resulted in largely unsuccessful tests, without any net overall impacts or reliable energy shift. The project team hypothesizes that this is a result of low flow through the primary storage and negatively impacted temperature stratification. The final, future full occupancy would likely result in a more successful, reliable load shift capacity as was observed in Building 2.

Conclusions and Recommendations

Overall, the system performed near its rated efficiency when extrapolated to full load conditions and with a reasonable swing tank setpoint. Under these conditions, the system was calculated to reduce GHG emissions by 86 percent and have a TSB of 61 percent over an assumed, equivalent, natural gas baseline system. These annual impacts are about the same as observed in another, similar configuration CHPWH retrofit in a custom design-build scenario at higher installed cost (Valmiki, Sweek, et al. 2023). This was all achieved at a per-apartment installed cost of about $3,125. However, this high-efficiency system was calculated to have an operating energy cost increase of about 88 percent. While this energy cost increase is less than seen in other studies, it is still a significant added burden to the end-users that needs further attention by technologists, energy programs, utilities, and regulators.

Some technology improvements are available. Including a balancing valve that correctly distributes return water to the swing tank and supply mixing valve would likely further improve performance. However, it was apparent that periods of low building occupancy and elevated swing tank temperatures both cause significant energy penalty and reduction of system efficiency. In comparison to a fully occupied state, the observed initial low occupancy of about 20 percent at Building 1 incurred an energy penalty of about 9,200 kWh over the first six months after the building was first opened to tenants due to reduced system efficiency at just the single CHPWH that was monitored. Assuming all four CHPWH systems at Building 1 had a similar extended period of transient low occupancy, the total building penalty would be four times this, equal to the consumption of about twelve average California households (U.S. Energy Information Administration 2020). While the energy penalties associated with low occupancy would likely resolve over time as the building is increasingly occupied and the impact would be small over the life of the system, perhaps there are steps that can be taken to help mitigate the consequences. Elimination of the swing tank, control measures, or other creative solutions may help reduce this transient low-occupancy penalty.

Load shift capacity was also found to be effective and could be even further improved with the addition of a swing tank lockout feature. Up to 52 percent of the peak demand energy was shifted to off-peak and partial-peak hours. This load shift results in a 4.9 percent reduction in annual GHG emissions and a 15.6 percent improvement in TSB. These load shift impacts are similar to what was observed in another similar non-packaged system (Valmiki, Johnson, et al. 2025). However, the calculated energy cost savings for the customer was only up to 0.6 percent of annual operating costs. This is quite different from past load shift study that observed an energy cost savings opportunity of up to 16 percent. This difference is likely due to rate structure differences. While this site has only time-of-use energy costs, other sites with additional peak demand charges have much higher energy cost benefit of load shifting.

Generally speaking, load shifting will have consistent GHG and TSB impacts regardless of energy rate context. However, customer energy cost benefits of load shifting are highly dependent on the rate schedule. Energy rate structures should minimize the cost to the customer and reflect the technologies benefits to utilities and society through appropriate rates. The combination of added electrical energy consumption, added peak demands, and load shift potential have a complicated interaction with different rate structures for both individual customers and in aggregate across the grid. Utilities, regulators, and programs should study this issue and determine feasible pathways to reduce the cost burden on customers who are adopting this beneficial technology. Energy incentive programs should continue to require load shifting as a daily, standard operating requirement but should perhaps further incentivize the feature to ensure building owners are receiving a share of the benefits that the grid, utilities, and society realize.

The installed, packaged products have some clear benefits over custom, design build solutions including lower costs. The packaged product simplifies the supply chain thereby simplifying customer technical support channels, maintenance protocols, and installation procedures. The installing plumbing contractor stated that the main benefit from their perspective is “the ease of installation.” They also stated that there were some small areas for improvement including “stub outs for water connections were not straight due to improper pressing of the fittings, stub outs were short and made soldering tough, there were lots of water leaks inside the skids, and the swing tank monitor could not be looked at without removing a panel which we did not want to do.” All these quality and design choice issues could easily be fixed at the factory, further streamlining and reducing the overall cost since they are otherwise issues that need more costly correction in the field. The installers stated that the heat pump package is “the simplest water heating system I have put in. Easy to install and there have not been any issues since installation. I highly would recommend the product if the customer is willing to pay a premium.”

While the systems monitored in this study provided valuable energy savings and GHG emission reduction, the team identified the following lessons learned and opportunities for improvement of system efficiency and load shift capability:

1. Always include a balancing valve on the recirculation return line to the swing tank and make sure that it is properly commissioned at start-up. While this item has since been added as a sheet note to the AWHS qualified piping configurations, it is easily missed and if it is not properly set at start up the system will incur a severe efficiency penalty (NEEA 2025).
2. Ensure that swing tank setpoints are set sufficiently lower than primary storage setpoints. The AWHS recommends a standard setpoint of 130°F. When possible, use equipment that has clear control displays such that the user can confidently select the desired setpoint. Furthermore, opt for swing tanks that have control temperature sensors in the top of the tank rather than the bottom.
3. Swing tank systems may be better suited for buildings that have a high probability of full occupancy, such as retrofits or low-income buildings. While Building 2 ultimately achieved full occupancy, Building 1 remains half empty more than a year after leasing began. This prolonged period of low occupancy leads to increased electric resistance usage, which offsets anticipated energy savings. Although a single year of lower efficiency might be acceptable over a system's 20-year lifespan, continued low occupancy poses a significant risk that the intended energy savings will not be fully realized.
4. Low occupancy can have a negative impact on total load shift capacity. Reduced hot water usage causes the primary storage tanks to be functionally oversized, which leads to reduced stratification and poor load shift performance. This condition also increases reliance on the electric resistance swing tank to maintain distribution temperatures. While this study did not include swing tank lock outs during load shift, a larger portion of the system's energy consumption was driven by the swing tank electric resistance heat, meaning that less of the total load could be shifted to off-peak periods. Primary storage should not be grossly over-sized for load shifting in buildings with low probability of full occupancy.
5. Load shift reliability was severely constrained by the cell network communication devices that were included on the system for the enabling of external load shift signaling. Many days of load shift signals did not receive any response from the CHPWH units or an incorrect response. While the hardware that was used is now an outdated model, reinforcing confirmation of load shift hardware reliability is needed in other ongoing studies. Programs that include load shifting as a requirement or adder may want to include confirmation or monitoring as part of their approval and evaluation process.
6. Load shift benefits could be improved by enabling more flexibility in the heat pump controls. For instance, more ability to stage the heat pumps could increase load shift impacts as would a swing tank lockout option.
7. Detailed monitoring, trending, and perhaps fault detection diagnostics can improve the value of CHPWH systems and ensure their benefits persist. Without the detailed M&V the team conducted, the low performance associated with the lack of balance valve, low occupancy, and swing tank setpoints may not have been identified. M&V that meets the minimum requirements of AWHS Appendix H is critical for the early installations of CHPWH systems and should be mandatory for installations receiving utility program support until product lines are more time-tested, mature, and reliable (NEEA 2024).

The team has confirmed that future instances of the particular product tested will have swing tank setpoint visibility, the necessary recirculation return water balancing valve, and commissioning that takes into account the findings of this study. These changes along with others observed over these early installs will result in improved, more reliable, more beneficial product lines as adoption increases. The fully packaged nature of the CHPWH system makes delivery of this highly-efficient product to early adopters simpler and easier to scale as market traction grows. This scalability, streamlining, and cost reduction will help building owners and utility programs realize greenhouse gas emissions reductions of 86 percent and TSB improvement of 61 percent over the dominant natural gas alternatives during these early stages of market transformation.

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Appendix – Average Daily Profiles

Figure 16, Figure 17, and Figure 18 show the average daily profile for the three steady state occupancy regimes at the two buildings.

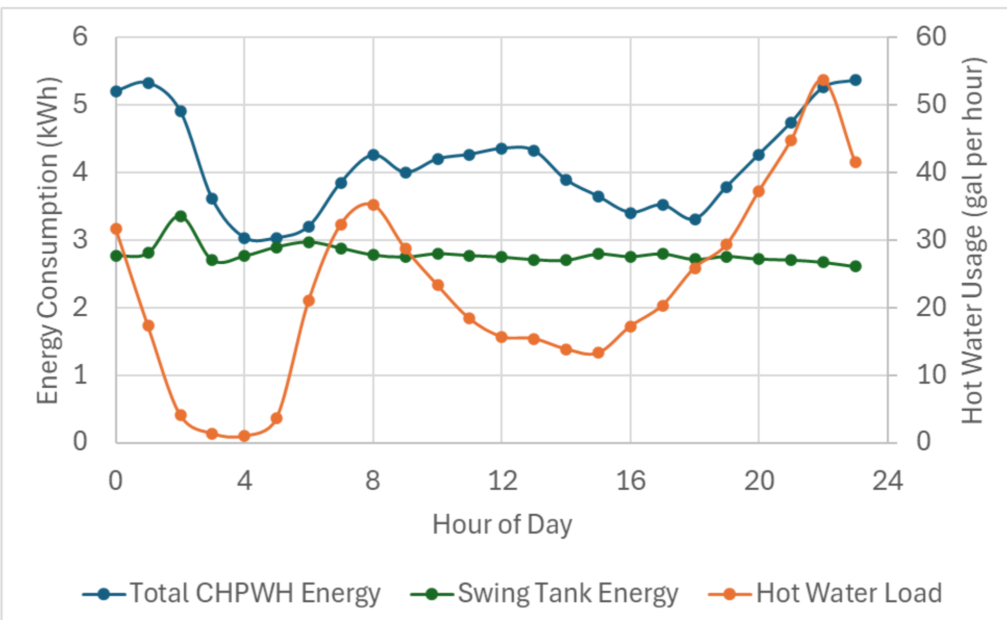

Figure 16: Building 1 daily profile before swing tank setpoint adjustment.

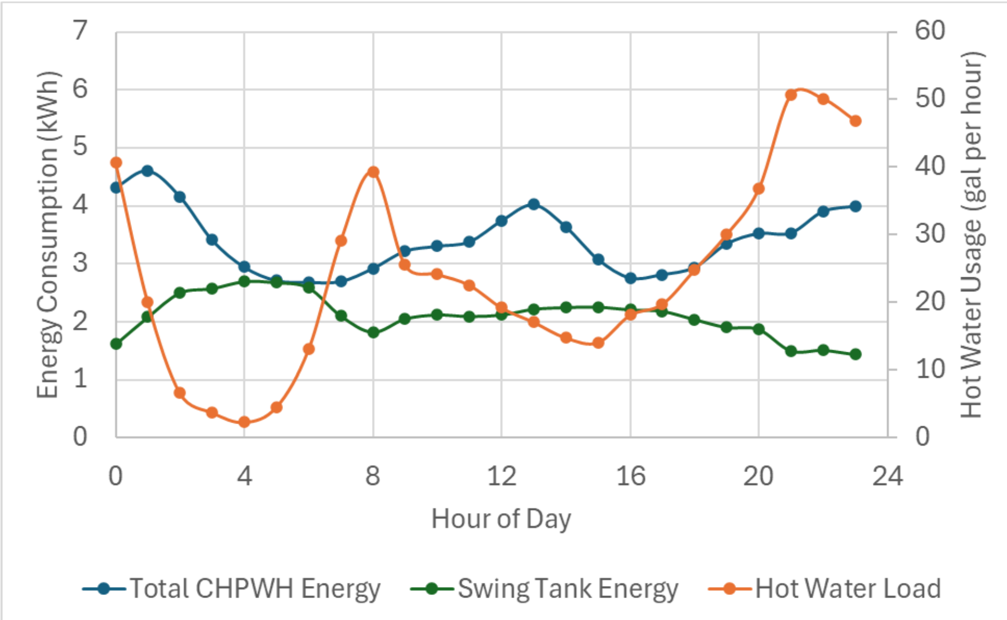

Figure 17: Building 1 daily profile after swing tank setpoint adjustment.

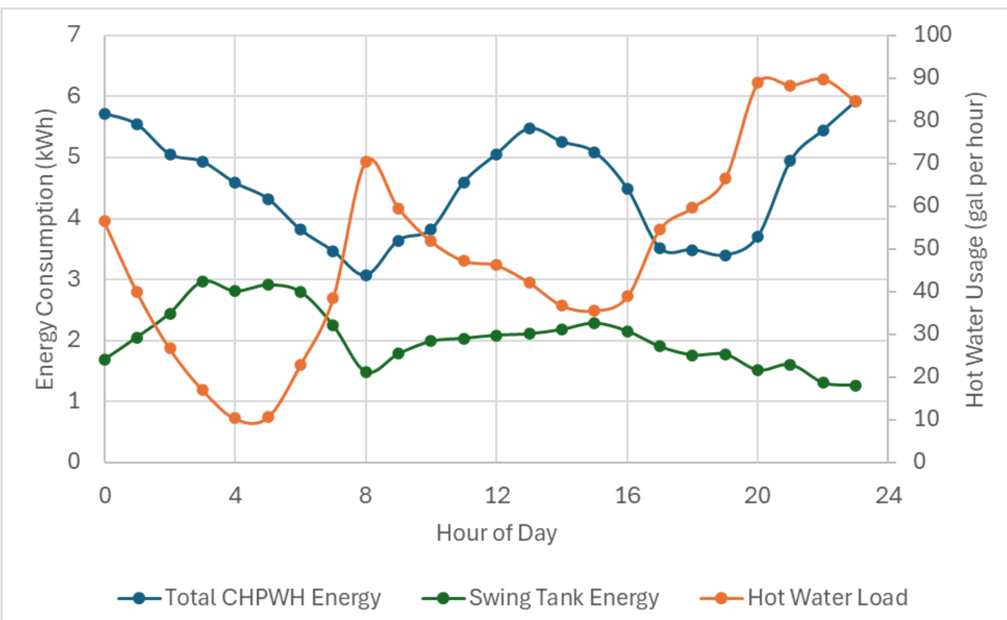

Figure 18: Building 2 daily profile during steady state occupancy.