FINAL REPORT:

PG&E and SCE HPWH Laboratory Testing and Software Updates for Multifamily Applications

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With funding by

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1 Executive Summary

A heat pump water heater (HPWH) is a high-efficiency, low-carbon electric solution for buildings in California, and an emerging market for central system HPWHs in multifamily buildings. Climate change advocates, utilities, regulators, and the building industry have a keen interest in this emerging technology but lack reliable information about which equipment, system types, and configurations perform best in different building types and climate zones. Further, if HPWH systems are configured and sized like traditional gas boiler systems, buildings will be left with functional issues and poor performance. This project's goal was to research, understand, and demonstrate good central HPWH system design so that efficiency and energy savings can be achieved.

Unlike the single-family residential market where a one-size-fits-most approach to HPWH systems is feasible, multifamily water heating systems require more varied designs targeted at specific building types and sizes. Design possibilities are myriad, beyond mere equipment selection, but many designs either do not provide adequate hot water or use too much energy or both. In fact, this research shows that system configuration determines the ultimate energy use as much as, if not more so, than the heat pump itself. Factors include different temperature-maintenance system configuration, sizing of primary and secondary storage tanks, piping configuration for recirculated water, range of distribution system losses, and storage water temperatures. Figure 1 and Figure 2 depict examples of different configurations studied in this project.

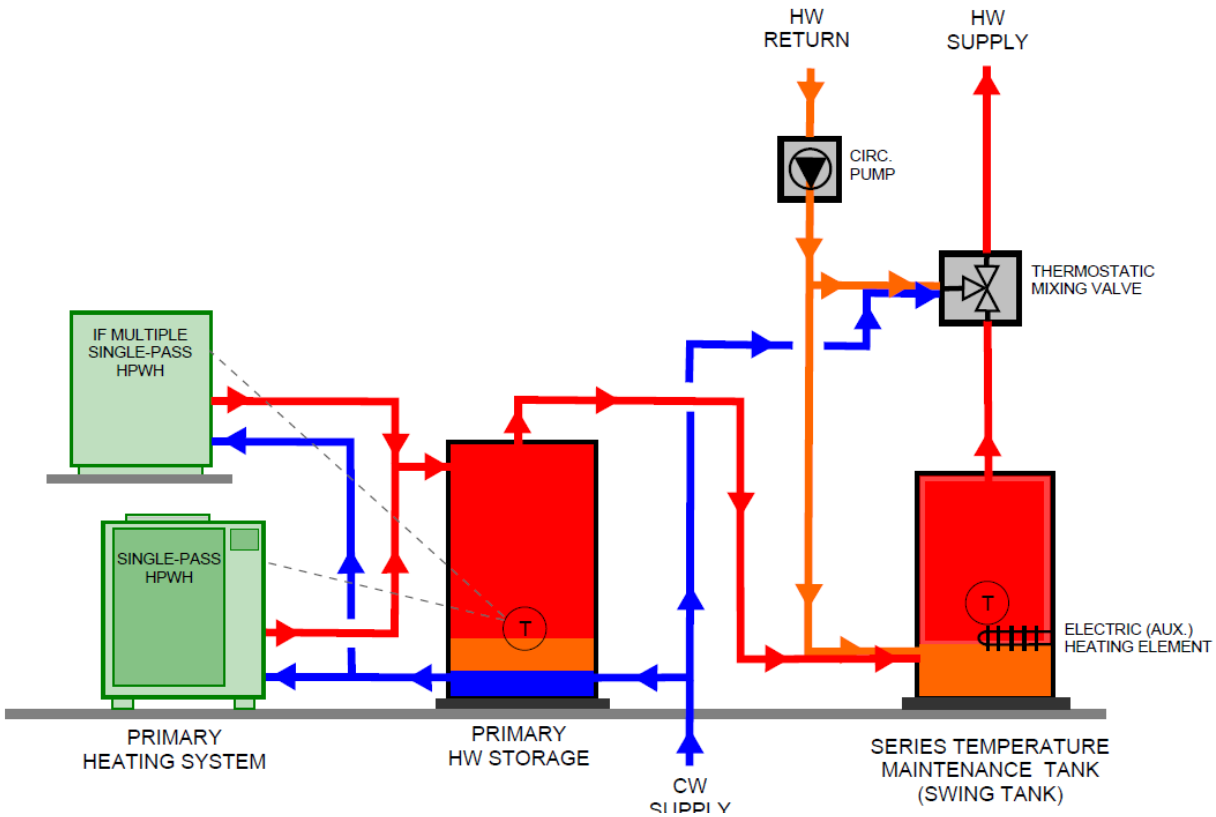

Figure 1. Example single-pass heat pump primary with series temperature maintenance.

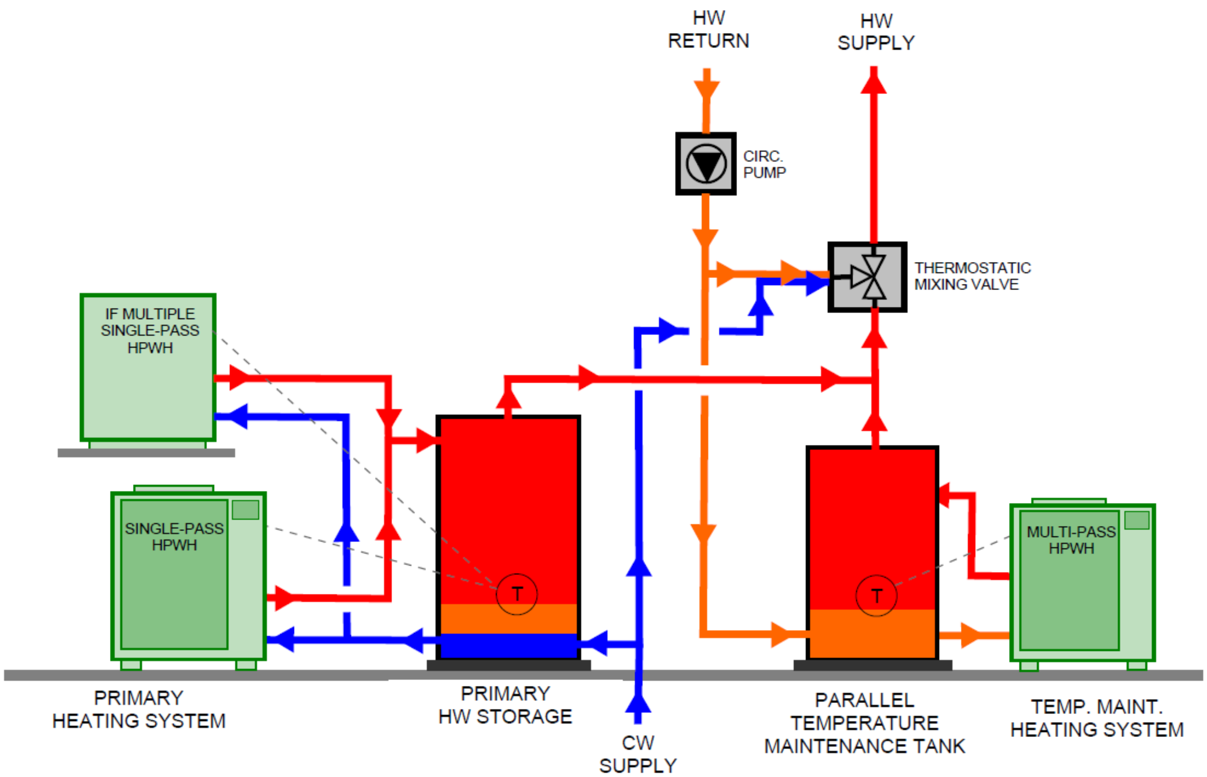

Figure 2. Example single-pass heat pump primary with multi-pass heat pump secondary.

In addition, California's Building Energy Code Compliance Software (CBECC) model of central multifamily water heating was developed for conventional gas boilers and excludes significant issues that are critical for heat pump water heating, such as the impact of the pumped distribution loop on inlet water temperature. Without reliable design criteria and performance data, it was not possible to accurately model multifamily HPWH systems in building energy simulation software applications such as CBECC-Res that are central to California's performance code. As a result, efficient heat pump water heating was not allowed in new multifamily buildings in California prior to updating the software through this project.

This project's overarching goal was to enable central heat pump water heating systems to be deployed in California in ways that realize substantial energy savings and carbon emissions reductions. To do so the project team set out to:

- Understand the impact of different system configurations on total system performance.
- Distill the current state of knowledge, informed by lab tests, about multifamily heat pump water heater systems into a set of design recommendations.
- Update and revise the simulation capability of CBECC to enable it to accurately model varied central heat pump water heating systems for multifamily buildings.

1.1 Setup

To achieve these project goals, the team pioneered a method for testing large-scale central heat pump water heating systems by constructing a robust and flexible test bed. Heretofore, due to the sheer size of such systems, measurement had only been possible in actual buildings where environmental conditions cannot be controlled. Further, in occupied buildings, it is not feasible to alter system setups to test different design variables. The results from this study highlight the value of laboratory testing in a controlled environment. Figure 3 shows the lab setup as it was being built for the project. This is one-half of the testing environment. The other half, in an adjacent thermally controlled chamber, held the heat pumps.

Figure 3. Lab test bed under construction.

The project team's overall approach to the research questions was to install the HPWH equipment in a controlled laboratory setting and measure efficiency response to various input parameter changes. In a series of application tests, we measured total system performance in different specified configurations for temperature maintenance, under different draw profiles, and with a range of storage tank sizing and configurations. These were simulated-use tests to observe system behavior for about 24 hours.

The lab testing plan was designed to explore performance and discover equipment limitations. Tests examined a range of products and refrigerants representative of the central HPWH market today,including CO_2, R-134a, R-410A refrigerants; single-pass heating; multi-pass heating; and integrated-tank HPWHs. Specific equipment tested included the Sanden Gen3, the Colmac CxA and CxV, and the AO Smith CHP-120.

1.2 Results

Lab testing successfully revealed how installation choices can optimize performance of numerous central HPWH system configurations. The tests showed ways to get the best efficiency from single-pass return-to-primary, multi-pass return-to-primary, single-pass with series swing tank, and single-pass with parallel multi-pass loop tank configurations, among others. Tests also revealed several design choices are likely to lead to failed hot water delivery or lower efficiency. The results are distilled in this report into a set of design recommendations to help achieve the best performance. The report also provides a guide to selecting overall system configuration.

Importantly, testing examined variations in system setup: combinations of temperature-maintenance system configuration, sizing of primary storage and secondary storage tanks, piping configuration for recirculated water, range of distribution system losses, and storage water temperatures. Although there are numerous nuances, testing showed overall that the major determinants of system efficiency were the heat pump entering water temperature and the heat pump control points. Using return-to-primary, single-pass, multi-pass, or return-to-secondary configurations all set up different entering water scenarios. Within those scenarios, there are specific design decisions that can minimize entering water temperature and maximize efficiency and hot water delivery. Designing central HPWH systems is fundamentally an exercise in managing heat pump entering water temperature and setting up controls to turn the heat pumps on and off at optimal times.

There is no one-size-fits-all configuration. Optimal system configuration for a given building depends on many factors, including climate, building size, and equipment availability and cost. The project team synthesized the test results into generalized findings that can be used to guide central HPWH system designs. Our synthesis identifies both good and bad practices and design considerations, which are distilled into this report's Design Recommendations Based on Test Results .

2 Introduction

A heat pump water heater (HPWH) is a high-efficiency, low-carbon electric solution for buildings in California, and an emerging market for central system HPWHs is in multifamily buildings. Climate change advocates, utilities, regulators, and the building industry have a keen interest in this emerging technology but lack reliable information about which equipment, system types, and configurations perform best in different building types and climate zones. Further, if HPWH systems are configured and sized like traditional gas boiler systems, buildings will be left with functional issues and poor performance. This project's goal was to research, understand, and demonstrate good central HPWH system design so that efficiency and energy savings can be achieved.

California's Building Energy Code Compliance Software (CBECC) model of central multifamily water heating was developed for conventional gas boilers for domestic water heating and excludes significant issues that are critical for heat pump water heating, such as the impact of the pumped distribution loop on inlet water temperature. And without reliable design criteria and performance data, it was not possible to accurately model multifamily HPWH systems in building energy simulation software applications, such as CBECC-Res, that are central to California's performance code. As a result, efficient heat pump water heating was not allowed in new multifamily buildings in California prior to updating the software using research done for this project.

Unlike the single-family residential market where a one-size-fits-most approach to HPWH systems is feasible, multifamily water heating systems require more varied designs targeted at specific building types and sizes. There are myriad design possibilities beyond equipment selection but many do not work well, either providing inadequate hot water or using too much energy, or both. Previous research indicated that the selected system configuration determines the ultimate energy use as much as, if not more so, than the heat pump COP. Design factors include combinations of temperature-maintenance system configuration, sizing of primary storage and secondary storage tanks, piping configuration for recirculated water, the range of distribution system losses, and storage water temperatures.

Ecotope's field measurements show that variable configuration of the same equipment or equipment types can have large effects on equipment energy use and even the ability to deliver hot water. Relevant factors include the sizing of the primary and secondary storage tanks, heat pump sizing, piping configuration for recirculated water (as it related to temperature maintenance), and storage water temperatures. To be successful in California, the project team anticipated the need to constrain the universe of design possibilities to a known, well understood, and well performing set.

Importantly, the Department of Energy does not set a required minimum efficiency standard for commercial heat pump water heaters, those products appropriate for large central systems. Further, for some products, there are no performance test results available. DOE does require manufacturers making efficiency representations for commercial HPWHs to do so according to

DOE's test procedure, located in Appendix E to Subpart G of Part 431, Title 10. Those claims on equipment are component COPs derived under standardized conditions, which is different than the System COPs observed in real-world applications and discussed in this report. Research available at the start of this project revealed the keys to successful applications in Pacific Northwest climates; there was a need to expand this research and adapt to California climates and building types.

This project's overarching goal was to enable central heat pump water heating systems to be deployed in California in ways that realize substantial energy savings and carbon emissions reductions. To do so, the project team set out to:

- Understand the impact of different system configurations on total system performance.
- Distill the current state of knowledge, informed by lab tests, about multifamily heat pump water heater systems into a set of design recommendations.
- Update and revise the simulation capability of CBECC to enable it to accurately model numerous and varied central heat pump water heating systems for multifamily buildings.

The primary focus of this report is on generalizing findings from the lab testing and making corresponding design recommendations. In testing, the project team necessarily used specific equipment however, we can make more general conclusions about how water temperatures and control strategy will affect performance. Those findings are distilled into the Design Recommendations Based on Test Results .

Separate, detailed appendices contain summary reports of three distinct laboratory testing efforts, which examined a range of products and refrigerants representative of the central HPWH market today. These included CO_2, R-134a, and R-410A refrigerants; single-pass heating; multi-pass heating; and integrated-tank HPWHs. The reader is encouraged to review those specific reports. This main report summarizes and generalizes the findings from the individual reports, and includes setup and methods used for all tests.

The results from this work highlight the value of laboratory testing in a controlled environment. The results identify both good and bad practices and design considerations for the specific products tested, but also more generally for a range of heat pump water heater types in a central domestic hot water plant application. This type of careful and controlled testing is valuable for improving emerging technologies like central heat pump water heating systems and to help users achieve reliable and repeatable energy savings.

2.1 Initial Project Scope

This project scope was developed in 2018 when CEC identified MF HPWH central systems as a gap in CBECC software for compliance credit. The first contract to complete this work was signed in November of 2018. The work covered by this report evolved over the years based on lab availability, data from the field, and COVID19. The initial project scope consisted of six tasks:

1. Improve the domestic hot water draw schedule to provide accurate results for multifamily buildings.
2. Develop sizing methodology for multifamily standard design heat pump water heating systems.
3. Improve distribution system modeling to account for recirculation loops and other multifamily issues.
4. Develop installation criteria for multifamily HPWH systems.
5. Conduct performance testing of multifamily HPWH components.
6. Enhance the CBECC-Res domestic hot water (DHW) simulation model to enable multifamily HPWH compliance.

Because of delays in the lab testing intended to inform software updates, the following two tasks were added:

7. Develop Interim Compliance Option
8. Incorporate UCSF Nyle Multi-Pass Case Study

The project team consisted of:

- Larson Energy Solutions
- Ecotope
- Big Ladder Software LLC
- Bruce A. Wilcox, PE, Inc.
- Charles S. Barnaby

This team also drew on the following expertise and experience, which were vital for project success:

- Developers and the support team for the CBECC-Res, California Simulation Engine (CSE), and HPWH software package used for performance calculations for both low-rise and high-rise residential buildings in the California Energy Code, including the revision and significant upgrade to the CBECC-Res domestic hot water calculations for the 2016

Standards with a minute-by-minute draw schedule based on measured water use in 700 representative California homes.

- Developers of the Northwest Energy Efficiency Alliance (NEEA) Heat Pump Water Heating listing program, including the additional required voluntary testing of integrated HPWHs. Also, implementers of the NEEA HPWH listing program in CBECC-Res for California compliance use.
- Designed, built, monitoring, and evaluating experience for several large central HPWH systems with support from Pacific Northwest utilities.

2.2 Evolution of the Scope

Initially the high-level goal of the project was to complete lab testing to inform CBECC software functionality for central system HPWHs in multifamily applications. Several software improvements were needed prior to adding this functionality; they are discussed in Appendix A.

The project began at the end of 2018 and by the time the team was ready to begin lab testing, there were significant delays at the lab due to the COVID19 pandemic and the complexity of the equipment needed for testing. During that time, field installations had been done with resulting data able to inform software functionality based on the physics model. Software updates to add different central system configurations based on field data were done in conjunction with testing.

This report summarizes test data that can be used to help inform designs and improve the accuracy of the CBECC software to model different multifamily central system water heating configurations. The next steps are to socialize these findings and compare the test results to software outputs.

2.3 Funding Structure

This project was jointly funded by Pacific Gas and Electric (PG&E) and Southern California Edison (SCE). PG&E covered tasks 1, 4, and 5, and added tasks 7 and 8; SCE covered tasks 2, 3, and 6.

3 Summary of Products Tested

3.1 Sanden Gen3

The Sanden Gen3 (Sanden GS3-45HPA) HPWH is a nominal 1.25-ton HPWH that uses R-744(CO_2) as the refrigerant. This product operates as a single-pass HPWH and was designed to serve large single-family loads, but multiple Sanden HPWHs can be combined to serve larger multifamily domestic hot water loads. This Gen3 equipment is no longer available and is being replaced with a Gen4 product line which has not yet been tested. Also, Sanden equipment has been rebranded as SANCO2 in the US market. In this report, we refer to this equipment as Sanden Gen3, to distinguish it from the newer product.

Figure 4. Two Sanden Gen3 units as installed for testing.

3.2 Colmac CxA and CxV

The Colmac CxA-15 is a nominal 17-ton HPWH using R-134a refrigerant. It is part of a line of product sizes from Colmac ranging from the CxA-10 to CxA-30. The heat pump can be configured to operate in either single-pass or multi-pass mode; both were explored in testing. The CxA was used as the primary heat pump in the system configurations.

The Colmac CxV-5 is a nominal 6-ton HPWH using R-410A refrigerant, which can be configured to operate in either single-pass or multi-pass mode; both were explored in testing. The CxV was used as the secondary heat pump to heat the temperature-maintenance loop in the system configurations.

Figure 5. Colmac CxA-15 (left) and Colmac CxV (right) as installed for testing.

3.3 AO Smith CHP-120

The CHP-120 is an integrated HPWH designed for light-commercial applications. Unlike the other products tested, the integrated product has both the heat pump and the tank in one unit. The heat pump condenser is wrapped around the tank. The tank has a nominal storage volume of 120 gallons. The heat pump uses R-134a refrigerant and has a rated heating output capacity of 11 kW (approximately 3-tons) according to the specification sheet from AO Smith. The unit has two 6 kW elements, one upper and one lower, which can operate independently or together.

Figure 6. AO Smith CHP-120 as installed for testing.

4 Lab Testing Methods

The project team's overall approach to answer the project's research questions was to install the HPWH equipment in a controlled, laboratory setting and measure efficiency response to various input parameter changes. Our major focus was on a series of application tests that measured total system performance in different, specified configurations for temperature, draw profiles, and storage tank sizing and configurations. The basic concept was to simulate use and observe system behavior for about 24 hours.

Across different water heating equipment types, and even for the same piece of equipment, there are multiple system configuration possibilities. We sought to examine these and their response to different primary hot water use loads and temperature-maintenance loads. The parameters varied among the configurations are described subsequently. Not all variations are relevant to all equipment types; our tests were designed to target the relevant ones.

Several parameters *not* varied during the applications were ambient air, inlet water, and delivered water setpoint. The ambient air was held to 67.5°F and 50% RH and inlet and delivered water were set to 58°F and 125°F, respectively.

4.1 Testing Configurations

4.1.1 Tank, Piping, and Circulation Loop Heating Configurations

The tank layout, the layout of the pipes connecting them and the heat pumps, and the method used to reheat the circulation loop water play a large part in determining both the efficiency and simple success of the system. Testing focused on configurations which, based on the team's experience, were likely to deliver adequate hot water. Nevertheless, some configurations failed to deliver adequate hot water. Appendices B-E document those details.

Our layout choices were broadly divided by where the circulation loop returns to the bank of storage tanks and how that water is reheated. The loops returned to either (1) the primary tanks or (2) the secondary, dedicated recirculation heating tanks. From there, there were cascading possibilities.

4.1.1.1 Recirculation Returned to Primary Tanks

In this configuration, the circulation loop returned to the primary storage tanks where it could mix with existing cool or hot water and eventually be reheated by the primary heat pump. The loop could return to one of three tank heights — high, medium, or low — leading to different levels of tank destratification and water temperatures that must be reheated by the heat pump.

4.1.1.2 Recirculation Returned to Dedicated Recirculation Tank

Returning to a dedicated tank opened several design possibilities. The system's complexity increases compared to returning to a primary tank but there is also greater opportunity for efficiencies. A dedicated recirculation tank can be set up in series or parallel with the primary tanks. The design choice is optimized based on the type of heat pump used for the primary heating and for any temperature-maintenance heating. Consequently, we explored both series and parallel arrangements. In either case, the circulation loop return piping was connected to the bottom of the dedicated tank. The low-tank return maintains stratification, creating optimal temperature conditions for the heating equipment – the main motivation behind having a dedicated recirculation tank. As such, no other return piping height configurations were tested.

4.1.1.2.1 *Primary and Recirculation Tanks in Series*

Placing the recirculation tank in series with the primary tank allows the primary tank water to mix in the secondary tank and, potentially, be heated in that secondary (recirculation tank). The series configuration enables a “swing tank” concept, providing overheated water from the primary tank to be mixed with cooler recirculation water in the swing tank. If there is enough overheated water from the primary tank, the mixed temperature in the swing tank will be greater than or equal to the needed-use temperature. This strategy has the potential to work effectively with heat pump cycles designed to impart a large temperature lift to the water, like transcritical CO_2. If there is enough hot water use to balance out the circulation loop losses, no additional heat is needed in the swing tank. If additional heat is needed, it can be supplied by resistance heat or a heat pump.

4.1.1.2.2 *Primary and Recirculation Tanks in Parallel*

Placing the recirculation tank in parallel with the primary tanks separates the two water heating loads. The primary tank and heat pump will heat the domestic-use water while the secondary tank and heater will heat the circulation loop. This configuration can offer advantages when a heat pump is used to reheat the loop water and is optimized for the exact temperature conditions expected from the loop.

4.1.2 Building Size

Building size drives system selection. Our testing was designed to align with standard California multifamily building prototypes: 4-, 8-, and 44-unit buildings. The 8-unit is a low-rise garden style building. The 4-unit building corresponds to half of the 8-unit. The 44-unit building size corresponds to half of a mid-rise, 88-unit building. Design concepts for the 44- and 88-unit used similar equipment selections with changes to the output capacity and storage. Larger buildings can use multiple, larger pieces of equipment but, for practical purposes of lab testing, we kept to smaller and fewer equipment pieces. Because meeting larger demands means installing more equipment capacity in parallel, we were able to scale down the testing and still expect accurate results.

The equipment was sized to meet the expected demand of the prototype building. Accordingly, heat pump output capacity and storage tank volume were paired to meet the demand. We did not parametrically vary the storage volume or output capacity. We did, however, vary the draw profile which, in effect, varied the apparent (relative to demand) storage volume and output capacity.

4.1.3 Draw Profiles

We sourced simulated use-patterns from draw profiles currently used by CBECC-Res, corresponding to appropriate unit counts in the range of multifamily prototypes. The project team tested each application configuration against these use profiles.

Draw profiles were sourced directly from CBECC-Res to correspond to standard California building prototypes. Three draw profiles are used per building size: “low,” “medium,” and “high,” corresponding to the 5th-percentile-, 50th-percentile, and 95th- to 99th-percentile daily draw volumes, on an annual basis. Table 1 shows the draw-volume distribution, as extracted from CBECC-Res. Graphical versions of the patterns used can be found in Appendix E. In general, the lab tested all three building sizes for a given physical configuration; occasionally it was restricted to only one use-pattern to reduce overall test time and count.

Table 1. Daily Draw Volume Distribution by Building Unit Count

Building Size	Distribution (Percentiles) of Daily Hot Water Use (Gallons)						
	1%	5%	25%	50%	75%	95%	99%
4 Units	37	52	80	105	139	193	243
8 Units	98	131	173	216	265	348	412
44 Units	920	987	1,152	1,278	1,438	1,752	1,927

4.1.4 Circulation Loop Heat Loss Rate

The amount of temperature maintenance needed is determined by the circulation loop heat loss rate, which can vary by building and building size. Field measurements, previous studies, and sample calculations show a range from 50 to 200 watts per unit. A typical plumbing layout drawn by Ecotope for the 8-unit prototype showed 100 watts per unit. If that were uninsulated piping, it could reach 200 watts per unit. A similar design exercise for the 88-unit building, cross referenced with previous building designs and measurements, showed a range of 50-100 watts, depending on the pipe layout: A compact design resulted in 50 watts while a more spread-out design resulted in 100 watts. Therefore, the test plan looked at three variations:

- 50 W/unit (low)
- 100 W/unit (med)
- 200 W/unit (high)

Examination of the draw profiles showed that hot water is needed at every hour of the day. The need to provide hot water to all fixtures, at all times, dictated the circulation loop be run continuously for the majority of the tests.

4.2 Laboratory Setup

The HPWH tests were conducted at PG&E's ATS Advanced Technology Performance Lab in San Ramon, California. The testing apparatus consisted of two adjacent test chambers with ambient conditions (i.e., dry bulb air temperature and humidity) controlled independently. See Figure 7 and Figure 8. Schematic of HPWH test chambers and control points 2.for a detailed schematic on control points.

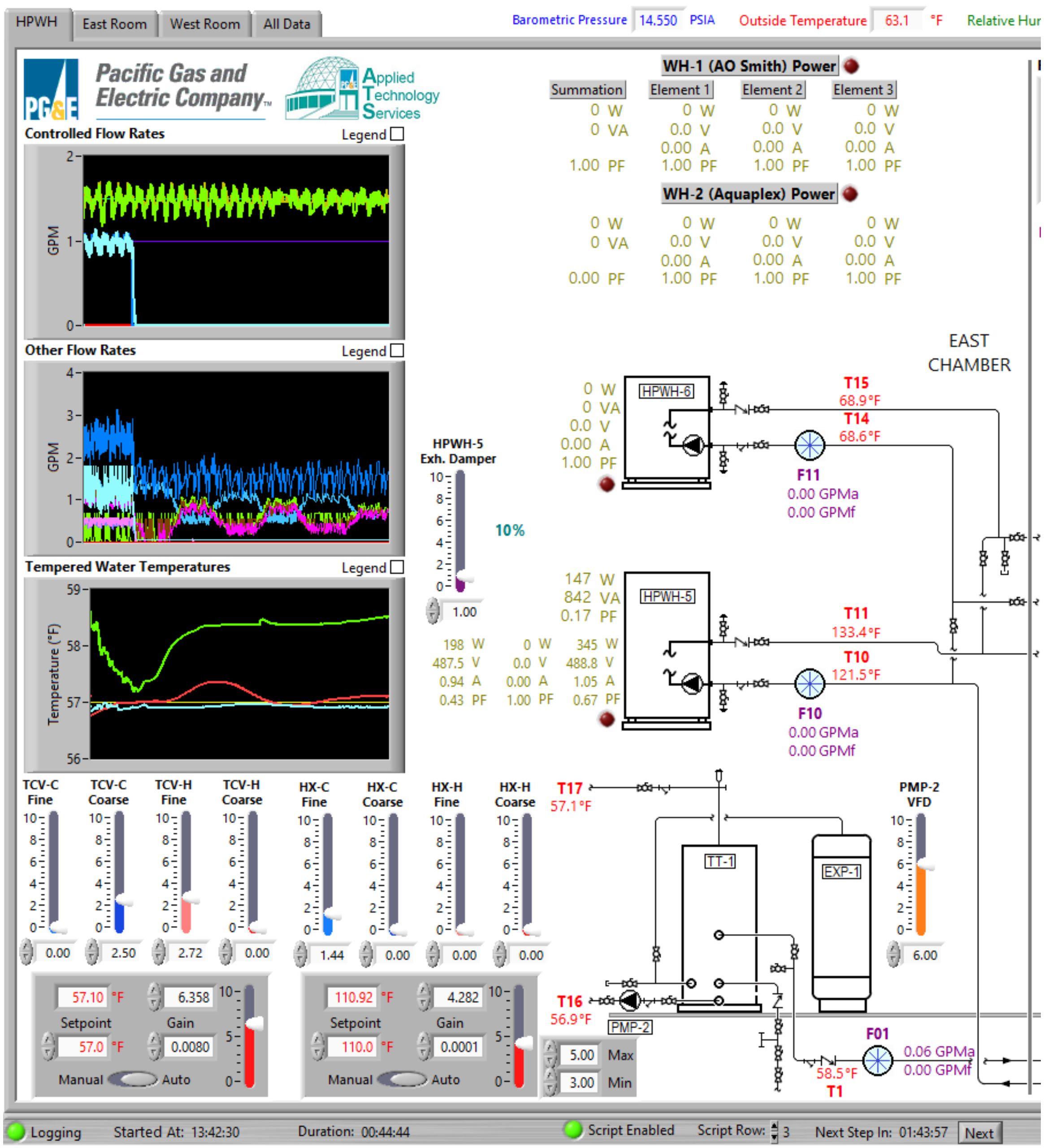

Figure 7. Schematic of HPWH test chambers and control points 1.

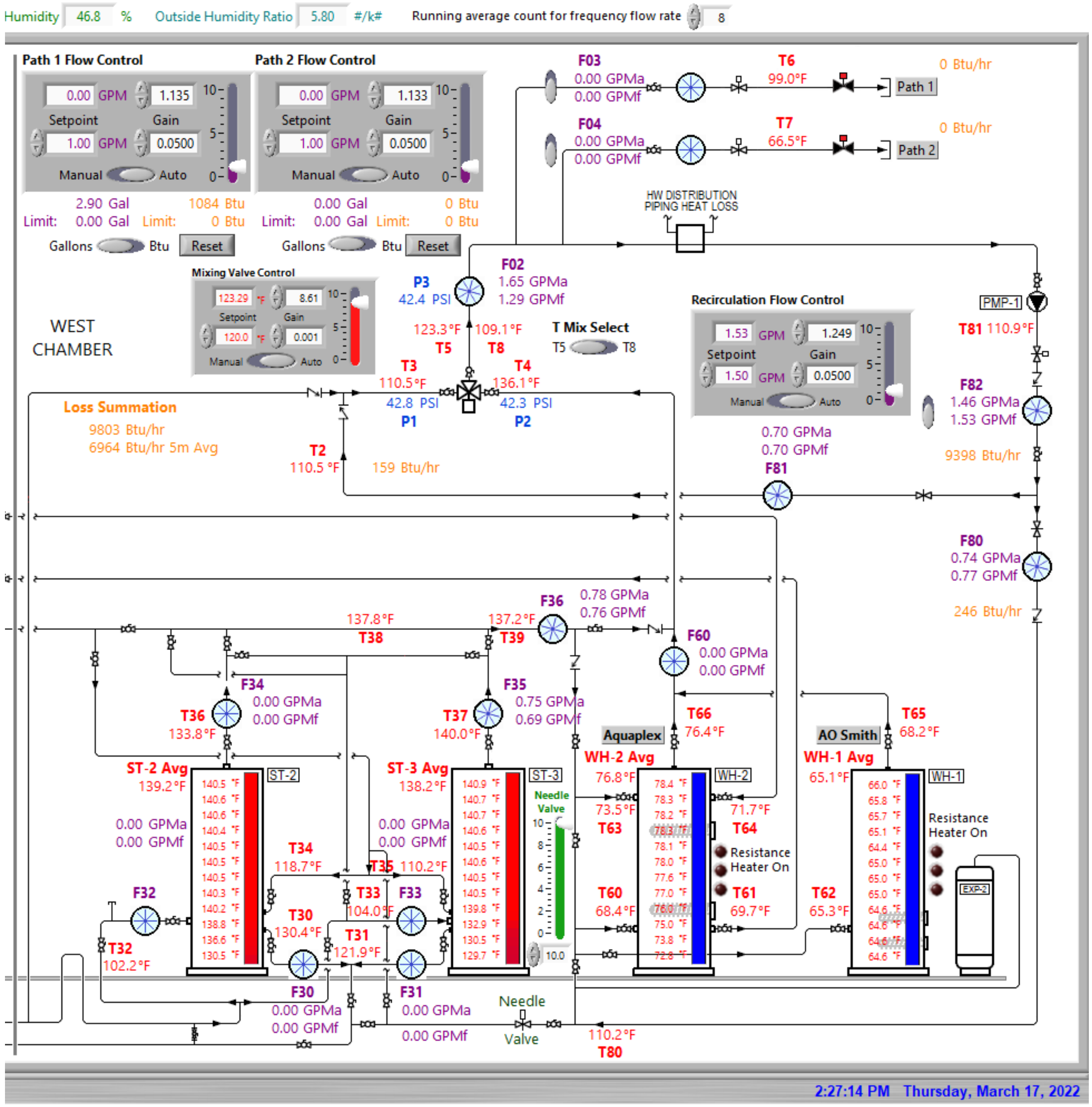

Figure 8. Schematic of HPWH test chambers and control points 2.

4.2.1 Test Chambers

The east chamber housed HPWHs under test as well as the city water tempering system and its pump. For each test, city water was tempered and stored in a separate tank to eliminate water temperature variation during tests. The west chamber housed the primary storage tanks, recirculation tanks, master mixing valves (one mechanical and two digitals), recirculation pump, two parallel draw stations, and the heat exchangers to replicate the hot water distribution heat losses. Copper piping connected the equipment with insulation levels according to California's Title 24 energy-efficiency code. Figure 9 and Figure 10 show the placement of the test equipment inside each chamber.

Figure 9. West chamber equipment placement.

Figure 10. East chamber equipment placement.

The test chambers were constructed with dimensions of 14.5' length, 12' width, and 12' height. The chambers' sizes and placement of equipment were chosen to adequately accommodate a range of HPWH sizes and configurations, providing sufficient space for airflow and maintenance activities. Chamber walls and ceilings are insulated with overall resistance value (R-value) of 19 hr-ft2-°F/Btu. The floor is concrete and not insulated. Chamber environments were tightly controlled during each test through separate air conditioning loops. The system can maintain ambient temperatures from 40°F to 140°F with a precision of ±1°F. Each space conditioning system consists of a chilled glycol cooling coil, a hot water heating coil, and a blower. Humidity levels in the east chamber were controlled and maintained within a range of 30% RH to 80% RH with a precision of ±5%, using five sets of humidifiers. Humidifiers were designed and manufactured by Smart Fog Inc. and can provide up to 4.0 GPH water flow with water droplets of 4.2 micron directly sprayed into the room.

4.2.2 Switchable Configurations Valving

To switch between the plumbing configurations, the lab set up a bank of valves to toggle flows on and off. Once this flow control station was built, it allowed the lab to switch between return-to-primary, return-to-secondary, series, and parallel layouts without disconnecting and reconnecting piping. Figure 11 shows the switching station with the various valves.

Figure 11. Main valve and configuration switching station before and after insulation was installed.

4.2.3 Circulation Loop

The lab created a way to simulate a building recirculation loop. Water was piped through several water-to-air heat exchangers which could be set to the varying heat transfer rates needed in the testing. Figure 12 shows the setup.

Figure 12. Simulated circulation loop.

4.2.4 Instrumentation

The project team treated the units under test (HPWHs) as black box devices with no instrumentation added inside the physical boundary of the heat pumps. All tanks, however, had temperature sensors immersed inside to observe water temperatures and stratification; this included the CHP-120 integrated product. The instrumentation goal was to provide precise control and data collection capabilities during tests.

4.2.4.1 Power Supply and Power Measurements

The power supply for the unit under test was a Chroma high-performance programmable AC power source. The power supply could be configured to single or three-phase output and deliver the required voltage. The project team measured power consumption of the unit under test as well as supplemental water heaters with Yokogawa power meters. The output from the Yokogawa power meters was read in the data acquisition system through a serial port.

4.2.4.2 Water Flow Measurements

To measure and control the flow of water in and out of units under test and across other components, 17 Badger Recordall Disc Meters were installed in different locations in the setup. The flow meters at the outlet of tempering tank and master mixing valve were Model 70 (1 in.), and the rest were Model 25 (5/8 in.).

4.2.4.3 Temperature and Pressure Measurements

Resistance temperature detectors (RTDs) were used to measure the air and water temperatures in various locations in the test setup. To measure and record the temperature and state of the thermal charge inside the water tanks, thermocouple trees were installed inside each tank. Twelve thermocouples with equal distances were added inside each tank (i.e., ST-2, ST-3, WH1, WH2, and AO Smith tank). Additionally, three pressure transducers were installed in inlets and outlets of the master mixing valve to record the variations of water pressure during different operation modes.

4.2.4.4 Instruments Calibration and Accuracy Ranges

All instruments were calibrated following NIST traceable calibration. Flowmeters, temperature, and pressure sensors were calibrated at the beginning of testing and again after the testing was finished to ensure that readings had not shifted. The other instruments, including the RH sensor and Yokogawa power meters, had current calibrations documented with NIST traceable calibration reports. The test instrumentation is listed in Table 2 below.

Table 2. Test Instrumentation

Measurement	Instrument	Make	Accuracy
Barometric Pressure	Multi-function weather station on roof of building	Vaisala WTX520	±0.007 PSIA (±50 Pa)
Chambers' dry bulb temperature as well as water temperatures in the setup	Fast-response resistance temperature detectors (RTDs)	Burns Engineering	±0.2°F
Temperature trees installed inside tanks	Type T thermocouple sensor	OMEGA	±0.2°F
Air humidity	HygroSmart S3 Probe	Michell's Instruments	±0.8% RH
Water pressure	General Purpose Pressure Transmitter ATM.ECO	PMC Engineering	≤0.2% FS
Water flow	Recordall disc meters	Badger	Model 70:[1] ±15% Model 25: ±1.5%
Supply power, voltage, and current	3-element true-RMS power meter with outputs for total power, voltage and current	Yokogawa WT330	±(0.1% of reading +0.1% of range)

4.2.4.5 Data Acquisition System

Instruments were connected to several National Instruments Compact-RIO chassis, dedicated for test chambers controls as well as for test data collection and recordings. The default chassis internal scan rate for reading the module inputs was 10 Hz, although the temperature and power meters readings were updated once every second.

Compact-RIO chassis communicated over an Ethernet network to a central host computer, which ran a custom data acquisition and control program developed with National Instruments LabVIEW™ graphical programming language. The program acquired readings from the chassis twice per second, applied calibration scaling and maintained a running average for each measurement, and logged the averages to a file every five seconds. The scaled values and other calculated values were also displayed on screen in both text and graphical form and used to generate feedback control signals to the space conditioning systems. The program used scripts to change the setpoints for the chamber conditioning systems at specific time intervals to switch from one test condition to the next. Logged data were saved in CSV format. The project team used a Python script to analyze the raw data files to make sure test conditions remained within range during each test, and for cleaning up the datasets.

[1] Model 70 operating range is 1.25 to 70 GPM, but during tests, flows dropped below 1.25 GPM for a considerable amount of time, which resulted in larger-than-expected total uncertainty. Hence flow meters 1 and 2 should not be used for mass and energy calculations.

5 Summary Findings

This section of the report summarizes the findings from the individual equipment to ascertain general trends and principles applying to central HPWH equipment and systems in general. Individual equipment testing reports (Appendices B, C, D) present highly informative conclusions on system efficiency and operation relevant to a specific product. The following sections describe what worked well (efficiently provided hot water) and what did not (did not provide hot water efficiently or failed to provide hot water).

5.1 Terminology Overview

Central water heating systems are composed of the following components and characteristics: the primary heating equipment, primary heating storage volume, location, circulation loops, secondary heating equipment, secondary heating storage volume, set point controls, mixing valves, and the way in which the components are plumbed. Table 3 lists definitions from the California Title 24 Alternative Calculation Method Manual Appendix B,[2] the Northwest Energy Efficiency Alliance Advanced Water Heating Specification,[3] and a design guide for the Energy Trust of Oregon.[4]

Table 3. Central Water Heating System Definitions

Term	Definition
Primary heating system and storage	Equipment that heats the cool water (domestic cold water or DCW) from the city or main to the hot water storage tank set point
Secondary heating system and storage	Equipment used to heat the circulation loop
Primary tank(s)	The storage volume, consisting of one or more tanks, heated by the primary heat pump.
Secondary tank(s)	The storage volume, consisting of one or more tanks, heated by the secondary equipment. The secondary tanks are most often associated with separating the heating of the temperature maintenance loop from the primary system.
Swing Tank	A special kind of secondary storage tank configuration. The secondary tank is installed in series with the primary system. See Section 5.3.1 for diagrams and further detail.
Backup heating	A supplementary water heating system that provides continuation of hot water delivery in the event the HPWH is not functioning or is unable to supply sufficient hot water to meet current needs

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[2] CEC 2022. 2022 Single-Family Residential Alternative Calculation Method Reference Manual: For the 2022 Building Energy Efficiency Standards Title 24, Part 6, and Associated Administrative Regulations in Part 1 Appendix B. https://www.energy.ca.gov/publications/2022/2022-single-family-residential-alternative-calculation-method-reference-manual

3 NEEA 2022. Advanced Water Heating Specification Version 8.0. https://neea.org/img/documents/Advanced-Water-Heating-Specification.pdf

4Ecotope 2023. Central Heat Pump Water Heater Design Guide. Prepared for Energy Trust of Oregon. https://www.energytrust.org/fact-sheets/new-buildings-design-guide-for-central-heat-pump-water-heaters/

Term	Definition
Effective storage volume	The amount of hot water in a tank that can be used to provide usefully hot water (Generally ≥ 120-125°F. For example, 90°F water in a tank is quite warm but not considered warm enough for a shower. Therefore, any water at this temperature is excluded from the effective storage volume.
System COP	The annual energy demand of the entire water heating system (primary water heating plus temperature maintenance) divided by the energy input required. See Figure 13. This will differ from the COP of a specific HPWH reported in literature tested under steady-state test conditions.
Circulation loop	A hot water distribution system where the water is circulated throughout the building on a continuous basis to maintain a delivery temperature (typically 120°F) to the unit entry points or end use fixtures.
Hot water draw pattern	The hot water used by fixtures in the building. In this project, they are 24-hour schedules where each minute can have a different hot water flow rate. See Appendix E: Draw Profiles for examples.
Single-pass	A split-system HPWH that regulates flow such that it heats cold water to the storage setpoint temperature in a single water pass through the refrigeration circuit, typically a 70°F to 100°F temperature lift in a single cycle.
Multi-pass	A split-system HPWH with constant flow that incrementally heats water to the storage setpoint temperature with multiple water passes through the refrigeration circuit, typically a 10°F temperature lift for each cycle.
Integrated system	A HPWH that contains the heat pump components and storage tank in one device. These may also contain one or two electric resistance heating elements.
Parallel storage tanks	A storage tank configuration in which multiple tanks are piped in parallel to achieve a larger storage volume. For example, with three tanks, and balanced inlet water piping, the water flow will split three-ways and enter the bottom of all three tanks simultaneously. See Figure 14.
Series storage tanks	A storage tank configuration in which multiple tanks are piped in series to achieve a larger storage volume. For example, with three tanks, water will enter the first tank before flowing through the tank into the second tank, and so on. See Figure 15.

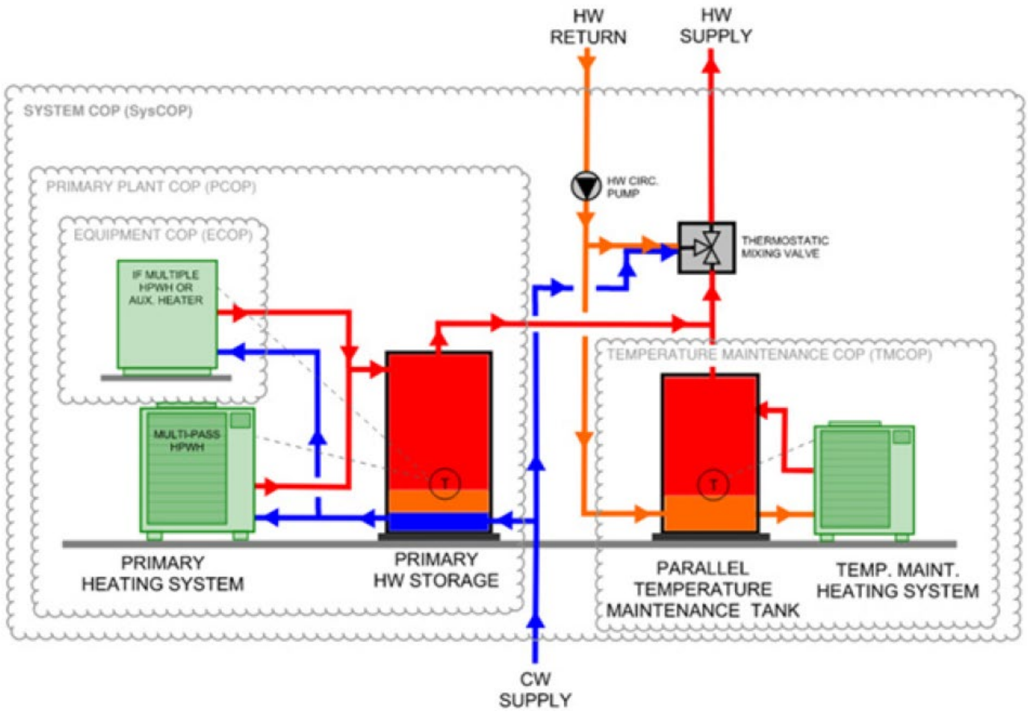


Figure 13. COP boundaries illustrated for a single-pass primary HPWH system with secondary temperature-maintenance tank and multi-pass HPWH.

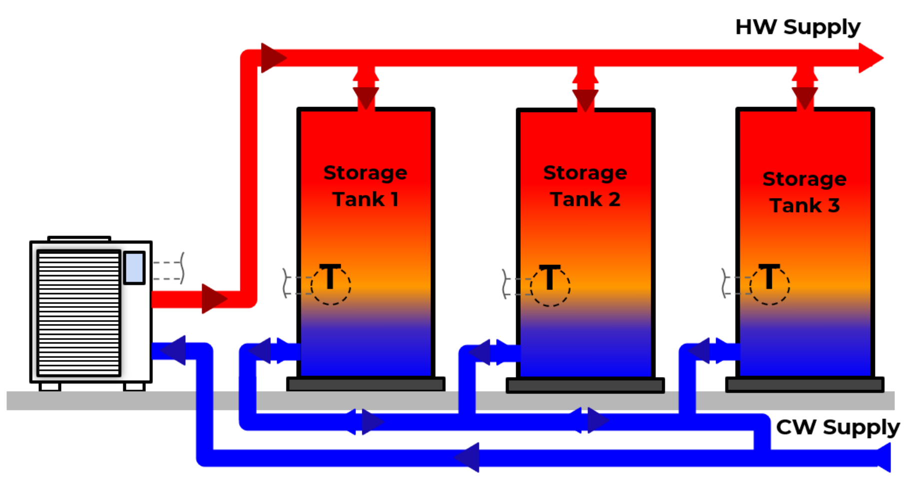


Figure 14. Parallel storage tank piping example.

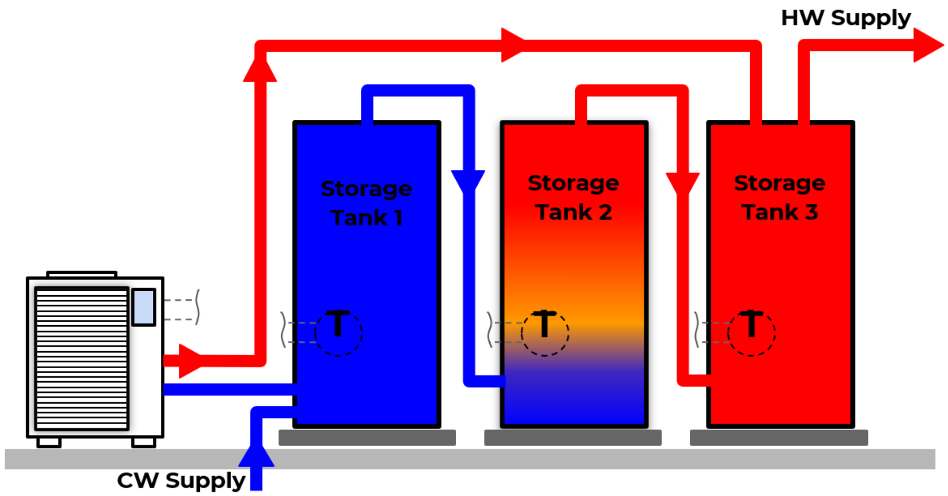


Figure 15. Series storage tank piping example.

5.1.1 Configurations Overview

All configurations discussed in this report are designs meant to work with a temperature-maintenance hot water circulation loop. The temperature-maintenance loop can be heated by the primary heat pump system or separately via a dedicated secondary water heater. There are four major configuration types, or variants, presented in the following section.

5.2 Return-to-Primary Systems

Both the SANDEN GEN3 and the Colmac CxA products were deployed as primary heat pumps with the temperature-maintenance loop returned directly to the primary tank. The efficiency and operational results depended on whether the primary heat pump operated in single-pass or multi-pass mode.

5.2.1 Single-Pass Heat Pumps

Figure 16 shows the schematic for single-pass return-to-primary configurations. The defining characteristic of the configuration is that both loads — the domestic hot water usage and temperature-maintenance heat loss — are satisfied by the same heat pump and storage tank.

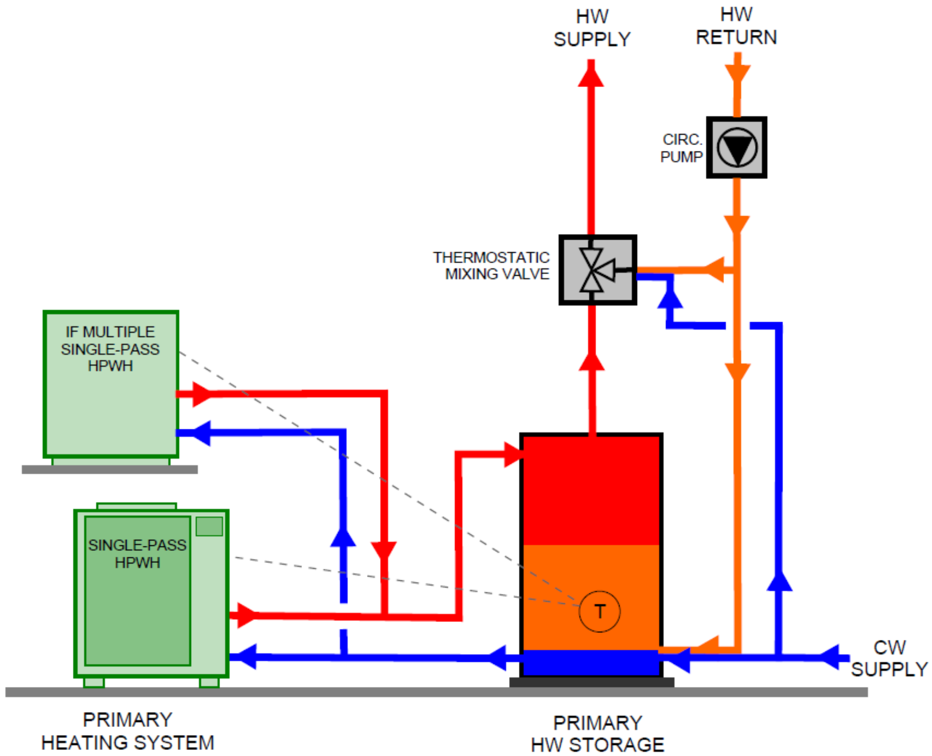


Figure 16. Single-pass primary HPWH system with hot water circulation returned to primary storage tank.

The system COP dependence varied based on the equipment:

- For the SANDEN GEN3, the COP changed based on the ratio of domestic hot water usage to temperature-maintenance losses. Greater temperature-maintenance losses led to lower efficiencies.
- For the CxA, the temperature-maintenance heat loss rate had little impact on this return-to-primary system. Domestic hot water (DHW) usage increase had a greater impact by decreasing inlet water temperature (Appendix C, Figure B07) and increasing system COP (Figure B09).
- The difference in response between the two systems was mostly due to the refrigerant differences: transcritical CO_2 vs. R-134a and their behavior relative to entering water temperature. Table 4 demonstrates that as the temperature-maintenance load increased, so did the heat pump entering water temperature. In turn, this led to a decrease in COP for the SANDEN GEN3 system but not the CxA.

Table 4. Return-to-Primary Entering Water Temperature Efficiency Comparison

Equipment	Draw Profile	Temperature-maintenance Loss per Unit	HP Entering Water Temperature	COP	Test Ref #
SANDEN GEN3	8 Medium	100 W	89°F	3.9	H201024
SANDEN GEN3	4 Medium	200 W	98°F	3.6	H201105
CxA	44 Medium	100 W	90°F	2.6	H220627
CxA	44 Medium	150 W	96°F	2.6	H220713

- Single-pass return-to-primary configurations performed well for the CxA heat pump product, producing the highest efficiency of all the tested configurations for this equipment. The average entering water temperature to the heat pump remained low enough, despite the warm recirculation loop water returned to the tank, that the equipment efficiency remained high. Specifically, in the baseline testing for this configuration, heat pump entering water temperature averaged 90°F.
- In general, the primary tanks remained somewhat stratified in the single-pass, return-to-primary configuration, even though there was a continuous flow of warm circulation loop water entering the tank. This water was still relatively colder than the water at set point in the tank and the cooler water stayed at the bottom.
    - This held true only for plumbing configurations where the temperature-maintenance loop return was plumbed to the bottom of the primary tank. In tests where the return was plumbed to the top of the tank, the storage de-stratified and often failed to provide hot water to the building. Returning the circulation loop water to the top of the tank should be avoided.
    - The return of circulated water to the primary storage tanks still disrupted the optimal thermal stratification. The main effect is a lower effective primary storage volume (about 25 percent lower). In other words, the water at the bottom was warm but not usably hot.
- In some circumstances, for the SANDEN GEN3 product, when circulated water was returned to the primary storage tanks, high temperature-maintenance losses paired with relatively low water usage caused the system to fail to deliver adequate hot water to the building. This occurred specifically when the recirculated water was >110°F and there was low hot water demand.
    - With the on and off temperature setpoints fixed for the SANDEN GEN3, the recirculated water temperature was not cold enough to signal the temperature sensor to turn the heat pump on.

- Overall, the failure observed here was due more to the setpoint control settings than anything else, including the different refrigerant types.
    - A heat pump will not run into problems if the on/off control settings can be configured such that they will trigger the equipment on at water temperatures reasonably in line with or much warmer than typical return water temperature.

5.2.2 Multi-Pass Heat Pumps

Figure 17 shows the schematic for multi-pass return-to-primary configurations. Again, the defining characteristic of the configuration is that both loads — the domestic hot water usage and temperature-maintenance heat loss — are satisfied by the same heat pump and storage tank. The only primary heat pump tested in multi-pass mode was the Colmac CxA.

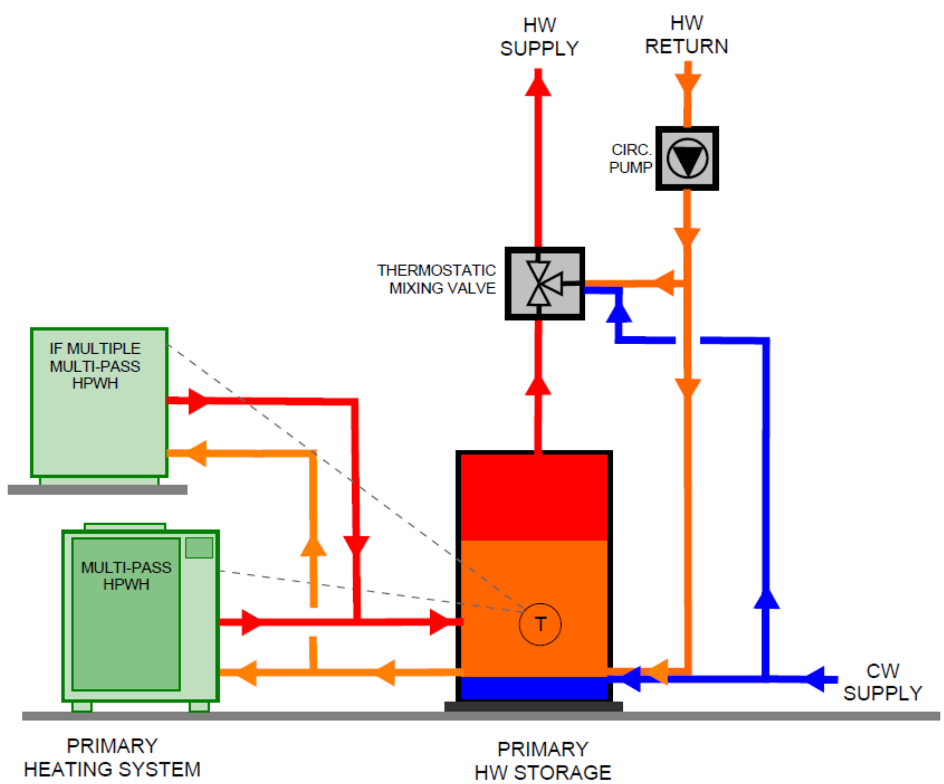


Figure 17. Multi-pass primary HPWH system with hot water return-to-primary storage.

- Of all the configurations, multi-pass return-to-primary showed the highest average entering water temperatures to the heat pump. This was due both to the nature of multi-pass heating and returning the warm recirculation loop water to the primary tank. Despite this, system COPs were still similar to those of other configurations.
    - The system COP was not particularly sensitive to changes in hot water load or temperature-maintenance load. The small differences observed in the Colmac

report graphs are merely due to testing artifacts and not general trends. This follows because multi-pass heat pumps are designed to operate with a range of entering water temperatures and must do so reasonably efficiently at both low and high temperatures.

- The storage tanks were observed to be partially stratified in multi-pass HPWH tests. This was somewhat surprising given the abundance of flow through the tank caused by the circulation loop and the multi-pass heating. The efficiency remained higher with a partially stratified tank compared to a fully mixed tank. In the specific tank piping arrangement, the tests revealed the following:
  - During large DHW draw events, hot water was drawn from the top of the tank as cool make-up water enters the bottom. The cool make-up water cooled the lower-tank first, then middle-tank, and the top of the tank cooled down last.
- When the HPWH is running, the lower tank and middle tank mixed: The middle tank cooled, the lower tank heated, and the upper tank remained hot. Once lower- and middle-tank temperatures converged and were about 15°F cooler than the upper-tank, the middle-tank and upper-tank become more mixed.
- HPWH outlet temperature varied throughout the HPWH run cycle and was warmer than the target (set point) tank temperature for over half the cycle. It was warmer during the last half of the cycle as the overall tank temperature had increased. The tests were run using Colmac's on-board circulation pump, which produces a constant flow rate in multi-pass mode, so variable flows were not tested, but we expect a higher flow rate would drive a lower outlet water temperature near the end of the HPWH run cycle.

5.3 Dedicated Temperature-Maintenance Systems

This section discusses findings from systems that separate the temperature-maintenance heating from the primary heating.

5.3.1 Primary Heat Pump – Secondary Electric Resistance

Figure 18 shows the schematic for single-pass-as-primary heat pump with the temperature-maintenance loop heated by a dedicated, secondary electric resistance tank. The secondary tank is installed in series with the primary tank. This piping configuration is also known as a swing tank. The defining characteristics of the configuration are:

- Separated domestic hot water and temperature-maintenance loads.
- A primary storage tank temperature great than the hot water supply temperature so that as water is used, the secondary tank is recharged with overheated water, which mixes down in temperature with the circulation loop return.

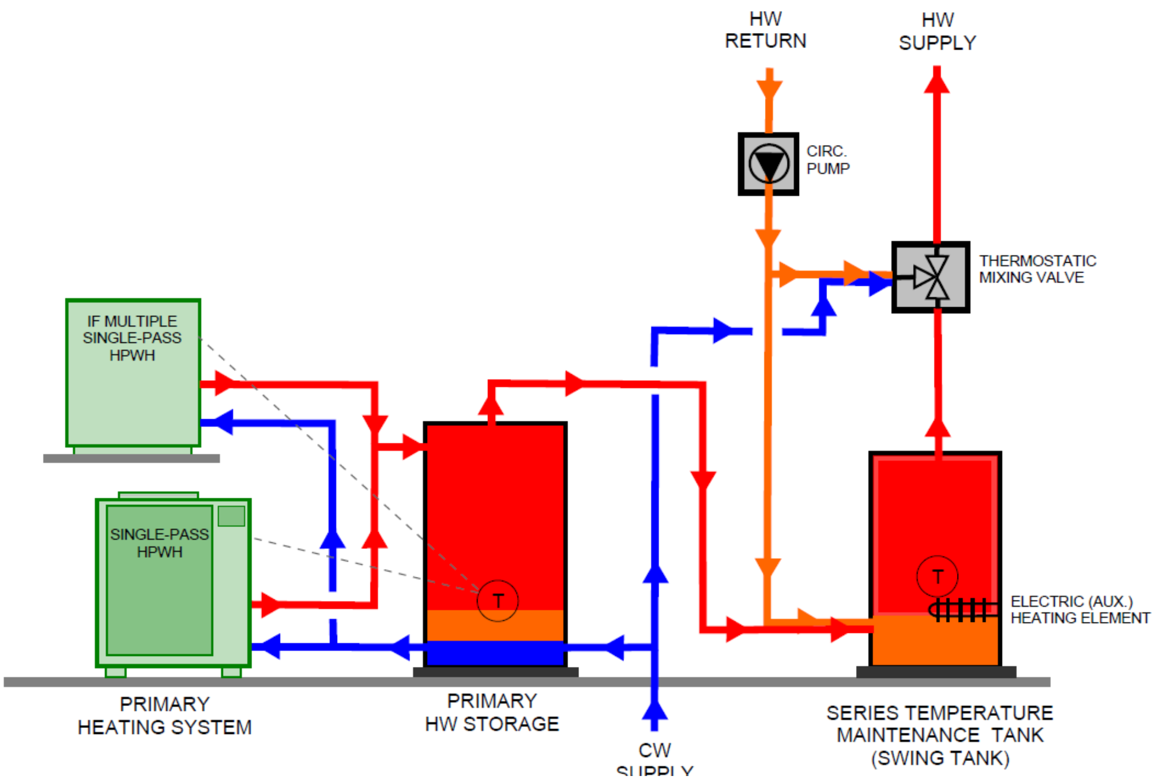


Figure 18. Single-pass primary HPWH system with series temperature-maintenance tank (swing tank).

- Of all the configurations, the swing tank system COP was most impacted by variations in DHW usage and temperature-maintenance losses. As DHW usage decreased relative to the temperature-maintenance losses, the system COP dropped. There was less overheated water to recharge the swing tank resulting in more resistance heat operation in that tank.
    - Please see Appendix C, Figure B06 and B09.
    - For the SANDEN GEN3 equipment, high temperature-maintenance losses degraded the average system COP by a full point in the swing tank configuration (from 3.8 to 2.8, a 26-percent drop).
    - For the CxA, the system COP dropped 14 percent from 2.1 to 1.8 as the temperature-maintenance losses increased from 50 W/unit to 150 W/unit. Due to different temperature sensor locations in the swing tank (based on lessons learned in the SANDEN GEN3 testing), the CxA tests were expected to exhibit less degradation than the SANDEN GEN3. Further, the CxA equipment COP is lower to begin with, so larger ER heat contributions will have a lower percentage effect on the COP change.
- In contrast to the SANDEN GEN3, return-to-primary configuration, the swing tank implementation always provided hot water to the building. The system COP was lower,

but the dedicated temperature-maintenance tank removed the risk of hot water run-out events.

- Compared to return-to-primary configurations, the swing tank design maximizes effective storage volume with well-stratified primary storage.
- The location and control of the aquastat and resistance elements in the swing tank is critical to overall energy use and electrical demand.
  - In the SANDEN GEN3 tests, the tank selected and its default controls resulted in more cycling of electric resistance than necessary. The aquastat was in the lower portion of the tank which was frequently subject to the cooler temperatures of the temperature-maintenance loop return water. This forced the resistance elements on early; the top of the tank was still hot and delivering hot water to the building.
  - In contrast, a different tank and control scheme was used for the CxA secondary tank tests. Specifically, that aquastat was located in the uppermost reaches of the swing tank. The result was that the resistance elements did not turn on until most of the tank temperature was depleted. This resulted in far less resistance heat use overall for the CxA swing tank tests.
  - These findings are not specific to the SANDEN GEN3 or CxA heat pumps, rather they are properties of the swing tank configuration. Restated, the SANDEN GEN3 results could have been better and the CxA results worse if the controls were reversed.
  - Last, another way to visualize the differences is that in the CxA swing tank tests, the electric resistance generally maintained the upper quarter of the tank as hot. In contrast, the configuration of the aquastats in the SANDEN GEN3 tests led to the upper three-quarters of the tank being maintained as hot by the ER elements. This meant fewer opportunities for the incoming overheated water from the primary heat pump to offset the inefficient ER heating.

5.3.2 Primary Heat Pump – Secondary Heat Pump

Figure 19 shows the schematic for single-pass as primary heat pump with the temperature-maintenance loop heated by a dedicated, secondary multi-pass heat pump installed in parallel with the primary. The defining characteristics of the configuration are separated domestic hot water and temperature-maintenance loads allowing the heat pumps for each to be optimized to the specific conditions under which they operate. Testing in this configuration was conducted with the CxA as primary and CxV as secondary heat pump.

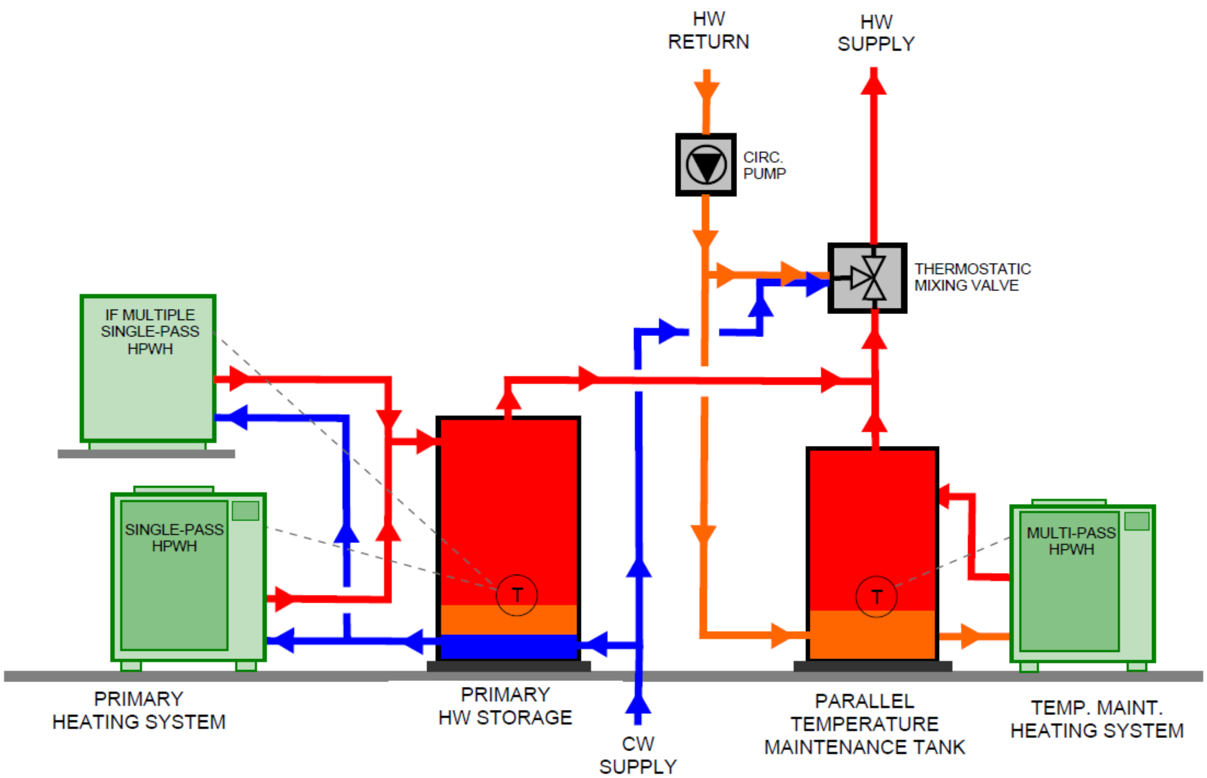


Figure 19. Single-pass primary HPWH system with parallel temperature-maintenance tank and multi-pass HPWH (parallel secondary tank).

- The single-pass primary HPWH with multi-pass secondary HPWH resulted in the most predictable operating conditions and the most stable output of all the configurations tested.
- The testing showed the system COP was nearly constant regardless of hot water draw or recirculation loop loss rate (Figure B06 and B09 Colmac Memo). The inlet water temperatures of the primary heat pump were steady and come directly from the incoming mains (Figure B07 and B07 Colmac Memo).
- The recirc loss rate did not meaningfully impact the secondary heat pump COP. The heat pump entering water temperatures were nearly identical at 50W/apt and 150W/apt.
- Higher outlet water temperatures in the secondary heat pump led to lower system COPs.
    - Additional testing with lower secondary heat pump outlet temperatures and secondary single-pass heat pumps may revealed more optimized designs.
- Based on the SANDEN GEN3 results, additional testing with a high-efficiency, transcritical CO_2 heat pump as primary may show higher overall system COPs for this configuration.

5.4 General Findings Regardless of Configuration Type

The findings summarized in this section pertain to all central heat pump water heating systems. They are both general and specific principles that can apply to all configuration types.

5.4.1 Piping Locations: Tank Height

Destratifying any tank leads to lower efficiency and effective storage volume, and it jeopardizes hot water delivery to the building. Across all testing configurations and all equipment, returning recirculation loop return water high in the tank led to rapid tank destratification and confused the temperature sensors controlling when to turn the heat pumps on.

5.4.2 Aquastat Sensor Locations: Tank Height

The location of the temperature sensors is critical to system operation, with different tank height locations leading to different operating behavior. Often, placing a sensor higher in the tank delays the turning on of the heating component. This can be desirable depending on what is being controlled.

5.4.3 Storage Tank Parallel vs. Series Configuration

Testing showed that piping the primary storage tanks in series or in parallel resulted in similar efficiencies. Further, the effective storage volume was similar across both piping arrangements. The parallel tanks self-balanced even when the project team intentionally unbalanced them at the beginning of testing. During high draws, an imbalance appeared in the parallel tanks, but they rebalanced when the heat pump reheated the system. The lab test team carefully built the test setup to have equal-length piping for the parallel tanks, which likely contributed to the success of that arrangement.

5.4.4 Primary Storage Temperature

Hotter storage temperatures lead to lower primary heat pump efficiency. This is exacerbated in R-134a systems which have a stronger leaving (outlet) water temperature dependence than CO_2 systems.

At a system level, the hotter temperature also led to lower system COPs for both return-to-primary and return-to-secondary configuration. Fundamentally, the higher primary storage setpoint always led to a lower primary equipment COP. The higher temperature in the primary did reduce the electric resistance heat use in the series swing tank but it was not enough to compensate for the drop in primary equipment COP. This was apparent both in the SANDEN GEN3 and the CxA testing.

5.4.5 Mixing Valve Incoming Plumbing

If a heat pump outlet is piped directly to the hot inlet side of the mixing valve, the mixing valve outlet temperature is erratic when the heat pump is running because the heat pump outlet water temperature changes, even with single-pass systems. Our testing showed that plumbing the heat pump outlet first to the storage tank created a buffer and smoother supply water temperature to the hot inlet of the mixing valve. This resulted in stable outlet water temperatures sent to the circulation loop.

5.4.6 Heat Pumps in Parallel

Testing showed that multiple heat pumps, plumbed and operating in parallel, performed more-or-less identically. This was an important validation of assumptions by designers and in software simulations.

5.4.7 Series Temperature-Maintenance Tanks

The swing tank design is the configuration most impacted by temperature-maintenance heat loss rate. Higher heat loss rates led to lower system efficiency, regardless of primary heat pump type.

5.4.8 Determinants of System Efficiency

The heat pump entering water temperature is the main differentiator across system configurations and system efficiency. The system configurations represent fundamentally different ways of setting up the entering water temperature to the heat pump. Using return-to-primary, single-pass, multi-pass, or return-to-secondary configurations all set up different entering water scenarios. Within those scenarios, there are specific design decisions to make that further minimize entering water temperature and maximize efficiency and hot water delivery.

The CxA heat pump efficiency, with the R-134a refrigerant, is not significantly impacted by entering water temperature over the range observed. Consequently, there was not much variation in system COP across the multitude of tested configurations. In contrast, the SANDEN GEN3, with the transcritical CO_2 refrigeration cycle, is much more sensitive to entering water temperature, hence the larger variation COP across configurations.

5.4.9 Integrated Heat Pumps

The AO Smith CHP-120, a commercial integrated HPWH, was tested as a stand-alone unit and with additional heating equipment. Installing an integrated HPWH with additional equipment takes away the integrated HPWH's key advantage: It is simple to install and operate compared to custom-engineered CHPWH systems. However, these tests led to key insights regarding ways the manufacturer could refine and support equipment design to satisfy various applications. Unfortunately, these results cannot be extrapolated to all integrated HPWHs because proprietary, manufacturer-specific controls setpoints impacted the way the CHP-120 managed DHW usage and temperature-maintenance loads. Still, these observations are useful for all integrated HPWH manufacturers to reference as they refine internal control setpoints.

- **Stand-alone HPWH serving a building with a temperature-maintenance loop**: The CHP-120 managed the DHW usage and temperature-maintenance loads efficiently – electric resistance only triggered during peak periods – but supply temperature cooled to 112°F when little DHW usage was present. This suggests AO Smith may need to allow deadband adjustment to accommodate operation with a HWC loop.
- **Thermostatic mixing valve:** Pairing the CHP-120 with a mixing valve and increasing its delivery temperature setpoint decreased electric resistance usage and stabilized supply temperature. However, it decreased system COP because the HPWH compressor operated less efficiently with a higher storage temperature.
- **CHP-120 operating as swing tank:** The CHP-120 operated efficiently as a swing tank and did not use any electric resistance to satisfy the temperature-maintenance load. This points to the potential to replace electric resistance swing tanks with integrated HPWHs in the future as more integrated HPWHs become available. We recommend that HPWH manufacturer supports the swing tank application with specific control setpoints including return water temperature requirements. As noted in Appendix D, unitary HPWHs should not be installed as a swing tank without explicit manufacturer approval. This configuration is not currently advertised by AO Smith.
- **CHP-120 operating in heat-pump-only mode as a pre-heater (swing tank configuration):** The CHP-120 operated efficiently when set to heat-pump-only mode and installed upstream of an in-series temperature-maintenance tank. This demonstrates the potential to install integrated HPWHs upstream of high-recovery gas or electric resistance water heaters to operate as preheaters in applications like kitchens. Installing a HPWH system that will satisfy the full DHW load is often the best solution for many applications, but California Health and Safety Code requires water heater recovery be sized to 100 percent of the peak hourly DHW demand in food facilities, which often makes HPWH installation in food service unfeasible: Relatively low recovery rates in HPWHs drive a very large footprint and first cost. Installing a HPWH as a preheater would allow the HPWH to satisfy most of the DHW load at a smaller footprint and first cost because the high-recovery water heater can be sized to satisfy 100 percent of the peak hour DHW load. HPWH pre-heaters can also make use of kitchen waste heat but would require more space than is required for a gas or electric resistance heater operating on its own. It is important that any attempt to use the HPWH in this application is fully supported by the manufacturer, that the downstream water heating system can satisfy the full DHW load, that alarms are installed to trigger if the HPWH pre-heater stops operating, and that a setting on the HPWH prevents the electric resistance element from running even when the storage tank is very cold.
- **Additional storage:** The CHP-120 was tested with an additional storage tank to simulate an integrated HPWH with a larger storage tank. It operated more efficiently this way because the electric resistance element did not trigger during peak usage periods.

Overall, the safest and simplest way to apply integrated HPWHs are as intended by the manufacturer: without any additional DHW equipment. That said, carefully designed, manufacturer-supported, custom-engineered systems may see additional energy savings when an integrated HPWH is properly applied to them.

Design Recommendations Based on Test Results

Taken as a whole, the test results suggest both good and bad design practices. This section summarizes the best design practices to follow. These recommendations are made with the goal of increasing energy efficiency; water quality was not considered as part of this research.

5.5 Overall System Configuration Selection

The specific system configuration to use for a given building depends on factors ranging from climate and building size to equipment availability and cost. This section describes where certain systems may be most appropriate and what heat pump, controls, and sizing requirements are needed for each configuration to function well.

5.5.1 Single-Pass Return-to-Primary

Notes:

- This configuration achieved the highest system COP when using R-134a refrigerant but requires a HPWH that can heat efficiently when inlet water temperature is above 100°F.

When to use:

- Recirculation return temperature is cooler than 120°F.
- Single-pass equipment can handle sustained high inlet water temperature efficiently.

HPWH requirements:

HPWH must be capable of the following throughout the entire design outdoor air temperature range:

- Single-pass operation.
- Sustain operation with outlet water temperature equal to target storage temperature.
- Sustain operation with inlet water temperature greater than recirc return temperature and “on” setpoint in “Controls Requirements.”

Controls Requirements:

- Locate “on” tank temperature sensor high enough in the tank to prevent short-cycling and set “on” setpoint equal to DHW supply temperature to the building.
    - Water volume below “on” sensor should be large enough to allow the HPWH to run at least 10 minutes when inlet water temperature is equal to recirc return temperature and outdoor air temperature is near the design hot day. The goal is to prevent short-cycling the heat pump.

- Locate “off” temperature sensor (preferably) at the HPWH inlet or low in the storage tank and set “off” setpoint 5°F warmer than DHW supply temperature.

Special Sizing Requirements:

- Add temperature-maintenance heat loss to required HPWH recovery.
- Ensure aquastat fraction is large enough to prevent HPWH short cycling when bottom of tank is equal to recirc return temperature.

5.5.2 Multi-Pass Return-to-Primary

Notes:

- Second-highest efficiency when using R134a equipment.
- Requires much larger storage or recovery than single-pass return-to-primary.

When to use:

- Single-pass equipment is not available.
- High recirculation return temperature.

HPWH requirements:

HPWH must be capable of the following throughout the entire design outdoor air temperature range:

- Multi-pass operation.
- Sustained operation with outlet water temperature 10°F warmer than target storage temperature.
- Sustained operation with inlet water temperature equal to target storage temperature.

Controls Requirements:

- Same sensor could be used for “on” and “off” triggers, but it is preferable to locate a separate “off” sensor lower in the tank or (preferably) on the HPWH inlet.
- Set “on” temperature 10°F warmer than DHW supply temperature.
- Set “off” temperature 15°F warmer than DHW supply temperature.

Special Sizing Requirements:

- HPWH recovery and/or storage must be increased substantially relative to single-pass HPWH system sizing. Clear recommendations are not currently available.

5.5.3 Single-Pass with Series Secondary Tank (Swing Tank)

Notes:

- System efficiency is impacted significantly by temperature-maintenance heat loss.
- Extra tank and heater are required to accommodate temperature-maintenance heat loss.

When to use:

- If single-pass equipment cannot run efficiently with high inlet water temperature.
- If temperature-maintenance heat loss is low or circ pump can be turned off when building is not in use (not recommended in most multi-family buildings)

HPWH requirements:

HPWH must be capable of the following throughout the entire design outdoor air temperature range:

- Single-pass operation
- Sustain operation with outlet water temperature equal to target storage temperature.
- Sustain operation with inlet water temperature greater than 125°F before turning off. This is an end-of-run condition that does not need to be accommodated efficiently.

Controls Requirements:

- Primary Tank
    - Locate “On” temperature sensor high enough in tank to prevent short-cycling and set “on” setpoint equal to DHW delivery temperature.
        - Water volume below “on” sensor should be large enough to allow HPWH to run at least 10 minutes when HPWH inlet water temperature is close to DCW temperature.
    - Locate “off” temperature sensor (ideally) on HPWH inlet or low in the tank.
    - “Off” temperature setpoint 5°F warmer than “on” setpoint.

Special Sizing Requirements:

- HPWH recovery and/or storage must be increased slightly since the primary HPWH will provide some temperature-maintenance heating. Ecosizer sizing software already adjusts for this.

5.5.4 Single-Pass Primary with Parallel Secondary Loop Tank

When to use:

- If single-pass equipment cannot run efficiently with high inlet water temperature.
- If temperature-maintenance heat loss is high

HPWH requirements:

Primary HPWH must be capable of the following throughout the entire design outdoor air temperature range:

- Single-pass operation.
- Sustain outlet water temperature equal to target storage temperature.
- Sustain inlet water temperature greater than 125°F before turning off. This is an end-of-run condition that does not need to be accommodated efficiently.

Parallel loop HPWH must be capable of the following throughout the entire design outdoor air temperature range:

- Multi-pass operation or single-pass operation with sustained high inlet water temperature.
- Sustain operation with outlet water temperature 10°F warmer than target temperature-maintenance tank temperature.
- Sustain operation with inlet water temperature 10°F warmer than recirc return temperature.

Controls Requirements:

Primary HPWH and storage:

- Place "on" temperature sensor high enough in the tank to prevent short-cycling and set "on" setpoint to 120°F.
- Water volume below "on" sensor should be large enough to allow HPWH to run at least 10 minutes once HPWH has been triggered on.
- Place "off" temperature sensor (preferably) on the HPWH inlet or low in the tank and set "off" setpoint 5°F warmer than "on" setpoint.

Secondary HPWH and storage:

- If an electric resistance water heater is used as a parallel loop tank: Electric resistance "on" sensor and electric resistance element location should be very high in the tank and set 5°F lower than HPWH "on" setpoint.

- Locate HPWH “on” sensor above 50 percent tank height but lower than electric resistance “on” sensor and set HPWH “on” setpoint 5°F warmer than desired supply temperature.
- Place HPWH “off” sensor (preferably) on the HPWH inlet or low in the tank and set HPWH “off” setpoint 10°F warmer than desired supply temperature.

Special Sizing Requirements:

- Parallel loop HPWH should be sized to exceed the temperature-maintenance heat loss rate at the cold design air temperature.

5.6 Do Not Destratify the Tank

Always introduce cold water to the bottom of the tank. Similarly, always return the mildly warm water from the temperature-maintenance loop to the bottom part of the tank. The rationale is threefold:

1. Mixing the tank decreases the effective storage capacity.
2. Mixing the tank increases the heat pump entering water temperature on average, leading to lower heat pump COP.
3. Single-pass heat pump controls often rely on (or assume) stratified storage to operate the heat pump correctly.

5.7 Connect Heat Pump Inlet and Outlet to Tanks

HPWHs and mixing valves both operate more effectively when water pressure and temperature are constant or change very slowly. Providing hydraulic separation between the mixing valve and HPWH can provide much steadier temperature and pressure to each component. This hydraulic separation or buffering applies to the HPWH inlet and outlet, mixing valve, and domestic cold water make-up pipe. See Figure 20 for a schematic example.

- Designers should provide hydraulic separation between the HPWH outlet and mixing valve inlet by specifying a dedicated tank connection for the HPWH outlet. Not doing so drives erratic mixing valve behavior and uncontrolled water temperature releases into the circulation loop.
- If using a series temperature maintenance configuration, the primary HPWH outlet may be connected to the pipe between the primary storage and temperature-maintenance tank since the temperature-maintenance tank acts as a buffer between the mixing valve inlet and HPWH outlet.
- Designers should provide hydraulic separation between the HPWH inlet and domestic cold water (DCW) make-up by piping the HPWH inlet directly to the storage tank. Not doing so drives erratic HPWH inlet temperature and mixing valve pressure imbalance, which could negatively impact HPWH reliability, efficiency, and hot water supply stability.

HPWH supply and return should be isolated from the DCW supply pipe and mixing valve inlet to ensure stable HPWH inlet and building supply temperatures. This could be accomplished by providing dedicated HPWH supply and return connections on the side of the storage tanks. This information should be incorporated into design best practice guidelines, HPWH-oriented storage tank model lines, and potentially into code.

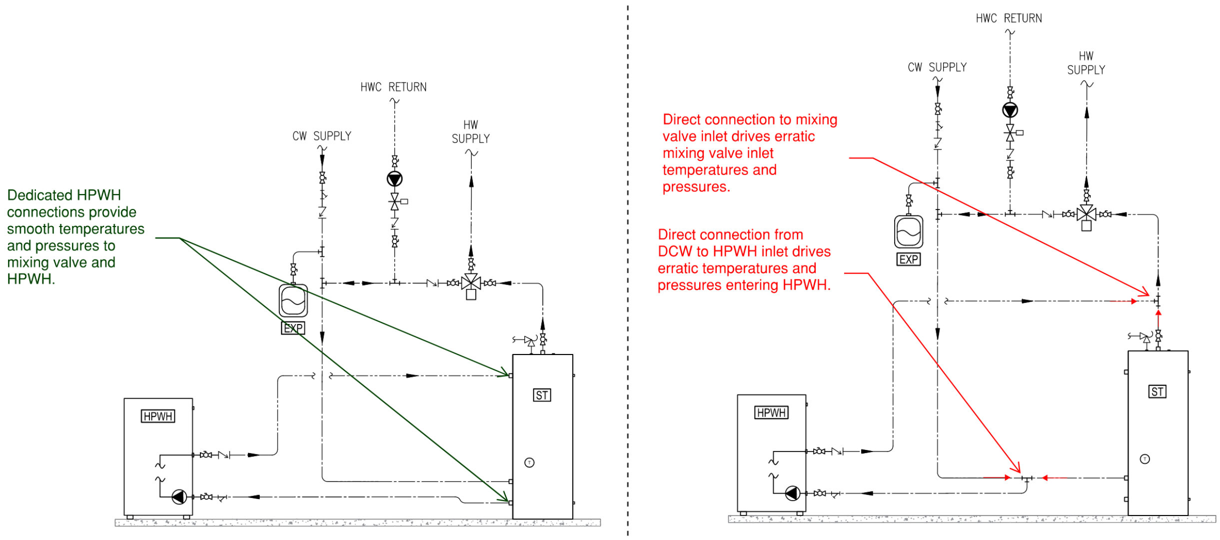


Figure 20. Left (correct): Dedicated tank connections for HPWH inlet and outlet provide hydraulic separation. Right (incorrect): HPWH inlet and outlet are piped to mixing valve inlet and DCW make up, driving erratic HPWH and mixing valve behavior.

5.8 Parallel vs. Series Tank Plumbing

When using parallel tank plumbing, use equal-length piping to create truly parallel flow paths into and out of the tanks so they remain balanced. Testing showed the tanks rebalanced themselves, but we tested only equal-length piping, not disparate-length setups. A practical benefit of parallel tank plumbing includes lower pressure drop through the tanks.

5.9 Temperature Sensor Location in Tanks

Carefully consider temperature sensor location in both single and multi-pass systems. Stratified storage tanks mean cycle times and effective storage capacity are dependent on on/off sensor locations.

5.9.1 Parallel vs Series Tank Sensor Placement

When designing either tank plumbing arrangement, it is necessary to consider the relative sensor height placement. For example, for two tanks in parallel with the sensor at half height, it is at half the total storage volume. For two tanks in series, with the sensor at same half height of the first tank, it is at one-quarter of the total storage volume. If it were in the second tank, it would be at three-quarters of the total volume. Because sensor location has implications for when the heat pump will turn on, it must be considered in system design.

5.9.2 Swing Tank Sensor Location

Place the aquastat that controls the electric resistance elements in the upper portion of the swing tank to minimize run time. Doing so essentially gives the supercharged water from the primary storage more chance to heat this secondary tank.

5.10 Multi-pass Heat Pump Specific Recommendations

Multi-pass heat pumps are appropriate for use in return-to-secondary, parallel tank configurations if the equipment can sustain operation with high entering water temperatures. Verify heat pump specifications before selecting.

Storage sizing should account for partial stratification and not assume fully mixed storage as this will lead to needlessly oversized storage. Data from the lab tests can be used to develop better multi-pass sizing algorithms. (This also applies to single-pass return-to-primary designs.)

Multi-pass heat pump systems do not require dedicated temperature-maintenance tanks. The multi-pass heating nature of the heat pump makes them suitable for return-to-primary configurations. Still, reduced effective storage volume must be taken into consideration in sizing of the storage tanks under return-to-primary configurations. The implications for design are that the tank will still be stratified but the bottom will be warm but not hot and useable.

5.11 Using Single-Pass Configurations

To improve performance of the swing tank configuration or to confidently recommend recirculation return to the bottom of the primary storage the following must be considered by both the design engineer and equipment manufacturer:

- A fully developed specification for the primary storage tanks, recirculation pump controls, swing tank, control system, any back-up heat, and all parts and pieces of a fully functional multifamily water heating system need to be provided by the manufacturer to reduce risks and produce reliable, repeatable results.
- For return-to-primary, inclusion of a variable speed pump or thermal balancing valve controlled to limit return water temperature from going below the thermal on-temperature of the heat pumps, and/or adjustment of the thermal on-temperature to a value meaningfully hotter than the circulation loop return temperature.
- For return-to-primary, primary tank storage volume should be increased to account for reduced thermal storage efficiency resulting from the tank being mixed.
- Guidelines of how to minimize temperature- losses in the design of the piping distribution are needed.
- In the absence of any electric resistance backup elements, recommend inclusion of an extra heat pump in the design sizing to provide redundancy and reliability.

To address one of the significant project goals, the next step in the project is for the team to compare the simulation output from the physics-based software model to the lab-measured data. The team then plans to revise the simulation with the information gleaned from the comparison to make the simulation more realistic and representative. Initial work on this comparison has begun.

To enable the comparisons, the team will set up a code infrastructure to directly run the lab application test scenarios through the simulation. That is, the team will run the 24-hour test periods, on a minute-by-minute basis. Inputs to the simulation are the exact test draw profiles, water temperatures, circulation loop flows, outlet water flows, etc. We will initialize the simulated tank temperatures to match the lab measured temperatures, collect all the simulation outputs, and then plot against the lab measured data.

We plan several levels of qualitative and quantitative comparison between simulation and measured data. Qualitative comparisons will examine, by test configuration, the energy input, output, and efficiency of the simulation to the lab tests. We can then rank the findings to see how the simulation order reflects the measured order. The quantitative assessment can run deep, however, there are several important values to start comparing, including the percent difference in COP of the simulation from the lab measurement. One of the big unknowns in implementing the physics-based model is how tank temperatures behave and evolve under actual use. Specifically, there is interest in the water temperature at different heights and how it changes. The tank can mix or stratify in response to water draw and heating events. We plan to overlayed measured and modeled temperature plots to show how the simulation compares to reality.

With the comparisons in hand, the team will summarize the general trends on agreement and disagreement and create a plan to update the simulation. After the updates, the team will revisit the qualitative and quantitative comparisons to demonstrate an improvement.

6 Conclusions

This project successfully conducted laboratory investigations of a wide range of central heat pump water heater equipment, configurations, and system efficiencies. The lab testing team pioneered a method for examining large-scale central heat pump water heating systems by constructing a robust and flexible test bed. The lab successfully simulated the hot water use and temperature-maintenance loads of multifamily buildings ranging in size from 4 to 44 units. The hot water loads reached nearly 2,000 gallons per day alone while the heat pump sizes exceeded a nominal 15 tons of capacity. Heretofore, due to their sheer size, measurement of such systems had only been possible in actual buildings and those were subject to uncontrolled environmental conditions. Further, in occupied buildings, it is not feasible to alter system setups to test different design variables. The results from this testing highlight the value of laboratory testing in a controlled environment.

The testing included examination of several different HPWHs. More importantly, the testing examined variations in system configuration — combinations of temperature-maintenance system configuration, sizing of primary and secondary storage tanks, piping configuration for recirculated water, range of distribution system losses, and storage water temperatures. For a given configuration, we varied hot water load and temperature-maintenance load to understand their impact on efficiency. Our major, generalized findings include:

- **Heat Pump Entering Water Temperature:** The heat pump entering water temperature is the main differentiator across system configurations and the key determinant of system efficiency. System configurations are fundamentally different ways of setting up the entering water temperature to the heat pump. Using return-to-primary, single-pass, multi-pass, or return-to-secondary configurations all set up different entering water scenarios. Within those scenarios, there are specific design decisions to make that further minimize entering water temperature, maximizing efficiency and hot water delivery.

- **Stratification:** Destratifying any tank leads to lower efficiency and effective storage volume, and it jeopardized hot water delivery to the building. Across all testing configurations and all equipment, returning recirculation loop return water high in the tank led to rapid tank destratification and poor performance.

- **Aquastat Location:** The location of the tank temperature sensors is critical to system operation. Different tank height locations lead to different operating behavior effecting efficiency and hot water availability.

- **Series vs. Parallel Primary Storage:** Piping the primary storage tanks in series or in parallel results in similar efficiencies as long as equivalent length piping methods are used for the parallel plumbing. Further, the effective storage volume is similar across both piping arrangements.

- **Primary Storage Tank Temperature:** Hotter storage temperatures lead to lower primary heat pump efficiency. Testing showed this was exacerbated in R-134a systems which have a stronger leaving (outlet) water temperature dependence than CO_2 systems. At a system level, the hotter temperature also led to lower system COPs for both return-to-primary and return-to-secondary configuration. Fundamentally, the higher primary storage setpoint always leads to a lower primary equipment COP. The higher temperature in the primary did reduce the electric resistance heat use in the series swing tank but it was not enough to compensate for the drop in primary equipment COP.
- **Mixing Valve Inlet Plumbing:** Testing showed that plumbing the heat pump outlet first to the storage tank created a buffer and smoother supply water temperature to the hot inlet of the mixing valve. This resulted in stable outlet water temperatures sent to the circulation loop.

The project team analyzed the lab test results for each unit and configuration to find commonalities. The project team synthesized those results into generalized findings that can be used to guide all central HPWH system designs. The synthesis identified both good and bad practices and design considerations. The major findings include:

- **System Configuration Choice:** There is no "one-size-fits-all" configuration. The specific system configuration to use for a given building depends on a number of factors ranging from climate and building size to equipment availability and cost. Refer to Section 5.5 for a discussion of pros and cons of system selection and what heat pump, controls, and sizing requirements are needed for each configuration to function well.
- **Do not destratify the tank**. To increase energy efficiency of the system, always introduce cold water to the bottom of the tank. Similarly, always return mildly warm water from the temperature-maintenance loop to the bottom part of the tank.
- **Provide Hydraulic Buffering**. HPWHs and mixing valves both operate more effectively when water pressure and temperature are constant or change very slowly. Providing hydraulic separation between the mixing valve and HPWH provides steadier temperature and pressure to each component. This hydraulic separation, or buffering, applies to the HPWH inlet and outlet, mixing valve, and domestic cold water make-up pipe.
- **Temperature Sensor Location**. Carefully consider temperature sensor location in both single and multi-pass systems. Stratified storage tanks mean cycle times and effective storage capacity are dependent on on/off sensor locations.
- **Single-Pass Heat Pump Specific Recommendations.** To confidently recommend recirculation return to the bottom of the primary storage or to improve performance of the swing tank configuration, the following must be considered by both the design engineer and equipment manufacturer:

  - For return-to-primary, include a variable speed pump or thermal balancing valve controlled to limit return water temperature to below the on temperature of the heat pumps and/or adjust the on temperature to a value meaningfully hotter than the circulation loop return temperature.
  - For return-to-primary, increase the primary tank storage volume to account for reduced thermal storage efficiency due to a mixed tank.
  - A fully developed specification for the primary storage tanks, recirculation pump controls, swing tank, control system, any back-up heat, and all parts and pieces of a fully functional multifamily water heating system need to be provided by the manufacturer to produce reliable, repeatable results.
  - Include guidelines for the minimization of temperature-maintenance losses in the design of distribution piping.
  - In the absence of any electric resistance backup elements, include an extra heat pump in design sizing to provide redundancy and reliability.
- **Multi-pass Heat Pump Specific Recommendations.**
  - Multi-pass heat pump systems do not require dedicated temperature-maintenance tanks. The multi-pass heating nature of the heat pump makes them suitable for return-to-primary configurations. Still, reduced effective storage volume must be taken into consideration in sizing of the storage tanks under return-to-primary configurations. The implications for design are that the tank will still be stratified and the bottom will be warm but not hot and useable.
  - Multi-pass heat pumps are appropriate for use in return-to-secondary, parallel tank configurations if the equipment can sustain operation with high entering water temperatures. Verify heat pump specifications before selecting.
  - Storage sizing should account for partial stratification and not assume fully mixed storage as this will lead to needlessly oversized storage.

In conclusion, it is the hope of the project team that the summary report, appended detailed reports, and the associated findings and recommendations will help all designers and installers of central HPWH systems to design and select components and layout which maximize system efficiency and energy savings.

Appendix A: Initial Software Improvements

In conjunction with the laboratory testing and simulation updates to enable the modeling of central HPWH systems for multi-family buildings, the team undertook necessary work to lay the foundations for further improvements. These included three early software update tasks, one for collecting equipment performance data, and, as the project evolved, a complete expansion of the physics-based model of central HPWH performance.

Hot Water Draw Schedule

The software team improved the structure of the domestic hot water draw model to eliminate spurious peak demands and give greater diversity and statistical accuracy in multifamily buildings. The approach was to add diversity to the draw patterns to create smoother, aggregate load profiles. Previously, in multifamily buildings, the draw profile generator would stack a limited number of draw schedules on top of another causing unrealistically high draws over short time periods instead of being more spread out in time as happens in the real world.

Sizing Methodology for Multifamily Standard Design HPWH

For the purposes of the comparison to the standard design building in CBECC-Res, there must be a method to automatically size the heat pump water heating system. Any proposed design in the simulation would then be compared against this system and be expected to meet or exceed its performance. The software team leveraged the simulation as a tool to determine a minimum size. For the climate zone in which the building is located, the simulation is run several times. The goal is to find the coldest day with the largest peak draw profile since this will be the most challenging case for the water heating system. A simulation is run with the exact number of dwelling units as the proposed building so a draw profile can be generated. Then, the primary storage is sized to meet the peak load. The heat pump is subsequently sized so that it can reheat the primary storage in 16 hours of runtime under the coldest outdoor temperatures. A generic HPWH capacity curve is used to determine the heating rate at the needed temperature. In this way, the system is iteratively sized for the standard design. The proposed design may use any sizing the user wishes.

Distribution System Modeling

Prior to this project, the multifamily recirculation loop model had been one simply conducting a heat loss calculation and adding that heat loss as additional load the water heater. In this task, the software team changed that model to be one of mass flow and temperature. This is especially important for HPWHs, where the returning water temperature from the loop directly changes the equipment efficiency.

In the best cases, keeping the water in a large multifamily distribution system hot typically adds 30% to the energy required to heat the water and in the worst cases keeps HPWH systems from successfully meeting the needs of residents. The update allows alternative temperature-maintenance approaches such as heat tape and special purpose dedicated HPWHs to be compared for specific buildings.

Next, the software team adapted the multifamily loop flow and temperature model for single-family HPWHs with recirculation systems to replace the antiquated distribution system multipliers (DSM) and improve accuracy. Distribution losses were previously modeled as increased gallons of hot water use, but this distorted the hot water loads and gave seriously incorrect signals about system design. For example, an in-dwelling unit continuously pumped loop was assigned a DSM of 9 and this resulted in every 10-gallon shower consuming 90 gallons of hot water at the water heater. But the real losses from this loop are independent of the number of showers and shower water usage actually drops compared to a distribution system with no loop. That approach was corrected by converting the rest of the DSMs for single dwelling units to an increased flow time model for increased accuracy.

Last, the software team enabled drain water heat recovery modeling for all the relevant DHW end uses and plumbing proposed in the 2022 CASE report. This measure is critical to electrification since the California Energy Commission decided to include it in the Electric Water Heating Standard Design.

Equipment Performance Data (Maps)

To accurately model the HPWH, it is necessary to know a product's input power and output capacity over a full range of ambient air conditions and inlet water temperatures. This data, although readily available for space heating systems from multiple manufacturers, is not so for HPWHs. It is also not practical for a third party to lab test every HPWH on the market to collect this information. Therefore, the team established a method to obtain HPWH equipment performance data from manufacturers for use in the simulation.

The project team created a standardized way for manufacturers to submit product performance data so the equipment could be modeled in CBECC software. It consists of a datasheet and declaration document.

- The California Energy Commission Site for Performance Map submission is here https://www.energy.ca.gov/rules-and-regulations/building-energy-efficiency/manufacturer-certification-building-equipment-8
- The Declaration Document is here https://www.energy.ca.gov/media/3566
- The Datasheet is here https://www.energy.ca.gov/media/3567

Physics-Based Simulation Model

The original project plan was to conduct the lab testing first and then create the simulation with those results. As the lab testing project progressed, it became clear the timeline was stretching too long and that the needs of Title 24 necessitated a different approach. Thus, the software team forged ahead without the lab results, relying on solid physical principles to design the simulation. The upside of this approach is that we could create simulations for a host of products rather quickly (single-pass, multi-pass, multiple piping configurations, etc.). The downside is that simplifications and assumptions are necessarily made to make the simulation tractable and, without measurements, we do not know how realistic those assumptions are. Therefore, the plan become to create the physics-based simulation first and then true it up later once lab data was available.

The implementation of the physics model was robust and wide ranging in capability. The team added the following abilities to CBECC:

- Multi-pass heating
- Central water heating system configurations and layouts
    - Multi-pass primary HPWH without hot water circulation
    - Multi-pass primary HPWH with secondary electric resistance trim heater tank and without hot water circulation
    - Multi-pass HPWH system with HW circulation returned to primary system
    - Single-pass primary HPWH with parallel multi-pass HPWH

The team also added the following products, using submitted performance maps, to the simulation:

- Mitsubishi QAHV; Heat-2-O; Rheem and Raypak lines; all Colmac products; all Nyle products

The current list of products that have submitted performance map data, available in the simulation here https://www.energy.ca.gov/media/4026.

Last, the team completed documentation for previously implemented and newly implemented layouts in the Alternative Calculation Method Reference Manual (ACM).[5]

[5] CEC 2022. 2022 Single-Family Residential Alternative Calculation Method Reference Manual: For the 2022 Building Energy Efficiency Standards Title 24, Part 6, and Associated Administrative Regulations in Part 1 Appendix B. https://www.energy.ca.gov/publications/2022/2022-single-family-residential-alternative-calculation-method-reference-manual

Appendix B: Sanden Gen3 Report

To: Bruce Wilcox

From: Jonathan Heller, Colin Grist, Paul Kintner, Ben Larson

Re: Summary Findings: PG&E HPWH Laboratory Application Testing

Date: May 17, 2021

Introduction

This memo summarizes findings from the PG&E ATS Laboratory Application Testing of Class 2 (small single-pass) heat pump water heater (HPWH) equipment. The intent was to explore performance and discover limitations for this equipment to improve systems design when serving typical multifamily loads.

The testing included examination of different piping configurations, one or two primary heat pumps, different water use levels, and different supply water temperatures. The results from this testing highlight the value of the laboratory testing in a controlled environment. The results identify both good and bad practices and design considerations for improving single-pass heat pump water heater systems in a multifamily application. Certain tests resulted in additional findings beyond the primary test purpose. This type of careful and controlled testing is valuable for improving emerging technologies like central heat pump water heating systems to achieve reliable and repeatable energy savings.

Overall, the heat pumps were found to function well, however the integrated *SYSTEM* designs still need improvement to achieve reliable and repeatable results in multifamily applications. Various system effects led to loss of hot water at the building supply under certain conditions and high temperature-maintenance losses led to dramatically reduced efficiency under certain conditions. There are possible improvements which could be made to the auxiliary component specifications and the overall system design which could alleviate these deficiencies, but more research, product development, and testing is required to validate a reliable high performing system.

Testing Description

Two prototype apartment buildings were simulated to represent 4 apartments (one primary HPWH) and 8 apartments (two primary HPWHs). Multiple levels of hot water use were tested in the laboratory. These represented a low (L), medium (M), and high (H) draw profile for the 4-unit or 8-unit apartments. These hot water draw profiles were created from CBECC-Res data and correspond to standard California prototypes. The water use rates were chosen to represent 5th percentile, median, and 95th percentile days. The tested daily water volume totals are as follows.

Table 1. Tested Daily Water Volume Totals

Hot Water Load Profile	4M: 4Apts, Med. Draw	8L: 8Apts, Low Draw	8M: 8Apts, Med. Draw	8H: 8Apts, High Draw
Total Volume (Gal/Day)	114	132	229	375

Some of the tests operated with two HPWH units in parallel serving the primary tank. These tests show that multiple heat pumps operated in parallel perform more or less identically. This was important to validate this assumption by designers and in software simulations.

The testing examined three primary ways to configure temperature-maintenance loops. These are shown in the schematics below. Equipment labels represent the following:

- HPWH – Heat Pump Water Heater
- ST – Storage Tank
- WH – Water Heater (Electric Resistance)
- EXP – Expansion Tank
- TMV – Thermostatic Mixing Valve
- PMP – Recirculation Pump
- CW – Cold Water
- HW – Hot Water
- HWC – Hot Water Circulation
- T – Temperature Sensor
- FM – Flow Meter

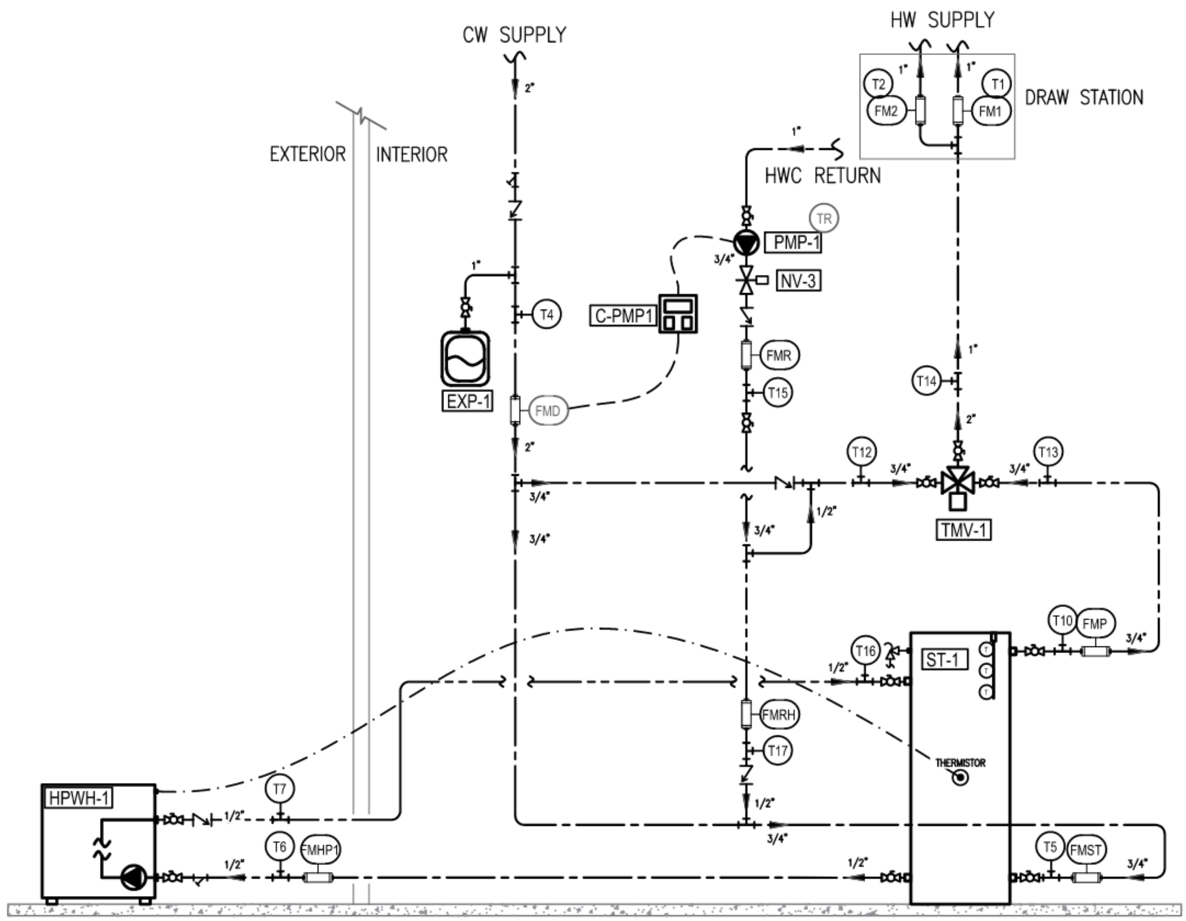


Figure 1. A6: Temperature Maintenance Returned Low to Primary Storage

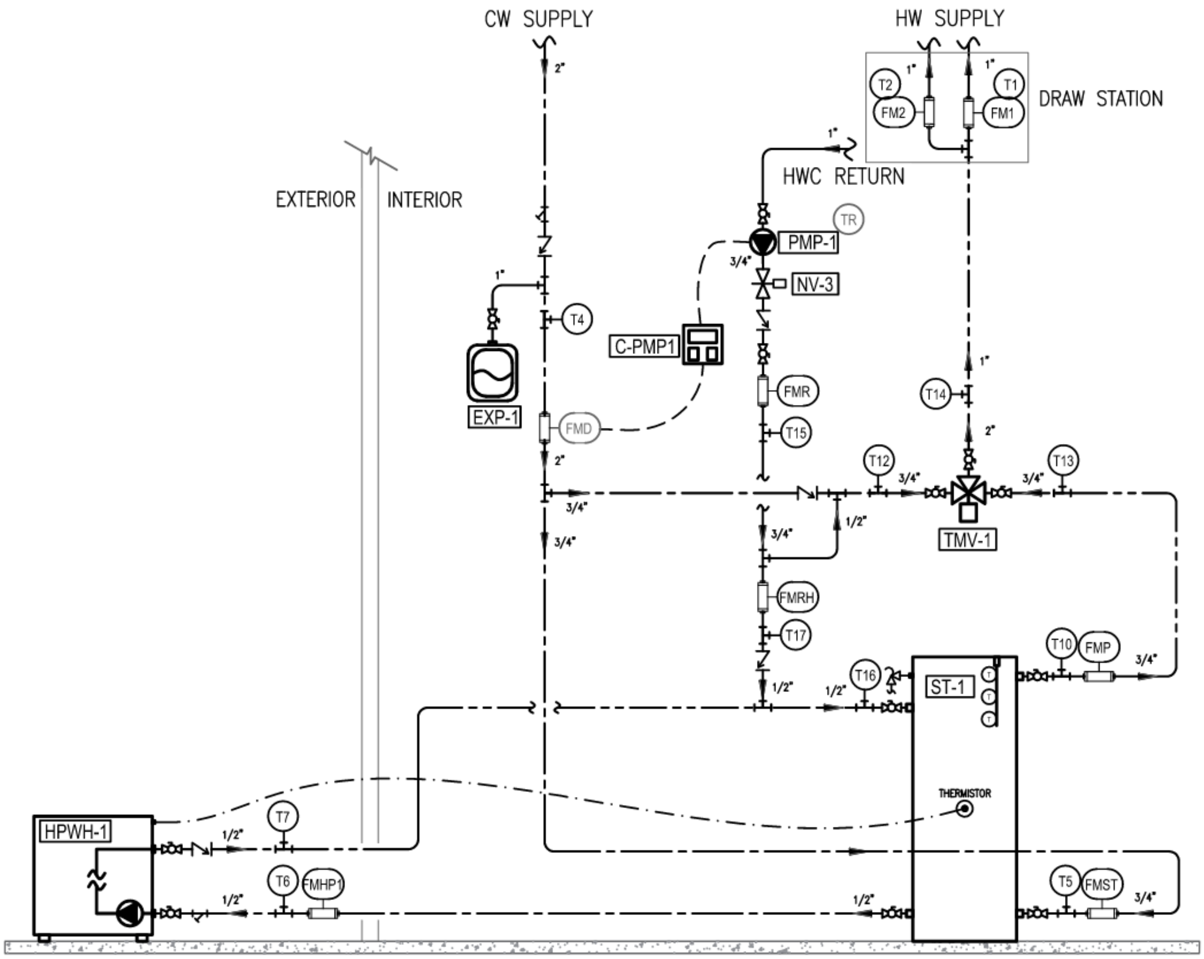


Figure 2. A8: Temperature Maintenance Returned High to Primary Storage

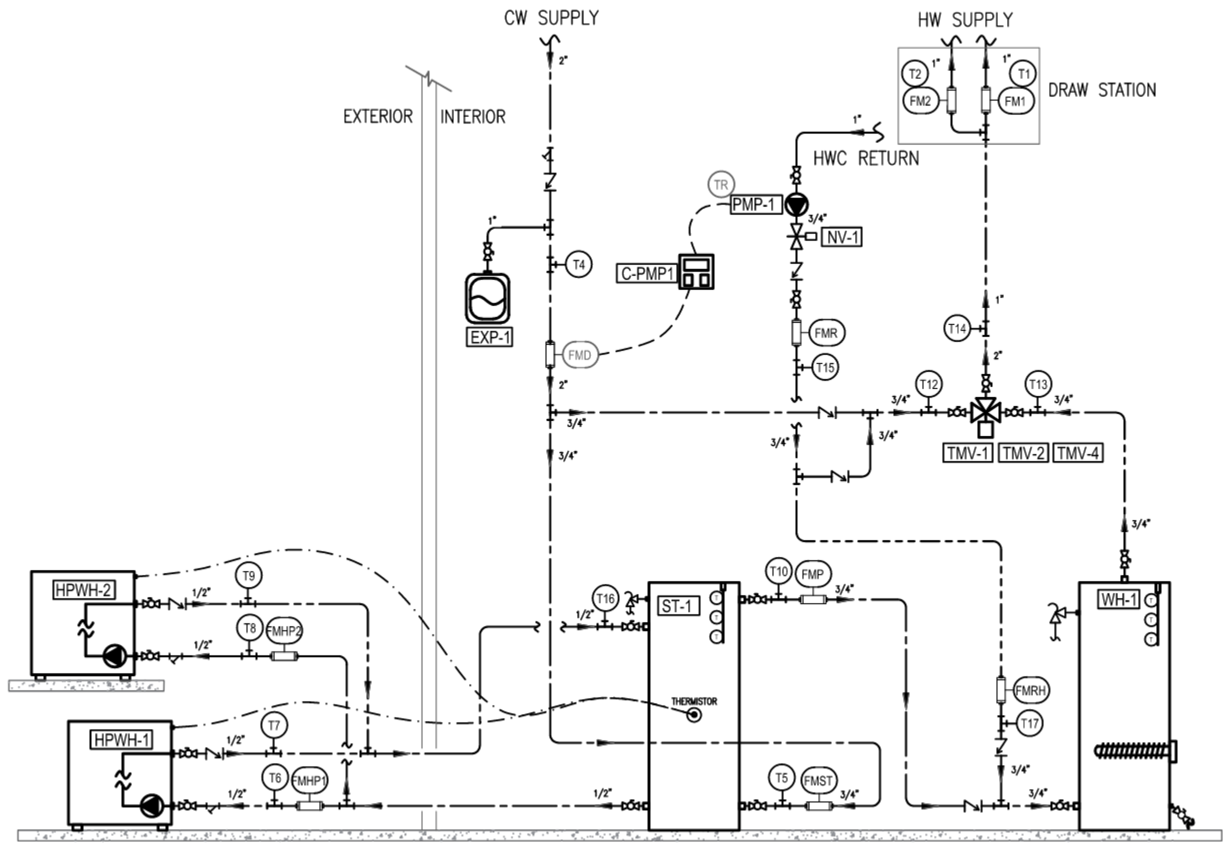


Figure 3. A10: Temperature Maintenance Swing Tank, Dedicated EWH in Series (Two HPWHs)

High-Level Findings Summary

The following is a summary of the high-level findings from the lab testing to date. All these conclusions are supported by specific lab test results.

Temperature-maintenance recirculation return to the primary storage tanks:

9. It is never a good idea to return circulated water to the top of the primary storage tanks. Relatively cool return water (<115°F) disrupts tank stratification and will lead to low supply water temperatures supplied to the building. This is a universal finding for all single-pass systems.

1. Returning water to the bottom of the Primary Storage is not recommended as a general practice at this time. This design configuration has the potential to provide reliable results delivering high System COP, however it is dependent on optimized control of temperature-maintenance loops to minimize losses and ensure that returning water is as cool as possible without leading to occupant complaints and that returning water is at least 3F below the thermal ON setpoint for the heat pump cycle.

2. Any return of circulated water to the primary storage tanks will disrupt optimal thermal stratification and result in lower effective primary storage volume (approximately 25% lower). This must be taken into consideration in sizing of the storage tanks.

Swing Tank Design – Recirculation to a Series Loop Tank:

1. Swing tank design is less risky; always resulting in adequate supply water temperature but resulting in lower System COP in comparison to returning to the bottom of the primary storage.
2. Swing tank design maximizes effective storage volume with well-stratified Primary Storage.
3. Research is needed to optimize swing tank design and controls to minimize or eliminate cycling of electric resistance elements.
4. The location and control of the aquastat and the electric elements in the Swing Tank is critical to overall energy use and electrical demand. The tank selected resulted in more cycling of electric resistance than necessary. The aquastat should be located in the upper part of the swing tank to prevent unnecessary cycling.
5. Higher primary storage water temperatures counter-intuitively increase System COP for swing tank designs. Comparable tests were completed where the primary storage setpoint was increased to 165°F from 149°F. This has the effect of decreasing the efficiency of the primary heaters. However, the higher water temperatures flowing into the swing tank mean that the electric elements cycle less frequently and the overall *System COP* is increased.

Other Findings:

1. This testing was not primarily designed to test mixing valves. It was found that some mixing valves functioned well within their design parameters and did a reasonable job with circulation pump cycling and varying hot water temperatures supplied to the hot side of the mixing valve. However, circulation pump control strategies resulted in less consistent and sometimes uncontrolled hot supply water temperatures to the fixtures.
2. The position of the tank inlets and outlets is critical to system performance. The primary storage tank tested here was not fitted with a dip-tube to draw water from the very top of the storage. As a result, the total effective storage volume was reduced by about 15% and the hottest supply water at the top of the tank was not accessible to the building.
3. The rate of temperature-maintenance energy loss has a critical impact on the performance of these HPWH systems. High temperature-maintenance losses degrade the Average *System COP* by a full point in the swing tank configuration (from 3.8 to 2.8). When circulated water is returned to the primary storage tanks high temperature-maintenance losses paired with relatively low water usage can cause the system to fail to deliver adequate hot water to the building.

Future Research

- The cooler the water returning to the CHPWH system, the better it will perform. Field research is needed to determine the lowest return water temperature which can reliably result in adequate hot water delivery temperatures to the apartments at the far end of the hot water distribution piping.
- Lower temperature-maintenance losses will result in higher System COP. More research is needed to identify and quantify the impact of a range of distribution/temperature-maintenance system measures which could reliably reduce losses to below about 50W/Apt?
- More research is needed to identify tempering valves that work well with fluctuating water temps and with on/off pumping.
- To better support the design community additions should be made to the Ecosizer to account for storage efficiency associated with different piping strategies (i.e., return-to-primary).
- Manufacturers need to continue development of their multifamily system packages to fully define all parts and pieces of their entire multifamily system as this testing shows that variations in the tank designs, piping configurations, electric back-up elements, and controls will impact overall system performance and reliability.

Appendix C: Colmac CxA and CxV Report

To: Multifamily Heat Pump Water Heater Project Stakeholders

From: Evan Green, Ecotope
Scott Spielman, PE, Ecotope
Jon Heller, PE, Ecotope
Madison Johnson, Ecotope
Ben Larson, Larson Energy Research
Mehdi Zeyghami, PhD, PE, ATS Lab, PG&E

Subject: Trends Observed from Colmac Application Tests

Date: August 15, 2023

Application Test Overview

ATS lab in San Ramon CA conducted Lab testing of Colmac's CxV-5 and CxA-15 heat pump water heaters. Ecotope used data from ATS labs' Colmac application tests and performed qualitative and quantitative analyses to better understand HPWH system performance: we first observed how various design practices drove system-level trends, then how the same design practices impacted key system performance metrics. It is important to consider the quantitative and qualitative trends to avoid pursuing design pathways or measures that theoretically drive high system efficiencies but result in poorly functioning systems in practice.

Design practices

The following design practices were tested in the lab:

3. DHW plant piping configuration:
    a. Multi-pass HPWH, recirculation returned to primary storage (labelled "Multipass: Return-to-primary" in plots)
    b. Single-pass HPWH, recirculation returned to primary (labelled "Single-Pass: Return-to-primary" in plots)
    c. Single-pass HPWH, recirculation returned to in-series temperature-maintenance tank labelled "Single Pass: Swing Tank" in plots)
    d. Single-pass HPWH, recirculation returned to parallel temperature-maintenance tank (labelled "Single Pass: Parallel Loop Tank" in plots)
4. Primary storage temperature: 140°F (baseline) vs. 160°F
5. Primary storage configuration: in-series vs. in-parallel storage tanks (in-series tanks were used for all single-pass baseline tests, in-parallel storage tanks were used for multi-pass baselines)

Simulated building characteristics

Several different building characteristics were simulated to assess their impact on each unique design practice:

6. Building type: simulated 44-unit multifamily building.
7. Recirculation heat loss rate: 0, 50, 100 (baseline), 150 watts per dwelling unit
8. DHW usage rate: 30, 36 (baseline), 46 gallons of 120°F water per day per dwelling unit

Control variables

The following variables were held constant throughout lab testing:

1. Test duration: 24-hour test simulating a single day of DHW usage in a multifamily building.
2. Ambient air temperature: 67.5°F
3. HPWH equipment: Colmac CxA-15 for primary heating, Colmac CxV-5 for secondary heating.
4. Mixing valve delivery temperature: 120°F

Qualitative observations

The following observations outline system characteristics that correlate with various design practices. The attachments to Appendix C contain plots that illustrate these qualitative observations.

Multi-pass return-to-primary configuration (Figure A1)

> Storage tanks are observed to be partially stratified in multi-pass HPWH tests. This has implications for system efficiency and sizing methodology.

- During large DHW draw events, hot water is drawn from the top of the tank as cool make-up water enters the bottom. The cool make-up water cools the lower-tank first, then middle-tank, and the top of the tank cools down last.
- When the HPWH is running, the lower-tank and middle-tank mix. The middle-tank cools, the lower-tank heats, and the upper-tank remains hot. Once lower- and middle-tank temperatures converge and are about 15°F cooler than the upper-tank, the middle-tank and upper-tank become more mixed.

HPWH outlet temperature varies throughout the HPWH run cycle and is warmer than the target tank temperature for over half the cycle. The tests were run using Colmac's on-board circulation pump that produces a constant flow rate in multi-pass mode so variable flows were not tested, but we expect a higher flow rate would drive a lower outlet water temperature near the end of the HPWH run cycle.

Parallel, stratified storage tanks (Figure A2)

Primary storage tanks piped in parallel appear to work as well as tanks piped in series. Hot water storage temperatures are observed to be relatively uniform across parallel stratified storage tanks.

Single-pass return-to-primary (Figure A3)

Single-pass return-to-primary configuration performed well for this Colmac heat pump product and provided the highest efficiency of all configurations that were tested for this equipment.

Note that this finding may not necessarily be relevant to HPWHs with transcritical refrigeration cycles, like those with CO_2, because of their higher primary storage temperatures and sensitivity to high inlet water temperatures.

Stratification occurs in the single-pass, return-to-primary configuration. We should not assume mixed tanks when designing controls, sizing, or modelling efficiency of this configuration.

The system can fail to deliver hot water if recirculation return water is returned to a tank downstream of the HPWH “on” sensor.

Dedicated connections between HPWH and storage tanks (Figures A4, A5)

HPWHs and mixing valves both operate more effectively when water pressure and temperature are constant or change very slowly. Providing hydraulic separation between the mixing valve and HPWH can provide much steadier temperature and pressure to each component. The following observations discuss hydraulic separation between the HPWH inlet and outlet, mixing valve, and domestic cold water (DCW) make-up pipe.

Connecting the primary HPWH outlet directly to the pipe between the storage tank outlet and mixing valve inlet (no hydraulic separation) drives erratic mixing valve behavior. Designers should provide hydraulic separation between the HPWH outlet and mixing valve inlet by specifying a dedicated tank connection for the HPWH outlet instead of teeing the HPWH outlet directly into the pipe between the tank outlet and mixing valve inlet. If using a series temperature maintenance configuration, the primary HPWH outlet may be connected to the pipe between the primary storage and temperature-maintenance tank since the temperature-maintenance tank acts as a buffer between the mixing valve inlet and HPWH outlet.

Designers should provide hydraulic separation between the HPWH inlet and domestic cold water (DCW) make-up by piping the HPWH inlet directly to the storage tank instead of connecting the HPWH inlet directly to the DCW make-up line. Supplying the HPWH directly from the DCW make-up line drives erratic HPWH inlet temperature and mixing valve pressure imbalance, which could negatively impact HPWH reliability, efficiency, and hot water supply stability.

Figure 1 shows a system with proper tank connections that allow for hydraulic separation (left) and a design that drives erratic HPWH and mixing valve behavior due to lack of hydraulic separation (right).

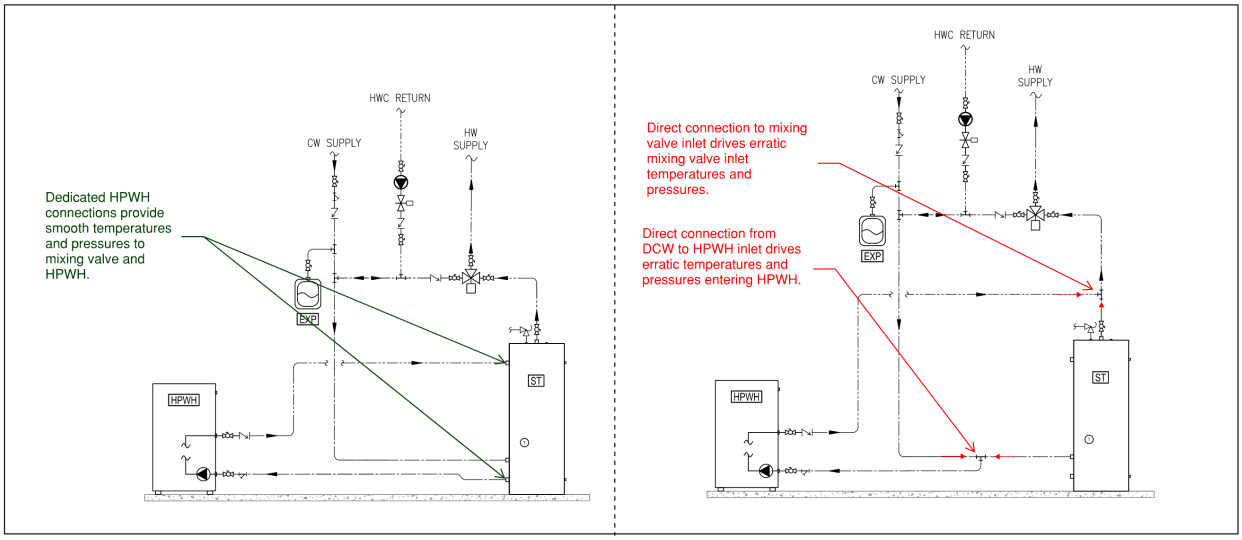


Figure 1: Left: dedicated tank connections for HPWH inlet and outlet provide hydraulic separation. Right: HPWH inlet and outlet are piped to mixing valve inlet and DCW make up, driving erratic HPWH and mixing valve behavior.

Quantitative comparisons

Ecotope observed the impact of various building characteristics and design practices on the following metrics of HPWH system performance:

1. System COP: Ratio of total DHW heating provided (DHW usage and recirculation heating) over total energy consumed by all DHW equipment. This factor is important because increasing system COP can significantly decrease total energy use, independent of occupant DHW use patterns.
2. Average HPWH cycle length: How long the HPWH runs each time it re-heats the DHW storage tanks. This factor is important because longer run times lead to increased equipment efficiency and longevity.
3. Average HPWH inlet water temperature: Average DHW temperature entering the HPWH when it is running. This factor is important because HPWH efficiency decreases as inlet water temperature increases.

Piping configuration vs. system performance

> Despite having the shortest cycle length [figure B1] and second-highest inlet water temp [figure B2], single-pass return-to-primary configuration yielded the highest system COP [figure B3]. The swing tank configuration had the lowest system COP [figure B3].

> Systems with dedicated temperature-maintenance tanks saw lower primary HPWH inlet water temperature on average [figure B2]. Although this colder inlet water at the heat pump did not result in higher system COPs with R134a equipment because of more resistance heat use in the temperature-maintenance tank, systems with other refrigerants are expected to fair differently.

DHW usage and recirculation heat loss impact on system COP

> A higher ratio of DHW usage vs. recirculation heat loss had the greatest impact on the swing tank configuration. As usage increases or recirculation heat loss decreases, system COP of the swing tank configuration increases [figures B6, B9].

> Recirculation heat loss rate had little impact on return-to-primary systems; DHW usage increase had a greater impact by decreasing inlet water temperature (Appendix C Figure B07) and increasing system COP (Figure B09).

Primary storage temperature

> Although an increased storage temperature increased HPWH cycle lengths [figure B11], it decreased system COP in all tested configurations [figure B12]. This is likely due to the lower HPWH COP associated with higher outlet water temperatures. This comparison should be repeated with a CO_2 HPWH since an increased outlet water temperature in CO_2 HPWHs has a lower impact on HPWH COP.

Primary storage configuration

> Metered system efficiency was approximately the same between in-series and parallel primary storage configurations [figure B15], even when parallel tanks were intentionally imbalanced.

> Parallel primary storage configuration saw increased HPWH cycle length [figure B14] because the position of sensors in the parallel storage configuration drives a higher relative storage depletion before the HPWH turns on. The similar system COP's between in-series and parallel storage suggests that cycle length, though important for HPWH reliability, may not need to be considered in energy modelling.

Modelling recommendations

The observations above highlight several areas where Ecotope, Wilcox, LER, and partners could use application test data to refine the current modelling approach. We can help enhance the model to further incorporate key factors that affect HPWH system performance. This would include thorough documentation of modelling logic to help justify results for designers, energy managers, and equipment manufacturers. The modelling team could take the following steps to make use of the Colmac test data:

1. Update Colmac CxA-15 performance maps to match Colmac performance testing.
2. Customize the energy modelling software script (without changing the simulation math) to simulate the 24-hour lab tests and plot the results.
3. Observe quantitative trends in comparison to the plots in the attachment to Appendix C. This includes observing relative changes as variables are manipulated and comparing the magnitude of key metrics.
4. Observe hour-by-hour results and further key metrics to explore differences that occur between simulation and lab results.
5. Compare qualitative lab observations with the simulation results. Do the same trends exist? A couple qualitative observations to explore and refine if necessary:
    a. Stratification characteristics in return-to-primary configurations.
    b. Variable and elevated HPWH outlet water temperature in multi-pass configurations: cool outlet water temperature at the beginning of the run cycle vs. outlet water temperature exceeding tank setpoint temperature at the end.

Design, codes, and standards implications

Several observations in the lab inform important HPWH system design decisions, which could drive best practices design guidelines and future codes and standards:

a. Carefully consider temperature sensor location in both single and multi-pass systems. Stratified storage tanks mean cycle times and effective storage capacity are dependent on on/off sensor locations. Useful information can be gleaned from the lab data to provide feedback to CPWH manufacturers and system providers regarding setpoint temperatures and sensor locations.

b. HPWH supply and return should be isolated from the DCW supply pipe and mixing valve inlet to ensure stable HPWH inlet and building supply temperatures. This could be accomplished by providing dedicated HPWH supply and return connections on the side of the storage tanks. This information should be incorporated into design best practice guidelines, HPWH-oriented storage tank model lines, and potentially into code.

c. In multi-pass systems:

    1. Designers should confirm selected HPHWs are capable of producing outlet water temperatures that exceed storage tank setpoint temperature. If the tank setpoint temperature is 140°F, the maximum HPWH outlet water temperature will likely exceed 150°F at the end of the cycle. This lab data could be used to help optimize the inherent trade-off between storage tank target temperature, storage volume, and HPWH efficiency.
    2. Storage sizing should account for partial stratification and not assume fully mixed storage as this will lead to needlessly oversized storage. Data from the lab tests can be used to develop better multi-pass sizing algorithms. (This also applies to single-pass return-to-primary designs.)

3. Tank stratification should be considered when sizing storage in load-shifting multi-pass systems. Ecotope has successfully delayed single-pass HPWHs from powering on during demand response shed periods in field tests by referencing a temperature sensor high in the storage tank. This lab data suggests the same strategy could work with multi-pass HPWHs to provide some degree of load shift capability.

d. More research should be conducted to establish design guidelines for single-pass return-to-primary configuration. When using R134a HPWHs, namely Colmac's R134a heat pumps, in mild ambient temperatures, this configuration reduces required equipment (no dedicated temperature-maintenance heating equipment) and performs more efficiently than the swing-tank design configuration in lab tests. The following research would inform how stable return-to-primary operation operates in a wider envelope of conditions:

    1. Performance map analysis of several manufacturers comparing efficiency and inlet temperature limitations of single-pass HPWHs on the market.

    2. Lab testing of single-pass return-to-primary configuration using a wider range of recirculation flow rates and temperatures.

e. Parallel primary storage tanks can be successfully paired with single-pass HPWHs. The practical benefits include potentially simplified piping and lower pressure drop through the tanks.

Conclusion

Data from Colmac lab testing will be paramount to the refinement of energy modelling and design considerations. Qualitative results and quantitative trends can be referenced to refine energy modelling software, and several observations were already made that verify current design assumptions and increase confidence in additional design practices.

Enclosures

- Qualitative Plots
- Quantitative Plots
- Table of Reference

FIGURE A1

APPENDIX A - Qualitative Plots

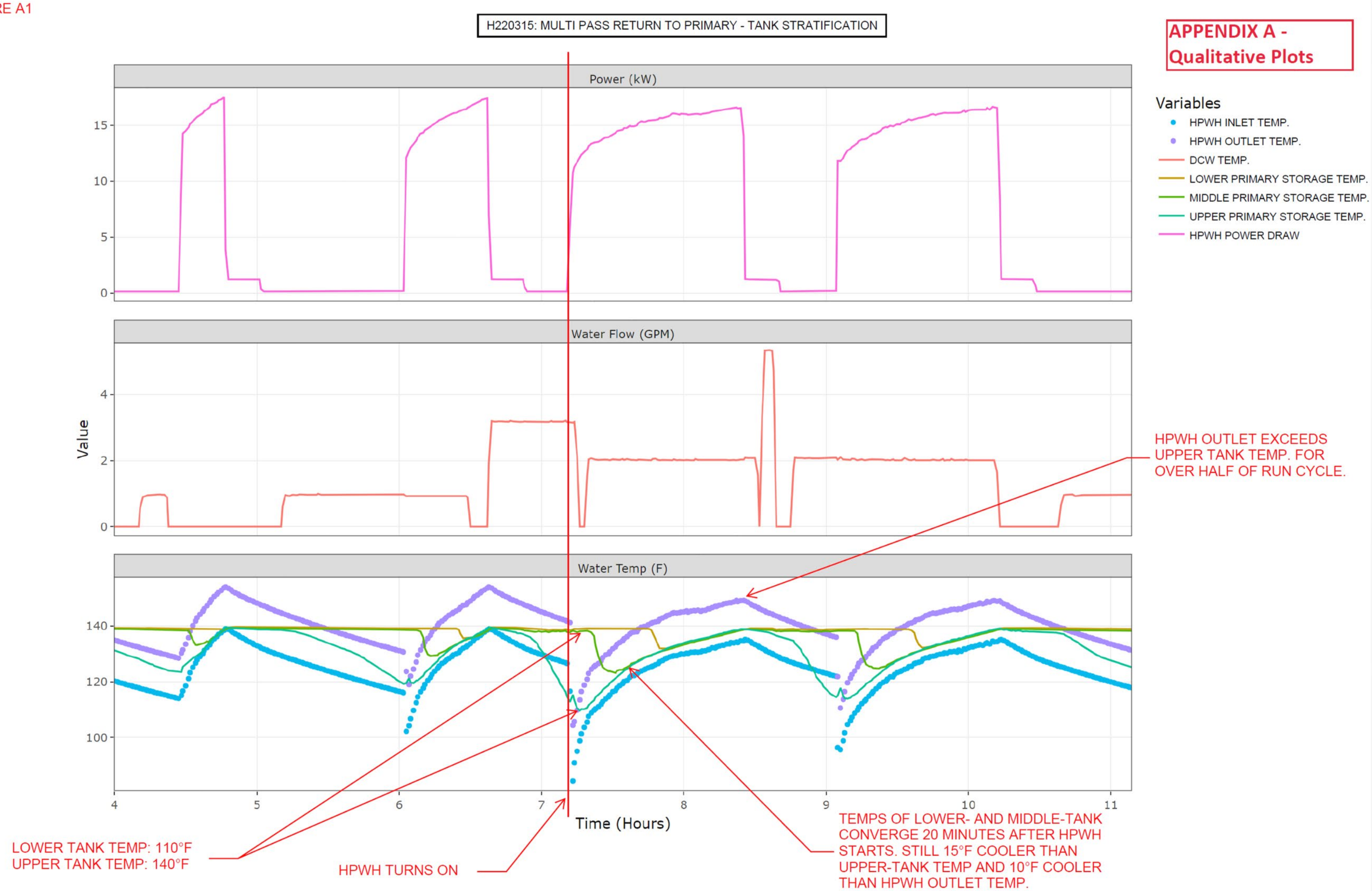
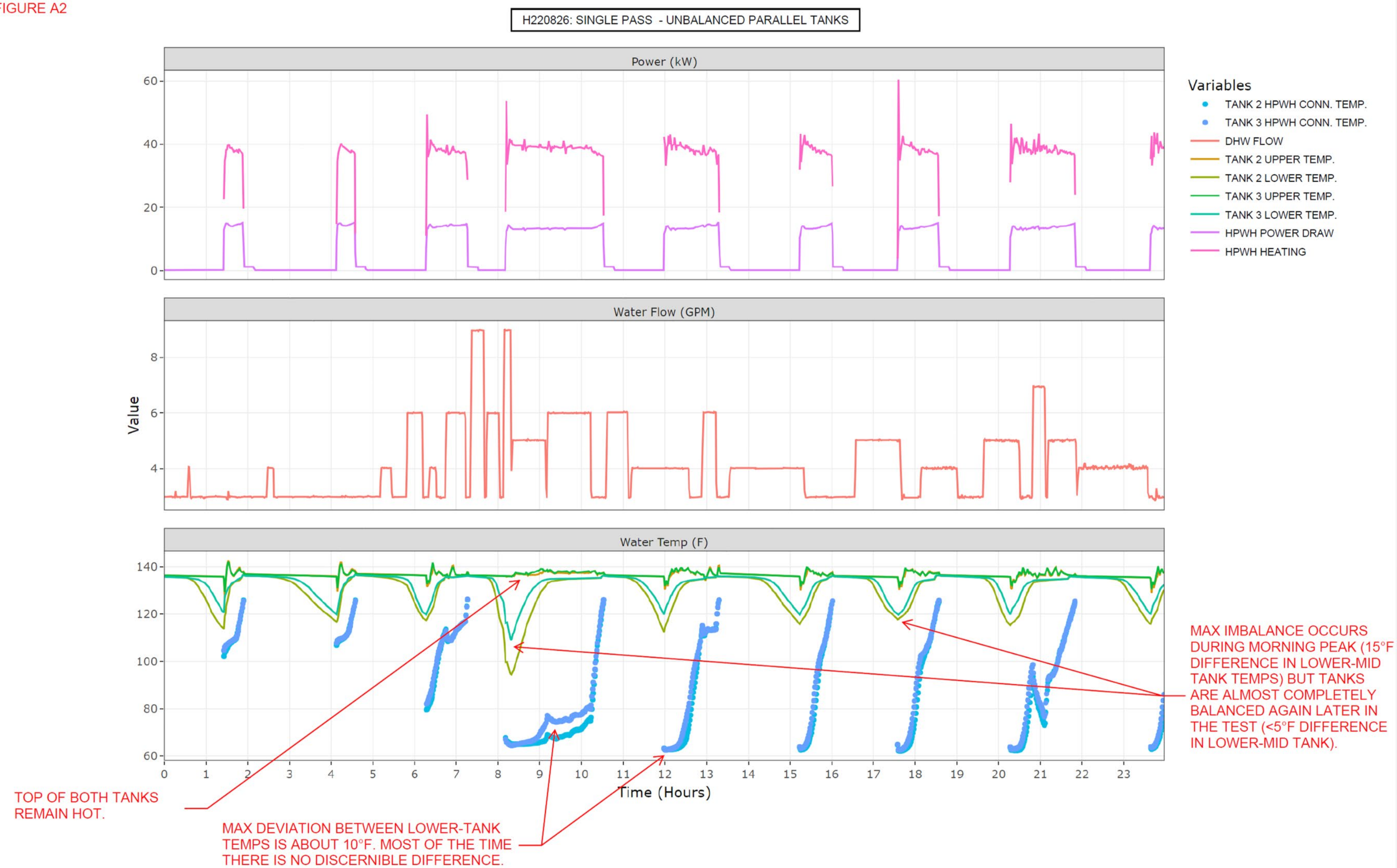


FIGURE A2



H220826: SINGLE PASS - UNBALANCED PARALLEL TANKS
Power (kW)
Water Flow (GPM)
Water Temp (F)
Value
Time (Hours)
Variables
TANK 2 HPWH CONN. TEMP.
TANK 3 HPWH CONN. TEMP.
DHW FLOW
TANK 2 UPPER TEMP.
TANK 2 LOWER TEMP.
TANK 3 UPPER TEMP.
TANK 3 LOWER TEMP.
HPWH POWER DRAW
HPWH HEATING
MAX IMBALANCE OCCURS DURING MORNING PEAK (15°F DIFFERENCE IN LOWER-MID TANK TEMPS) BUT TANKS ARE ALMOST COMPLETELY BALANCED AGAIN LATER IN THE TEST (<5°F DIFFERENCE IN LOWER-MID TANK).
TOP OF BOTH TANKS REMAIN HOT.
MAX DEVIATION BETWEEN LOWER-TANK TEMPS IS ABOUT 10°F. MOST OF THE TIME THERE IS NO DISCERNIBLE DIFFERENCE.

FIGURE A3

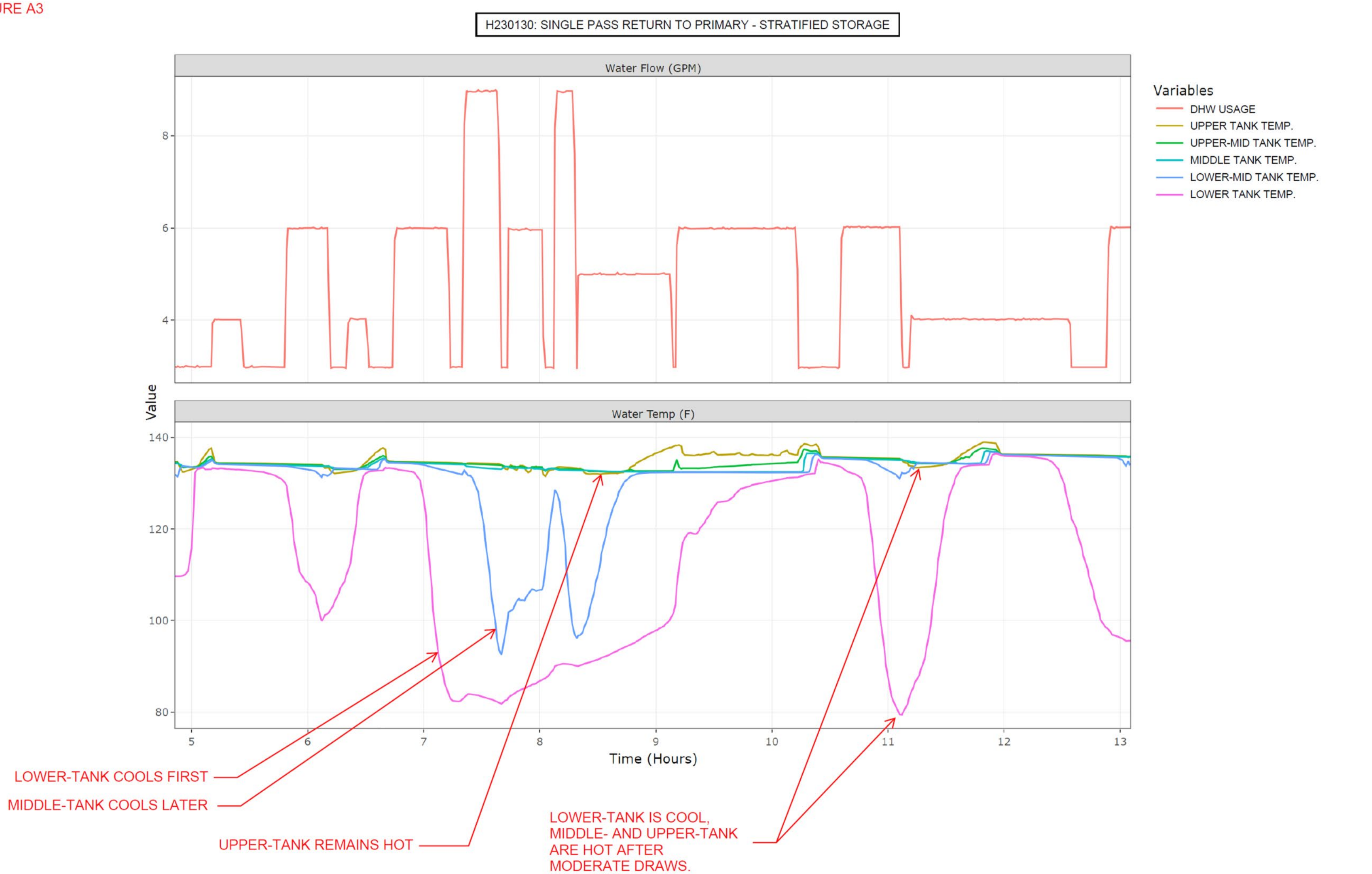

H230130: SINGLE PASS RETURN TO PRIMARY - STRATIFIED STORAGE
Water Flow (GPM)
Water Temp (F)
Value
Time (Hours)
Variables
DHW USAGE
UPPER TANK TEMP.
UPPER-MID TANK TEMP.
MIDDLE TANK TEMP.
LOWER-MID TANK TEMP.
LOWER TANK TEMP.
LOWER-TANK COOLS FIRST
MIDDLE-TANK COOLS LATER
UPPER-TANK REMAINS HOT
LOWER-TANK IS COOL, MIDDLE- AND UPPER-TANK ARE HOT AFTER MODERATE DRAWS.

FIGURE A4


H220627: SINGLE PASS - DIRECT CONNECTION BETWEEN HPWH OUTLET AND MIXING VALVE
HPWH ON
HPWH OFF
HPWH ON
Power (kW)
Water Flow (GPM)
Water Temp (F)
Value
Time (Hours)
Variables
HPWH OUTLET TEMP.
DHW FLOW
MIXING VALVE HOT INLET TEMP.
MIXING VALVE OUTLET TEMP.
HPWH POWER DRAW
10°F DROP AND RISE IN SUPPLY TEMP.
15°F RISE AT HOT MIXING VALVE INLET
17°F TEMP DROP, THEN RISE IN SUPPLY TEMP.
10°F DROP, 15°F RISE AT HOT MIXING VALVE INLET

FIGURE A5

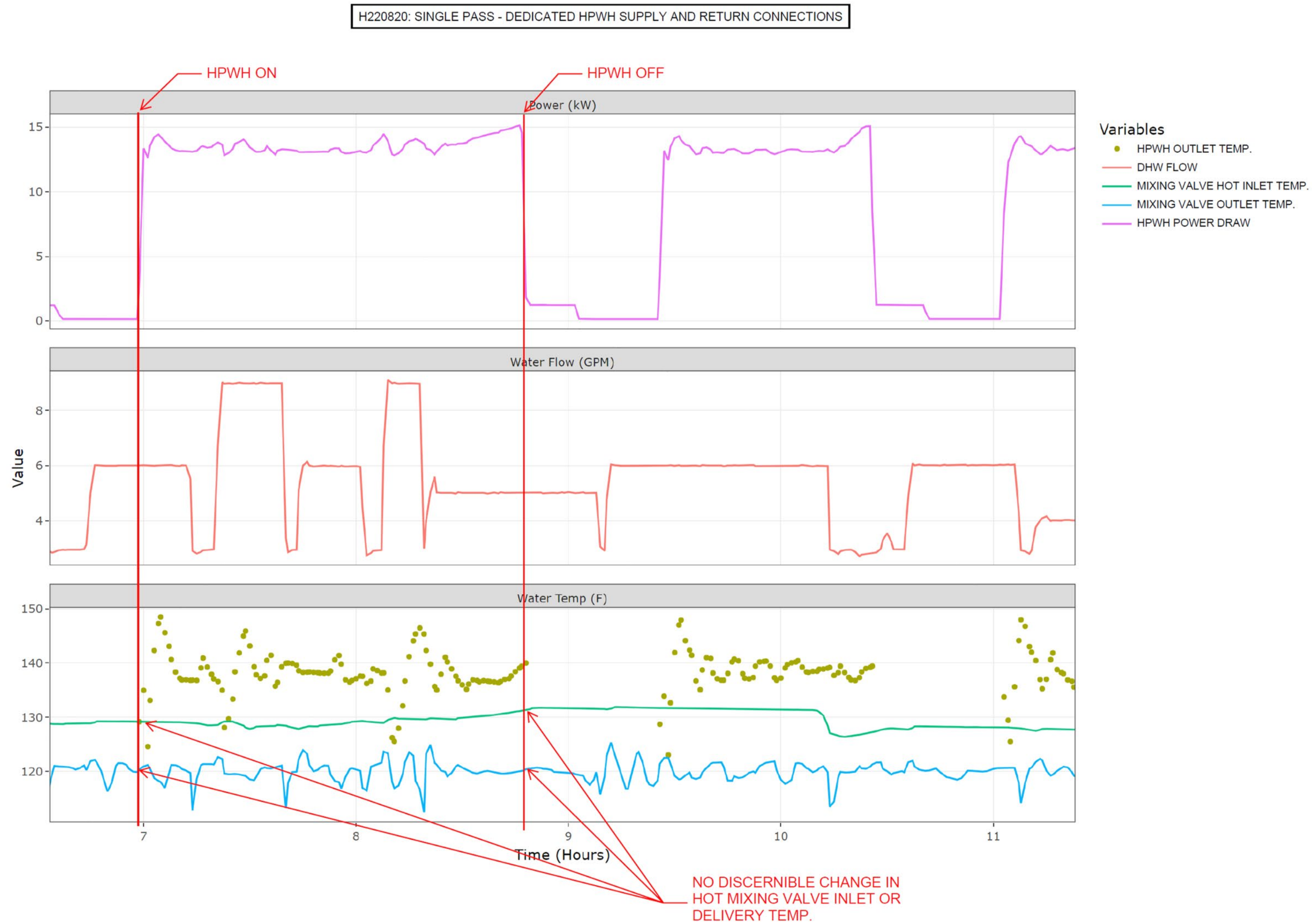

H220820: SINGLE PASS - DEDICATED HPWH SUPPLY AND RETURN CONNECTIONS
HPWH ON
HPWH OFF
Power (kW)
Water Flow (GPM)
Water Temp (F)
Value
Time (Hours)
Variables
HPWH OUTLET TEMP.
DHW FLOW
MIXING VALVE HOT INLET TEMP.
MIXING VALVE OUTLET TEMP.
HPWH POWER DRAW
NO DISCERNIBLE CHANGE IN HOT MIXING VALVE INLET OR DELIVERY TEMP.

Figure B01

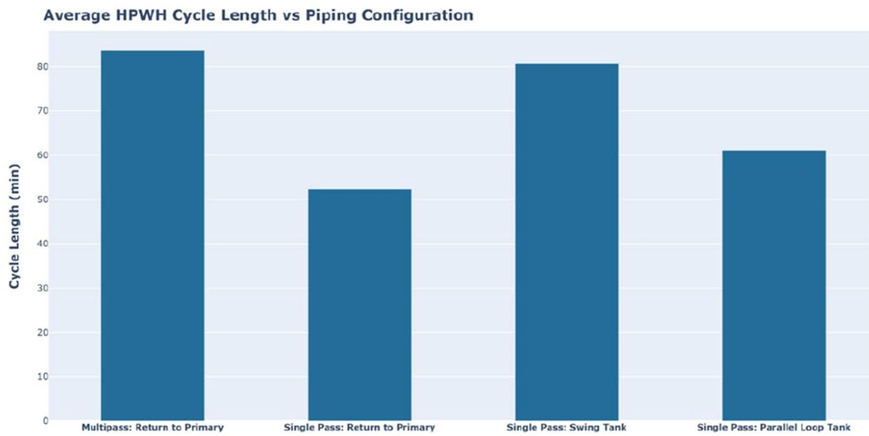


Figure B02

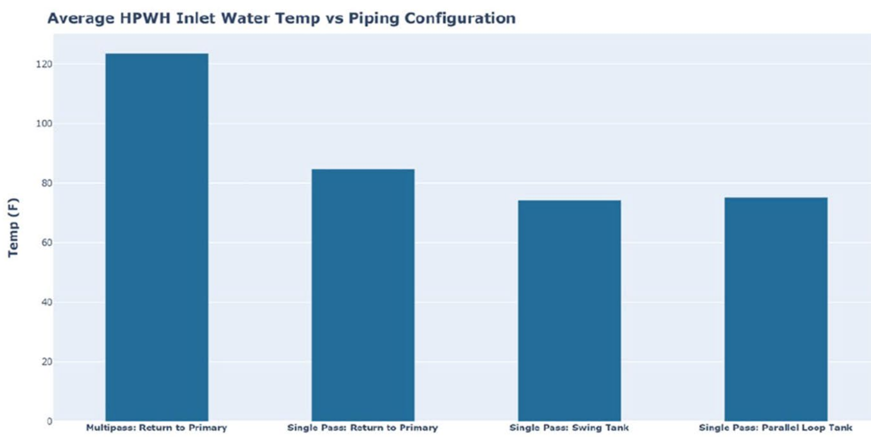
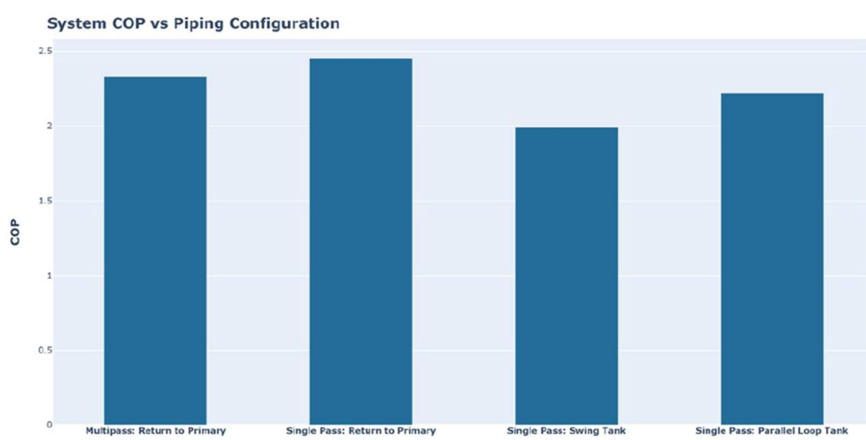


Figure B03



ECOTOPE

Figure B04

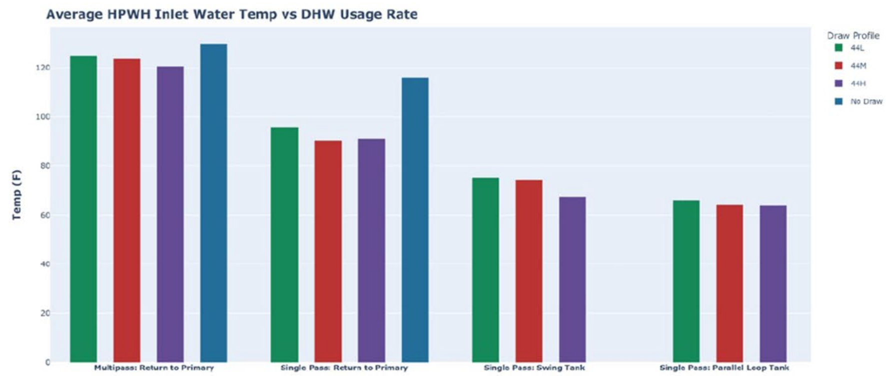


Figure B05

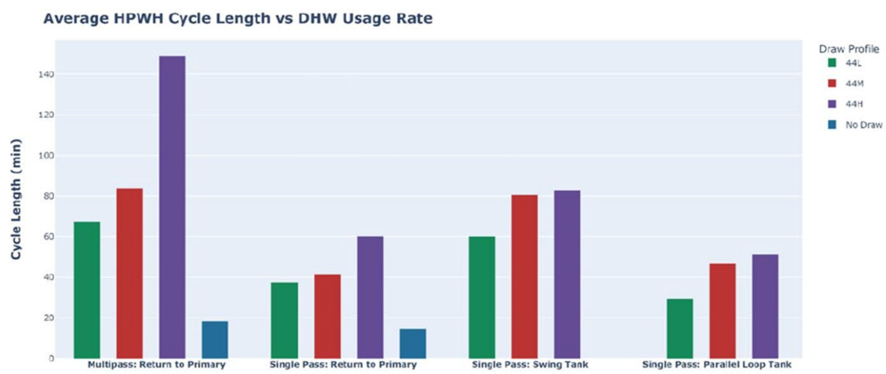


Figure B06

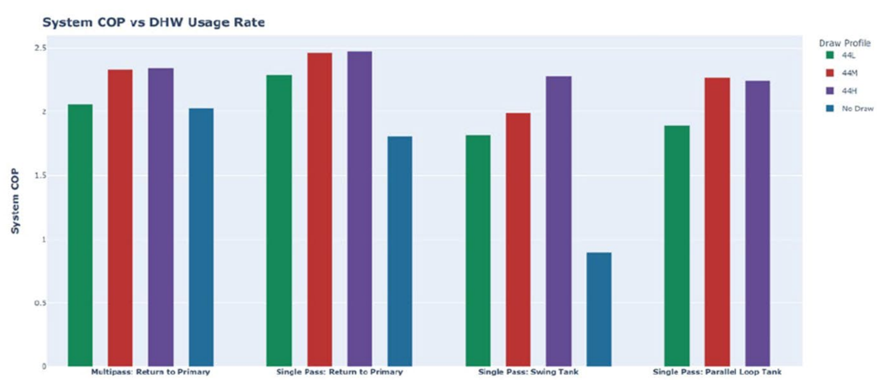


Figure B07

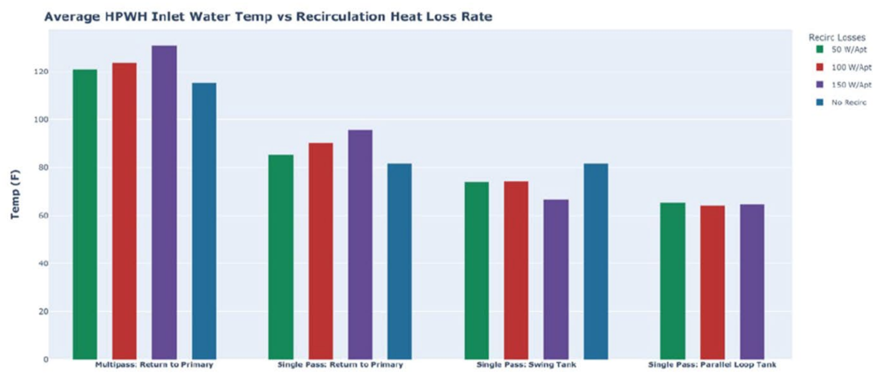


Figure B08

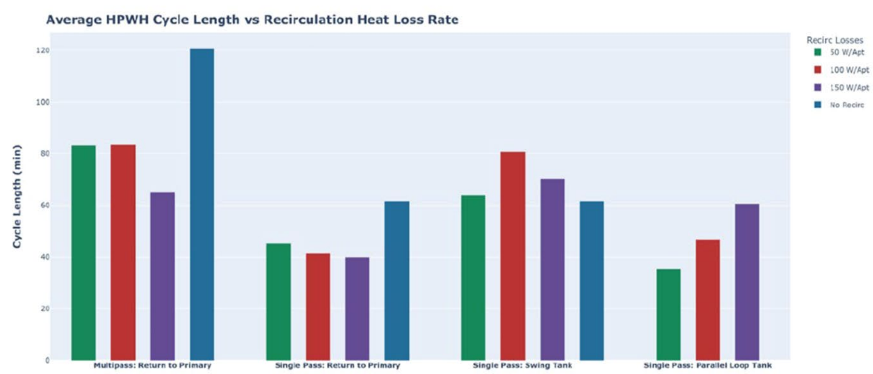


Figure B09

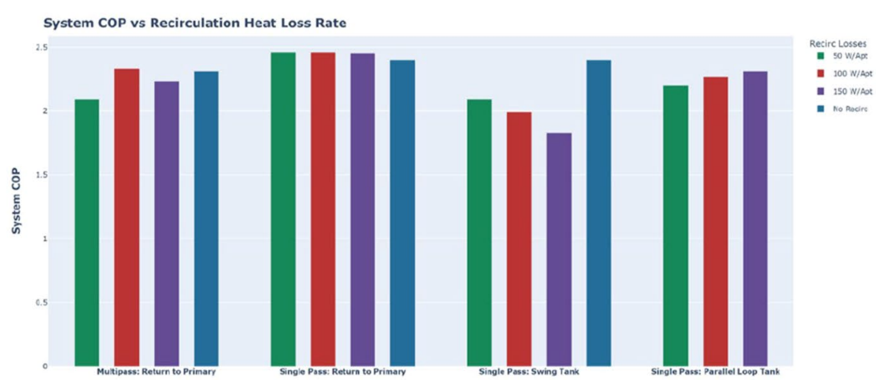


Figure B10

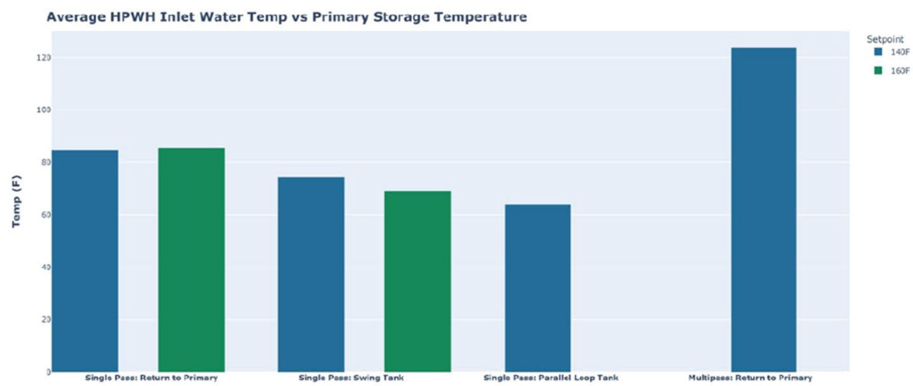


Figure B11

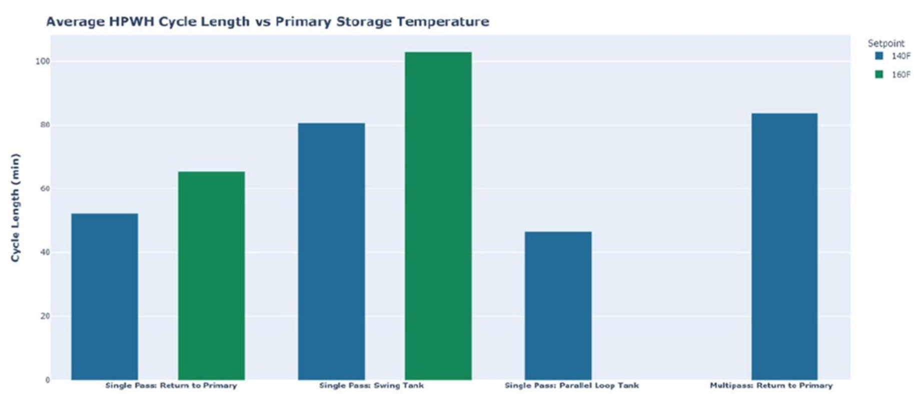
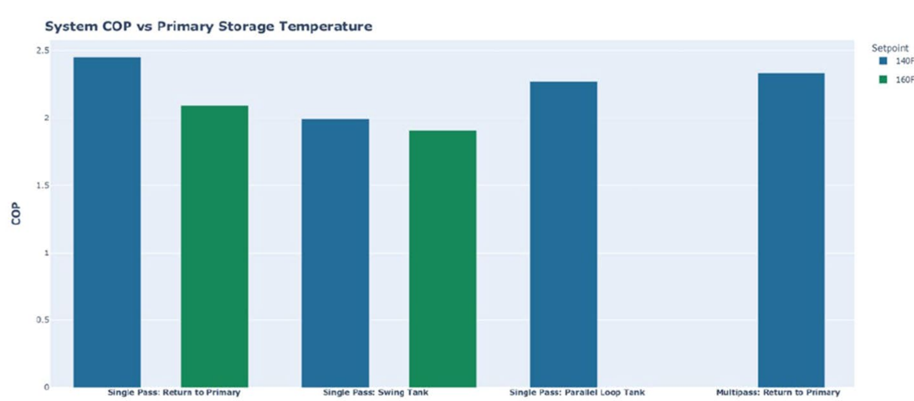


Figure B12



ECOTOPE

Figure B13

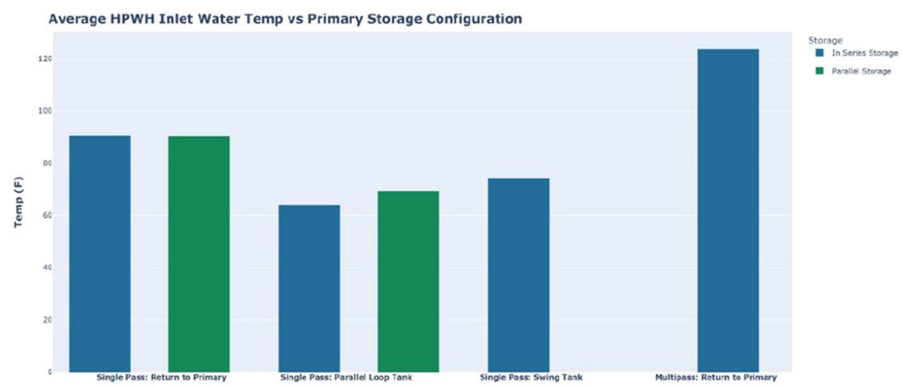


Figure B14

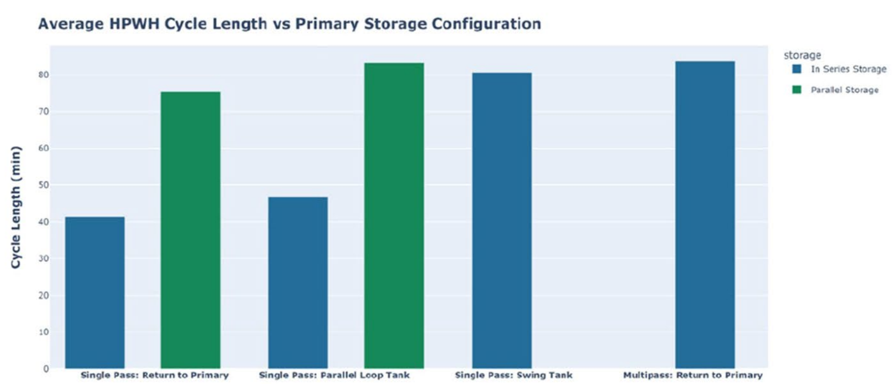
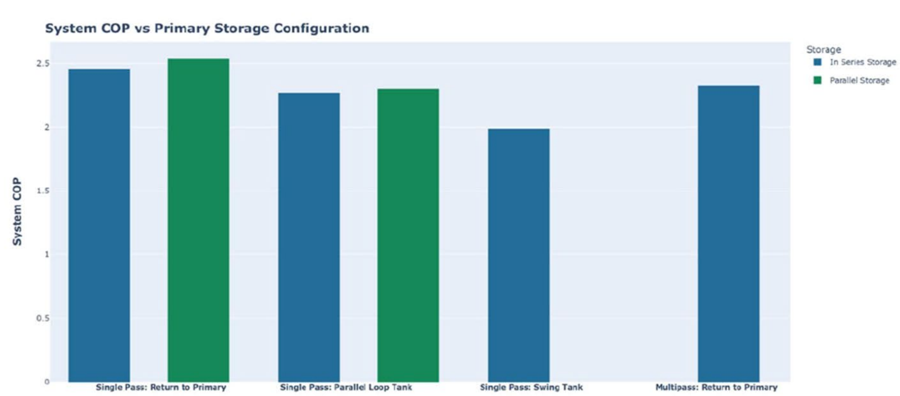


Figure B15



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Configuration	Baseline	150W/Apt recirc	50W/Apt recirc	no recirc loss	44H draw profile	44L draw profile	no draw	160F supply temp	parallel storage
Multipass Return to Primary	H220318	H220320	H220317	H220421	H220322	H220321	H220425	NA	NA
Single Pass Return to Primary	H220627/H230130[1]	H220713	H220701	H220810	H220712	H220703	H220626	H220815	H220805
Single Pass Singtank	H221202	H221220	H221215	H220810[3]	H221214	H221213	cop=.9	H221228	NA
Single Pass Parallel Loop Tank	H220922/H230126[2]	H221022	H220926	NA	H221020	H221001	NA	NA	H221102

[1] Test H230130 used for comparing configurations and storage temperature. Test H220627 used for comparing recirculation loss rates, draw rates, and storage configurations.

[2] Test H230126 used for comparing configurations. Test H220922 used for comparing storage temperatures, recirculation loop rate losses, and storage configurations.

[3] Test H220810 is a return to primary with no recirc configuration.

ECOTOPE

Appendix D: AO Smith CHP-120 Report

To: Multifamily Heat Pump Water Heater Project Stakeholders

From: Evan Green, Ecotope
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Subject: Trends Observed from AO Smith Application Tests

Date: January 23, 2024

Application Test Overview

ATS lab in San Ramon CA conducted Lab testing of the AO Smith CHP-120 heat pump water heater. Ecotope used data from ATS labs' tests to perform qualitative and quantitative analyses to better understand its performance: we first observed how various design practices drove system-level trends, then how the same design practices impacted key system performance metrics. It is important to consider both quantitative and qualitative trends to avoid pursuing design pathways or measures that theoretically drive high system efficiencies but result in poorly functioning systems in practice.

Unitary HPWHs offer an effective solution for mitigating complexities associated with designing central heat pump water heating systems. While adherence to manufacturer guidelines is advised for installation of unitary HPWHs, AO Smith testing provided insight on potential improvements to these systems. Test configurations incorporating additional storage tanks exhibited some of the highest COPs in CHP-120 testing, as the compressor met demand independently, effectively eliminating the unit's need for electric resistance on a typical demand day. Additionally, the impact of an increased primary setpoint paired with a thermostatic mixing valve was also studied in lab testing to see if effective storage volume could be increased without increasing physical storage volume. Higher storage temperatures reduced the need for electric resistance; however, this generally did not lead to increased efficiency as the overall energy consumption was increased. While it is not currently recommended that the CHP-120 be installed with additional storage tanks, this testing suggests that retaining the unit's current heating capacity and increasing storage volume may improve efficiency while maintaining the advantages of a fully packaged system. Future testing should be done to confirm how to arrange the condenser and tank to maximize efficiency with a larger storage volume.

Design practices

Unitary HPWHs were designed to deliver DHW reliably and efficiently without any additional water heating components. The primary application for most unitary HPWHs is to serve DHW to single dwelling units but the CHP-120 has enough capacity to provide DHW to ~ 16 dwelling units as a central system in a multi-family building. It may also be suited to satisfy other commercial DHW loads including office buildings, schools, kitchens, and other buildings that require moderate amounts of DHW. Tests were performed to evaluate how a large unitary HPWH performs in a central DHW plant serving a simulated multi-family building with a hot water circulation loop. Configurations tested in the lab may be applicable to the other applications mentioned above, but these tests focused on DHW draw profiles representative of a multi-family building.

In addition to testing the unitary HPWH on its own (how the manufacturer recommends it be applied), several custom configurations were tested that were originally designed for single-pass and multi-pass HPWHs. These custom configurations have a high likelihood of failure if the DHW system is not carefully engineered with full support from the unitary HPWH manufacturer. While these have potential to provide significant energy savings the need for additional components offsets the main value unitary HPWHs provide –they are simple to install and do not require additional components. However, testing with additional components revealed ways in which unitary HPWH design could be improved.

The following design practices were tested in the lab:

1. DHW plant piping configuration:
    a. Unitary HPWH, 120°F setpoint temperature, with and without hot water circulation (HWC) loop returned to HPWH (Return-to-primary) (Figure A1)
    b. Unitary HPWH, 140°F setpoint temperature, with thermostatic mixing valve (TMV), RTP (Figure A2)
    c. Unitary HPWH acting as in-series temperature-maintenance tank (swing tank) (Figure A3)
    d. Unitary HPWH, heat pump only mode, with swing tank (Figure A4)
    e. Stratified storage tank charged by unitary HPWH (conversion to single-pass RTP) (Figure A5)
2. HPWH setpoint temperature and mixing valve:
    a. 120°F setpoint temperature without mixing valve.
    b. 140°F setpoint temperature with mixing valve set to 120°F.

Simulated building characteristics

Several different building characteristics were simulated to assess their impact on each unique design practice:

1. Building type: simulated 16-unit multifamily building.
2. Hot water circulation loop heat loss: 100W/Apt
3. DHW usage rate: 30, 36 (baseline), 46 gallons of 120°F water per day per dwelling unit

Control variables

The following variables were held constant throughout lab testing:

1. Test duration: 24-hour test simulating a single day of DHW usage in a multifamily building.
2. Ambient air temperature: 67.5°F
3. HPWH equipment: AO Smith CHP-120.
4. Target delivery temperature: 120°F
5. City Water Temperature: 58°F

Quantitative Summary

The table below shows system COPs of highlighted test configurations. Note that system COP will differ from the HPWH component COPs reported in literature tested under standardized conditions.

Schematic	Setpoint	System COP		
		Low Draw	Med Draw	High Draw
Baseline Unitary HPWH	120	2.48	2.37	-
Baseline Unitary HPWH	140	2.03	2.08	-
Unitary HPWH with No Recirc	120	2.28	2.69	-
Unitary HPWH with No Recirc	140	2.29	2.38	-
CHP-120 with Swing Tank	120	1.83	1.98	-
CHP-120 with Swing Tank	140	1.74	2.03	-
CHP-120 with Swing Tank and Additional Storage	120	-	-	-
CHP-120 with Swing Tank and Additional Storage	140	2.18	2.16	2.21
CHP-120 with Additional Storage	120	-	-	-
CHP-120 with Additional Storage	140	2.76	2.81	2.88
CHP-120 as Swing Tank	-	2.64*	2.66*	2.67*

Qualitative Observations

The following observations outline system characteristics that correlate with various design practices. Appendix A contains plots that illustrate these qualitative observations.

Unitary HPWH, 120°F setpoint temperature, with and without HWC loop returned to HPWH (Figure A1, C1)

Purpose of Test:

Large unitary HPWHs like the CHP-120 are large enough to serve several dwelling units in a multi-family building. Multifamily buildings with central DHW plants use a hot water circulation (HWC) loop to maintain water temperature throughout the building. The unitary HPWH was tested with and without a HWC loop to observe the impact of the HCW loop on unitary HPWH performance.

Observation without HWC loop:

- The HPWH compressor managed most of the DHW load, while the electric resistance turned on for about 90 minutes total during peak use periods.
- HPWH upper tank temperature remained around 125°F during low flow periods and only dropped to 120°F during high flow periods.
- The tank remained stratified throughout the test: lower tank temperature was below 80°F most of the test, mid-tank temperature fluctuated between 80 and 120°F, and upper tank temperature remained around 125°F. This should drive efficient HPWH performance.

Observations with HWC loop:

- Electric resistance triggered more frequently than tests without a HWC loop, but only during high-draw periods.
- Upper-tank and delivery temperature fluctuated between 112°F and 125°F during low flow periods because the entire tank cooled to 112°F before the HPWH turned on. This is likely due to internal setpoints that are optimized for systems without a HWC loop.

HWC Loop Impact on System Efficiency:

The presence of a HWC loop decreased COP, as shown in figure B1.

Unitary HPWH, 140°F setpoint temperature, with thermostatic mixing valve (TMV), HWC returned to HPWH (Figure A2, C2)

Purpose of Test:

Some unitary HPWHs are installed with a thermostatic mixing valve and elevated storage temperature to combat bacterial growth and increase usable storage capacity. These tests were run to help clarify the impact a TMV has on a unitary HPWH.

Observations:

> Mixing valve sizing is crucial: The lab re-used a large mixing valve from the Colmac Application testing, which resulted in rapid DHW supply temperature oscillations that still averaged 120°F per the test target. These rapid oscillations did not impact HPWH performance but would have a significant impact on occupant comfort if installed in a real building.

> HPWH outlet temperature remained above 135°F, which supplied the mixing valve with sufficient hot water to target a consistent delivery temperature if properly sized.

> Electric resistance did not trigger during the "evening" peak usage period when using the TMV. This suggests the TMV and elevated setpoint temperature drive a higher usable storage capacity.

> Decrease in electric resistance usage did not correspond with increased system efficiency. While the heat pump handled more of the load, the overall energy consumption of the system increased.

Unitary HPWH acting as in-series temperature-maintenance tank (swing tank) (Figure A3, C3)

Note: the CHP-120 and other unitary HPWHs should not be installed as a swing tank without explicit manufacturer approval. This configuration is not currently advertised by AO Smith but has been observed in the field with mixed results.

Purpose of Test:

Swing tank configuration is a common CHPWH system configuration defined in the Northwest Energy Efficiency Alliance (NEEA) Advanced Water Heating Specification (AHWS). Swing tank configurations use an electric resistance tank water heater during periods of low DHW usage to maintain recirculation loop temperatures. These tests explore how a swing tank system will perform with unitary HPWH as a replacement for the electric resistance tank water heater to avoid this electric resistance usage. The drawback to implementing a unitary HPWH as a swing tank heater is its proprietary control sequence that prevents the system designer from knowing whether electric resistance will trigger, or sufficient supply temperature will be maintained when the unitary HPWH is exposed to very warm inlet water temperature. Unitary HPWHs should only be used as a swing tank if the manufacturer has carefully reviewed HPWH controls and tested their product in this context.

Observations:

> The lab ran these tests with a 120°F HPWH setpoint temperature and no mixing valve because the "cold" water supply system that feeds both the cold mixing valve inlet and HPWH inlet was heated to 150°F to simulate a primary heating system that feeds the swing tank with 150°F water. Therefore, there was no way to supply cold water to the

mixing valve using existing test stand piping. The lack of mixing valve and low HPWH setpoint temperature drove the same supply temperature fluctuations as the stand-alone tests without a mixing valve and would have drove unsafe DHW supply temperature if DHW draw was higher. To make this swing tank system more robust, a mixing valve is required to provide safe and consistent supply temperature and the HPWH would require a higher setpoint and a tighter HPWH control deadband to prevent HPWH outlet temperature from cooling below the 120°F supply temperature. A higher swing tank temperature setpoint, however, will require the swing tank to cover more HWC loop heating, which would lead to a decreased system COP compared to the same system with a lower swing tank temperature setpoint.

- The HPWH ran several times during low-use periods and electric resistance was never triggered.
- No compressor or electric resistance usage between 5AM and 3PM.
- The tank was stratified during low draw periods and mixed during high draw periods.

Impact on System Efficiency:

- The unitary HPWH provided all required auxiliary heating without using any electric resistance. The impact on system COP by providing swing tank heating using a HPWH instead of electric resistance will vary significantly depending on HWC loop heat loss and proprietary HPWH setpoints.
- Because primary heating was simulated for this test, system COP was estimated by assuming a primary equipment COP of 2.7 (based on data from Colmac lab testing) and calculating the amount of heating provided based on a makeup water temperature of 58 degrees. This provided a ratio of energy consumed by the primary heater and swing tank, which enabled the Equipment Method of COP calculation to be applied. To quantify the increase in system COP of replacing electric resistance with the CHP-120 as the swing tank, this calculation was repeated, replacing the observed swing tank equipment COP with an assumed equipment COP of 1, as seen in electric resistance heaters. This replacement increased system COP by approximately 0.5 points. It is important to note that this metric is based off a particular test case assuming 100 watts per apartment temperature-maintenance heat loss. In new buildings with well-insulated pipes and primary heat pumps capable of producing high water temperatures, marginal increases in COP may be significantly lower.
- The larger single-pass CHPWH swing tank test with 160°F supply temperature and 100W/apt heat loss relied on the swing tank to provide 23W/Apt of heating. Efforts should be made to decrease loop heat loss to achieve the greatest savings, but if a unitary CHPWH in a warm climate with proper setpoint temperatures (set by the manufacturer for this application) is serving a HWC loop that exceeds 100W/Apt in a

swing tank configuration, energy savings could exceed 100kWh/yr/apartment[6] compared to an electric resistance swing tank.

Unitary HPWH, 140°F setpoint, heat pump only mode, with in-series temperature-maintenance tank (swing tank) (Figure A4, C4)

Purpose of Test:

The RTP configuration testing shows the unitary HPWH does not need a dedicated temperature-maintenance tank to manage a HWC loop, but there are applications where a unitary HPWH could be installed upstream of an existing gas or electric resistance DHW plant in heat pump only mode to provide high-efficiency heating to some or all the DHW load. The existing plant would then be available for HWC loop heating, supplemental heating in cold outdoor temperatures and/or high DHW usage periods, redundancy, or trim heating. There are drawbacks to this configuration:

1. If the HPWH is connected to the CW supply line incorrectly, the HPWH may not provide sufficient heating or may drive excessive pressure drop. Design and installation errors are less likely if the DHW plant is completely replaced with sufficient HPWH capacity.
2. If the HPWH is not set to "HPWH only" mode, high DHW draws could drive excessive electric resistance usage.
3. If the HPWH fails to start or goes into alarm, the original, downstream DHW plant will provide most or all of the DHW heating without the building manager noticing. Or, even if the HPWH fails and alarms, building managers could choose to ignore the alarm and simply allow the gas or electric resistance system to provide heat.
4. The HPWH has little impact on energy usage associated with HWC loop heating.

Observations:

> When in heat pump only mode, the unitary HPWH didn't use any electric resistance.

> The swing tank heater did not turn on during most draw events, but turned on to satisfy the recirculation load when DHW usage was low.

> Upper-HPWH-tank temperature dropped to 130°F during the high usage period.

Impact on system efficiency:

The AO Smith HPWH provided all the DHW usage heating with a COP greater than 3.0 but the swing tank still covered a significant portion of HWC loop heating. Like the larger, single-pass CHPWH systems, this configuration is most efficient when HWC loop heat loss is low.

---

[6] Assumes annual HPWH COP =2.0, annual EWH COP = 1.0, constant HWC loss of 100w/apt, 160°F primary storage temperature.

Stratified storage tank charged by unitary HPWH (conversion to single-pass RTP) (Figure A5, C5)

Purpose of Test:

A storage tank and circulation pump were paired with the CHP-120 to demonstrate the benefits of incorporating a larger stratified storage volume than what is integrated with the CHP-120. Excessive electric resistance and DHW delivery failure has been observed in field installations of unitary HPWHs with additional storage tanks and circulation pumps, so custom installation of additional storage with unitary HPWHs is not recommended. Instead, this testing illustrates the potential impact of manufacturers increasing integrated storage volume.

Observations:

- Electric resistance did not trigger in the unitary HPWH, even in the high usage case.
- Roughly 1/3 of the additional storage tank remained hot during the high use period.
- Upper tank temperature in the integrated HPWH tank remained hot, sometimes reaching 155°F.
- When a HWC loop was not used, electric resistance usage was observed in the integrated HPWH even though the stratified storage tank had plenty of hot water left. This is likely because a constant HPWH draw-down rate with lower HPWH inlet water temperature (city water temperature instead of HWC return temperature) caused the drawdown of the HPWH to exceed the compressor heating capacity. This illustrates one of many potential issues associated with applying a unitary HPWH to a custom-designed system with additional storage.

Impact of larger storage volume on system efficiency:

Additional storage volume allowed the HPWH to cover the full DHW load without using any electric resistance because it provided sufficient DHW during peak draw periods, increasing system COP by ~0.5.

Quantitative Comparisons

Ecotope observed the impact of various building characteristics and design practices on the following metrics of HPWH system performance:

1. System COP: Typically calculated by ratio of total DHW heating provided (DHW usage and recirculation heating) over total energy consumed by all DHW equipment, however the test stand designed for much larger multifamily buildings for Sanden and Colmac testing, led to increased heat loss in pipes between heat pump inlet/outlet and nearby temperatures sensors used in COP calculations. To remedy this, equipment COP was calculated for the CHP-120 and swing tank (if applicable), and the system COP was

found by weighting these efficiencies respective to their respective energy consumption. This factor is important because increasing system COP can significantly decrease total energy use, independent of occupant DHW use patterns.

2. Electric Resistance Consumption: Amount of electric resistance energy required to help the heat pump meet heating demands.

Hot water recirculation vs. no hot water circulation

> Systems without a hot water circulation loop yielded higher COPs than systems with a hot water circulation loop due to decreased inlet water temperatures [figure B1].

Mixing valve vs. no mixing valve

> Despite having reduced electric resistance use [figure B2], systems with a mixing valve and 140 °F setpoint had a lower system COP [figure B3] than systems without a mixing valve and 120 °F setpoint. While reliance on electric resistance was reduced, total energy consumption increased as the heat pump became less efficient with higher storage temperatures.

Non-unitary configurations

> Due to relatively lower HPWH outlet temperatures, swing tank systems did not exhibit high system performance, especially in tests with a primary setpoint of 120 °F. Swing tank systems are most efficient when they receive high water temperatures from the primary system, as this allows the primary heat pump to cover a large portion of the temperature-maintenance load. However, in CHP-120 testing, the swing tank typically delivered temperatures between 120-130 °F, causing it to operate excessively throughout the test [figure B4].

Modelling recommendations

The observations above highlight several areas where Ecotope, Wilcox, LER, and partners could use application test data to refine the current modelling approach. We can help enhance the model to further incorporate key factors that affect HPWH system performance. The modelling team could take the following steps to make use of the AO Smith test data:

1. Customize the energy modelling software script (without changing the simulation math) to simulate the 24-hour lab tests and plot the results.
2. Observe quantitative trends in comparison to the plots in Appendix B. This includes observing relative changes as variables are manipulated and comparing the magnitude of key metrics.
3. Observe hour-by-hour results and further key metrics to explore differences that occur between simulation and lab results.

4. Compare qualitative lab observations with the simulation results. Do the same trends exist? A couple qualitative observations to explore and refine if necessary:
    a. Electric resistance usage in unitary configuration.
    b. Unitary HPWH tank stratification and usable storage.

Design, codes, and standards implications

Several observations in the lab inform important HPWH system design decisions, which could drive best practices design guidelines and future codes and standards:

1. Sizing tools should be created to size unitary HPWHs such that electric resistance is not triggered regularly. Drawdown percentages that trigger compressor and electric resistance operation should be defined by manufacturers to make equipment sizing and operation more predictable.
2. Installing a mixing valve and applying a higher setpoint temperature could yield a more consistent supply temperature, higher DHW delivery capacity, and less electric resistance usage, but may result in lower system COP due to lower compressor efficiency associated with high setpoint temperature. If a mixing valve is installed, it should be carefully sized and supplied with enough recirculation flow to maintain a smooth supply temperature.
3. The CHP-120 satisfies a hot water recirculation loop well when installed with a mixing valve and elevated setpoint temperature. Unfortunately, this finding cannot be generalized to all unitary HPWHs because each manufacturer has unique control setpoints to trigger compressor and electric resistance usage.
4. One of the greatest advantages of using unitary HPWHs is their installation simplicity compared to larger CHWPH systems. Applying unitary HPWHs in configurations designed for single-pass or multi-pass HPWHs may drive significant energy savings compared to electric resistance or gas water heating systems but eliminates the simplicity unitary HPWHs provide. The design practices below could be further analyzed by unitary HPWH manufacturers to provide energy savings in targeted applications but do not guarantee energy savings as part of a custom application due to high likelihood of installer error or proprietary setpoints interfering with design intent.
    a. Using a unitary HPWH instead of an electric resistance heater as a swing tank could yield significant energy savings if the manufacturer's controls and guidance support it.
    b. Larger integrated storage volume could reduce or eliminate electric resistance usage associated with high DHW usage periods.
5. Installing a unitary HPWH upstream of an existing DHW system in heat pump only mode could yield significant energy savings associated with DHW usage if installed in the correct location and properly sized. However, this configuration will not provide significant HWC loop heating if HWC loop heat loss is high. During testing, the CHP-120 was in a closed, conditioned room with heating equipment to maintain 68°F room temperature. HPWHs use heat from the air to heat the water, so they cool the air around them. Therefore, HPWHs should be placed in a room with sufficient outside air exchange in warm climates, or in a room with sufficient waste heat or energy efficient space conditioning. In a closed room with no conditioning or air exchange, the

HPWH will cool the room until its compressor operates inefficiently and it will eventually use excessive electric resistance to satisfy the DHW load.

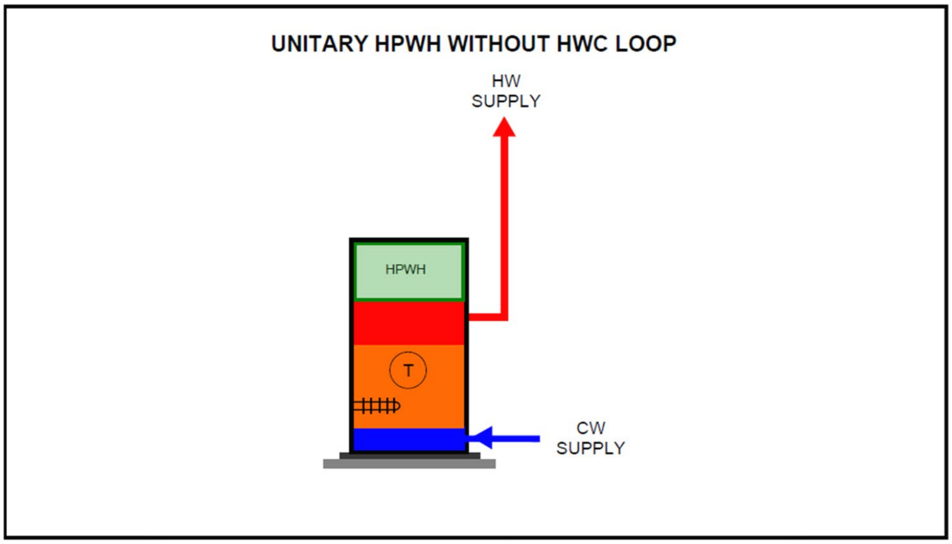
Conclusion

Data from CHP-120 lab testing will be paramount to the refinement of energy modelling and design considerations around unitary HPWH systems. Qualitative results and quantitative trends can be referenced to refine energy modelling software, and several observations were made that verify current design assumptions and increase confidence in additional design practices.

Enclosures

- Test Configurations
- Quantitative Plots
- Qualitative Plots

FIGURE A1: UNITARY HPWH, 120°F SETPOINT TEMPERATURE, WITH (BOTTOM) AND WITHOUT (TOP) HWC LOOP RETURNED TO HPWH



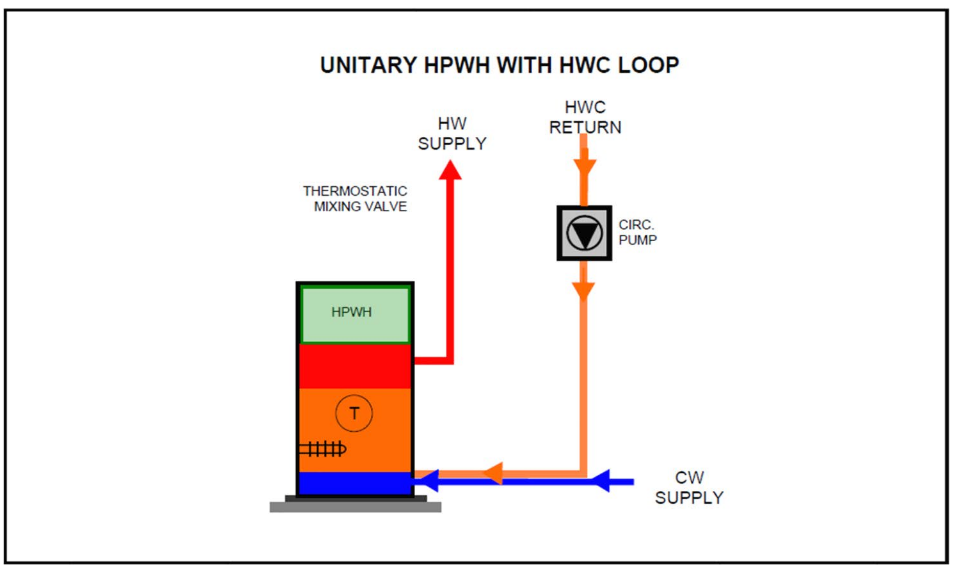


FIGURE A2: UNITARY HPWH, 140°F SETPOINT TEMPERATURE, WITH THERMOSTATIC MIXING VALVE (TMV), HWC RETURNED TO HPWH

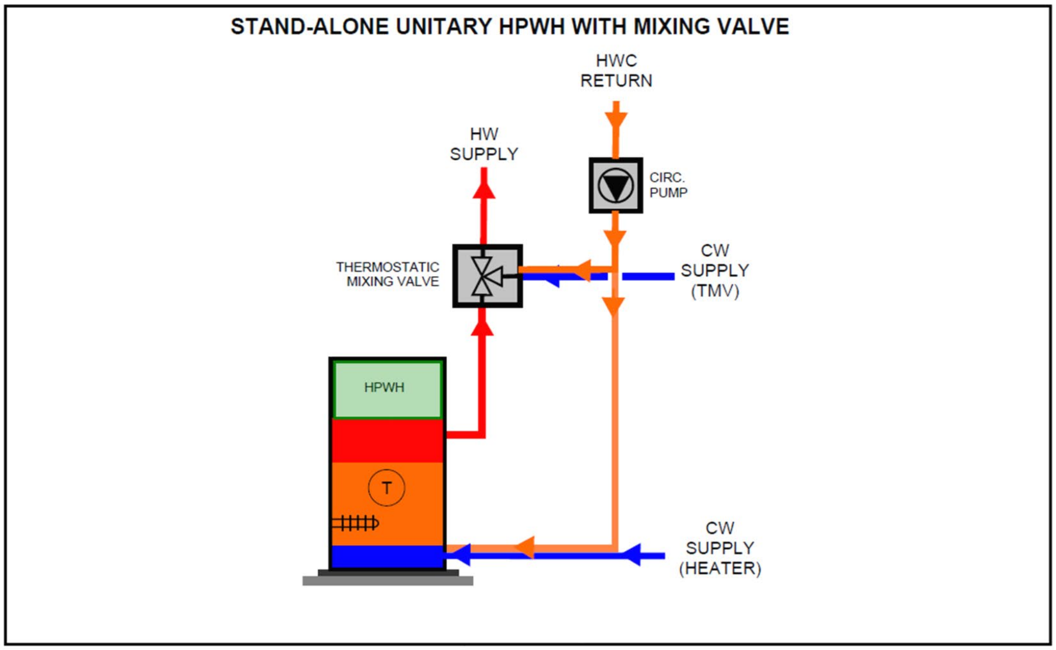
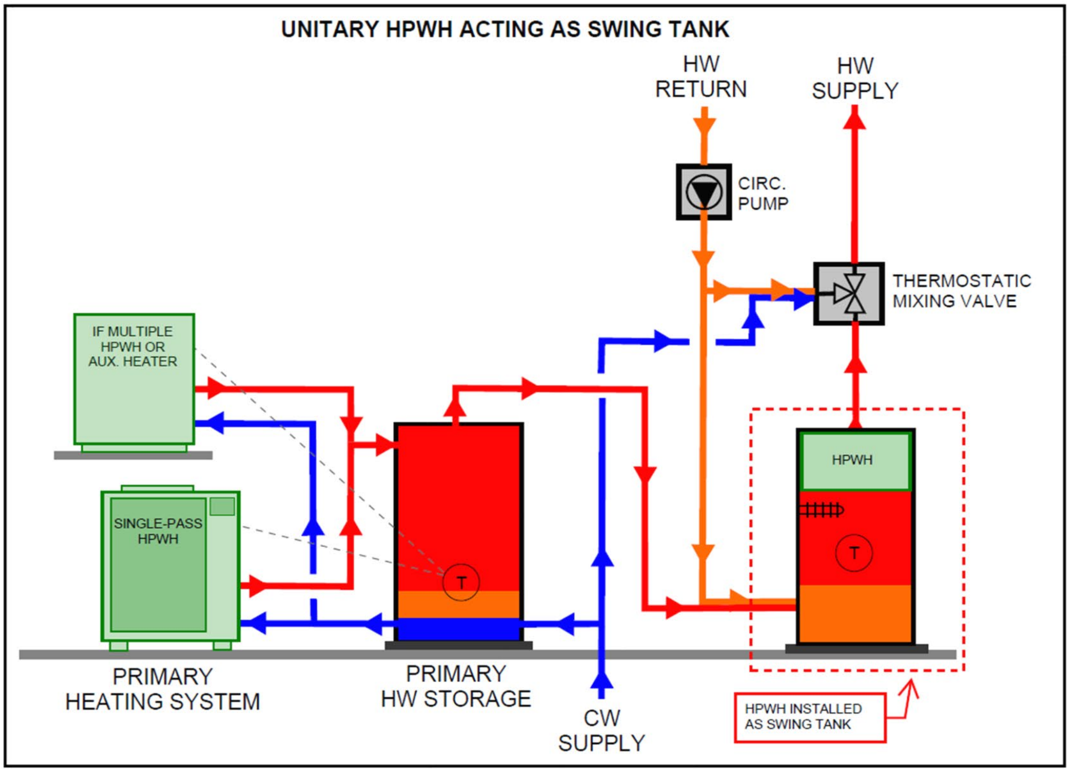


FIGURE A3: UNITARY HPWH ACTING AS IN-SERIES TEMPERATURE MAINTENANCE TANK (SWING TANK)



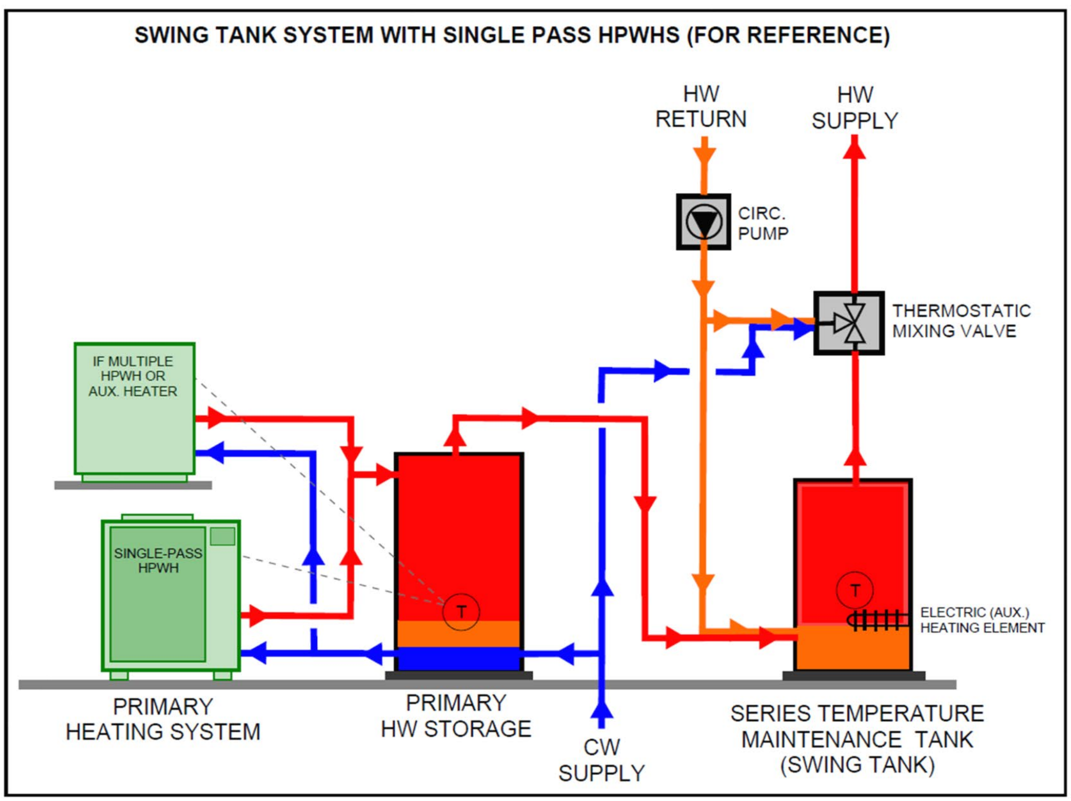


FIGURE A4: UNITARY HPWH, 140°F SETPOINT, HEAT PUMP ONLY MODE, WITH IN-SERIES TEMPERATURE MAINTENANCE TANK (SWING TANK)

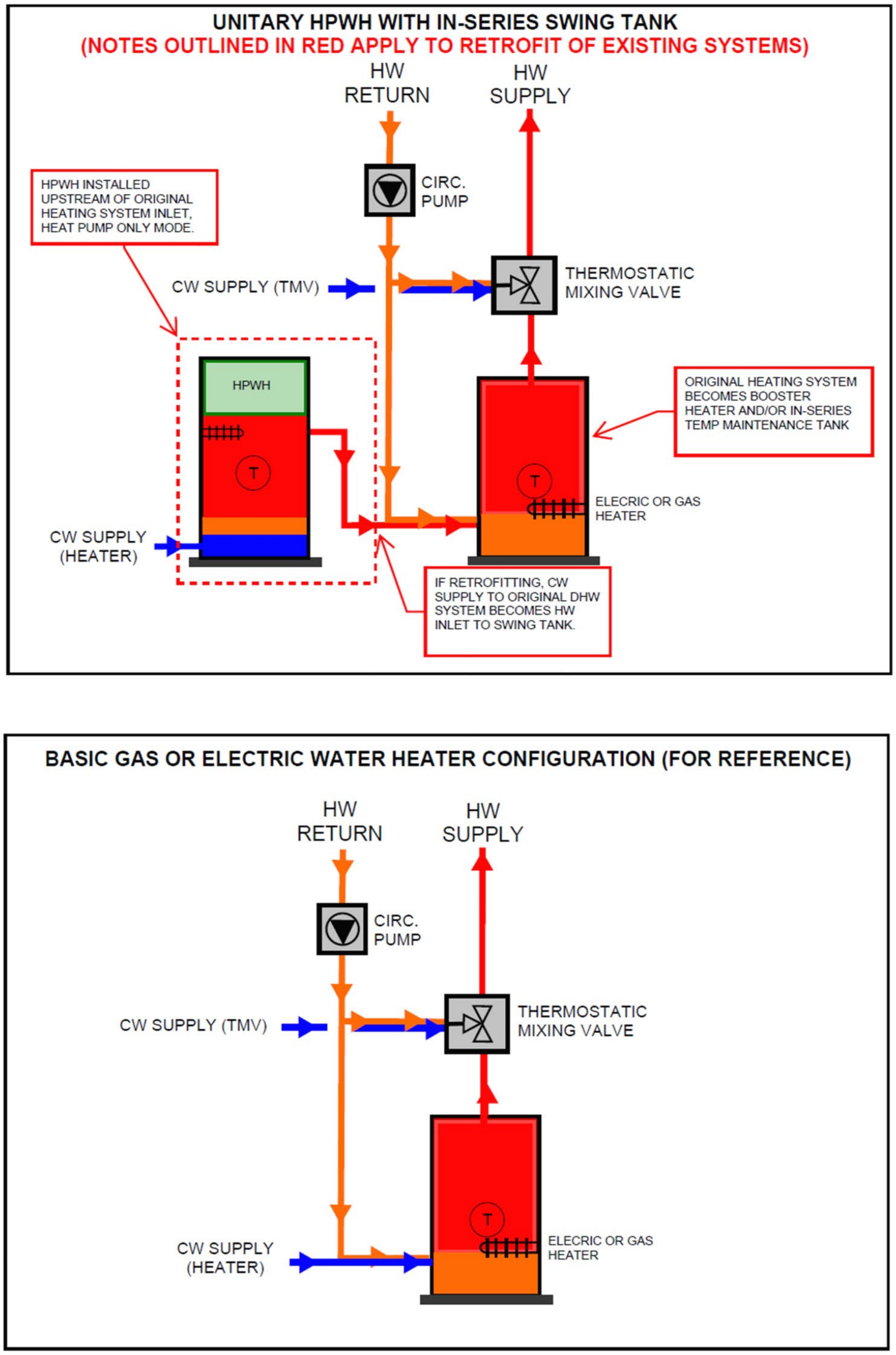
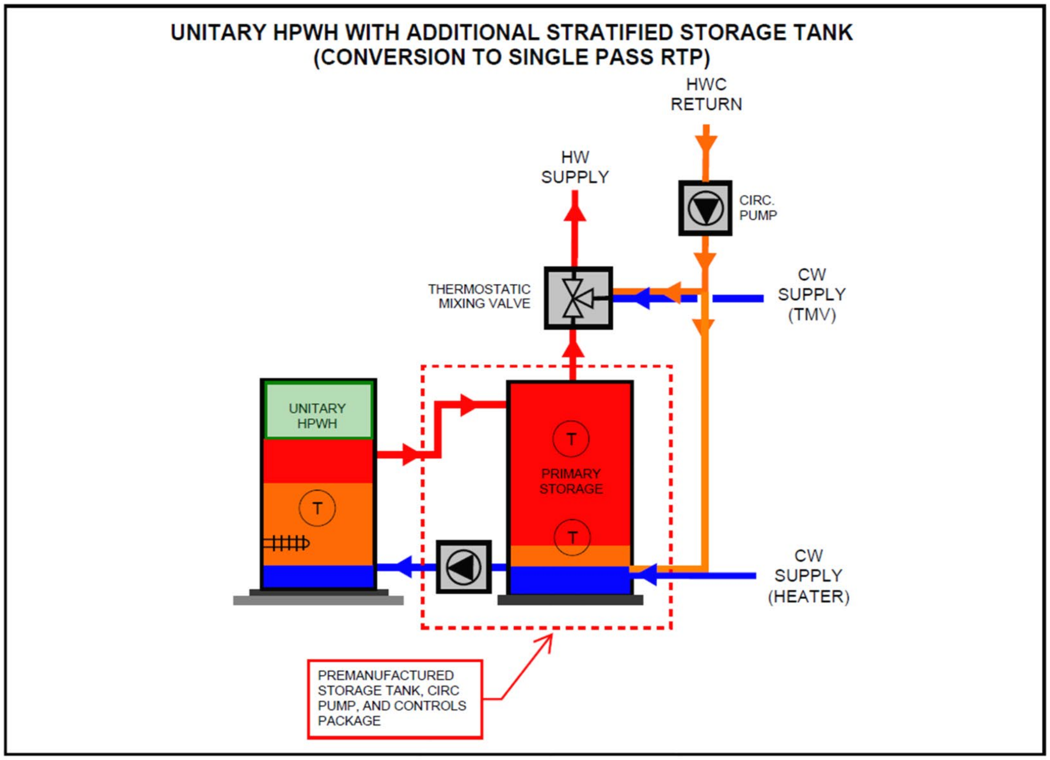


FIGURE A5: STRATIFIED STORAGE TANK CHARGED BY UNITARY HPWH (CONVERSION TO SINGLE PASS RTP)



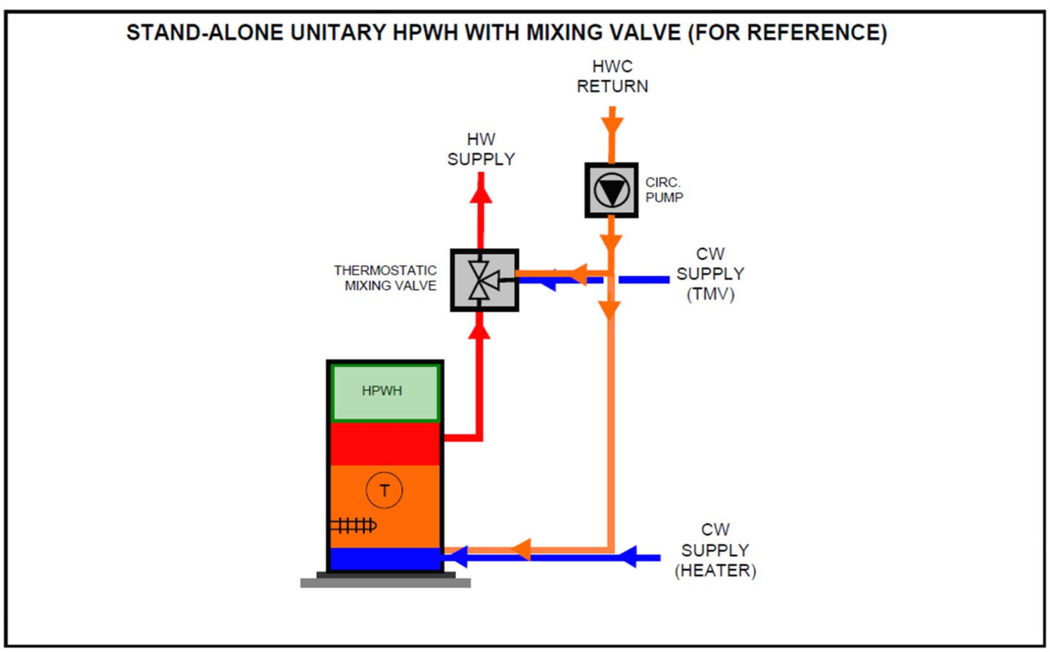


FIGURE B1

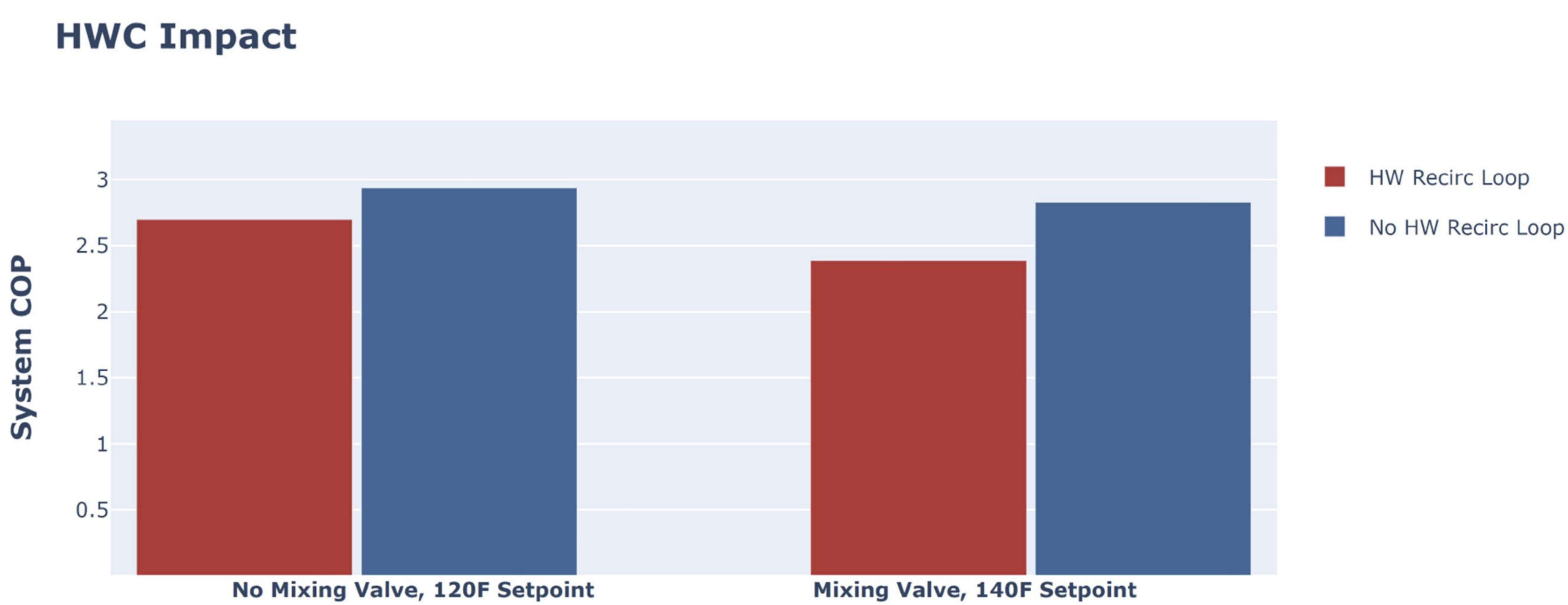

HWC Impact
System COP
3
2.5
2
1.5
1
0.5
No Mixing Valve, 120F Setpoint
Mixing Valve, 140F Setpoint
HW Recirc Loop
No HW Recirc Loop

FIGURE B2

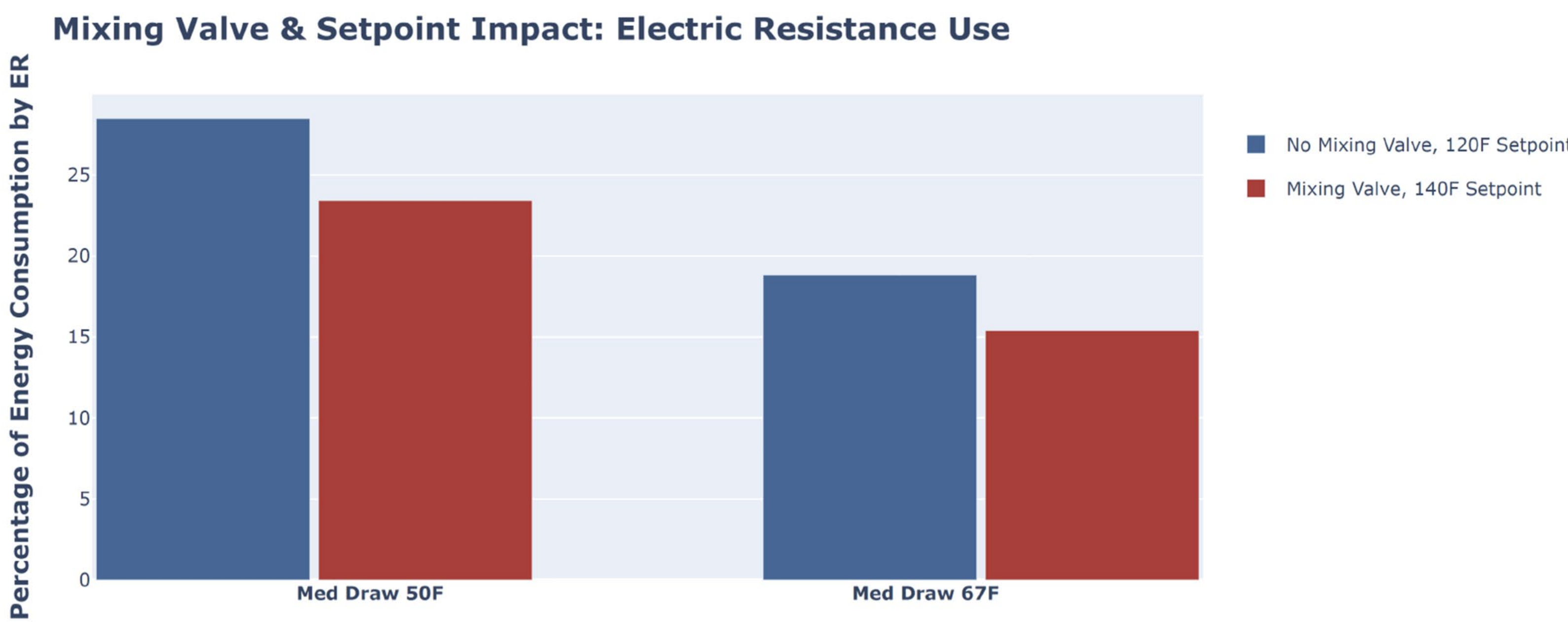

Mixing Valve & Setpoint Impact: Electric Resistance Use
Percentage of Energy Consumption by ER
0
5
10
15
20
25
Med Draw 50F
Med Draw 67F
No Mixing Valve, 120F Setpoint
Mixing Valve, 140F Setpoint

FIGURE B3

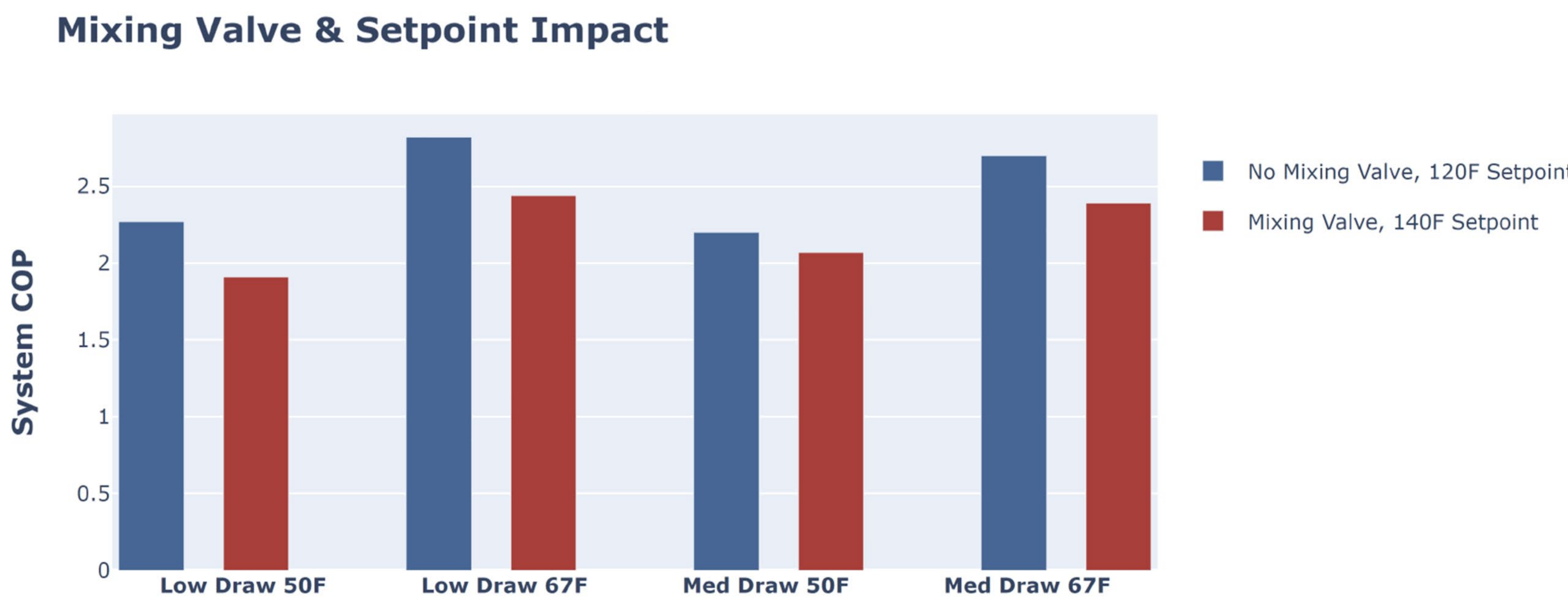

Mixing Valve & Setpoint Impact
System COP
2.5
2
1.5
1
0.5
0
Low Draw 50F
Low Draw 67F
Med Draw 50F
Med Draw 67F
No Mixing Valve, 120F Setpoint
Mixing Valve, 140F Setpoint

FIGURE B4

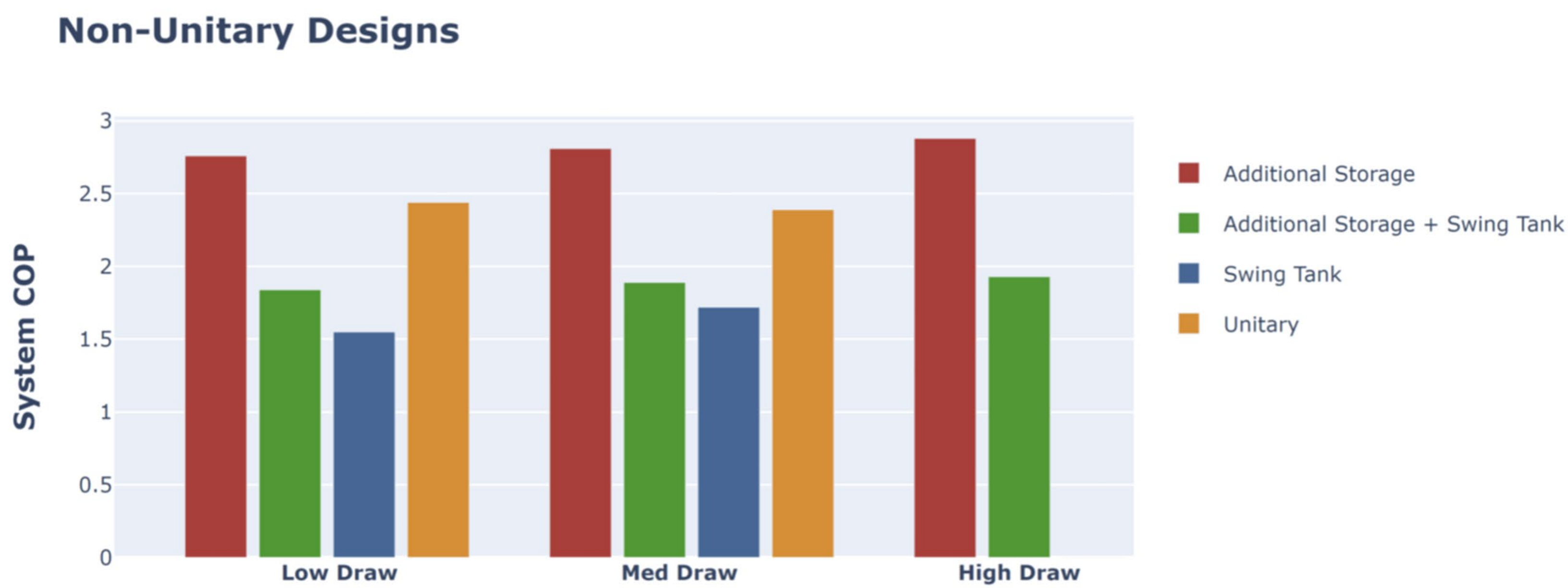

Non-Unitary Designs
System COP
3
2.5
2
1.5
1
0.5
0
Low Draw
Med Draw
High Draw
Additional Storage
Additional Storage + Swing Tank
Swing Tank
Unitary

FIGURE C1: UNITARY HPWH, 120°F SETPOINT TEMPERATURE, WITH (LEFT) AND WITHOUT (RIGHT) HWC RETURNED TO HPWH

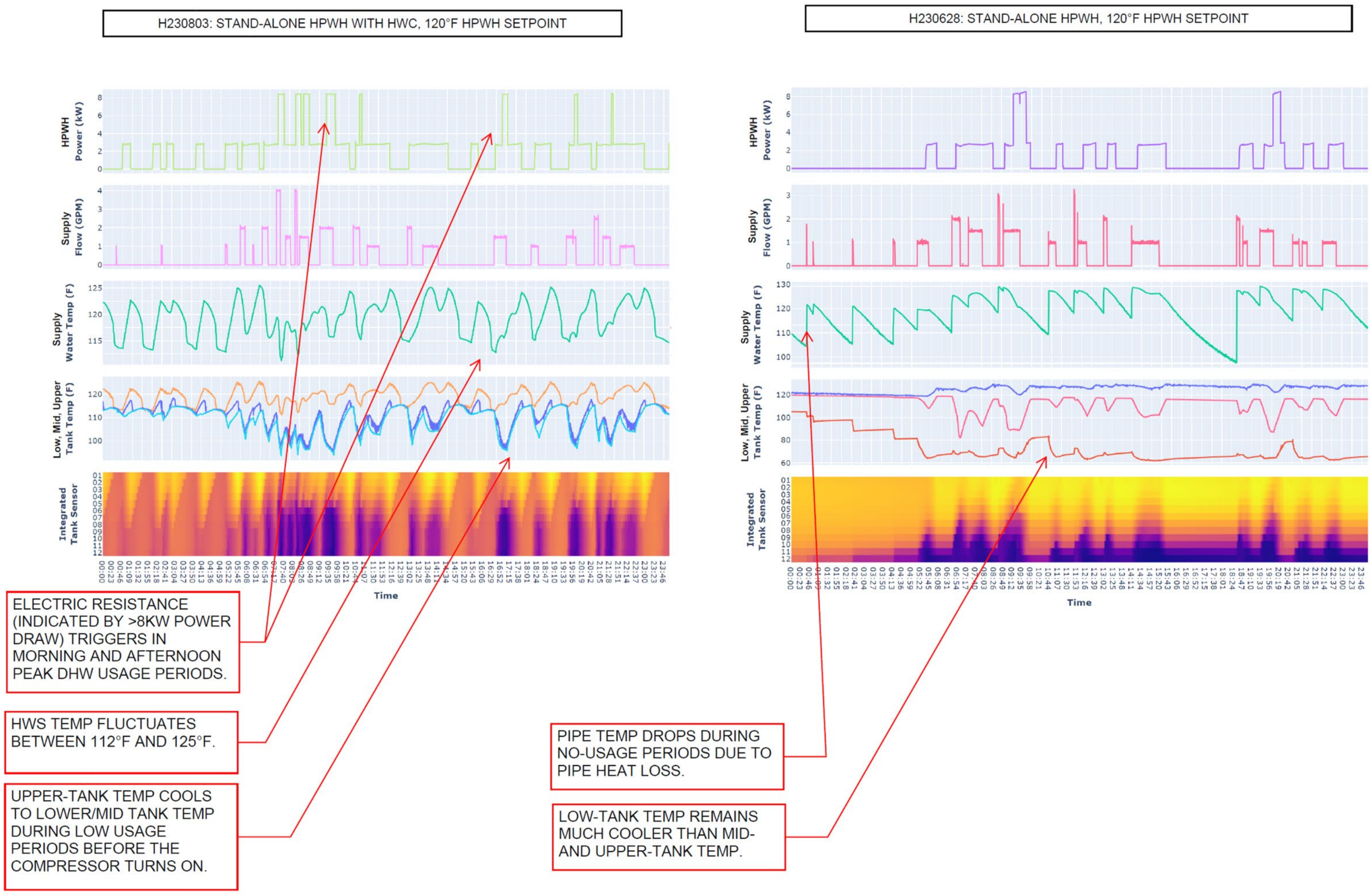


FIGURE C2: UNITARY HPWH, 140°F SETPOINT TEMPERATURE, WITH THERMOSTATIC MIXING VALVE, HWC RETURNED TO HPWH

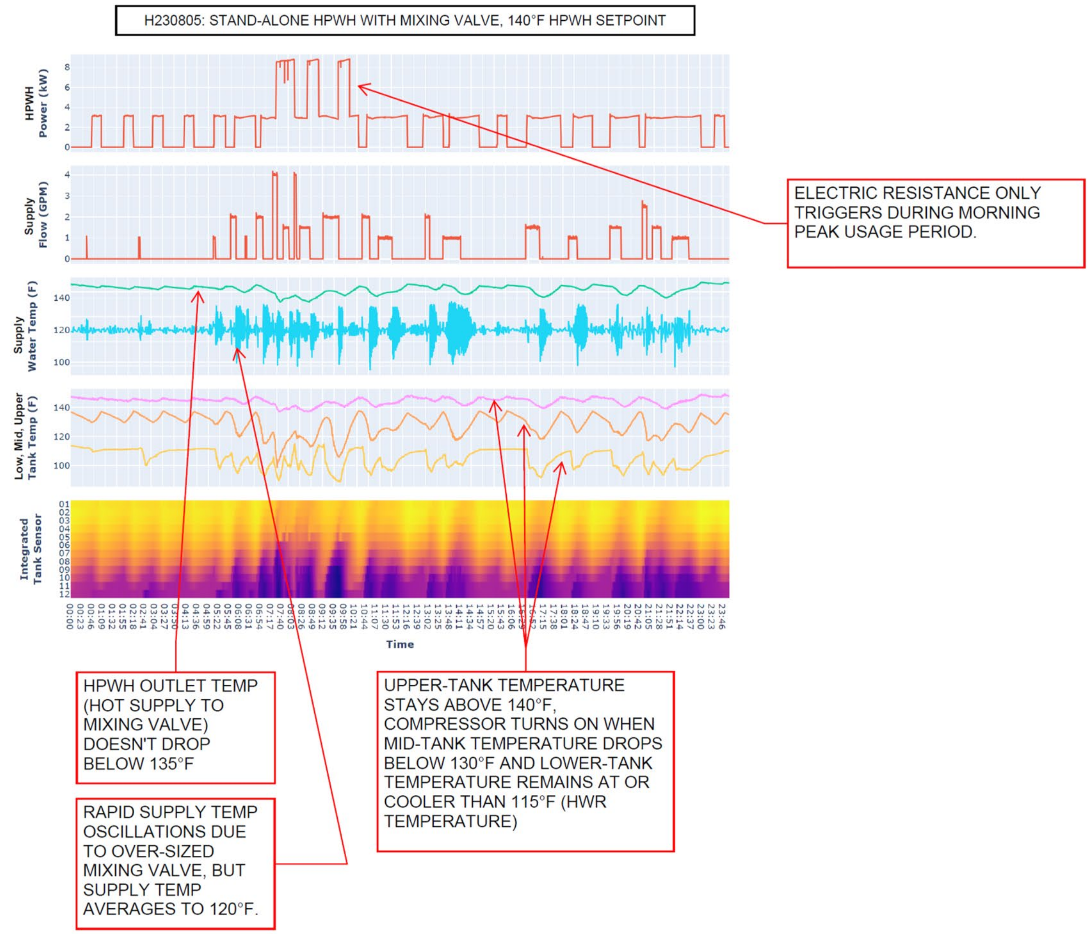


FIGURE C3: UNITARY HPWH ACTING AS IN-SERIES TEMPERATURE MAINTENANCE TANK (SWING TANK)

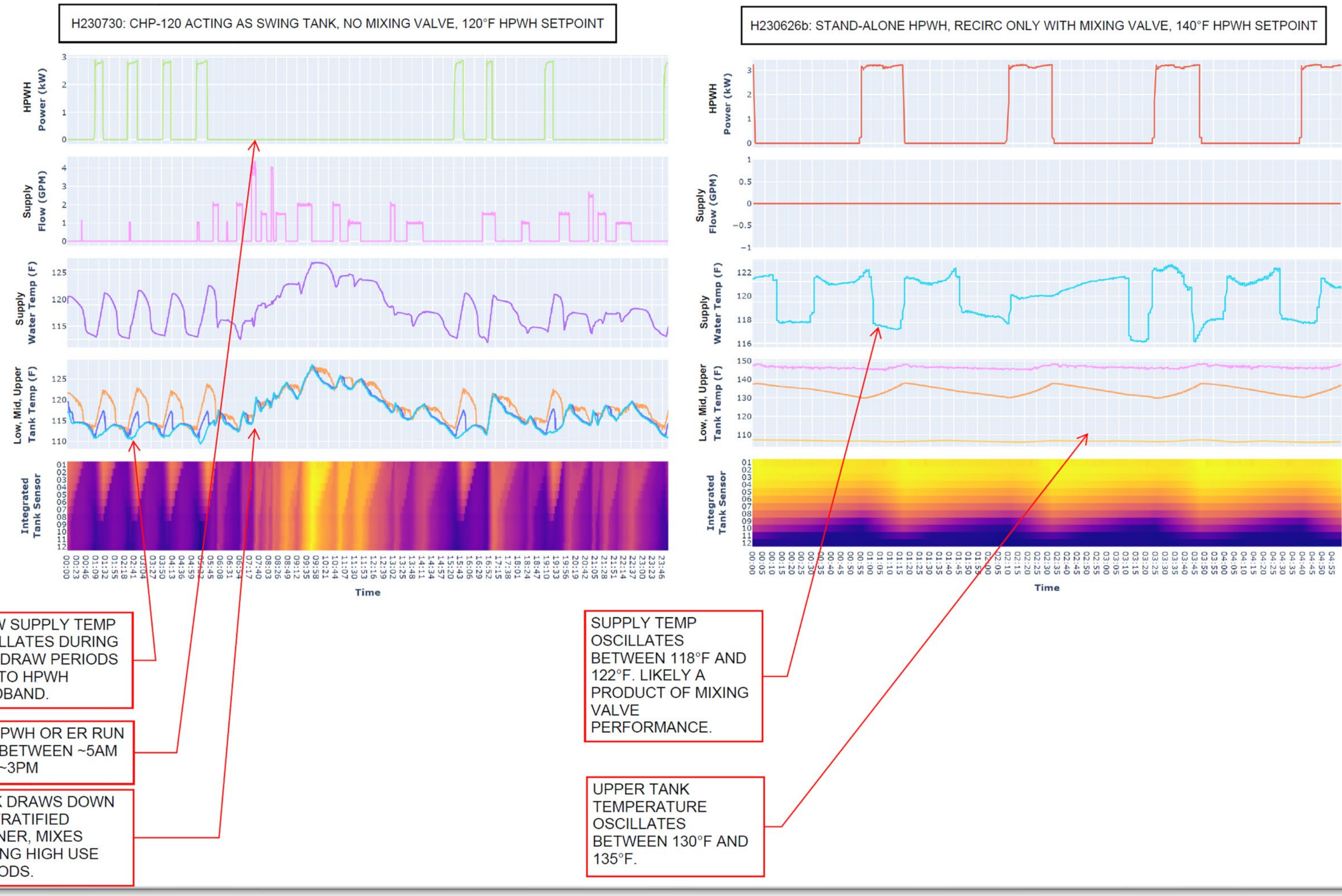


FIGURE C4: UNITARY HPWH, 140°F SETPOINT, HEAT PUMP ONLY MODE, WITH IN-SERIES TEMPERATURE MAINTENANCE TANK (SWING TANK)

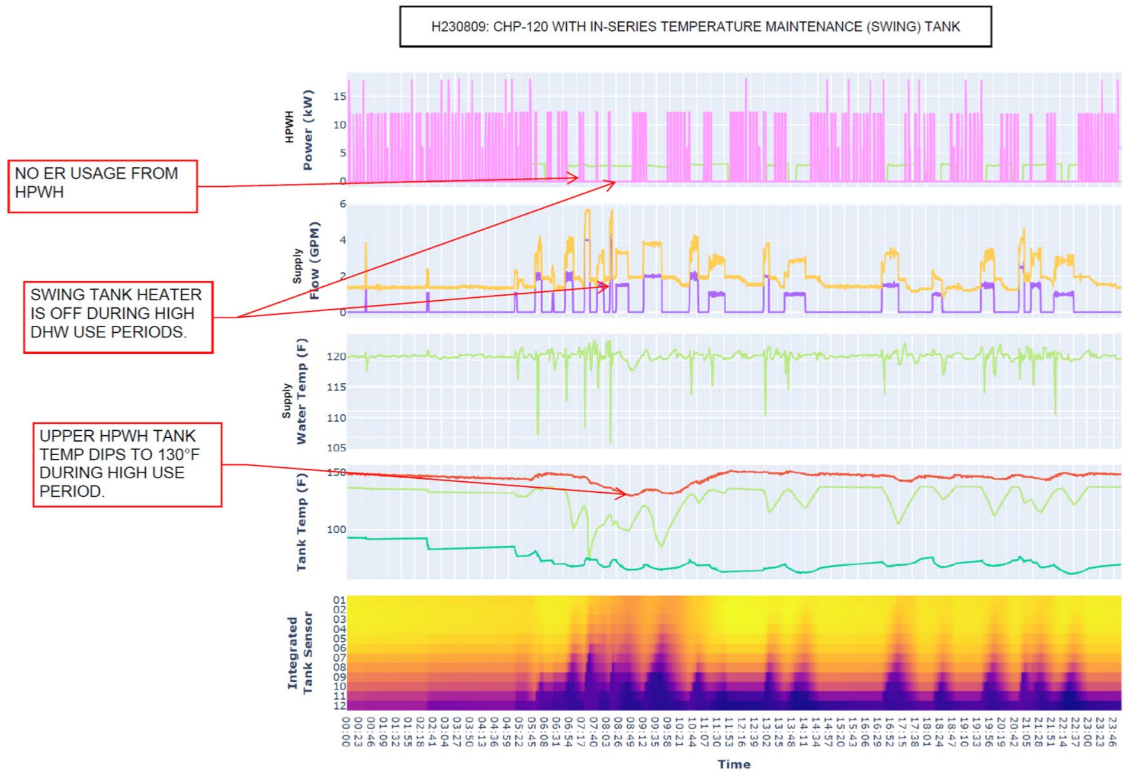
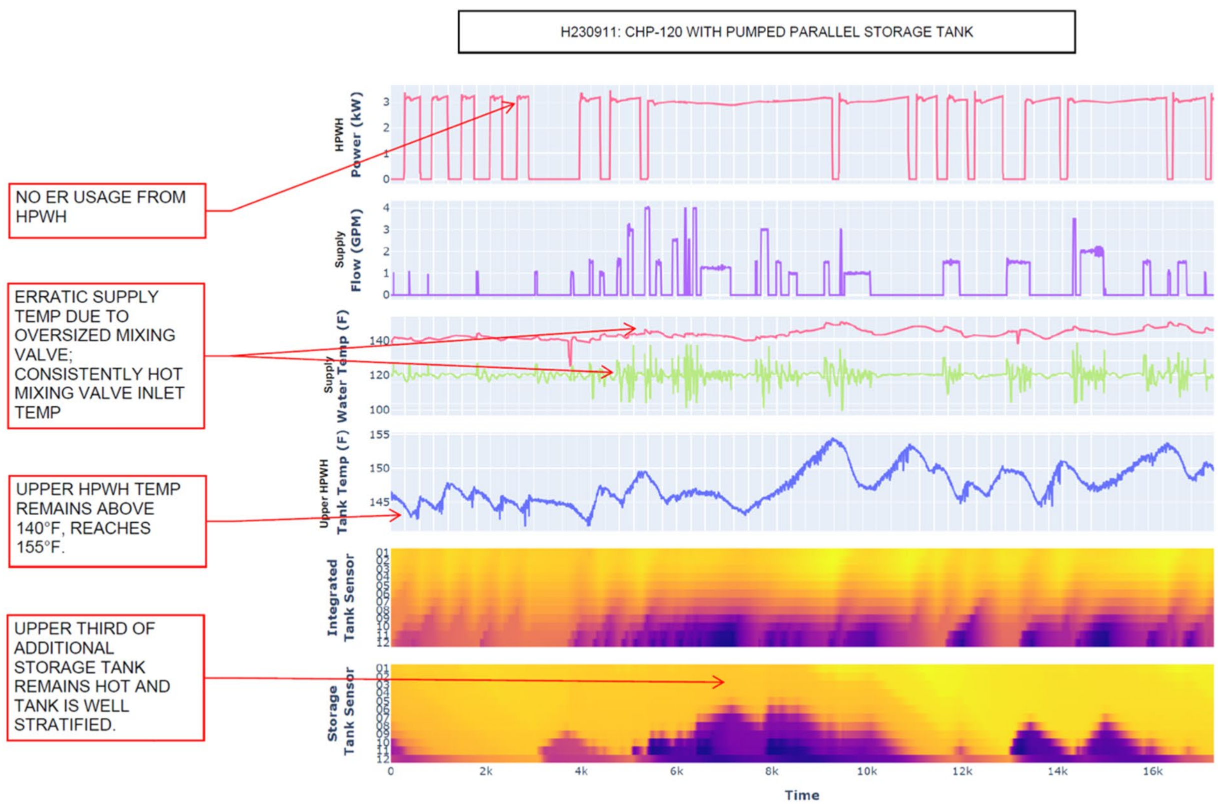
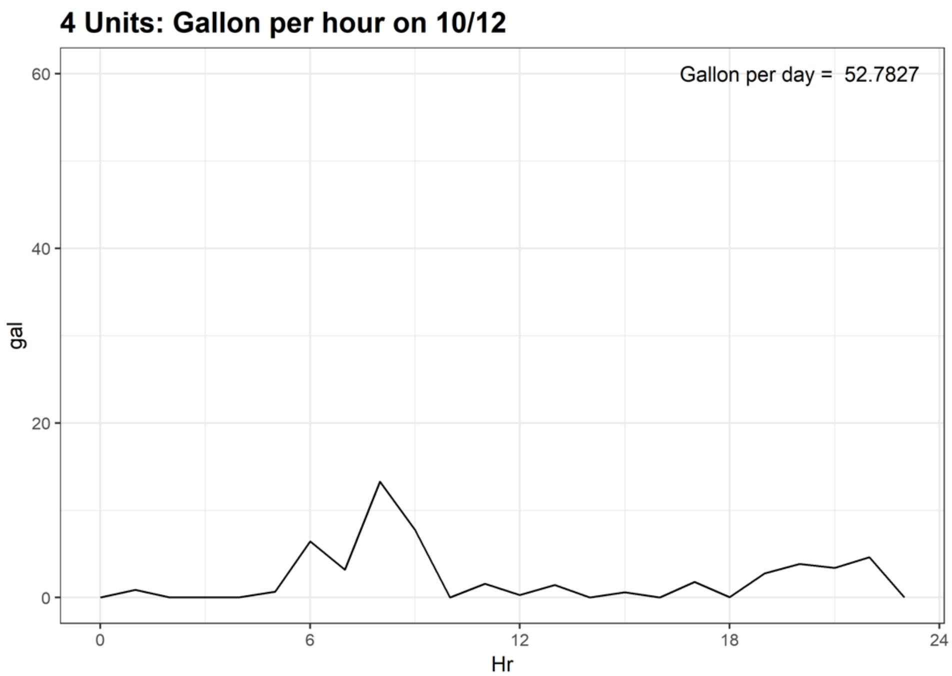


FIGURE C5: STRATIFIED STORAGE TANK CHARGED BY UNITARY HPWH (CONVERSION TO SINGLE PASS RTP)

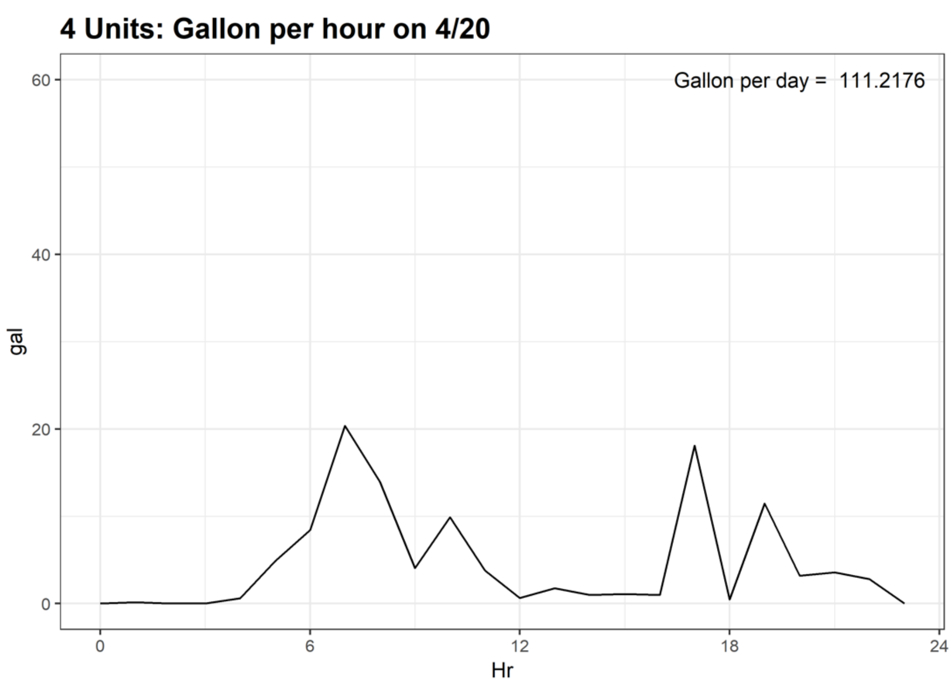


Appendix E: Draw Profiles

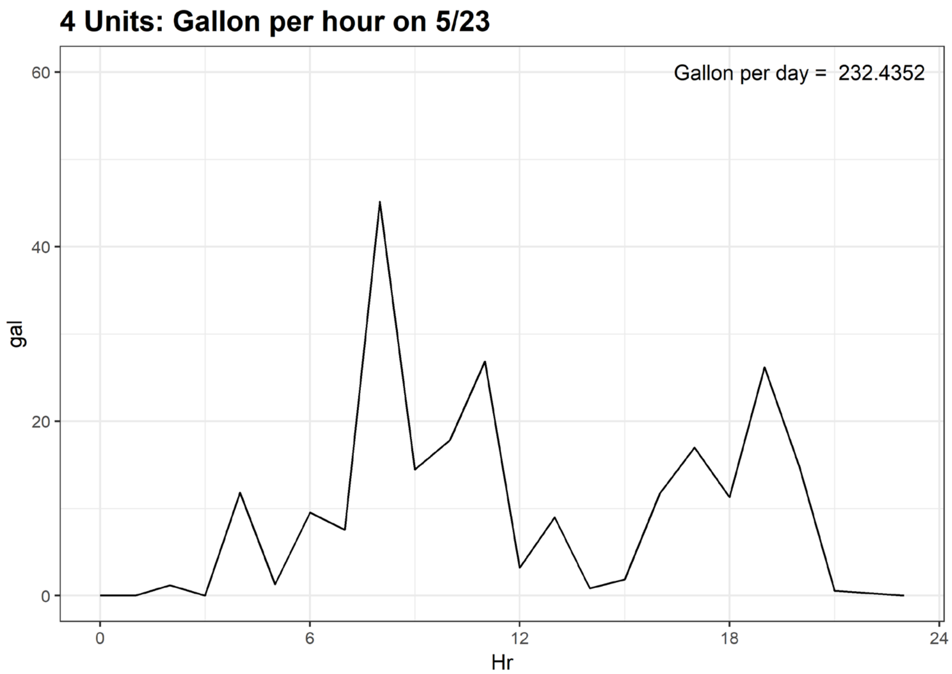
4-Unit Low



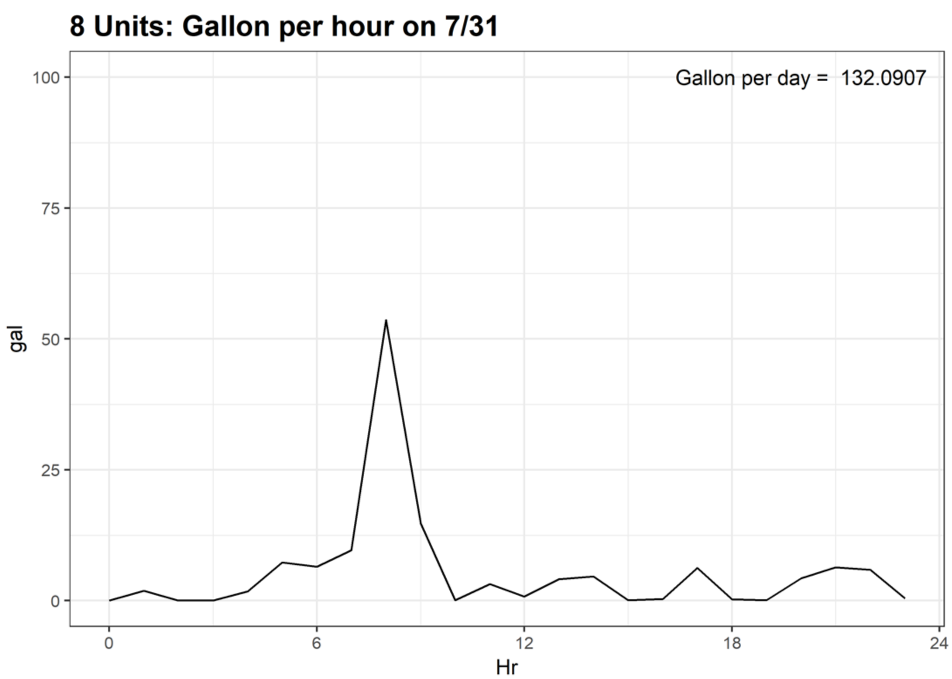
4-Unit Medium



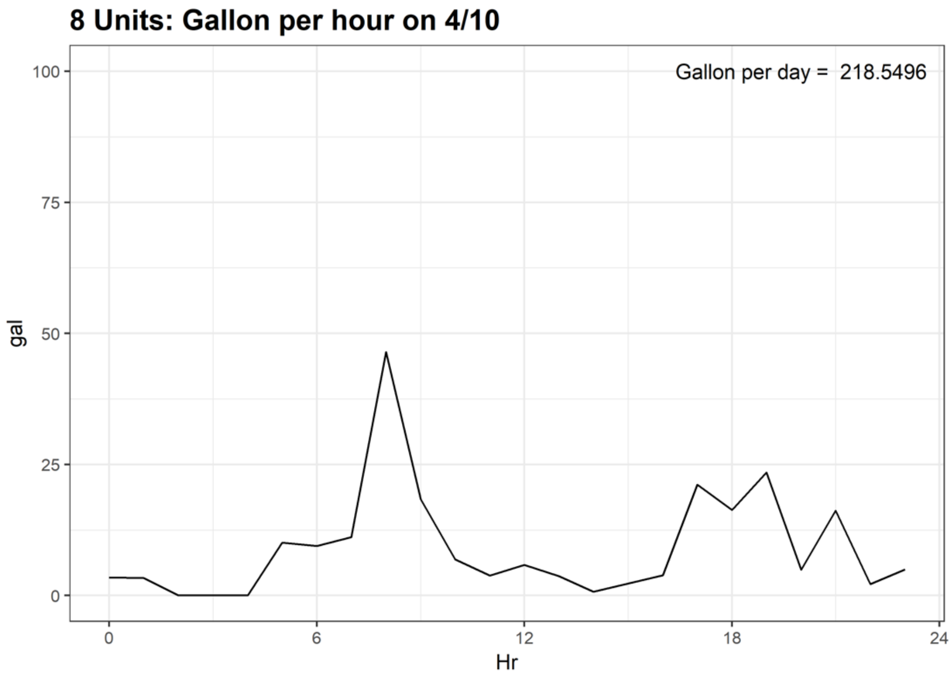
4-Unit High



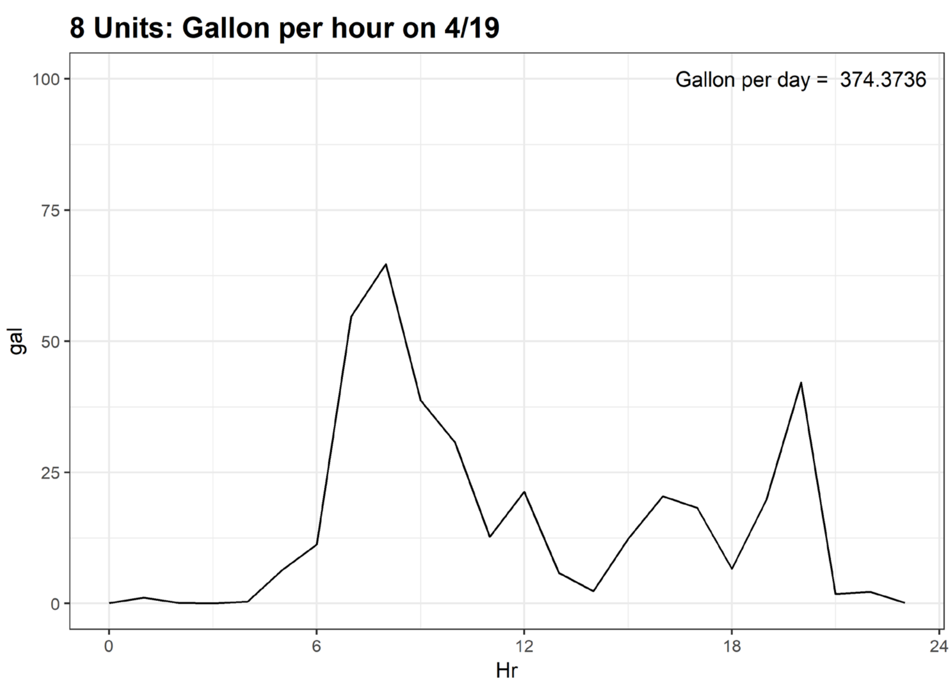
8-Unit Low



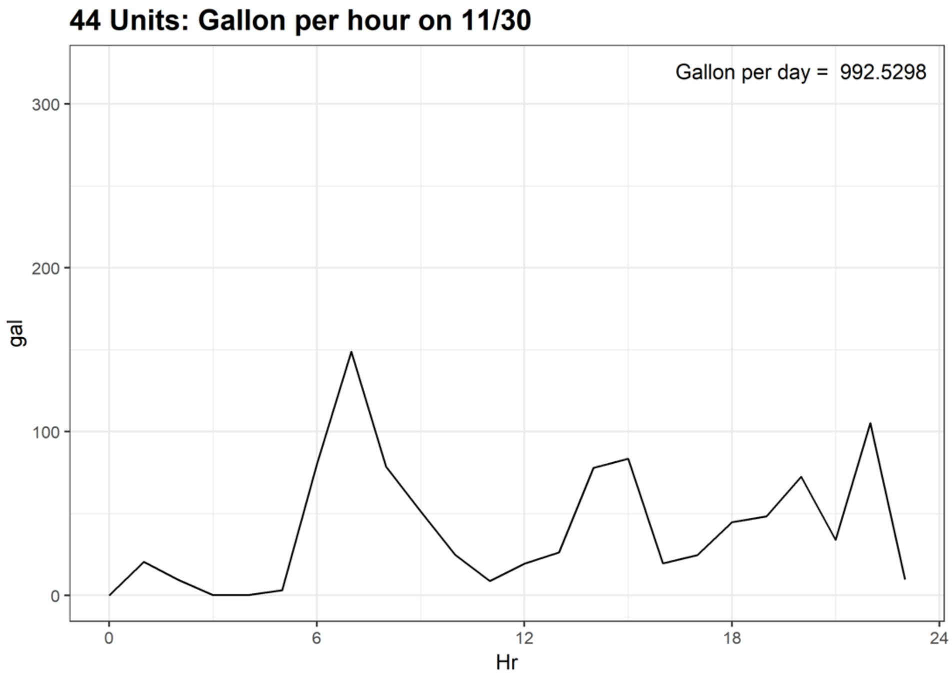
8-Unit Medium



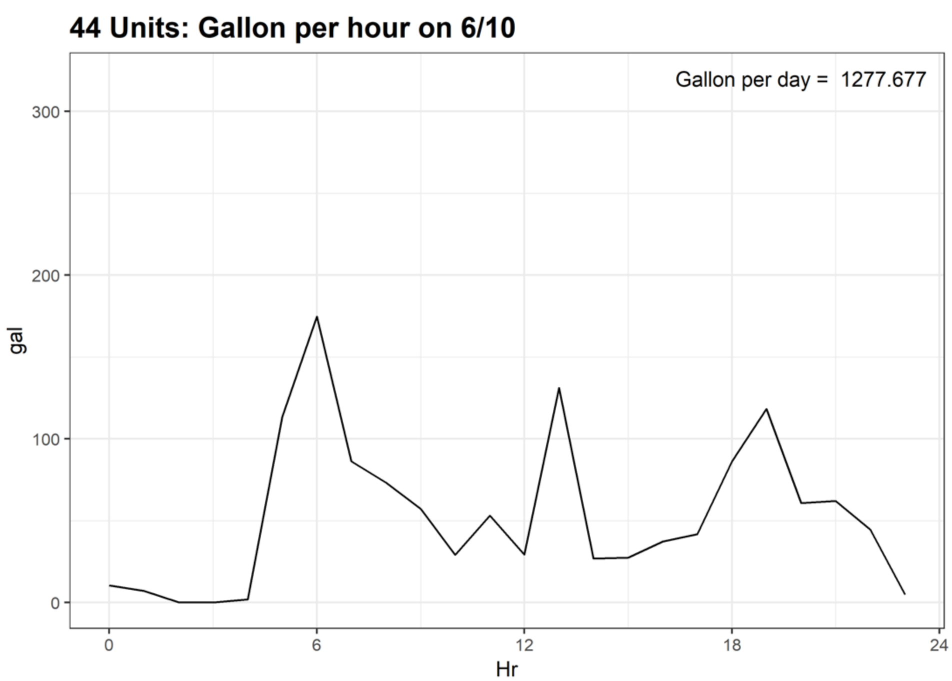
8-Unit High



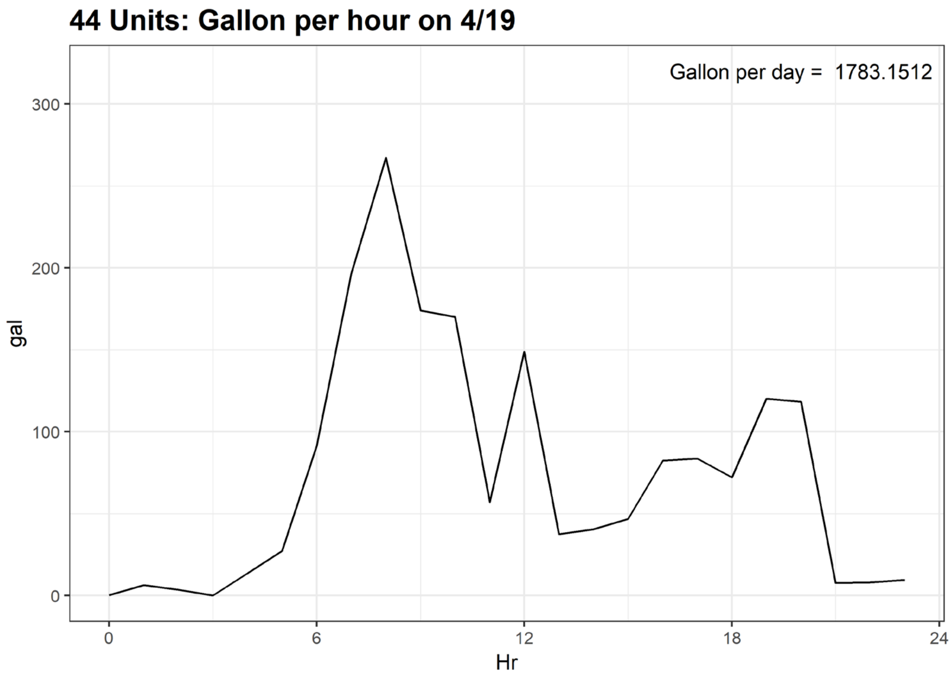
44-Unit Low



44-Unit Medium



44-Unit High


44 Units: Gallon per hour on 4/19
Gallon per day = 1783.1512
300
200
100
0
gal
0
6
12
18
24
Hr

Appendix F: Demand Response Lab Testing

To: Multifamily Heat Pump Water Heater Project Stakeholders

From: Madison Johnson, Ecotope

Evan Green, Ecotope

Scott Spielman, Ecotope

Cc:

Subject: Demand Response Lab Testing

Date: February 1, 2023

Demand Response Testing Overview

Central Heat Pump Water Heaters (CHPWHs) possess inherent load shift capabilities due to their substantial storage volumes, but the extent of such capabilities and how to maximize them is not yet fully understood. Programs incentivizing the installation of load shift capable CHPWHs are already being deployed, but a lack of research prevents such programs from maximizing their potential. While there are a handful of CHPWH load shift demonstrations in the United States to draw insight from, there is a lack of formal lab testing to quantify specific load shift metrics and standard guidance for successful CHPWH load shift deployment. Additionally, it was not well understood to what extent mulit-pass systems, unitary systems, or systems with a return-to-primary temperature maintenance system would be capable of load shifting. This round of lab testing aimed to quantify load shift metrics for specific system types and to better understand how to optimize load shift controls.

Test Design

Two types of tests were developed during the planning phase. The tests do not include testing the communication protocol, CTA-2045B. Instead, they simulate the HPWH equipment response to grid Load Up and Shed requests — which could be sent through CTA-2045B or OpenADR — and quantify total energy usage shifted as a result of the change in equipment operation.

The first type of test was a 24-hour simulated multifamily building, which mirrored the applications testing previously conducted in the lab. Systems were sized for a 16, 33, or 44-unit multifamily building with a medium draw profile and a recirculation loss rate of 60 W/apt. A typical multifamily loadshape was used to simulate domestic hot water demand. For these tests, a load shift schedule was created based on Pacific Gas and Electric (PGE) Time of Use (TOU) pricing. The primary storage tanks were charged from 2pm-4pm and the systems were scheduled to shed from 4pm-9pm, aligning with PGE's peak demand period. The objective of the 24-hour test was to investigate how the load shifting controls would work in a simulated environment and verify that the load shifting would not compromise the tenant's access to hot water. Figure 1 highlights the scheduled demand response programming and data for the single-pass return-to-primary 24-hour test. The top row of the plot shows the power draw of the primary heat pump, illustrating the length of shed the system maintained. The domestic hot water demand (row 2), HPWH inlet water temperature (row 3) and tank stratification (row 4) are also shown.

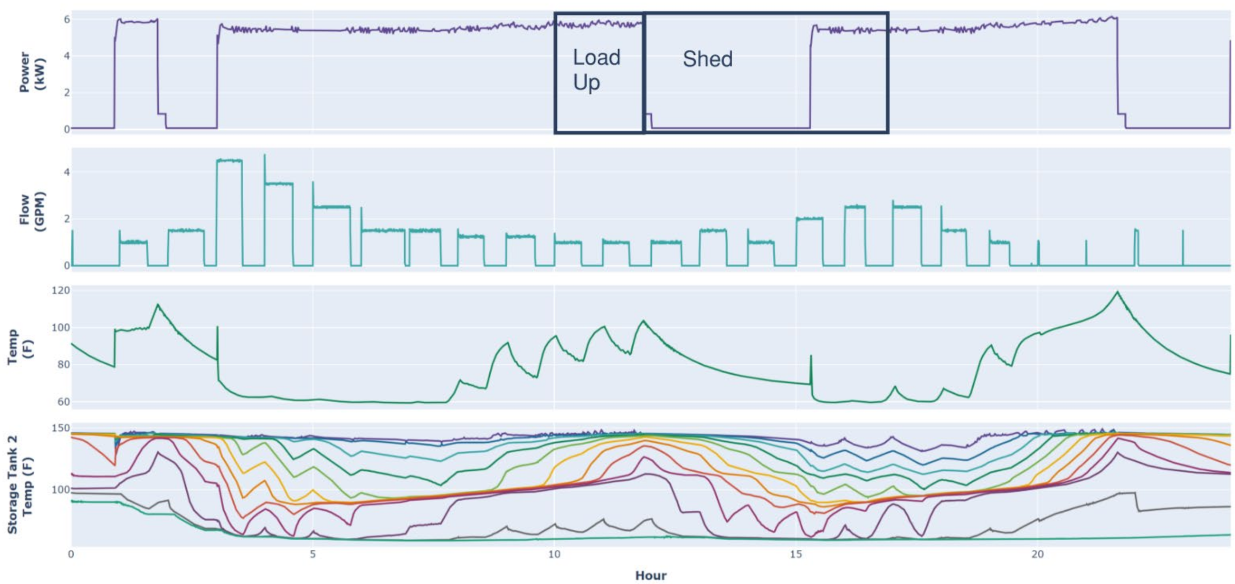


Figure 21: 24-Hour Multifamily Building Load Shift Test

The second type of test was the Single Draw test which was developed in collaboration with Northwest Energy Efficiency Alliance (NEEA) to quantify load shift potential for products listed on NEEA's Qualified Products List (QPL). Single Draw tests followed a series of discrete steps which allowed for direct measurement of the charge of the tank, volume of water available during a shed period, and the length of time the tank takes to charge without domestic hot water demand. Table 1 shows the steps of the Single Draw test.

Table 1: Single Draw Test Steps

Step	DR Mode	Action
1	HPWH DISABLED	Start with the storage tank full of cool water to ensure consistent starting point.
2	LOAD UP	Heat pump charges the tank until "load up off" sensor senses warm water.
3	SHED	Water is drawn from the tank at a constant rate until "shed on" sensor senses cool water. This quantifies energy available in the tank for a shed period.
4	SHED	Heat pump recharges the tank until "shed off" sensor senses warm water. No DHW is drawn from the system and heat pump recovery is tracked.
5	NORMAL	Hot water is drawn from the tank until the "normal on" sensor senses cold water.
6	NORMAL	Heat pump recharges the tank until the "normal off" sensor senses warm water. No DHW is drawn from the system and heat pump recovery is tracked.
7	LOAD UP	Heat pump recharges the tank until the "load up off" sensor senses warm water.

Steps 2-6 are repeated for quality control of the test. Figure 2 illustrates the steps of the single draw test for the single-pass return-to-primary test with parallel storage tanks.

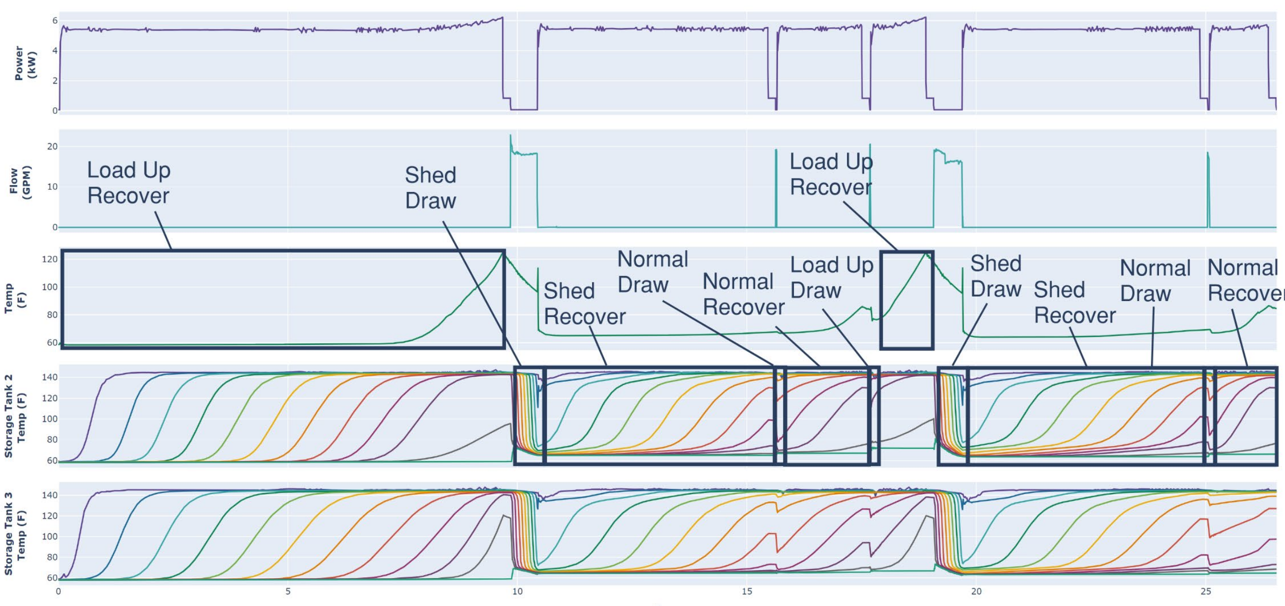


Figure 2: Single Draw Load Shift Test

Quantitative Metrics

Single Draw tests produced key demand response metrics that will help guide load shift sizing and incentive programs for the installation of load shift capable systems. The following metrics were computed for Single Draw tests:

Load Up Capacity

Load up capacity is defined as the hot water energy stored between normal and load up modes. That is, the ability for the system to absorb additional energy in anticipation of a shed event or when excess renewable energy is available from the grid. It is the stored thermal energy increase (kWh) from when the CHPWH turns off in normal operation to when the CHPWH turns off in load up operation, or the difference between what the system considers sufficient charge under normal operation and the system's maximum thermal storage charge.

Thermal Shift Capacity

Thermal shift capacity denotes the hot water energy released between load up and shed modes. It is a proxy for how much energy can be shifted away from peak periods. Thermal shift capacity measures the difference in stored energy from when the CHPWH turns off in load up operation to when the CHPWH would be triggered on during shed operation. Thermal shift capacity translates to the volume of supply temperature water the system can deliver during a shed period without turning on the heat pump.

Electrical Shed Capacity

Electrical shed capacity is the electrical energy which can be avoided during a grid's peak demand period. Because the electrical shed capacity is dependent on the system's efficiency, more efficient systems have lower electrical shed capacities. HPWH efficiencies are impacted by ambient conditions, so this metric is estimated based on a given set of weather conditions. CHPWHs see increased efficiency with warmer air temperatures, so systems will have decreased shed capacity in the summer because they are consuming less energy overall.

Efficiencies will be determined for summer and winter in the four Advanced Water Heating Specification (AWHS) climate zones: hot, mild, cold, and very cold. The coefficient of performance (COP) used to calculate electrical shed capacity will be the COP listed in the Primary HPWH Performance Data submitted on the Product Assessment Data Sheet (PADS).

Results

24-Hour Tests

Single-Pass Systems

Two single-pass systems were included in 24-hours testing: return-to-primary temperature maintenance and swing tank temperature maintenance with a single storage tank.

The swing tank system and return-to-primary system had very similar stored energy when they entered the shed period, 67 kWh 65 kWh respectively. The two systems had differing stratification profiles, but they both stored the equivalent of just under 370 gallons of supply temperature water in the primary storage tanks at the beginning of the shed. However, the swing tank system was able to shed for a longer period: the swing tank system avoided activating for 4.2 hours during the scheduled shed period versus 3.2 hours seen by the return-to-primary configuration.

Both tests delivered roughly 140°F water out of the primary storage during the shed period, so there was no shortage of 120°F supply water for the simulated building. Note that because high water temperatures out of the primary storage were maintained, the swing tank was not needed for temperature maintenance heating during the shed period.

While the control strategies for the single-pass tests appeared to be effective, there are some important caveats to note. It's clear that both systems continued to gain thermal charge throughout the load up period, and certainly charged enough to conduct a partial shed, neither system reached the criteria for fully charged during the load up period. That is, HPWH inlet temperatures of 120 °F were not achieved prior to the scheduled shed period, and thus the impact of reaching a fully loaded up state could not be measured in the 24-hour test. Additionally, the swing tank system maintained better stratification within the primary storage tanks and therefore delivered lower water temperatures to the heat pump, especially during the load up period. During the load up period, the average water temperature supplied to the heat pump for the swing tank system and return-to-primary system was 65°F and 92°F, respectively. Maintaining low heat pump inlet water temperatures is important for heat pump efficiency, particularly in systems that use CO_2 as a refrigerant. This is one clear advantage the swing tank design has over RTP when implementing demand response controls.

Multi-pass Systems

Two multi-pass return-to-primary systems were tested in the lab, one with a single primary storage tank and another with two primary storage tanks piped in parallel. The multi-pass test with two primary storage tanks in parallel was sized for a building with 44 units. Unfortunately, this was too much hot water demand for the system to handle. The heat pump was not able to maintain storage temperatures of 120 degrees let alone initiate a shed period.

The multi-pass system with one primary storage tank, sized for a smaller building with 33 units, also struggled to maintain the storage setpoint during the morning peak demand period, resulting in a lack of hot water delivery before any load shifting controls had been implemented. This was one of the first tests conducted by the lab, and upon reviewing data, it was evident that the hot water demand and load shift schedule were mistakenly shifted by the lab, making them out of synch with the other tests. Time restrictions did not allow for retests, but despite these circumstances, the test still provided important insights.

During the scheduled load up period and into the beginning of the scheduled shed period, the system was still recovering from the morning peak's depleted storage, thus the system was not able to 'load up. ' Once the system had replenished storage temperatures to above delivery temperature, the scheduled shed period had already begun. The system reached its 'shed OFF' setpoint and was able to remain off for a little under 2 hours, the system then turned on and recharged, and then turned back off at the end of the shed period with no further disruptions to the domestic hot water supply. Interestingly, while the heat pump was recovering mid-shed period, the temperature out of primary storage dropped to just above 120, indicating that allowing the tank to drain any further during the shed period likely would have resulted in a disruption to the hot water supply. This is significant because the multi-pass 'shed OFF' sensor was positioned less than halfway up the tank, much lower than in the single-pass configurations. This test highlights the difference in the ability to leverage thermal storage tanks in multi-pass vs single-pass systems. See Appendix A for detailed information about aquastat staging.

Unitary Systems

The lab was unable to override existing controls with the unitary system, so simulated load shifting controls on the unitary system required cutting power to the unit when specific criteria were met during the shed period. This meant that it was not feasible to simulate a load up period. Additionally, the system was set to only operate in heat pump mode, which caused a significant drop in storage temperatures during the morning peak period.

At the beginning of the scheduled shed, the power to the unit was cut, and the system remained off until the 'shed ON' criteria was reached. Unfortunately, this off period was only slightly longer than the typical breaks observed during normal operation between cycles. Once the heat pump turned back on, it turned off via its own internal programming, effectively ending the demand response test. There was no impact on hot water delivery during the scheduled shed, so it is possible that a more aggressive control sequence may have resulted in load shift. However, it's important to note that the current manufacturer controls do not allow for such custom programming.

Single Draw Tests

Table 2 shows the load up, thermal shift, and electrical shed capacities of the tested configurations. Electrical shed capacities were computed using Colmac CxV PADS.

One of the advantages of the single draw tests is that it allows for comparison of parallel vs in-series storage tanks. While the parallel and in-series tanks had very similar thermal shift capacities, the load up capacity was notably higher in the parallel configuration. That is, in the series configuration, there is very little change in charge between the normal state and load up state. This is significant because the 'load up OFF' state is reached when 120°F water is sent to the heat pump. This indicates the stratification in the in-series tanks is such that hot water is sent to the heat pump sooner, impacting its efficiency.

It's important to note that all single-pass tests were ran with constant aquastat percentages, while the multi-pass system was staged less aggressively due to its slower recovery time. See the Appendix A (below) for test parameters, including aquastat staging and setpoints.

Table 2: Single Draw Metrics

Test	Load Up Capacity (kWh)	Thermal Shift Capacity (kWh)	Electrical Shed Capacity 5 deg (kWh)	Electrical Shed Capacity 34 deg (kWh)	Electrical Shed Capacity 68 deg (kWh)	Electrical Shed Capacity 95 deg (kWh)	
Single- pass RTP In-Series Storage (800 gal)	2.33	99.46		60.65	45.62	34.53	28.26
Single-ass RTP Parallel Storage (800 gal)	13.15	106.36		64.85	48.79	36.93	30.22
Single-pass RTP Single Tank (400 gal)	2.67	50.22		30.62	23.04	17.44	14.27
Multi-pass RTP Single Tank (400 gal)	8.22	19.2		19.2*	19.2*	6.34	5.07

*COP of 1 at low ambient temperatures.

Lessons Learned/Next Steps

Demand response lab testing was a critical step in designing demand response tests and quantifying capabilities of CHPWH systems. Single draw tests provided valuable metrics for understanding how differing systems compare in their ability to shift load and created a foundation for future demand response testing that can help align initiatives conducted in California and in the Pacific Northwest.

This round of lab testing was designed and performed on a tight schedule, and credit is due to ATS labs for implementing demand response control logic on such a short timeline. Ideally, demand response testing would be an iterative process that would allow the team to test varying control strategies, review results, and select new control strategies based on results to determine optimal controls that could be deployed in the field. It is important to build on this foundational work and continue to investigate how to effectively leverage CHPWHs for demand response. More tests are needed to test additional control strategies and sizing combinations for multi-pass systems. Additionally, there is a lack of guidance for sizing multi-pass and single-pass return-to-primary systems, particularly in the cases of load shifting, so more work is needed to support designers of such systems.

Appendix A of Appendix F: Load shift Test Matrix

Load Shift Test Matrix

Test Stand Configuration								HPWH Settings		24-Hr Test Conditions					
										Recirc				Water Usage	
Test Category	System Configuration Identifier	Primary Heating Equipment	Temperature Maintenance Config	Mixing Valve	Ambient Air Temp		DCW Temp	HPWH Flow Setting	Outlet Water Temp	Recirc Loss Rate	Total Loss	Delta T	Flowrate	Demand Profile	# of Units
					F, DB	RH	F		F	(W/apt)	BTU/hr	F	GPM		
SP RTP Single Tank	C049	CxA	Return to Primary	Digital	68	0.5	58	SINGLE PASS	140	60	6758	6.7	2	33M	33
SP Swing Single Tank	C035	CxA	In-Series ER	Digital	68	0.5	58	SINGLE PASS	140	60	6758	6.7	2	33M	33
MP RTP Single Tank	C061	CxA	Return to Primary	Digital	68	0.5	58	MULTI PASS	NA	60	6758	6.7	2	33M	33
MP RTP Parallel	C060	CxA	Return to Primary	Digital	68	0.5	58	MULTI PASS	NA	60	9010	9	2	44M	44
SP RTP Parallel	C041	CxA	Return to Primary	Digital	68	0.5	58	SINGLE PASS	140						
SP RTP In-Series	C040	CxA	Return to Primary	Digital	68	0.5	58	SINGLE PASS	140						
Unitary RTP	C011	CHP		Digital	68	0.5	58	HP ONLY MODE	140	60	3276	3.3	2	16MS	16

	NEEA Test Conditions				DR Mode-Specific Setpoints										Test Comments	
	Recirc															
Test Category	Total Loss Rate	Delta T	Flowrate	Water Usage (Gal/min, Constant)	NORMAL ON Temp	NORMAL OFF Temp	SHED ON Temp	SHED OFF Temp	LOAD UP ON Temp	LOAD UP OFF Temp	NORMAL ON/ SHED OFF Sensor	SHED ON Sensor	LOAD UP ON/ NORMAL OFF Sensor	LOAD UP OFF Sensor	Notes	Type
	BTU/hr	F	GPM		F	F	F	F	F	F						
SP RTP Single Tank	27304	10	5.5	20	120	130	120	130	120	125	ST2-T08	ST2-T02	ST2-T10	Tr14	Baseline (compare stored energy to parallel and in-series)	gle Draw, 24-h
SP Swing Single Tank					110	130	110	130	120	125	ST2-T08	ST2-T02	ST2-T10	Tr14	Baseline (compare stored energy to parallel and in-series)	24-hour
MP RTP Single Tank	27304	10	5.5	20	120	130	120	130	130	140	ST2-T10	ST2-07	ST2-T10	Tr14	Baseline (closely matches SGIP controls but with higher shed AQ)	Single Draw, 24-hour
MP RTP Parallel					120	130	120	130	130	140	ST3-T10	ST3-T07	ST3-T10	Tr14	Baseline w/ larger storage volume (closely matches SGIP controls but with higher shed AQ)	24-hour
SP RTP Parallel	27304	10	5.5	20	120	130	120	130	120	125	ST3-T08	ST3-T02	ST3-T10	Tr14	Baseline	Single Draw
SP RTP In-Series	27304	10	5.5	20	120	130	120	130	120	125	ST2-T03	ST3-T04	ST2-T07	Tr14	Baseline (compare stored energy to parallel)	Single Draw
Unitary RTP					NA	NA	120	130	NA	NA	TcHPWH-11*	TcHPWH-06	NA	NA	HP ONLY MODE baseline	24-hour

*TcHPWH-11 is only relevant in shed mode. CHP-120 onboard logic covers normal mode.

Appendix B of Appendix F: Tank Illustration With Sensors