BONNEVILLE POWER ADMINISTRATION

Emerging Technologies

CO_2 Heat Pump Water Heater Study: Hopeworks Station Place, Everett, WA

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Acronyms

aCOPDHWSys	Annual Coefficient of Performance of the Domestic Hot Water System
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPA	Bonneville Power Administration
BUH	Backup Heater
BtuH	British Thermal Unit-hours
BTU/Hr	British Thermal Unit per Hour
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CW	City Water
DHW	Domestic Hot Water
EB	Electric Boiler
EWH	Electric Water Heater
EPDPP	Energy Use per Day per Person
F	Fahrenheit
GPD	Gallons per Day
GPDPP	Gallons per Day per Person
Gal/yr	Gallons per Year
GPM	Gallon per Minute
GWP	Global Warming Potential
HPWH	Heat Pump Water Heater
HW	Hot Water
kBTU	Thousand British Thermal Units
kW	Kilowatt(s)
kWh	Kilowatt-hour(s)
kWh/yr	Kilowatt-hour(s) per Year
M&V	Measurement and Verification
NOAA	National Oceanic and Atmospheric Administration
OAT	Outside Air Temperature
PHPWH	Primary Heat Pump Water Heater
ST	Storage Tank
TMV	Temperature Mixing Valve

Introduction

Domestic hot water heating in multifamily buildings represents a substantial energy load. Energy used in domestic hot water heating can be broken into two categories; primary heating and distribution (or temperature maintenance) heating. Primary heating is the energy required to heat incoming city water up to the desired hot water temperature. Distribution heating is the heating required to maintain temperature within the distribution piping so that hot water is delivered promptly to building occupants. Properly designed heat pump water heater (HPWH) systems have the potential for increased efficiencies in both water heating and temperature maintenance processes. Additionally, new CO_2 heat pump technology represents a shift from traditional refrigerants to low global warming potential (GWP) refrigerants.

This case study monitored the performance of multiple Sanden (CO_2) HPWHs distributed throughout the top floor of a 65-unit multifamily building. The Sanden unit was designed for use in single family homes but was adapted for multifamily use in this project by using a distributed heat trace design. At HopeWorks Station thirteen (13) hot water storage tanks are distributed around the fourth (top) floor with a corresponding Sanden HPWH above, on the rooftop. Each tank serves three (3) to six (6) apartment units. Instead of using a traditional recirculation loop, heat trace is wrapped on the main supply piping to keep distribution piping at a temperature of 120°F and no return piping is needed. Field-collected data showed that the system delivered a coefficient of performance (COP) of 2.4, while Sanden CO_2 heat pumps operated at a COP of 3.3.

A similar study at Elizabeth James House also monitored the Sanden CO_2 HPWH. However, at Elizabeth James House, a central system with a swing tank configuration was used. Comparing results of these two studies showed that although less distribution piping is needed and temperature maintenance heating is reduced at HopeWorks Station, the temperature maintenance heat trace did not heat as efficiently as the swing tank at Elizabeth James House. This is likely due to the swing tank's ability to provide heat to offset distribution losses with the heat pump which operates at a COP up to 3.8 in warm conditions and the unusually low distribution losses at Elizabeth James. At HopeWorks Station distribution losses can only be offset using electric resistance heat trace, which operates at a COP less than 1. The average system COP at Elizabeth James House was 3.3 compared to just 2.4 at HopeWorks Station. However, Elizabeth James has unusually low distribution losses and the energy used per person per day was about 15% higher at HopeWorks.[1]

Additionally, the Elizabeth James project served a 60-unitapartment building (and 60 people) with only four (4) Sanden HPWHs, whereas at HopeWorks Station's 65 units (and 102 people) were served with thirteen (13) HPWHs. At HopeWorks Station more HPWHs, mixing valves, tanks, and heat trace are needed. The distributed system creates more potential points of failure and is more difficult to monitor. When possible, using a central system, or multiple central systems, is a better approach on larger multifamily buildings . However, on smaller commercial building and some low-rise multifamily buildings, like HopeWorks Station, distributed systems have a place.

Background

The HopeWorks campus consists of two buildings in Everett, WA. The first building built on the HopeWorks campus, HopeWorks Station South, contains administrative offices and two social enterprises that offer job training in landscaping and retail.

The second building, which completed construction in 2019, is known as HopeWorks Station North. HopeWorks Station North is a first-of-its-kind hybrid venture which combines HopeWorks and Housing Hope. Housing Hope manages 22 affordable housing properties in Snohomish County. HopeWorks Station North includes the Kindred Kitchen Café, community development team, and 65-units of low-income housing. The Kindred Kitchen Café is a social enterprise program in culinary and beverage services. The community development team is a group of full time HopeWorks staff that provide administration services and community development. The residential portion of HopeWorks Station North is referred to as HopeWorks Station. This study focuses on the residential hot water energy system in HopeWorks Station.

In 2017, Ecotope bid to provide full design for HVAC, Plumbing, and Energy Services on the HopeWorks Station North, planned to be an all-electric, Net Zero Energy low-income housing and job training facility in Everett, Washington with Dykeman Architects. Once the bid was accepted, Ecotope identified the site as an opportunity to provide energy efficient CO_2 HPWHs, which had been successfully designed and operated by Ecotope at Elizabeth James House.

HPWHs transfer heat energy from one source (typically air) to potable water. This is three to four times more efficient than a fossil-gas boiler or electric-resistance water heater. Ecotope selected a CO_2 HPWH for its low global warming potential, its ability to function outdoors in cool climates, and the high efficiency. CO_2 delivers a high coefficient of performance (COP). Although the selected HPWH product was originally designed for the single-family residential market, multiple units can be used to meet the demands of a larger multi-family building.

At HopeWorks Station, the design team opted to try a distributed system with heat trace temperature maintenance to reduce recirculation losses. Heat trace is an electric resistance heater attached along the length of the pipe. This distributed design reduces the amount of distributed piping, because instead of a supply and return pipe, creating a recirculation loop, there is only a supply pipe. Less piping decreases heat transfer area between hot water supply pipe at 120°F and ambient air, which reduces the amount of heat lost in distribution. Previous studies have shown that distribution accounts for between 30% and 45% of the heat used in a typical multifamily hot water system, or about 55 to about 90 watts per apartment.[2,3] Because there is no recirculation loop, hot water supply pipe is wrapped in temperature maintenance heat trace, set at 120°F to keep the supply pipe hot during periods when no water is being used and ensure hot water is always available. In addition to reducing piping, using heat trace prevents the need for a swing tank (used at Elizabeth James House). The purpose of the swing tank is to decouple the primary hot water load from secondary distribution losses. Primary and distribution heating are described in more detail under “System Design”. Below is a description of the components used at HopeWorks Station and Elizabeth James

House.

Equipment used at HopeWorks Station new construction project:

- Thirteen (13) 15,400 btu/hr Sanden HPWH (Model GS3-45HPA-US)
- Eleven (11) 120-gallon hot water storage tanks, two (2) 84-gallon hot water storage tanks
- Thirteen (13) thermostatic mixing valves
- Thirteen (13) temperature maintenance heat trace pipe heaters (~30′ each)

Equipment used at Elizabeth James Sanden retrofit project:

- Four (4) 15,000 btu/hr Sanden HPWH (Model GUS-A45HPA)
- Three (3) existing storage tanks
- Three (3) existing instantaneous electric water heater and pump
- Existing building hot water circulation pump
- A new 175-gallon storage tank
- A new electronic mixing valve

The building was completed in the Winter of 2020 and monitoring began in March. The results in this case study show system performance from June to August 2020.

System Design

The Sanden HPWHs used in this project contain R-744 refrigerant commonly referred to as CO_2. This refrigeration cycle does not function well at warm incoming water temperatures (above about 100°F). In a traditional multifamily hot water system, a recirculation pump is used to ensure water at 120°F is always available at remote fixtures. Building hot water circulation pumps typically return water at 115°F to the storage tanks. In DHW systems based around fossil gas or electric resistance, this warm water can go directly back to the primary storage tanks or primary heaters. However, the HPWHs will not respond or perform well to this warm incoming water temperature. A critical design feature of HPWH systems with hot water circulation systems is to separate these two distinct building DHW loads – the primary load and the distribution load . In doing so, the DHW system design can prioritize delivering cool water to the HPWHs while maintaining thermal stratification in the primary tanks. This results in optimal equipment efficiency, less cycling of the heating equipment, and better reliability of the system. However, in this design, a dedicated system to maintain hot water in the distribution system ("temperature maintenance") is required.

> ***A critical design feature of HPWH systems with hot water circulation systems is to separate these two distinct building DHW loads- the primary load and the distribution load.***

Figure 1 shows a single riser of the Sanden HPWH system used at HopeWorks Station. The system includes an outdoor condensing unit, hot water storage tank, mixing valve, distribution riser and piping, temperature maintenance heat trace and freeze protection heat trace. Freeze protection heat trace will not be monitored. Thirteen (13) Sanden HPWH tanks are on Level 4, serving residential hot water and laundry rooms. The outdoor condensing units are located on the roof above their associated storage tank.

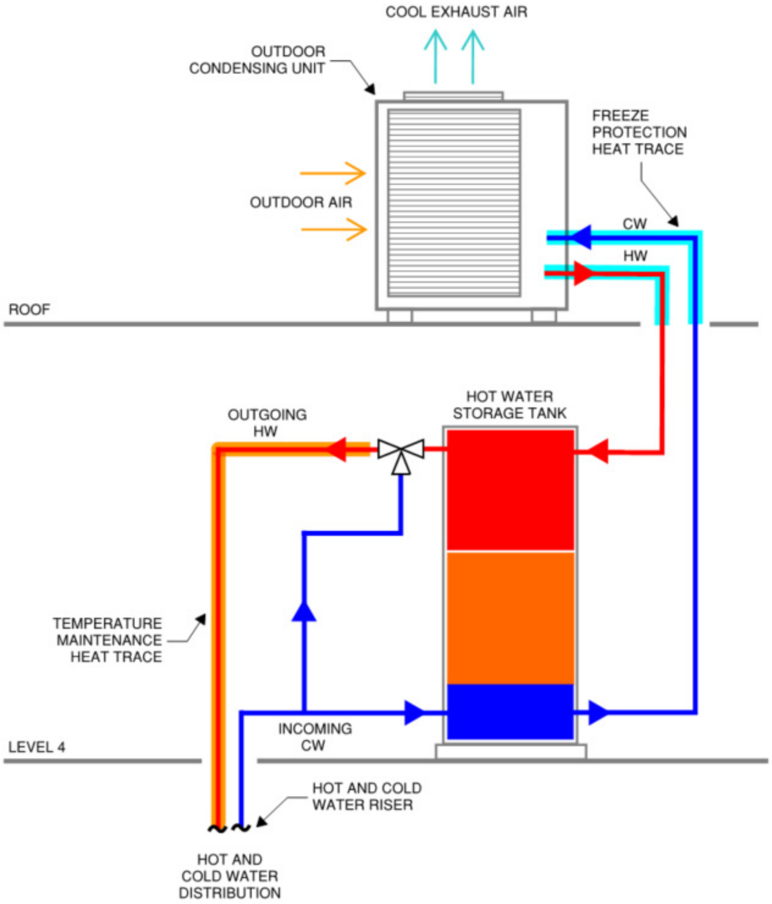


Figure 1: One-line diagram for single hot water riser

The HPWH unit, which sits on the roof, extracts heat from outdoor air and heats water to a setpoint temperature of 140°F for storage. In addition to the CO_2 refrigerant compressor the rooftop, the HPWH contains a water circulating pump to pull water from the bottom of the storage tank, heat it, and return the hot water to the top of the storage tank. A single-phase 208-volt connection with a 30-amp breaker serves outdoor units from sub-panel H4A. HPWHs are grouped in pairs that are served by the same 208-volt circuit.

The hot water storage tank is thermally stratified and accepts cold city water at the bottom. All but two hot water storage tanks used on the project were 120-gallons. Two 83-gallon storage tanks were used to serve risers with fewer bedrooms.

Each storage tank is paired with a thermostatic mixing valve which mixes hot water, stored at 140°F to 150°F, with cold city water to supply hot water to residential units at 120°F. 120°F water is distributed throughout the building through piping which is wrapped in temperature maintenance heat trace designed to keep the water at 120°F without recirculation.

The following narrative provides more detail to the major components in the HopeWorks Station HPWH system.

Single Pass: The design is based around a "Single Pass" heat exchange strategy as opposed to the typical "Multi Pass" strategy employed in most hydronic space heating applications. This means that the flow of water through the heat pump is regulated by a control valve or variable speed pump to maintain a target output temperature of 150°F. This results in a variable flow rate and variable temperature rise across the heat pump, as opposed to the typical fixed flow rate and fixed 10-20°F temperature rise on the water. The heat pump can therefore output 150°F water with incoming water temperatures ranging from 45-110°F. The advantage of the "Single Pass" arrangement is that a usable water temperature is always delivered to the top of the storage reservoir. The CO_2 refrigerant cycle of the Sanden HPWH only works in a single pass arrangement.

Distributed Storage Tanks: This design is based around the use of multiple storage tanks dispersed around the building and paired with a corresponding heat pump. This strategy minimizes distribution piping distance between the storage and fixtures, reducing distribution losses.

Storage Temperature: The water is heated to a relatively high temperature (~150°F) to effectively increase the stored heating capacity and to control possible legionella bacteria. To prevent scalding, outgoing water is tempered with incoming city water down to approximately 120°F before delivery to the apartments.

Temperature Maintenance Heat Trace: Unlike traditional hot water systems, which use recirculation loops to keep pipe temperatures hot, the system at HopeWorks Station uses heat trace. When the pipe temperature drops below the setpoint temperature, the heat trace will turn on and heat the pipe until the water reaches the desired setpoint.

Controls: There is no central hot water controller for HopeWorks Station. Each HPWH, mixing valve, and temperature maintenance heat trace operate independently. Each Sanden HPWH has built-in control logic to cycle ON or OFF based on a thermocouple reading in the corresponding storage tank. Thermostatic mixing valves are controlled mechanically, with an internal element that expands and contracts due to changes in pressure and temperature allowing the appropriate amount of hot and cold water through to meet the setpoint. Heat trace is controlled using a temperature sensor within the corresponding distribution pipe.

Photographs

The following photographs show details of the DHW system, including the HPWH units, piping, storage tanks, mixing valves, and heat trace .

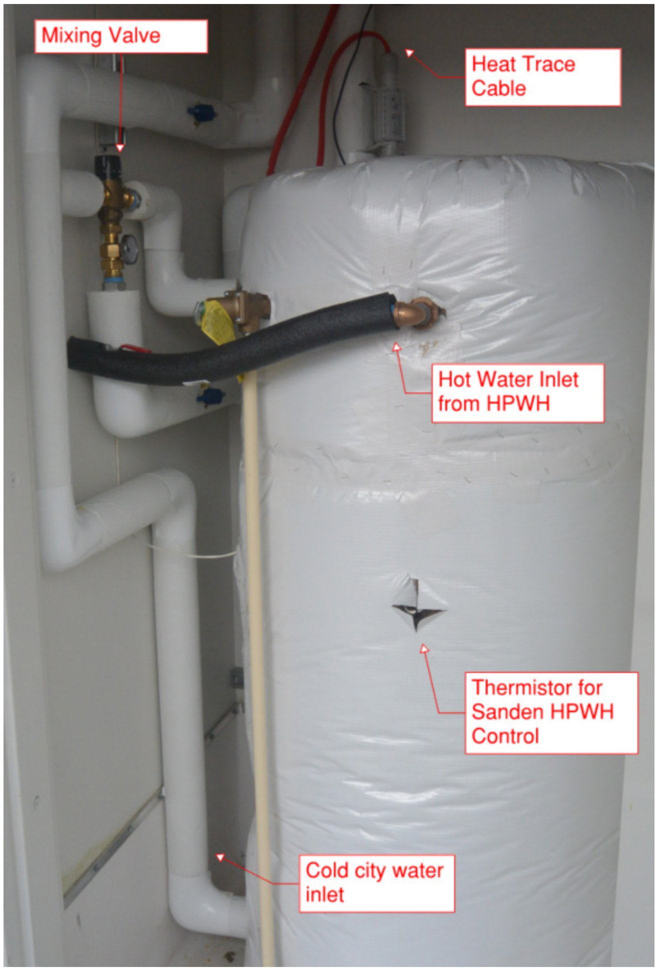


Figure 2. Hot Water Storage Tank on Level 4

Figure 3. Thermostatic mixing valve with water temperature outlet of approximately 120°F.

Figure 4. Temperature Maintenance heat trace set to maintain 116°F in distribution piping.

Figure 5. Rooftop Sanden HPWH with freeze protection heat trace.

Methods

This section describes the methods used to monitor the Sanden HPWHs and heat trace. Electrical metering was done on all HPWHs and temperature maintenance heat trace but flows and temperature were only recorded at four (4) storage tanks. To assess heat trace performance, a performance test was completed, and a tenant survey was distributed.

Electrical Metering

Electrical sub-panel H4A, located on Level 4 provides power to the HPWHs and temperature maintenance heat trace. The Level 4 plan shows the location of the sub-panel and the roof plan shows circuit labels. Each HPWH circuit supplies power for two (2) HPWHs and each temperature maintenance heat trace circuit supplies power to three (3) heat trace risers. Circuit labels corresponding to heat trace and HPWHs are shown in Table 1. The grouping of Sanden HPWHs and heat trace on circuits complicates the Measurement and Verification (M&V) setup. It means that, if metering equipment is set up at the panel, COP for the Sandens can only be calculated when six (6) total hot water tanks are monitored or electrical metering for an individual heat trace is done remotely. Ultimately, Ecotope decided to focus on 4 tanks for COP calculations. This required one heat trace to be monitored remotely. Tanks 5, 6, 7, and 8 are used for COP calculations, shown in green in **Table 1**. Remote heat trace is monitored on tank 8, shown highlighted.

Electrical monitoring at the main electrical panel is done using an eGauge and current transformers. Before hot water M&V gear was installed, HopeWorks already had an eGauge system installed in the electric panels to monitor electrical usage throughout the building. However, there is no eGauge installed at panel H4A. Ecotope purchased a new eGauge device to add to the existing eGauge system. This will not only allow for the electrical usage of the Sandens to be monitored for this study, but also allow for HopeWorks to trend energy used to heat hot water over the life of the building. Ecotope collected data directly from the HopeWorks eGauge website to calculate COP.

Table 1. Heat Pump and Heat Trace Circuits

	Tank # / Riser Served													
Circuit	1	2	3	4	5	6	7	8	9	10	11	12	13	Equipment Served
H4A-12, 14	X												X	HPWH
H4A-16, 18											X	X		HPWH
H4A-17, 19	X										X	X		Heat Trace
H4A-20, 22									X	X				HPWH
H4A-21, 23								**X**	X	X				Heat Trace
H4A-24, 26							**X**	**X**						HPWH
H4A-25, 27					**X**	**X**	**X**							Heat Trace
H4A-28, 30					**X**	**X**								HPWH
H4A-29, 31		X	X	X										Heat Trace
H4A-32, 34				X										HPWH
H4A-36, 38		X	X											HPWH

To directly monitor heat trace power for tank 8, a Dent PowerScout with current transformers was installed in the hot water tank closets. Data from the PowerScout was communicated wirelessly back to a central datalogger (Acquisuite) also used to collect flow and temperature data.

Flow and Temperature Monitoring

Flow and temperature used to calculate both system and equipment efficiency was measured using pulse count flow meters, wet-thermistors, and dry-thermistors. A plumber was hired to install the flow meters and three wet-thermistors provided by Ecotope.

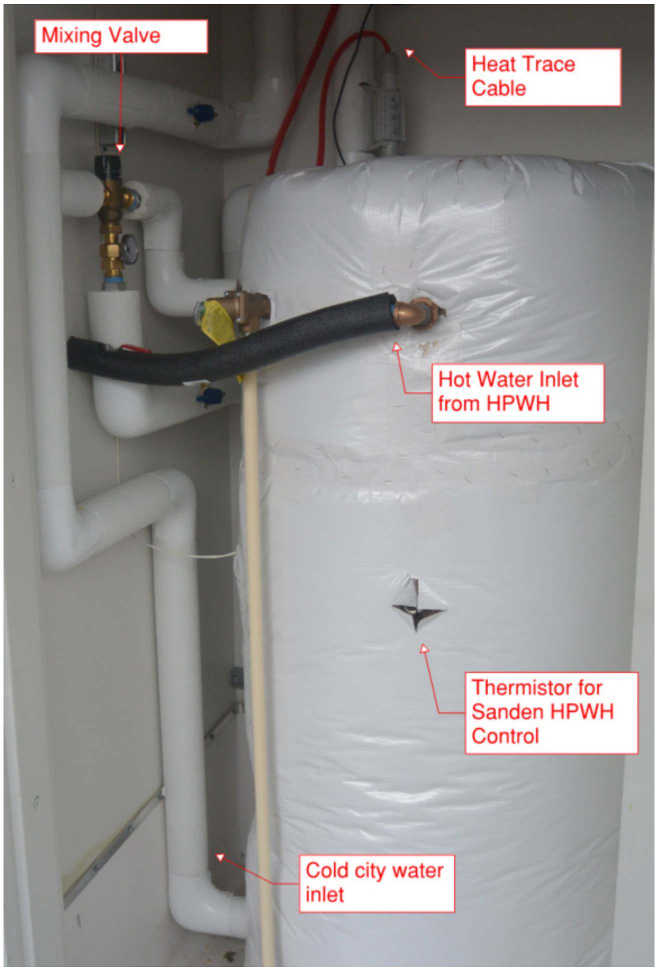


Figure 2. Hot Water Storage Tank on Level 4- Flow and temperature monitoring points.

The **Figure 2** diagram shows where temperature sensors (TS) and flow meters (FM) were placed within the hot water storage tank closets on Level 4. The Dent PowerScout, mentioned in the previous section, is shown as a power meter (PM) in **Figure 2**.

Wet-thermistors were threaded into t-fittings and installed in pipe. Dry-thermistors were installed on the outside surface of the pipe, under the insulation with a thermal paste to increase conductivity between the pipe and thermistor. While wet-thermistors were only installed on two (2) hot water tanks, dry-thermistors were installed on all hot water tanks. Wet-thermistors were used to calibrate dry-thermistors to ensure accurate temperatures were recorded at each tank.

The flow meter, a 3/4” Minomess 130 Minol pulse output flow meter, was installed in the pipe leading to the tank inlet. Pulse count flow meters have no time-step; instead, they signal a pulse with each gallon used.

After flow meters and temperature sensors were installed, Ecotope installed all low-voltage wiring from each sensor to Flex IOs, ModHoppers, and the Acquisuite. The ModHopper is used to wirelessly transmit flow, temperature, and power data to the Acquisuite data logger, installed in the electrical room. Four (4) hot water tanks were monitored, in three (3) hot water tank closets, requiring three (3) remote ModHoppers and a single ModHopper in the electrical room to collect the signals.

Data Processing

Flow, temperature, and electrical data is downloaded nightly from the Obvius Acquisuite 8812 and eGauge data loggers. Acquisuite data includes all temperatures and flows, as well as the energy used by the heat trace serving tank 8, logged as averages over one-minute intervals. eGauge data includes all HPWHs and heat trace (although they are grouped together – two (2) heat pumps to a circuit and three (3) heat trace to a circuit) logged as averages over five-minute intervals.

The city water temperature used in the efficiency calculations for each tank was based on the wettable thermistor installed in tank 5. A daily average "site city water temperature" was calculated based on periods when hot water was being used in the apartment stack associated with tank 5. Within a day, records were filtered to focus on periods when:

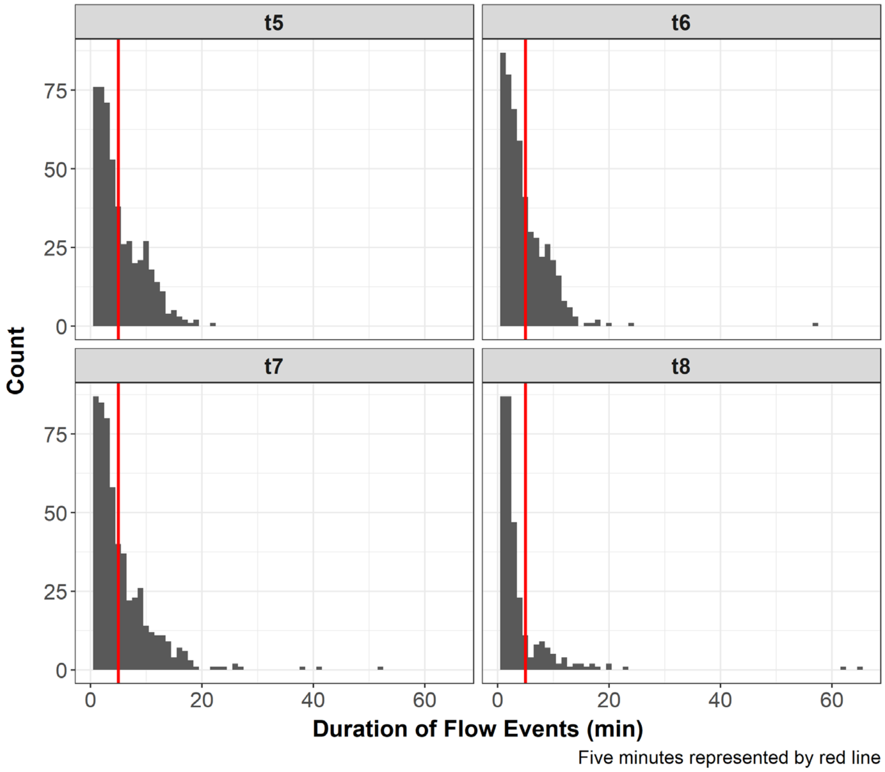
- There was a flow event
- The event was 4 minutes or longer in duration
- The first three minutes of flow were excluded

This subset was used to calculate the average site city water temperature to be used in analysis, and minimized the influence of short events and initial flow event minutes when the measured temperature may be influenced by water warmed from resting in the pipe.

Although most flow events last less than five minutes (**Figure 7**), tank 5 typically had longer events that could be sampled for this daily temperature calculation.

To reduce the costs associated with monitoring multiple tanks, immersion (wettable) thermistors installed on two (2) of the four (4) tanks were used to calibrate surface (dry) thermistors on the other tanks. Tanks 5 and 6 have immersion and surface thermistors for the tank outlet and post mixing valve temperature measurements. The other two tanks have pipe surface temperature sensors only. Pipe surface measurements for tank outlet and mixed

Figure 7. Flow Events at Each Monitored Tank



water are lower than the actual water temperature (as measured by an immersion thermistor). In order to approximate the outlet and mixed water temperatures at tanks 7 and 8, which had only surface temperature measurements, the difference between immersion and surface temperatures in tanks 5 and 6 were used to create an average adjustment for the other tanks. This average was calculated on a weekly basis, so that any seasonal changes in the temperature relationship could be accounted for.

Ecotope set up an online tool to view raw data and both hourly and daily averages for each of the monitored points on the HPWH system, as well as calculated values like COP and heat output. This data was automatically updated nightly, allowing the engineers and installers commissioning the project to quickly receive feedback on changes they made to the system. Data has been collected and available through the online tool since September of 2020.

Findings

Energy use findings were calculated at a building level and at a sample level. Building efficiency calculations use the electrical energy metered by the eGauge combined with average data from the sample of hot water tanks monitored to calculate building-wide results. Sample efficiency calculations look only at the subset of tanks monitored and calculated COP on only those tanks based on flowrates, temperature, and electric power usage.

Both equipment and system COPs were calculated at HopeWorks Station. Those COPs were compared to the equivalent COP at Elizabeth James House. In 2020 Ecotope has standardized nomenclature for domestic hot water COP calculations. Some important definitions are outlined below.

- ***Equipment COP:*** The amount of heat produced in water by the equipment divided by the amount of energy used by the equipment. The equipment COP changes based on outdoor air temperature, incoming water temperature, and outlet water temperature. This data can be calculated in a performance map by the manufacturers.
- ***System COP:*** The amount of heating required by the system, in both primary and distribution loads, divided by the amount of energy used by the system to supply the heating. Calculating the system COP requires both the primary and distribution loads to be known.

At HopeWorks Station, the lack of return piping meant there was no temperature change and flow that could be used to calculate distribution losses. For this reason, to calculate the system COP, the heat trace was assumed to be 100% efficient at HopeWorks. Note that unusually low distribution losses at Elizabeth James House make its COP look very low in comparison to HopeWorks. Because of the way the piping is configure at Elizabeth James House only 15 watts per apartment is lost in distribution. Research suggests average building losses are closer to 90 watts per apartment – more than six times that at Elizabeth James.

Summary Findings

The high-level data summaries from annual monitoring are provided in **Table 2.** COP results summarized in the table are based on the annual adjusted building efficiency calculation method. The method was used to capture the effect of all the temperature maintenance heat trace in the building and adjust for outdoor air temperature.

Table 2. Summary Measurements

HPWH Energy (kWh/day)	Heat Trace Energy (kWh/day)	Heat Pump COP (Annual Adjusted)	System COP (Annual Adjusted)	Average Outdoor Air Temperature (°F)	Average Inlet Water Temperature (°F)	Average Water Temperature Produced by Heat Pumps (°F)	Days of Monitoring
76	49	3.3	2.4	66	62	145	82

Table 3 compares overall system performance metrics of Elizabeth James and HopeWorks Station. In both metrics of comparison, the central swing tank system at Elizabeth James outperformed the distributed heat trace system at HopeWorks Station.

Table 3. System Performance Comparison

	HopeWorks Station - Distributed Heat Trace	Elizabeth James - Central Swing Tank
System COP	2.4	3.3
Energy Use Per Day Per Person [kWh/day/person]	1.22	1.05

System COP does not account for a poorly designed temperature maintenance system creating additional hot water use. For example, if a recirculation system has large "dead zones", where water is not recirculated, tenants may have to run water for a longer period of time before it becomes hot enough to be useful. As a result, more hot water will be used. The COP calculation shows performance independent of the amount of hot water used whereas the energy use per day per person (EPDPP) shows how much energy the hot water system is responsible for using per person. Together system COP and EPDPP tell the whole picture of system efficiency. By both accounts the central swing tank system performed more efficiently. However, the unusually low losses at Elizabeth James suggest that the central system will not always perform better.

> *Together, system COP and EPDPP tell the whole picture of system efficiency. By both accounts, the central swing tank system performed more efficiently.*

Building Efficiency Calculation

Building Efficiency Calculation serves both as a way to compare the distributed heat trace design used at HopeWorks Station with the central swing tank design used at Elizabeth James and provide an annual adjusted COP. This calculation provides a building level system COP. The HPWHs are the same and therefore should operate at nearly the same efficiency in the same outdoor air conditions. Only the temperature maintenance load is handled differently, which will affect system COP.

The calculation combines data from previous case studies and lab testing to calculate a gallon per day (GPD) based on the energy used by all thirteen (13) HPWHs. The gallons per day value is checked for reasonableness at a building wide level. This calculation shows that HopeWorks Station tenants used about 17 gallons per day per person (GPDPP), which is expected when compared to similar studies and aligns with monitored tanks. The building GPD was calculated using average daily temperatures in and out of the four (4) monitored tanks to calculate the energy delivered by all the systems in the building. The energy delivered was then divided by the total energy used in the hot water system for HPWH heating and heat trace heating to calculate a building level COP as shown in **Equation 1** below.

Equation 1.

$$buildingCOP_{DHW\_system} = \frac{Delivered_{Energy\ Out} + HTR_{Energy\ In}}{HPWH_{Energy\ In} + HTR_{Energy\ In}}$$

Where:

- $Delivered_{\text{ENERGY OUT}}$ = Heat delivered to the water used in the building
- $HPWH$ = Primary HPWH energy (sum of all HPWHs)
- HTR = Heat trace energy (sum of all heat trace)

Because thirteen (13) HPWH units and tanks were distributed around the building, it was not practical to monitor flows and temperatures on all thirteen systems. Instead, four (4) tanks were chosen. The building level calculation is limited because the total gallons per day per person of hot water used in the building was not measured. However, previous studies and lab test data have provided more than enough valuable data to back-calculate the total GPD accurately and the final answer aligns with what was expected.

The large variation in heat trace energy usage from hot water system to system suggests that further research could be done to understand best practices for design, construction, and commissioning to improve distributed systems

Temperature maintenance heat trace on the tanks monitored used less energy proportionally than the rest of the temperature maintenance heat trace in the building. Monitored systems 5, 6, 7, and 8, used just 14% of the heat trace energy, although they accounted for 30% of the hot water systems. This discrepancy made it important to use the building efficiency calculation to determine the overall system performance instead of the sample efficiency calculation. Aligning the numbers in both calculations proved to be a valuable exercise in ensuring the accuracy of both calculations. Additionally, the large variation in heat trace energy usage from hot water system to system suggests that further research could be done to understand best practices for design, construction, and commissioning to improve distributed systems.

After aligning the building efficiency calculation and sample efficiency calculation an annual adjusted building efficiency calculation was used to adjust for outdoor air temperature over the monitored period. The annual adjusted calculation assumes the amount of hot water delivered remains the same, but the outdoor air temperature and incoming city water temperature change. To adjust for outdoor air temperature, the known equipment performance is used to adjust the amount of energy consumed by the HPWHs. To adjust for city water temperature, the energy consumed by the heat pump water heaters is increased to account for the extra heating they must provide, and the energy delivered is increased. No adjustments were made to heat trace energy usage. Over the monitoring period, heat trace energy showed no correlation with outdoor air temperature. This is potentially because pipe chases remain closer to indoor temperature than outdoor temperature. Adjustments are shown in **Equation 2** below.

Equation 2.

$$buildingCOP_{DHW\_system} = \frac{Delivered_{Energy\ Out} * \left(\frac{\Delta T_{annual}}{\Delta T_{monitored}}\right) + HTR_{EnergyIn}}{HPWH_{Energy\ In} * \left(\frac{COP_{monitored}}{COP_{annual}}\right) * \left(\frac{\Delta T_{annual}}{\Delta T_{monitored}}\right) + HTR_{EnergyIn}}$$

Where:

- *ΔT_annual* = Water setpoint minus annual city water temp
- *ΔT_monitored* = Water setpoint minus monitored city water temps
- *COP_annual* = Annual COP, based on annual air temp average
- *COP_monitored* = Monitored COP, based on monitored air temps

Table 3 shows building efficiency COPs calculated over the monitoring period and adjusted for annual performance. Because the monitoring period occurred over the summer, the annually adjust COP is lower than the COP during the monitoring period.

Table 3. Monitored and Annual COP Comparison

	Monitoring Period	**Annual Adjusted**
Equipment COP	3.6	3.3
System COP	2.5	2.4

Sample Efficiency Calculation

Sample Efficiency Calculations focused on the M&V data collected over the monitoring period. Although EGauge data was available starting in early May 2020, installation of temperature sensors, and flow and power meters occurred shortly after, in early` June. Sample Efficiency Calculations, therefore, reflect system performance over the summer months through August.

DHW system COP as well as Equipment COP were calculated using measured data and daily temperature averaging. In large multifamily buildings, with many occupants using water at any given time, measured water temperatures are fairly accurate because the water is being used almost constantly. Smaller multifamily buildings have use profiles that more closely resemble single-family residences due to the lower occupancy. As a result, water may rest in the pipe, sometimes for several hours. This can create a drift in the temperature measurements as idle water influences the initial moments of any flow event after a period of non-use. To correct for this, daily average temperatures were calculated for each of the water temperature points, using only periods when there was active flow measured. The temperature averaging protocol closely resembled the process used to calculate the site city water daily average as described in the Data Processing section of this report. Daily average water temperatures were then used to calculate the energy output for each monitored tank.

As with the Building Efficiency Calculation, a DHW system COP (which includes the primary water heating and the temperature maintenance heating equipment) is intended to capture all energy inputs and primary water heating. Equipment COP focuses just on the heat pump equipment itself, so the denominator from Equation 1 is simply $HPWH_{Energy\ In}$. The monitoring period calculations showed an equipment COP of 3.6, and a DHW system COP of the monitored tanks was 2.8. However, the building system COP was calculated at only 2.5 during the same period because, as described above, the monitored tanks used less heat trace energy proportionally when compared to all the tanks in the building.

Water Temperatures

Tank outlet and mixed (hot water supply) temperatures for each tank were consistent throughout the measured period. However, between-tank values varied, sometimes significantly. Tank outlet was more consistent between tanks and averages mostly stayed

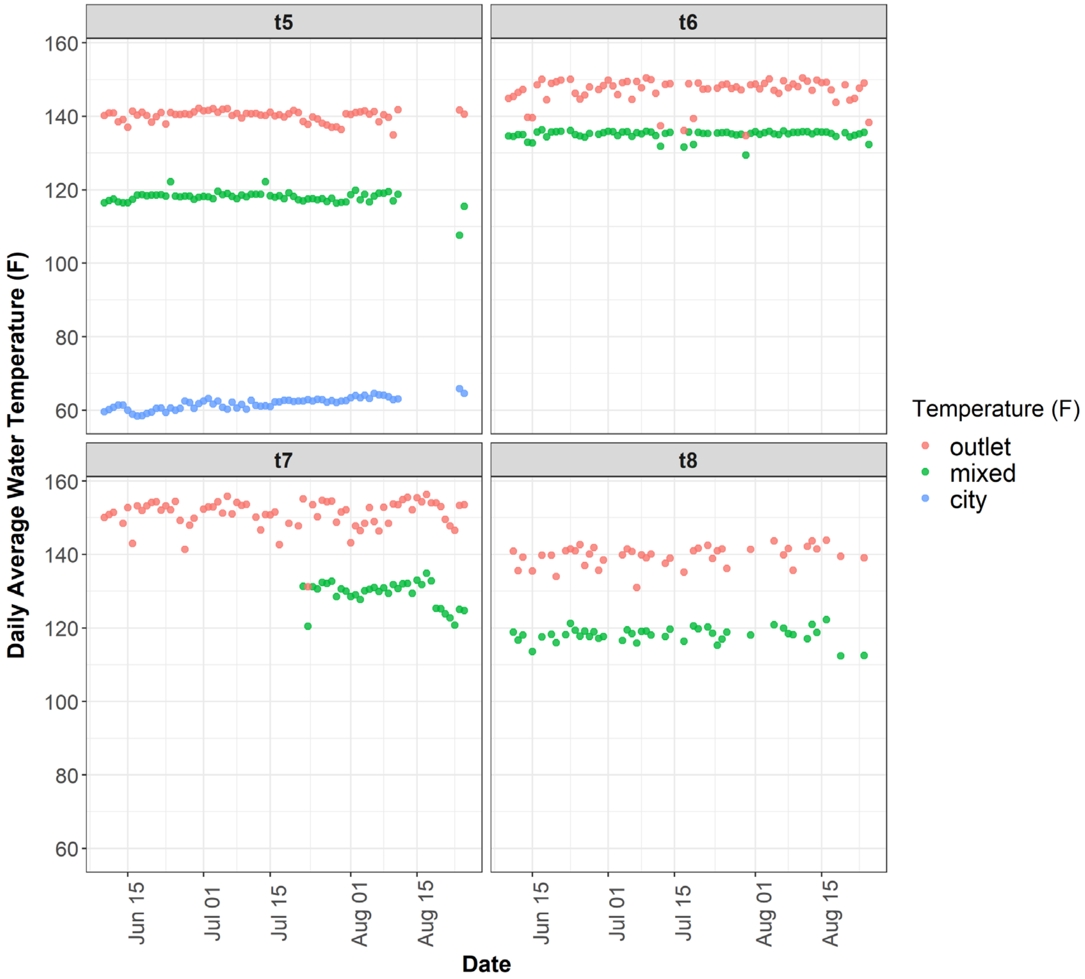


Figure 8. Daily Average Tank Outlet, Mixed, and City Water Temperatures for Monitored Tanks

between 140°F to 150°F. Mixing valves outlets ranged from 115°F to 135°F.

Figure 8 shows daily averages for outlet and mixed temperatures on each tank. Tank 5 shows remarkably steady temperatures from day to day but has a brief period in August with missing data due to equipment damage. Tank 5 also shows the city water inlet temperature. It is the only tank to monitor city water temperature because city water temperature was assumed to be the same at the inlet of each tank. Tank 6 also showed steady temperatures from day to day, with a few outlier days where the outlet temperature appears to drop close to mixed water temperature. Tank 7 and 8 show more variability because these tanks used surface mounted dry temperature sensor calibrated as described under Data Processing. Tank 7 shows a period of missing data due to a misplaced sensor at installation in June. The sensor was moved to the correct location in July.

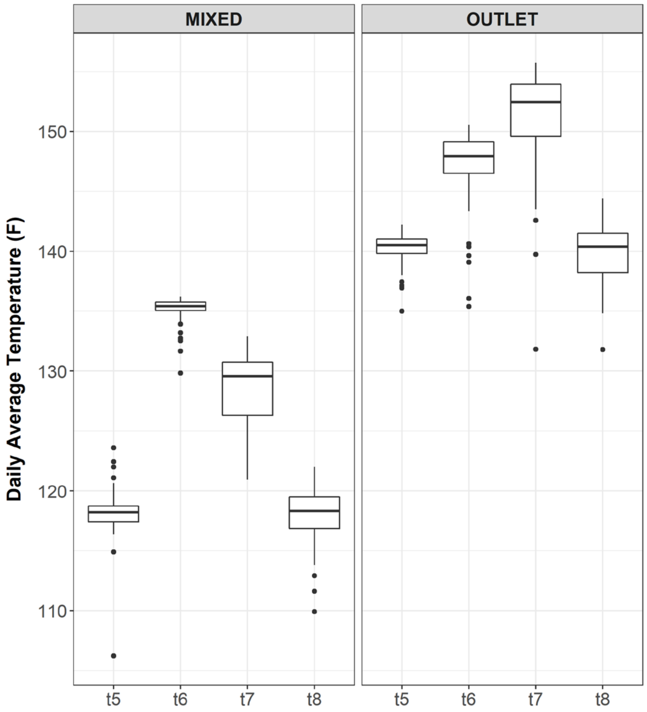


Figure 9. Tank Outlet and Mixed Temperature Boxplot for Monitored Tanks

Figure 9 shows mixed and outlet temperatures from tanks 5, 6, 7, and 8 as boxplots for easy comparison. The tighter boxes for tanks 5 and 6 are likely because of the more accurate immersion thermistors. This plot clearly shows higher than desired temperatures at the outlet of tanks 6 and 7.

The distributed design used at HopeWorks means equipment used to heat hot water is spread out around the 4th floor and the roof. As a result, there are more pieces of equipment in more locations around the building. Installing more equipment, spread out around the building, can create more labor and extra challenges for the commissioning agent. As a result, the hot water temperatures at HopeWorks likely did not get as much attention as if the system were a central system. It is much easier for the commissioning agent to fine tune temperatures on just one mixing valve outlet than thirteen (13) spread around a building.

Water Use

Each hot water tank monitored served between three (3) and six (6) apartments and six (6) to twelves (12) tenants. Apartments are studio, one-bedrooms, or two-bedrooms, and tenants are a mix of adults and children. **Table 4** below summarizes the apartments and tenants served by each monitored tank.

Table 4. Apartments and Tenants Served by Monitored Hot Water Tanks

Tank Number	Apartments Served	Tenants Served
5	3x 1 BR, 3x Studio	7 (1 Child)
6	3x 1 BR, 3x Studio	12 (6 Children)
7	3x 2 BR	6 (3 Children)
8	1x 2 BR, 4x Studio	6 (1 Child)

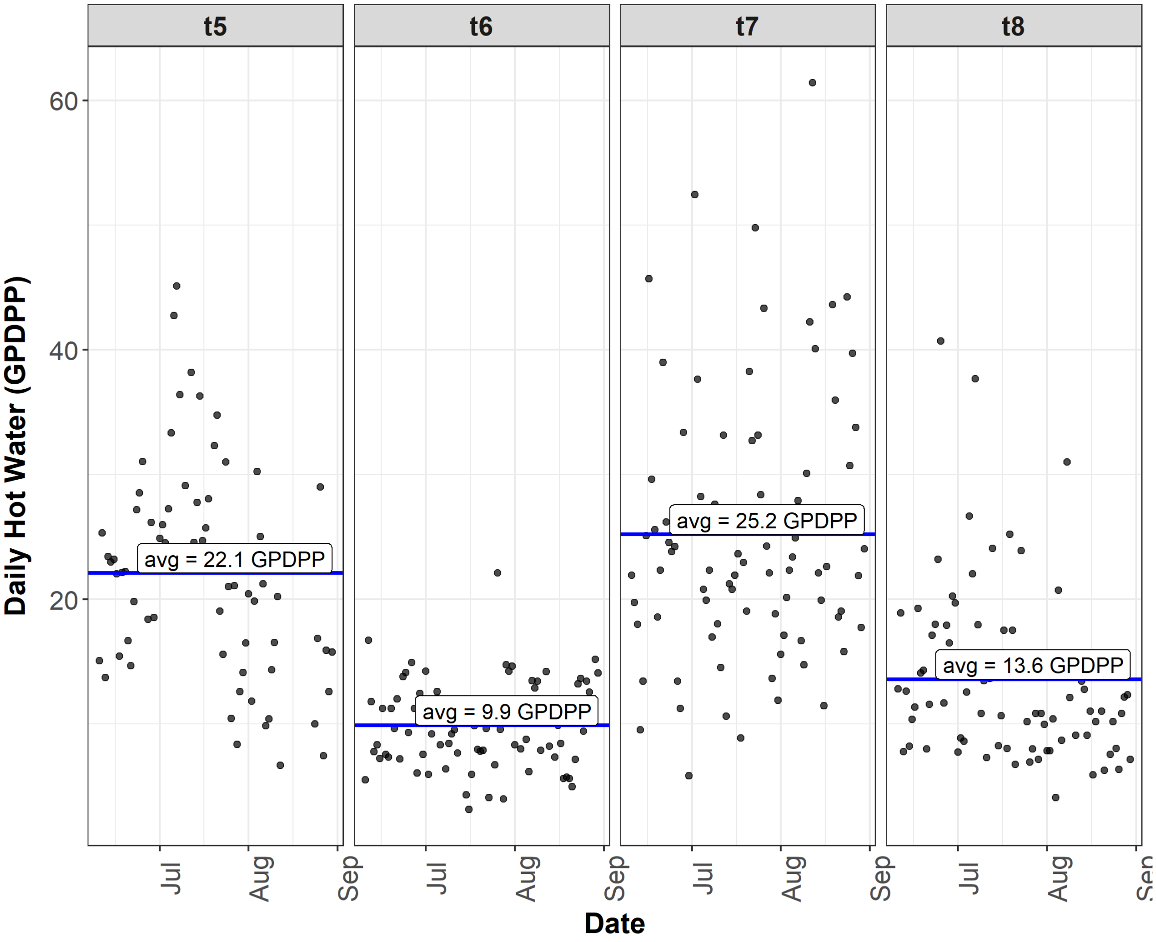


Figure 10. Hot Water Usage in Gallons Per Day Per Person (GPDPP) at Each Monitored Tank

Figure 10 shows the hot water used per person in gallons per day per person (GPDPP) at each tank over the monitored period. However, because laundry is served by a separate HPWH, hot water used for laundry by the tenants is not included.

Of the tanks monitored, there appears to be a significant spread in water use habits. The mean, standard deviation, and coefficient of variance were calculated for each of the tanks. Mean is a measure of location and gives us an understanding of usage on the average day. Standard deviation is a measure of spread and informs us of the degree of variability from day to day. Coefficient of variance is the ratio of the standard deviation to the mean which allows for comparison of the degree of variance between data sets with different means. The coefficient of variance was below 0.5 on all the tanks. This suggests that although there is a wide range of water used habits in the tenants from tank to tank, their habits are consistent from day to day. The coefficient of variance of all the tanks combined was low when compared to similar studies. This could be because the flows were only monitored over the summer months, and seasonal habit changes are not captured.

Table 5 summarizes the calculation GPDPP for each tank individually and all together. A small amount of hot water for laundry usage was added to these values based on a 2002 study by the National Research Center.[4] The study metered laundry water usage, cold and

Table 5. Gallons per Day per Person Calculated per Tank and Combined

Service	Gallons Per Day Per Person (Laundry Estimate Included)
Tank 5	24
Tank 6	11
Tank 7	26
Tank 8	16
All Tanks	**18**

hot separately, at apartments with in-unit and common laundry to quantify the difference associated with the different laundry layout. The study found that roughly 2.3 gallons of hot water per day per apartment was used for laundry in apartments with common laundry room.

The data shown in **Table 5** gives a sense of the water usage from the tanks monitored. Despite the high degree of variability between tanks, the average for all tanks combined aligns closely with the estimated GPDPP calculated in the building efficiency calculation which calculated 17 GPDPP.

Heat Pump Usage

Figure 11 shows the energy used by each of the heat pump circuits over the monitoring period. In all cases, except for HPWH-4, heat pumps were grouped two (2) per circuit. Temperatures and flows for tanks 5, 6, 7, and 8 were monitored separately for the sample efficiency calculation.

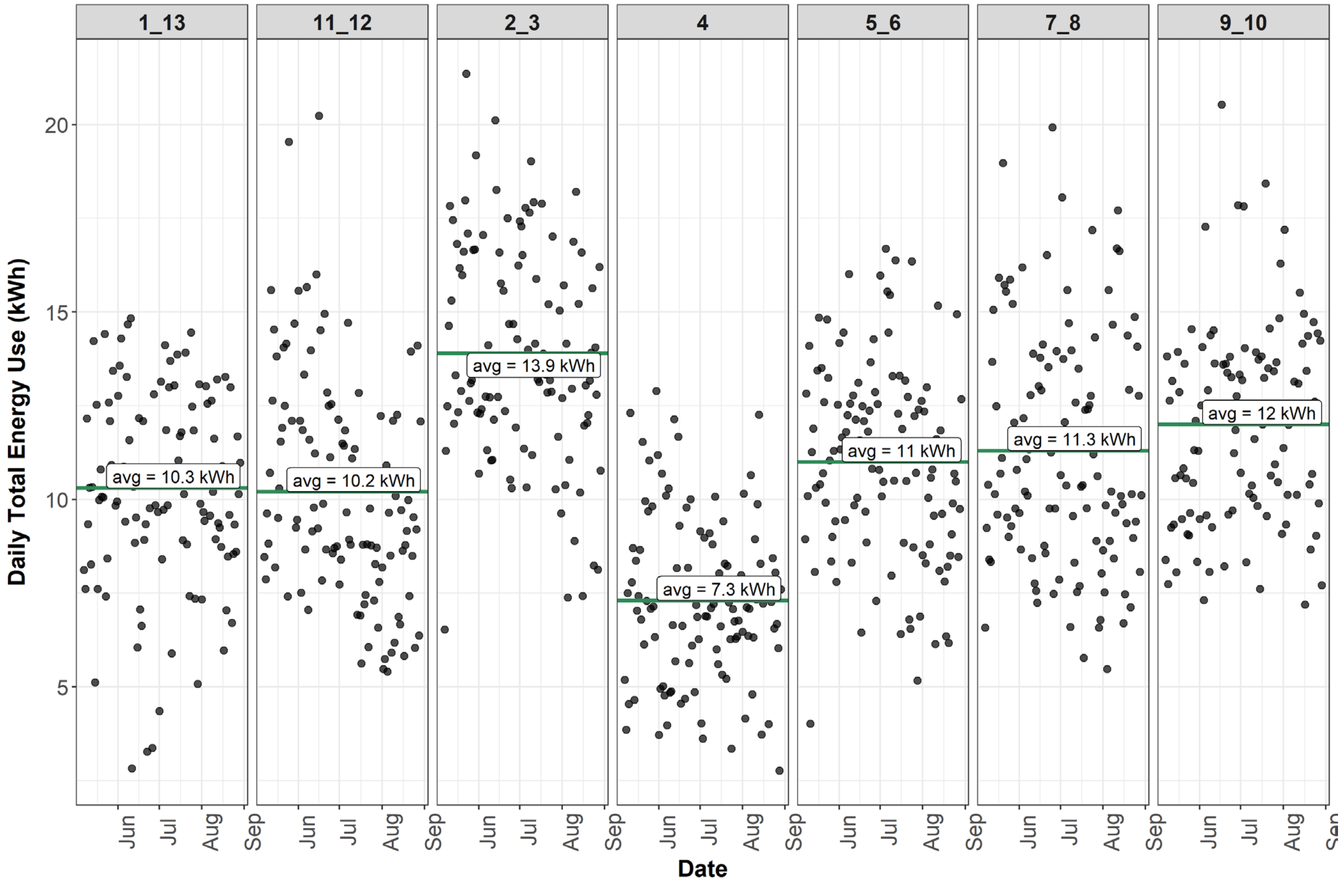


Figure 11. Daily Heat Pump Water Heater Energy Usage

The thirteen (13) Sanden HPWHs use an average of 76 kWh per day, 5.8 kWh per HPWH. Typical HPWH groupings use between 10 and 12 kWh per day, with HPWH group 2/3 using nearly 14 kWh per day and driving the average up slightly. Tank groups 5/6 and 7/8 correspond with the tanks monitored for the Sample Efficiency analysis. HPWHs energy usage corresponding with these groups was near 11 kWhs in both cases, which indicated nearly median energy usage. This suggests that the hot water usage in the tanks monitored was also nearly median.

The duty cycle of the HPWHs was also assessed. **Figure 12** shows run hours per day for each heat pump supplied by the circuit. The average run hours across all heat pumps is six hours and is shown as a red line in the figure.

Temperature Maintenance Heat Trace

Temperature maintenance heat trace was assessed for both performance and efficiency. Assessing performance shows

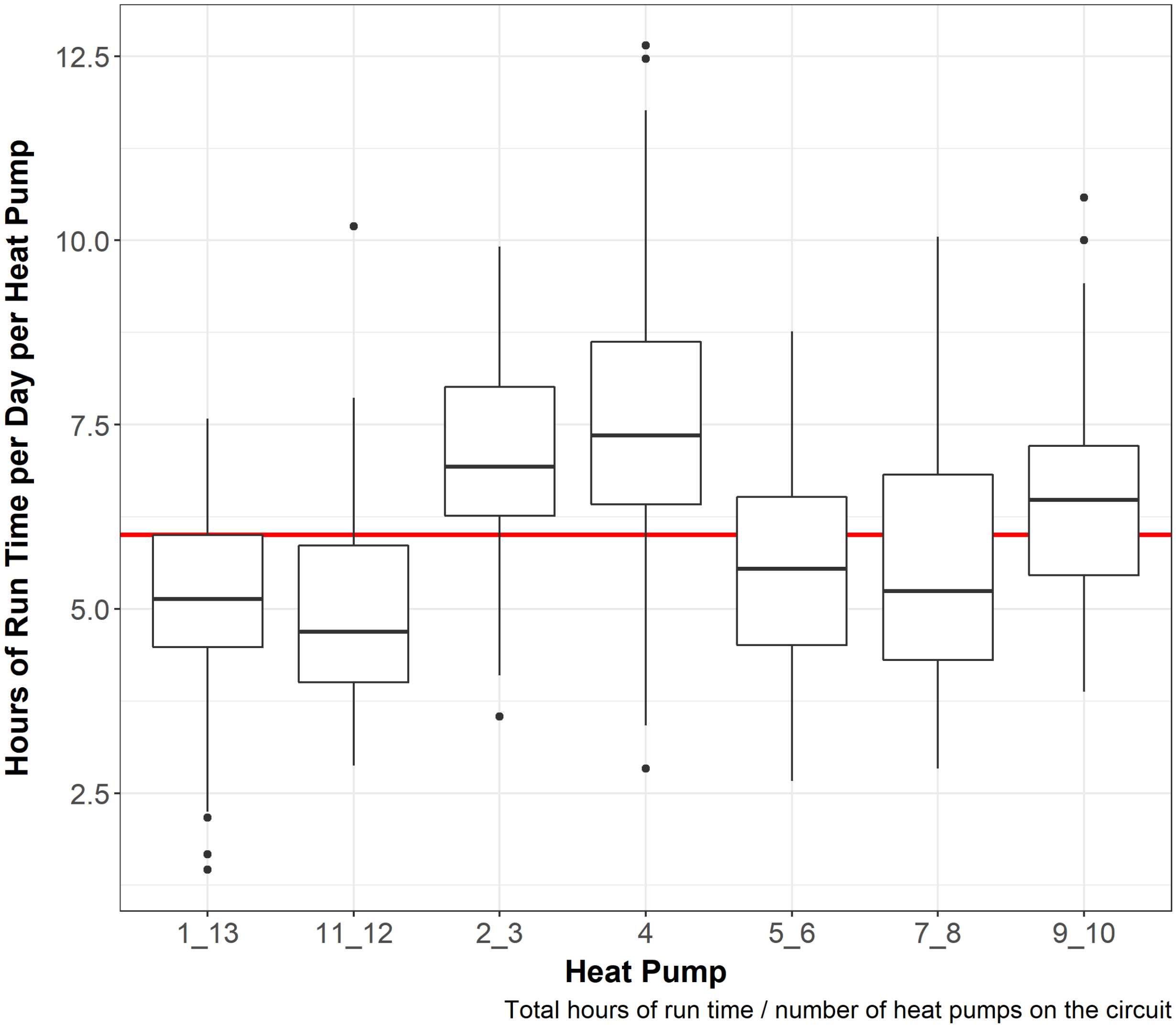


Figure 12. Duty Cycle by Circuit- Total Daily Run Hours per Heat Pump

whether the heat trace successfully kept risers warm enough to deliver hot water. Assessing efficiency shows how efficiently heat trace performed its function. Findings show that distributed risers with temperature maintenance heat trace both performed as intended and significantly reduced distribution losses.

Both the survey results and onsite testing suggest heat trace is performing adequately to maintain temperature.

To assess the performance, the time delay in getting hot water at Level 2 was measured. The laundry room and a residential unit on level 2, were used to test heat trace effectiveness. Before laundry room tests, the laundry room was closed for a minimum of a 16-hour period to ensure piping had time to fully cool and force heat trace usage. The laundry room riser was used as the control and compared to a residential unit. Hot water was observed to be readily available suggesting that heat trace was performing as expected.

In addition to performing hot water testing, a survey was distributed to the tenants. The survey only included three questions:

1. Which floor do you (the tenant) live on?
2. Does the hot water take a long time to reach your tap?
3. Is the hot water reaching your apartment hot enough?

Thirteen (13) tenants responded to the survey, five (5) from the 2nd floor, six (6) from the 3rd floor, and two (2) from the 4th floor. Of the respondents, eleven (11) said they received hot water without having to wait very long, and all thirteen (13) agreed that the hot water was warm enough. Anecdotally, respondents reported that it took longer for hot water to get to the kitchen sinks than the showers. This is likely because, in most units, the kitchen sink is located farther from the heat trace heated riser. Both the survey results and onsite testing suggest heat trace is performing adequately to maintain temperature.

To assess efficiency, energy usage of all temperature maintenance heat trace and HPWHs was measured and analyzed. The goal of the distributed riser system was to reduce distribution losses by reducing the amount of piping throughout the building. Using temperature maintenance heat trace reduces the amount of piping by half, because only supply pipe is needed. Additionally, using distributed HPWHs further reduces the amount of piping required by reducing the pipe length from the storage tank to the apartment. As previously mentioned, distribution losses in a typical system account for 55 to 75 watts per apartment. At HopeWorks Station, only 30 watts per apartment was used by temperature maintenance heat trace , suggesting that the distributed riser heat trace system operated with less distribution losses.

At HopeWorks Station, only 30 watts per apartment were used by temperature maintenance heat trace.

Temperature maintenance heat trace was observed to cycle on and off several times an hour very consistently in all circuits. **Figure 13** takes information from the eGuage website displaying this duty cycle.

In addition to a consistent duty cycle from

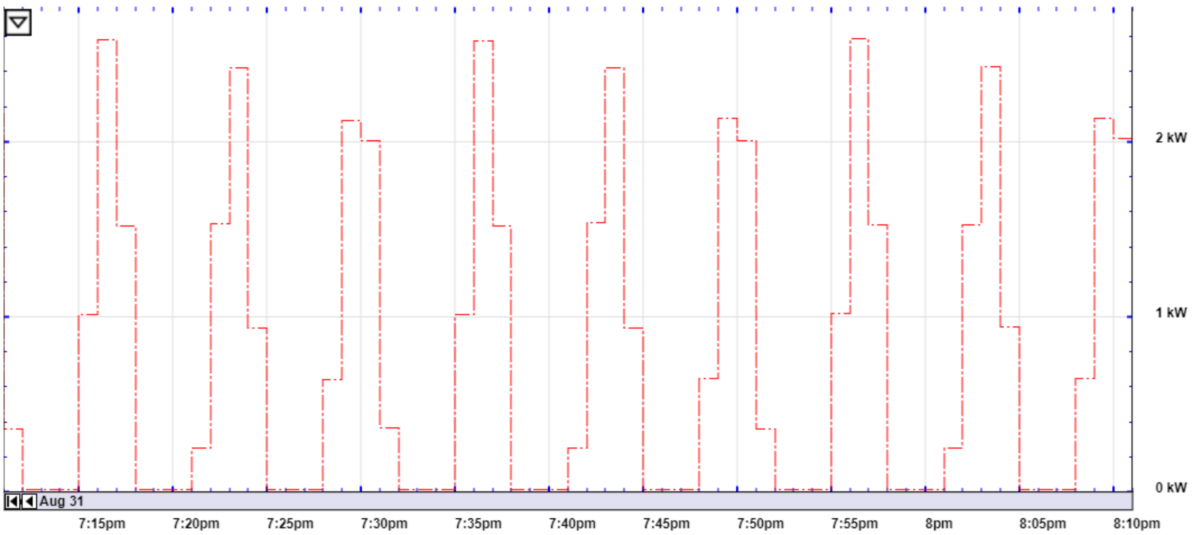


Figure 13. Temperature Maintenance Heat Trace Duty Cycle

day to day, heat trace used a very consistent amount of energy from day to day. Energy used from heat trace circuits is shown in Figure 13 below. Heat trace was grouped three (3) heat trace per circuit, so the combined energy of three (3) heat traces is shown in each of the four plots in **Figure 14** .

Although the energy use for each of the circuits was nearly identical from day to day, energy use varied greatly from circuit to circuit. This can likely be explained by different pipe lengths per riser. The longer the pipe, the longer the heat trace, the more kWh will be used to keep the pipe warm.

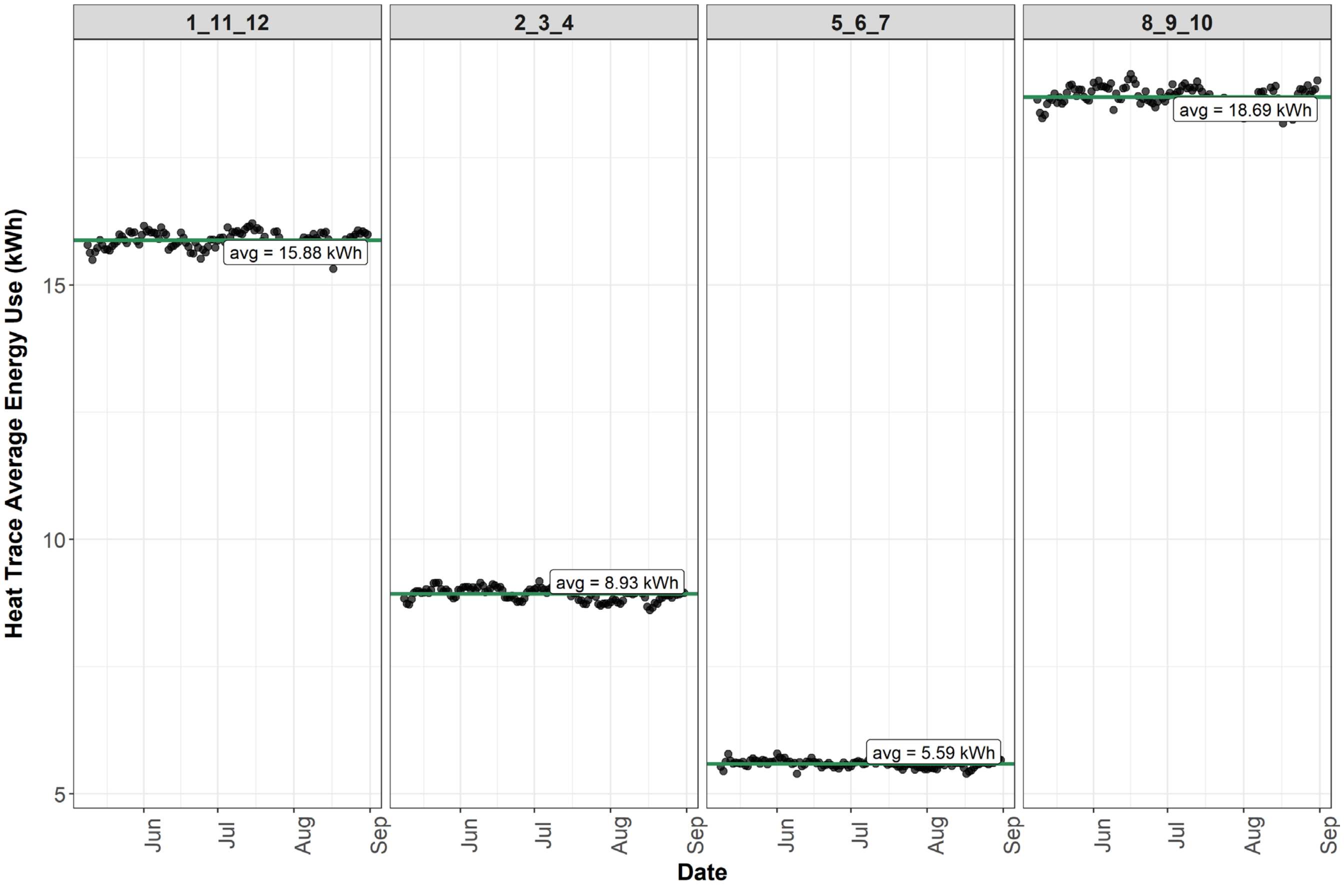


Figure 14. Heat Trace Energy Consumption per Circuit

Conclusions and Recommendations

This project demonstrated that a distributed heat trace heat pump water heater system can efficiently provide hot water to building tenants. It shows that using a single riser, with no return piping, and heat trace for temperature maintenance significantly reduces distribution heat losses. Typical heat losses are from 55 to 75 watts per apartment, and HopeWorks Station was able to achieve 30 watts per apartment. After monitoring the system for 82 days, it is clear the system is operating as intended. However, when compared to the central swing tank design used at Elizabeth James House, the distributed heat trace system has some disadvantages.

A distributed heat trace system is distributed, meaning heat pumps, tanks, valves, and corresponding piping are in multiple places around the floor plan. The major system components are not combined to a single location. Distributing equipment around the building creates challenges for design, construction, reliability, and efficiency including:

- More HPWHs are required to serve the same load.
- Difficulty in commissioning multiple systems in different locations.
- No redundancy.
- Temperature maintenance load is heated by electric resistance.
- More difficult to monitor and future proof.

Each HPWH in a distributed system serves fewer apartments than HPWHs in a central system which has an adverse impact of the diversity factor. Diversity factor (or simultaneity factor) is the sum of the individual non-coincident peak loads of various subdivisions of a system (various units or people served by a hot water system) to the peak demand of the complete system. At HopeWorks most HPWHs serve six (6) units. When only six (6) units are being served, if one unit is an outlier, and uses significantly more hot water than expected, it can drastically change the peak demand of the system. When 65 units are being served by a central system, if one unit is an outlier, there is a smaller percent change in peak load from that outlier. As a result, more capacity per apartment is needed when HPWHs serve fewer apartments. Elizabeth James House uses four (4) Sandens to serve 60 people; HopeWorks Station uses thirteen (13) Sandens to serve 102 people (although it was designed to serve closer to 150). At Elizabeth James House, each Sanden serves 15 people; at HopeWorks Station, each Sanden serves less than 8 people (under full design occupancy each Sanden would serve about 11 people). The building must install more Sandens to serve the same number of people when a distributed system is used .

Multiple HPHWs distributed around the building are more difficult to commission than a central plant of HPWHs. A central plant has one location in which the contractor and commissioning agents must run tests and adjust setpoint temperatures. In a central plant there is one supply temperature setpoint to adjust; in a distributed system there are multiple. In a central plant there is one recirculation pump to adjust; in a distributed heat trace system there are multiple heat trace setpoints. In a central plant there is one mixing valve to adjust; in a distributed system there are multiple. Additionally, in a distributed system the components are located all over the building, so the contractor and commissioning agent must walk from system to system and adjust each individually resulting in less time spent adjusting each system and potentially more time overall.

In addition to commissioning and spatial considerations, reliability must be considered. Consider a central Sanden plant with four (4) Sandens serving a large thermal storage system in a swing tank configuration. If one Sanden fails, it may stop producing hot water, but the remaining heat pumps will still be able to meet the load on most days by running more hours. When a heat pump fails in a distributed system, there likely is no redundancy, and the problem must be addressed immediately or the tenants served by that system will not receive hot water.

Finally, although a distributed heat trace system does reduce thermal loss through the distribution piping, it does not necessarily reduce the amount of power needed to maintain a distribution temperature. Heat trace is electric resistance and therefore operates at a much lower COP than a HPWH. In a central swing tank system, analysis has shown that about 50 watts per apartment of distribution losses can be accounted for without the use of electric resistance heating. At HopeWorks Station 30 watts per apartment were used to heat distribution piping. Consider a comparable new construction central swing tank building that loses 60 watts per apartment in its distribution system. If 50 of those 60 watts are produced with the HPWH at a COP of 3.3 and the remaining is produced with electric resistance, only about 25 watts is used to heat distribution piping.

Central systems offer many advantages and, as demand response and continuous monitoring enter the market, buildings with central systems will be able to adapt to market changes more easily. In a central system, fewer piece of equipment can be modified or updated to incorporate demand response. Additionally, central systems serve more people and can take advantage of diversity when providing load shifting. Monitoring central systems for potential equipment operation issues is also easier. At HopeWorks Station, due to the complexity of setting up multiple remote monitoring systems, only four (4) of the thirteen (13) HPWHs are monitored. In a central system only one central monitoring system must be set up.

The temperature maintenance system installed at HopeWorks is operating as intended and has significantly reduced distribution losses. However, because the distribution load can only be served by electric resistance heating, it still uses more energy when compared to a well-designed and -insulated swing tank system. Considering energy use, design and construction, commissioning, reliability, and building space allocation, the distributed heat trace system at HopeWorks does not perform as well as a central swing tank system.

For the reasons outline, large new construction multifamily buildings, where hot water loads are significant, should strive to install central systems. However, due to economies of scale, on smaller multifamily buildings and commercial buildings that use less hot water, central systems are not always economically feasible. Distributed systems are likely simpler to install when DHW loads are small and therefore reduce cost on certain project types. For these reasons, they likely have a place in retrofits, light commercial – strip malls, grocery, restaurants, etc. – and some low-rise multifamily buildings.

There are some advantages to distributed systems. Distribution piping losses are reduced and if the temperature maintenance load were delt with more efficiently, a distributed system would use less energy. Additionally, in commercial buildings other than multifamily, where hot water usage is low and usage points are spread out, distributed systems have potential to simplify designs and save energy.

The market sector that could benefit from distributed systems is large. Many light commercial new construction buildings may find distributed systems to be simpler to install and less expensive overall. More research is needed to understand when it is appropriate to use a central system vs a distributed system. Additionally, research to understand when temperature maintenance is needed in a distributed system and the best practices for providing temperature maintenance could significantly benefit projects that use distributed systems

Citations

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[2] Heller, Jonathan, and Shawn Oram. Seattle, WA, Reverse Cycle Chiller (RCC) Best Practices Design Guidelines.

[3] https://ecotope.shinyapps.io/MFSandenRetrofit/

[4] A National Study of Water & Energy Consumption in Multifamily Housing In-Apartment Washers vs. Common Area Laundry Rooms. November 2002 (revised). https://www.mla-online.com/pdf/NRC-2002-A-National-Study-of-Water-and-Energy-Consumption-in-Mutli-Family-Housing.pdf

Appendix A

Event	Year	Month	Event / Observation	Cause	Resolution
1	2020	May	Some repairs were done to the condenser for HW heat pump #6, and it is now functioning, but the heat trace line is not working. The error for the heat trace system reads "all 3 temp bus failed".	When temperature sensor and flow meter installation, air was allowed to enter the system and reach the condensing unit on the roof.	The system was purged by Wolfe Plumbing and reset by Zoe.
2	2020	June	Unusually low flows, especially from ST-8	Confirm pulse count set up correctly, confirm units served by ST-8 are occupied.	Confirmed pulse output is correct. Need to ask Eve about the number of tenants in different rooms and Cynthia to do a survey for hot water.
3	2020	June	Temp_t7_ST_mix appears to be Temp_t7_ST_cw	Temperature sensors misplaced at site.	Confirmed temperature sensor is misplaced. Moved to mix at 9:45am on 20200722
4	2020	June	Flows for t6 and t7 appear to be flipped	Acquisuite variable name flip or inputs flipped. T6 and T7 are the same room so this is very possible.	Confirmed sensors fliped and flipped sensors at 10:15am on 20200722
5	2020	June	No current used at t7 heat trace remote meter.	Faulty power meter.	COP Calculation can be performed on all four tanks without power meter. However, we cannot provide COP for each set of two tanks. First report will provide a combined four tank COP ignoring this power meter.
6	2020	June	Double checked t8 heat trace (by volt/amp monitoring). Expect ~5kWh/day - this suggests that 2_3_4 may have an issue with at least one heat trace, and 5_6_7 may have issues with two of the HTs	Data analysis check	Heat trace 8 is monitoring as expected.
7	2020	June	t6 tank outlet temperature is low.	error in heat pump.	Confirmed onsite in July. Mixing valve outlet temperature is at ~70°F. Heat pump needs to be reset Second site visit in August shows heat pump was reset successfully and is operating at the desired temperature.
8	2020	Aug	M&V event. Lost data in channel 009 - this is all the temperature data for tank 5	Flex IO and power supply was damaged. Power strip and Modhopper antenna were missing. All temperature and flow signal wiring unplugged.	Flex IO, power strip, antenna, and extension cord replaced.
9	2020	Aug	High outlet temperatures observed on tanks 6 and 7.	Uncommissioned thermostatic mixing valve	Recommend to building maintenance to adjust valve.