BONNEVILLE POWER ADMINISTRATION

Emerging Technologies

Sitka Apartments Wastewater Heat Pump Measurement and Verification

December, 2020

Sitka Apartments
Wastewater Heat Pump
Measurement and Verification

Emerging Technologies

Final Report

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ABSTRACT

This project set out to research, design, pilot, verify, and document a heat pump water heating system for large multifamily buildings using the building sewage as the heat pump's heat source. The design and implementation of such a system is complicated, but the underlying physics of the process have proven out at Sitka Apartments, a multifamily building with approximately 400 units. The system was designed as a single-pass system, where the primary heating loop includes R134a water-to-water heat pumps and a heat exchanger system installed inside the wastewater vault. A temperature maintenance loop is required for this type of building, and the heating demand for this loop is met by a separate, air-source heat pump system optimized for the task. (All mechanical equipment is located in a below-grade parking garage, so the recirculation loop heat source is the ground- buffered air in the garage.)

An extensive measurement system was installed so that key data points could be monitored; this was very helpful in identifying and resolving several problems that occurred during the system's initial operation.

The water source heat pumps treating the primary load are successfully extracting heat from the wastewater vault and are operating at a COP of 2.95. There is an 8°F drop in temperature across the source loop to and from the vault. The vault water averages a temperature of 75°F during periods where the WWHPs are extracting heat from the vault.

The overall system COP, which includes the temperature maintenance load, averaged 2.6 between August 20 and September 10, 2020, a period where the overall system controls and water heating equipment were operating substantially as designed. Prior to this, the system COP ranged from 0.91 to 2.6 depending on if the DHW load was being met with inefficient fossil gas equipment or the more efficient heat pump water heaters.

Because of the amount of custom engineering required for this system, and because of ongoing concerns about the condition of the primary heat exchanger and control components, the type of system cannot be regarded (yet) as a turnkey solution for efficient heating of hot water in multifamily buildings. Wastewater management is a significant challenge in wastewater heat recovery systems like the one at Sitka. More mitigation techniques are likely needed to prevent fouling of the source heat exchanger system. In mild climates like Seattle, wastewater heat pump systems do not yield sufficient efficiency improvement compared to air-source CO_2 systems.

ACRONYMS

ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BPA	Bonneville Power Administration
Btu	British thermal unit
Btu/hr	British thermal unit per hr
C	Celsius
CW	Cold Water
CO_2	carbon dioxide
COP	coefficient of performance
DHW	domestic hot water
DOE	Department of Energy
F	Fahrenheit
GPM	gallons per minute
GPD	gallons per day
HPWH	Heat Pump Water Heater
HW	Hot Water
HWC	Hot Water Circulation
HX	Heat exchanger
kW	kilowatt
kWh	kilowatt hours
NOAA	National Oceanic and Atmospheric Administration
OAT	outside air temperature
R-22	Refrigerant 22
R-134a	Refrigerant 134a
R-410a	Refrigerant 410a
R-744	Refrigerant 744 (CO_2)
RCC	Reverse cycle chiller
WWHP	Wastewater heat pump

EXECUTIVE SUMMARY

Under contract to the Bonneville Power Administration (BPA) and in partnership with Vulcan Real Estate, Ecotope has performed a feasibility study, designed, and overseen construction of a wastewater heat pump water heating system for a large, multifamily building in Seattle, and installed measurement and verification (M&V) equipment to monitor its performance. This report describes details of each of these steps and provides recommendations for further related work.

This project follows directly from previous Ecotope projects that pioneered the use of air-source heat pump water heaters (HPWH), or reverse cycle chillers (RCC), located in below-grade parking garages of mid-rise multifamily buildings in Seattle. One of these projects was written up in detail (Heller 2015)[1]. That project effectively delivered systems with annual full-system coefficients of performance (COPs) of 2.6-2.8 using the air in the underground garage as a heat source. In response, multifamily developers in Seattle, such as Vulcan, are asking for RCCs as the system of choice in their new buildings. The WWHP project was thought to be able to yield higher COPs given the temperature of the heat source might typically average around ~70°F. Much like the RCC projects before it, a major goal of this project is to design and pilot a new, extremely low energy water heating system that can be deployed by designers and developers in buildings across the Northwest.

To optimize the WWHP design, Ecotope created a simulation tool with a web app interface (https://ecotope.shinyapps.io/WWHP_Simulator), driven by hot water usage data from similar multifamily Seattle apartment buildings and a collection of settable inputs describing design parameters. The inputs included hot water storage volume, wastewater vault size, heat pump equipment type and control logic, building occupancy, and pumping strategies for controlling the vault level. The simulation tool helped to inform and optimize design decisions. After this project has been proven, this simulation tool could be refined and made available to other designers seeking to apply WWHP technology to reduce energy use.

Using the WWHP simulation and informed by lessons learned from the previous RCC projects, the design includes five 1,000-gallon hot water tanks plumbed in series, three 12-ton Colmac water-to-water reverse cycle chillers operating in parallel, a 26,000-gallon wastewater vault, and 56-tons of flat-plate heat exchanger capacity submerged in the vault. Satisfying heating demand for continually recirculating hot water is met by a separate, air-source heat pump system optimized for the task.

Now the project has completed construction and is operating effectively utilizing the wastewater as a source of energy for domestic hot water. The system is primarily operating on the heat pump equipment with intermittent backup fossil gas water heating equipment. Both the wastewater heat pumps and the air source RCC heat pump fully meet the primary and temperature maintenance heating loads. However, there have been periods since the building was occupied that utilized the backup fossil gas water heaters to meet part or full DHW load. These events and occurrences are discussed in further sections and include data collection system electrical code infractions, flowmeter failure, Watt

[1] Heller, J. and Oram, S. (2015). *RCC Pilot Project: Multifamily Heat Pump Water Heaters in Below Grade Parking Garages in the Pacific Northwest*. Prepared for Bonneville Power Administration.

transducer failure, sensor calibration issues, RCC control board failure, vault maintenance issues, and a WWHP communication issue.

The water source heat pumps treating the primary load are successfully extracting heat from the wastewater vault and are operating at a COP of 2.95. There is an 8°F drop in temperature across the source loop to and from the vault. The vault water averages a temperature of 75°F during periods where the WWHPs are extracting heat from the vault. The WWHPs are configured in a single-pass arrangement to deliver 135°F water to the primary storage tanks upon activation, utilizing the wastewater as a thermal source.

The system COP, which includes the temperature maintenance load, averaged 2.6 between August 20 and September 10, 2020, a period where the overall system controls and water heating equipment were operating substantially as designed. Prior to this, the system COP ranged from 0.91 to 2.6 depending on if the DHW load was being met with inefficient fossil gas equipment or the more efficient heat pump water heaters.

Construction costs are highly variable and especially hard to predict for nascent technologies. It is difficult to extract a true incremental cost in this case due to the interactive effects of various design decisions and the impact of the system design across trades including architectural, structural, HVAC, plumbing, and electrical. A preliminary estimate places the incremental cost at about $250,000 for this building over comparable baseline systems. Once this system has been piloted and proven, the incremental costs to apply it to more buildings is expected to decline compared to this pilot project. From the consumer side, assuming an electric cost of $0.08/kWh, this system saves about $45,000/yr compared to electric resistance for a simple payback time for this building under 6 years.

BACKGROUND

Runberg Architects contracted with Ecotope to provide mechanical and plumbing designs for the Vulcan Real Estate Sitka Apartment building in the spring of 2015. Originally, air-source heat pumps, located in the garage, were planned to provide hot water based on a previously successful installation of that technology in another building in the adjoining block. Vulcan, the developer, was interested in ideas for advancing the energy performance of the Sitka project further, so a wastewater heat pump system was suggested based on some early work done with the SHARC[2] system in Vancouver BC. Due to the Sitka site location, a wastewater vault was required because the low point in the building was below the level of a nearby storm water pipe, and sewage needed to be pumped over the stormwater pipe to reach the sanitary sewer pipe. As a result, the project was identified as a potential candidate for wastewater heat recovery and Ecotope began working with Bonneville Power Administration (BPA) and Seattle City Light (SCL) to solicit funding for a wastewater heat pump (WWHP) pilot project with Measurement and Verification (M&V) installed to monitor the system performance post-occupancy.

On July 7th, 2015 Ecotope was Awarded a Technology Innovation Funding Opportunity by BPA for a "Waste Water Heat Pump Design and Pilot Study" and Technology Innovation Project #341 (TIP 341) was initiated to provide a WWHP at Sitka Apartments. In the fall of 2015, TIP 341 was fully accepted by BPA and six Stage Gates were identified for the project:

- <u>Stage Gate 1</u>**:** A feasibility study shows the concept is possible and potentially cost-effective.

[2] https://www.sharcenergy.com/false-creek/

- Stage Gate 2: The bids and incentives for the system are suitable for Vulcan to proceed with construction.
- Stage Gate 3**:** The measurement and verification plan is suitable to collect enough information to meet the project goals.
- Stage Gate 4**:** Building construction is proceeding as appropriate.
- Stage Gate 5**:** The measurement and verification system is collecting data properly and in a way to effectively evaluate the project.
- Stage Gate 6**:** Building construction is complete and the WWHP system is determined to have the potential to operate as intended.

In the fall of 2015, TIP 341 was fully accepted by BPA and Ecotope quickly began work on both research and design fronts. In January of 2016 Ecotope presented preliminary project research and design plans at the Technology Innovation (TI) Summit. One month later Ecotope had performed background research, created an WWHP Simulator, prepared Design Development (DD) documents for pricing, and finished the Feasibility Study, thus completing Stage Gate 1.

Shortly after DD documents were complete, Vulcan opened the project up to contractors for bidding. Bids for the WWHP design came within Vulcan's expected budget, and the project was accepted. As a result, Ecotope entered contract arrangements with Seattle City Light and Vulcan to complete design and construction management efforts, completing Stage Gate 2.

During the next few months Ecotope's efforts were heavily focused on working with contractors and architects to complete the design of the WWHP system and develop documentation for permitting. Ecotope presented project plans to Seattle's head plumbing inspector in the summer of 2016. Initially, he was not excited about the concept, but Ecotope rallied further support from engineers at the King County Wastewater Division and the City of Seattle's Energy Code Director, whose support allowed for the project to be permitted.

Construction Documents (CDs) for the WWHP were issued in November of 2016, and shortly after in early 2017 Ecotope drafted a Measurement and Verification Plan for the WWHP system, completing Stage Gate 3. This included a schematic diagram of measurement points as well as a narrative description of the project and how various analyses would proceed from the measured points. Finalizing parts lists, and placement of M&V components continued as design progressed in 2017.

In the fall of 2019, Sitka Apartments finished construction of the pilot project in the Seattle South Lake Union neighborhood, completing Stage Gate 4. Shortly after construction was completed, Ecotope finished installing and commissioning M&V equipment and set up the data transmission system. However, some M&V components failed, discussed in more detail in the M&V section of this report, delaying completion of Stage Gate 5 until winter of 2019.

Stage Gate 6 is complete, building construction was completed in 2019. The system was commissioned and operating in 2019 to serve partial building occupancy. Between 2019 and 2020 there have been multiple retro-commissioning activities to optimize the system performance and address multiple system issues, discussed later in this report. Currently the system is operating per specifications to deliver domestic hot water to the building occupants at a high efficiency.

Research

In order to determine the viability of a wastewater heat pump, Ecotope conducted background research consisting of general research into wastewater heat extraction, existing case studies of existing, similar projects, wastewater handling concerns and best practices, and products available for system components.

General research included a comparison of different methods of wastewater heat recovery – drain water heat recovery vs. wastewater heat pump – and detailing the availability of heat in wastewater. This research was crucial in developing an energy balance for the WWHP Simulator.

Existing case studies included several sites in British Columbia where sewage wastewater has been used as a source of district heat for multiple buildings. The first wastewater heat recovery system in North America is in Vancouver B.C. and supplies heat to 12 buildings.

Wastewater handing concerns and best practices focused on the design of the sewage vault. Many buildings need sewage vaults to collect and then lift sewage to connect with the city sanitary system. Typically, these detention vaults are relatively small, with large capacity pumps designed to empty the vault quickly and repeatedly over the course of the day. The only uncommon feature of the Sitka Apartments vault is the heat exchanger, and the vault was designed similarly to other sewage vaults without heat exchangers. As a result of this research, the floor of the vault was sloped towards the ejector pumps, the ejector pumps were installed on rails so they could be easily serviced, a redundant pump was installed, and an overflow drain was installed in case of electrical failure. The main unknown that remained is how the heat exchangers would perform in the vault over time and how this research could inform best practices for vaults with heat exchangers in future projects.

The main components critical to the WWHP operation include vault lining, pressure transducers for ejector pump control, heat exchangers, heat pump equipment and hot water storage tanks. A durable, thick product called Linabond (EP30-HS) was used as a vault lining. This material covered all surfaces of the vault to ensure water tightness. Most ejector pumps operate via a float switch, which is challenging to adjust after installation, so a pressure transducer was used to control the fluid level. This pressure transducer allowed for multiple pumping setpoints and allowed for easy adjustment to calibrate the system for maximum performance post occupancy. Multiple Slim Jim model heat exchangers from AWEB Supply—which is commonly used in pond, lake, and ocean water applications-- were used for the heat exchanger. The heat exchangers are comprised of 304 stainless steel to resist corrosion yet efficiently transfer heat. Seven of the heat exchangers were engineered on a skid platform in a reverse return pipe configuration for ease of installation in the vault.

For the heat pumps, Ecotope chose to use three Colmac HPW12s (using R134a) to serve the primary heating load and one Colmac HPA07 for the air source heat pump to serve the temperature maintenance (recirc) heating load. Ecotope considered using the Mayekawa CO_2 heat pump but decided against it due to its need for an additional heat exchanger between the refrigerant and potable water, its lack of a UL label, and limited availability of maintenance support in the United States. Additionally, Ecotope had had success with Colmac on previous air-source heat pump pilots and, due to the complexity of the rest of the system, wanted to use a proven product.

Simulation Tool

A physics-based simulation was developed during the Feasibility Study Phase to allow Ecotope to predict what would happen to the building water heating system under various conditions. Further, it allowed designers to size system components to see how changing them may, or may not, meet differing water use patterns. The simulation is hosted online and is accessible to anyone with the web link. Figure 1 shows a sample screen shot of the simulation interface. For a full list of simulation inputs and outputs, refer to the Feasibility Study[3].

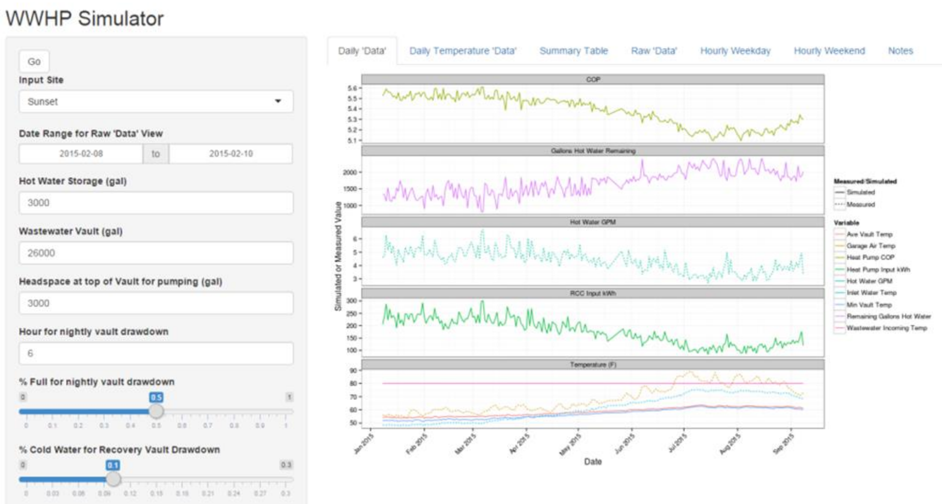

Figure 1. WWHP Simulator Screen Shot

The simulation proved especially useful in several design areas. First, it suggested the infeasibility of drawing heat for the recirculating water loop from the wastewater vault. This was not obvious at the project outset so having the simulation reveal potential problems allowed them to be corrected up front. Second, the simulations indicated that strategically pumping the vault down based on hot water availability would improve the efficiency by several tenths of a COP point.

Figure 2 illustrates the energy balance on which the Simulator is based. It considers a control volume which includes the hot water storage tanks, heat pumps, and wastewater vault. Variable descriptions are as follows.

$\dot{Q}_{in}$ is the energy contained in the city mains water flowing into the system
$\dot{Q}_{out}$ is the energy contained in the spent wastewater flowing out of the system
$\dot{Q}_{ww}$ is the energy entering the vault
$\dot{Q}_{hot}$ is the energy in the hot water supplied to the building
$\dot{Q}_{cold}$ is the energy in cold water supplied to the building
$\dot{Q}_{motor}$ is Input energy in the form of compressor and pump motors
$\Delta\dot{Q}_{cold}$ is heat gained by the cold mains water on its journey through the building
$\Delta\dot{Q}_{hot}$ is heat lost by the domestic hot water on its journey through the building

[3] Larson, B., Logsdon, M., and Heller, J. (2016). *Waste Water Heat Pump Design and Feasibility Study*. Prepared for Bonneville Power Administration.

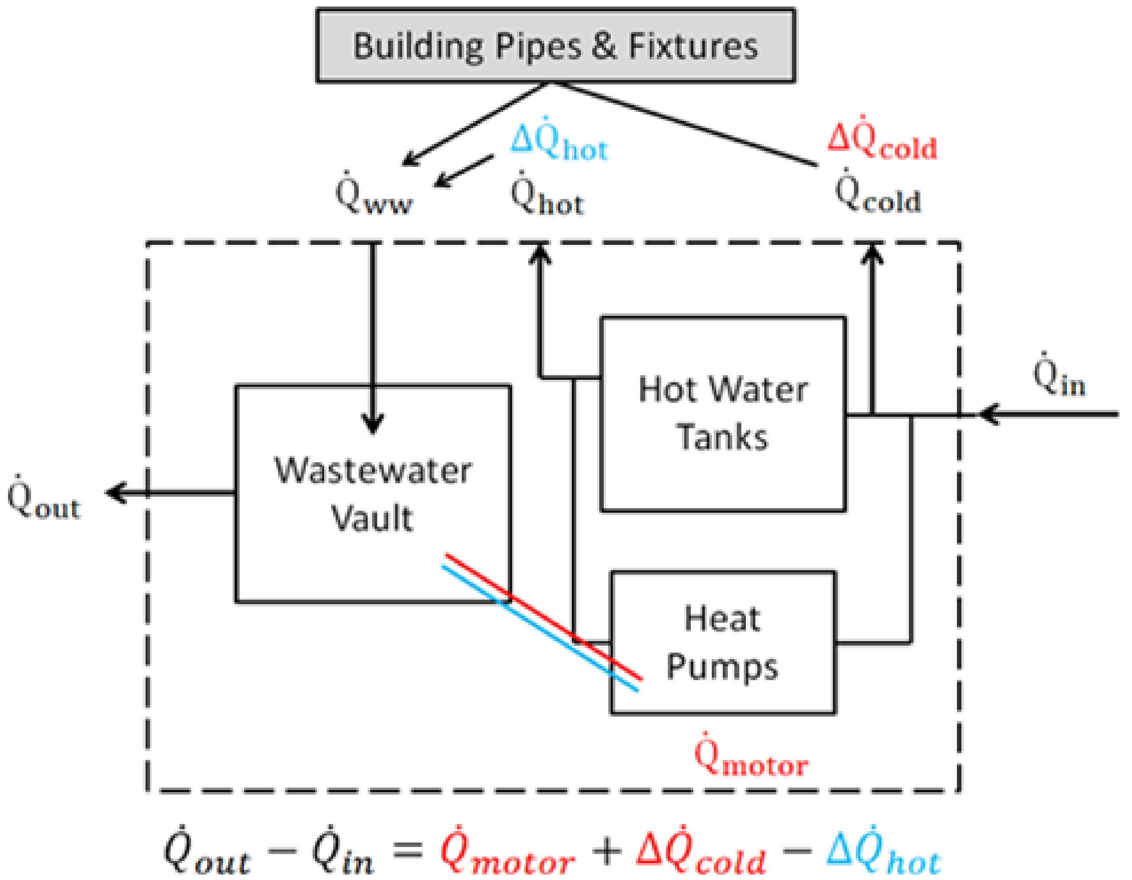

Figure 2. Wastewater Heat Pump Energy Balance

The first major unknown from this energy balance is $\Delta\dot{Q}_{hot}$ and $\Delta\dot{Q}_{cold}$, which ultimately determines $\Delta\dot{Q}_{ww}$, so assumptions were made to complete the energy balance and develop the Simulator.

To refine assumptions made in the Simulator, Ecotope measured and logged the temperature on a Seattle multifamily building wastewater pipe during the coldest part of the year. Figure 3 plots those hourly temperatures, aggregated from 5-minute intervals, over the two-month period. Each grey line is one day while the thick, black line is the average of all days. Since there was no flow meter in the pipe, we do not definitively know when the water was flowing and the corresponding temperature. That limits the conclusions we can draw; however, we can make conclusions from the minimum and maximums. The maximum temperatures occurred when the water was flowing, and they consistently reach 80°F and above. The minimum temperatures likely occur when no water is flowing, and the pipe cools off to the garage air temperature. Those rarely approach 50°F. Even in the winter, the worst-case scenario, the wastewater is likely to be warm enough for an effective system.

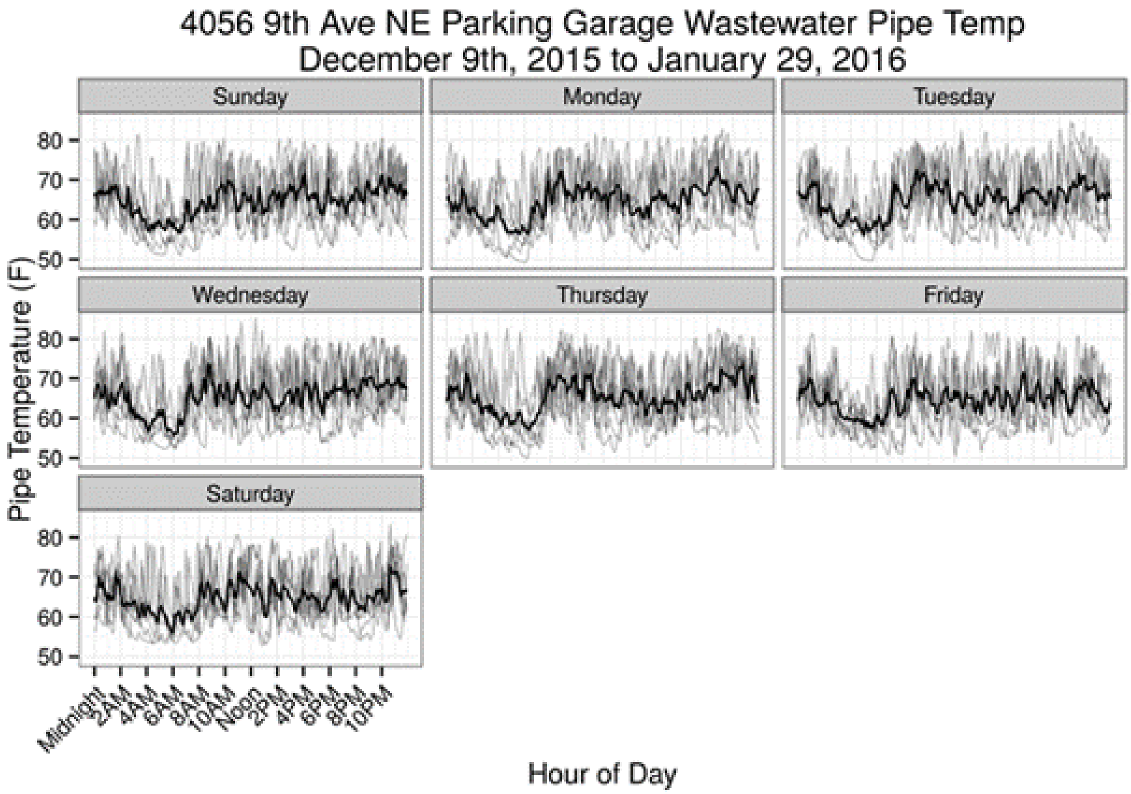

Figure 3. Wastewater Pipe Temperatures – Winter

Wastewater temperature is not a direct input to the Simulator; instead, hot- and cold-water temperatures and flows are used to determine the energy entering the vault. Meter data from Stream Uptown, a site in Ecotope's RCC research, was used to estimate 45% of the water was once hot while 55% was once cold. This 9:11 ratio is what the simulation uses.

The second major assumption is hot- and cold-water usage. The simulation uses measured hot water flow from the RCC pilot project Sunset Electric and Stream Uptown buildings, scaled appropriately based on the relative living unit (apartment) counts of those buildings vs. Sitka Apartments. This has the advantage of capturing seasonal patterns, daily patterns, and the full spectrum of usage rather than simply an overall average. Figure 4 shows seasonal and daily variation in the average daily flow at the two RCC buildings which directly fed into the Simulator.

Parts of the Simulator were the basis for Ecotope's newest simulation tool, Ecosizer. This tool has been further developed and has added capability to model combined single-pass plus dedicated recirculation loop systems. A full description of the Ecosizer is found in the appendices; the tool itself lives at ecosizer.ecotope.com.

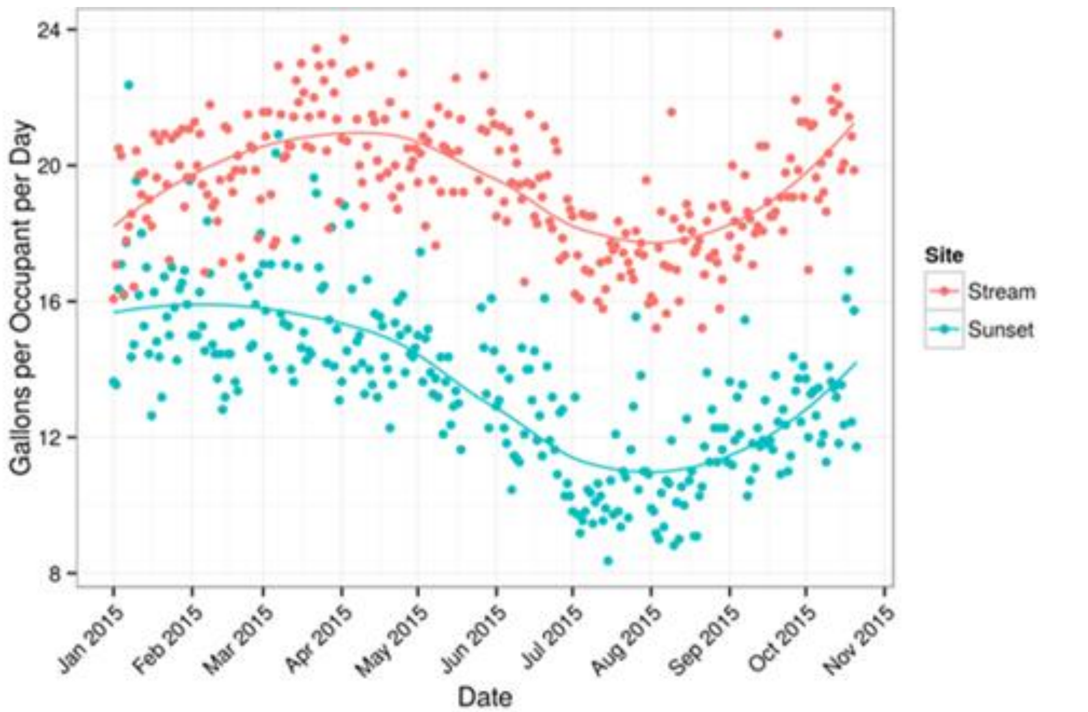

Figure 4. Daily flow per occupant for Stream and Sunset in 2015

Additional assumptions made in the simulation include the following:

- A well-mixed vault. The simulation assumes the holding vault is at a uniform temperature. It both increases and decreases uniformly as heat is added or removed. In reality, the vault is likely to be somewhat stratified, with colder water at the bottom. However, constant inflows of water at the middle height and the evacuation by pumps at the bottom will act to mix the vault.
- The source water temperature – the water nearest the flat plate heat exchangers is taken to be the vault temperature minus 5°F. This accounts for some stratification and local cooling.
- The vault enclosure is adiabatic – it does not exchange heat with its surroundings. An uninsulated vault will conduct heat in and out based on the ground and garage temperatures, but this is likely to be a small effect.
- The input power, output capacity, and COP are estimated from Colmac literature and supplemented by lab testing data of an A.O. Smith R-134a residential heat pump water heater.
- The hot water storage tanks are set to 130°F. The delivery temperature to the circulation loops is 120°F.
- The hot water storage tanks are divided at a clean thermocline between a hot side at setpoint and a cold side at the mains inlet water temperature (in other words, they are perfectly stratified). In reality, the thermocline will not be as abrupt, but the tanks will still be significantly stratified.
- Pump energy or any water circulation loop energy is not modeled.
- The inlet, cold water temperature is that from either one of the two metered draw pattern datasets (either Sunset or Stream).

Simulation Tool Energy Savings Estimates

The values we used to estimate energy savings are presented in Table 1. They require further explanation. The hot water use of 18.2 gallons/person/day is what Ecotope observed for the RCC pilot project buildings. The total energy required to heat the water assumes an average increase of 70ºF (from 50°F to 120°F). The baseline system is assumed to be in-unit resistance tanks which, when standby losses are accounted for, have an annual COP of at least 0.9. All other values are documented elsewhere in this report. Overall, Sitka is projected to save about 450,000 kWh/yr.

Table 1. Estimated Energy Savings

Units in Building	385
Occupants/Unit	1.2
Total Occupants	462
Gallons/Occupant/Day	18.2
Total Gallons/Year	3,069,066
kWh/Year at COP = 1	522,452
kWh/Year at COP = 0.9	580,502
kWh/Year at COP = 4	130,613
kWh/Year Savings	449,889

ENGINEERING

System Design

Sitka Apartments was developed by Vulcan Real Estate and consists of a 385-unit mixed-use apartment building in the Seattle South Lake Union neighborhood. It consists of two concrete floors below grade for parking, and two floors of concrete topped by five wood-framed above grade stories for residential occupancy and commercial storefront.

The system design relied on the WWHP simulation tool outputs, lessons learned from the RCC projects, and the criteria for this building. The primary considerations were optimization of overall system efficiency through combination of a top-performing heating plant with a piping and controls layout intended to reduce both fossil fuel back-up usage and temperature maintenance losses (while maintaining acceptable service hot water temperatures to all living units).

Previous RCC projects provided clear design guidance: install the hot water storage tanks in series, configure the heat pumps to run in parallel, heat water in a single pass over the heat pump to maximize stratification in the storage tanks, and minimize temperature maintenance (recirculation) loop losses. While it is straight-forward enough to satisfy the first three guidelines in a design, providing an effective solution to dealing with recirculation losses is always challenging.

Engineering calculations showed that this building could have recirculation losses of up to 48,000 Btu/hr. Hot water is provided to the loop at 120°F and comes back only moderately colder at 110-115°F. This lukewarm water needs to be reheated before being circulated again. For any heat pump, the efficiency of raising 110°F to 120°F with a much lower temperature source (say 60°F, which could be a typical wastewater vault temperature) is low. Further, when compared to providing a large temperature lift to incoming mains water, the refrigeration cycling pressure and temperature regimes for smaller lifts are disparate. Effectively, a better design choice would be to have two different heat pumps – one set for primary heating and another dedicated to serving the recirculation loop. Figure 5 illustrates the conceptual layout of this approach.

Loop or Swing Tank with Single Pass

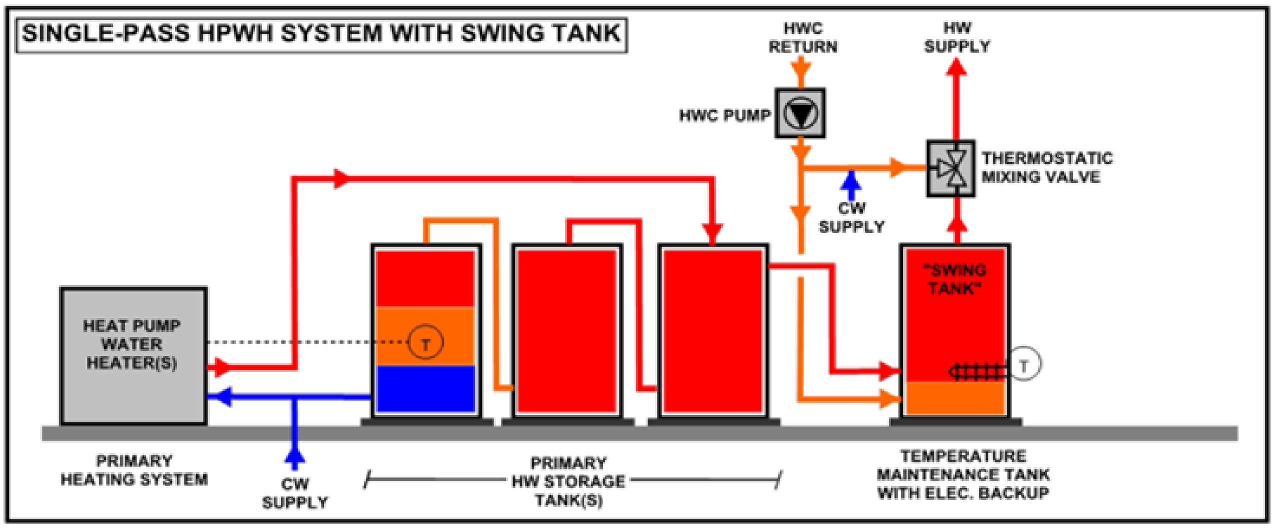

Figure 5. Single-Pass Primary HPWH System with Parallel Loop Tank

System Components

The Wastewater Heat Pump (WWHP) system provides domestic hot water for the Sitka Apartment building. Sewage from the building is routed to a sewage vault in the parking garage. The vault includes heat exchangers connected via a closed hydronic loop to a bank of water-to-water heat pumps. The water-to water heat pumps extract heat from the sewage vault to heat a series of hot water storage tanks that supply domestic hot water to the project. The WWHP system consists of three inter-related systems with two control systems. The three systems include the Primary Domestic Water Heating system, Temperature Maintenance heating system, and Sewage Management System.

The Primary Domestic Water Heating system includes the equipment associated with maintaining hot water in the domestic hot water storage tanks. A closed loop circulates water between the heat pumps and the sewage vault heat exchangers. Temperature sensors in the storage tanks are used to stage in the heat pumps. If the hot water storage is drawn down too far, gas water heaters will kick-in to back-up the heat pumps. The gas water heaters were also used to prime the system during commissioning and startup procedures. The parts of this system include the following:

- Five 1000-Gallon hot water storage tanks (ST-1, 2, 3, 4, 5)
- Three 12-ton Water-to-Water heat pumps (WWHP-1, 2, 3)

- Two back-up gas tankless water heaters (GWH-1, 2)
- Five pumps paired with the heat pumps and gas water heaters (PMP-W1, W2, W3 and PMP-G1, G2)
- Seven flat plate heat exchangers (HX-1, 2, 3, 4, 5, 6, 7,) on an engineered skid
- Hot water tempering station (TMV-1)
- Temperature sensors for control located in each storage tank (T-1, 2, 3, 4, 5)
- A Custom Controller for staging equipment ON/OFF and alarming on system errors
- Hot water piping and insulation and associated valves and appurtenances

The Temperature Maintenance Heating system, or Recirculation Loop Heating system, circulates hot water continuously throughout the building to provide for quick hot water delivery to all apartments. The water temperature in this loop is maintained between 110-122°F by an air-to-water heat pump (Reverse Cycle Chiller—RCC) located in the garage. The parts of this system include the following:

- One Reverse Cycle Chiller (RCC-1)
- One hot water temperature maintenance tank (ST-6)
- One back-up gas water heater (GWH-3)
- Two circulation pumps (PMP-R1 and PMP-G3)
- Hot water circulation pump serving the three building distribution loops
- Temperature sensor (T-6)
- A Custom Controller for staging equipment ON/OFF and alarming on system errors
- Hot water piping and insulation and associated valves and appurtenances

The Sewage Management system is used to empty the sewage vault each night and periodically throughout the day to the City of Seattle sewer system. A pump down sequence is initiated every night at 4 am and multiple vault level control pump sequences are initiated throughout the day to keep the waste level in the vault below the 6' level. The sewage management system is a standalone system and not controlled from the staging controller for enhanced system reliability. A backwater valve was provided in the pipe from the pump to the sewer connection to prevent backflow of effluent into the building wastewater vault. Components of the system include the following:

- Two sewage ejection pumps (PMP-1A, 1B)
- Pressure Transducer (PT-1)
- Vault temperature sensor (T-7)
- Digital PLC Pump Lead/Lag Controller with time clock
- Manual Pump Override Service switch to empty vault for service

DHW System Sizing

The obvious driver for total hot water use is the number of occupants in the building. This is not precisely known ahead of time, but we assumed that occupancy will be similar to recent new buildings like the RCC pilot projects which averaged 1.2 occupants per unit. At 385 units, this is 462 occupants. We used that occupancy count to scale the hot water draw profiles in our simulation, which in turn, we used to size system components.

There are two distinct building loads in large multi-family buildings with central domestic hot water plants. These include the primary heating load and the temperature maintenance heating load. More specifically, making the cold water hot for occupant use, and keeping the hot water in the distribution piping at temperature to minimize occupant wait time for HW at the fixture.

Previous findings on HPWH systems concluded that stratification in HW storage tanks is critical for steady and reliable equipment operation. Temperature maintenance systems rely on nearly 24/7 circulation of water in the distribution piping. This water returns to the central plant 10°F cooler than when sent out. If this water is returned to storage volume the flowrate and low temperature cause mixing and destratification. This results in control issues and HPWH equipment error alarms. Therefore, the two distinct loads, primary heating and temperature maintenance heating are separated. This allows for stratification in the primary storage volume and stable, efficient, reliable operation of the single-pass HPWHs. These systems were sized independently to meet the load and provided with redundant equipment for backup purposes.

The water source heat pumps were sized to meet primary heating load at the peak day and at engineering design conditions for the site. The system was sized using water usage data recorded in the Seattle area for similar large midrise multifamily buildings. As well as simulation tools discussed in earlier sections. A fossil gas back up water heating system was provided and sized as 100% capacity back-up. This was necessary for the early occupancy period and during startup and commissioning due to the lack of thermal energy in the wastewater vault during those periods.

The primary storage volume was engineered to provide enough HW storage volume for the three-hour peak load period. In multifamily buildings that peak three-hour period coincides with the weekday morning when many building occupants are getting ready for work. This sizing methodology minimizes the required heat capacity and prioritizes large storage volumes. There is an economic benefit in this approach as heat pump capacity is typically more expensive than storage volume in commercial equipment lines. There is an additional thermal benefit at the project by taking this sizing approach, as there is a time delay as the warm shower water makes its way into the vault allowing for peak heat transfer efficiencies.

The minimum capacity of the primary heating system defined the required heat capacity of the heat exchangers in the vault. The heat exchangers were oversized to offset deficiencies in the heat transfer rate if the heat exchangers get fouled over time.

The minimum capacity of the primary heating system defined the required heat capacity of the heat exchangers in the vault. The heat exchangers were oversized to offset deficiencies in the heat transfer rate if the heat exchangers get fouled over time.

The wastewater vault was to provide enough storage capacity for one day. This allows for the timing and frequency of pumping to be adjusted to optimize the stored heat capacity of liquid in the vault. However, the vault is pumped multiple times a day to keep the warm water closet to the heat exchangers and to minimize effluent build up in the vault.

Multiple simulation runs and engineering calculations resulted in the following system sizing outcomes:

- Sewage Detention Vault 15,000 gallons

▪ Vault Heat Exchanger	50-tons heating capacity
▪ Primary Heater	30-tons of primary water heating capacity
▪ Primary Hot Water Storage	4,500 gallons of primary storage
▪ Temperature Maintenance Heat Pump	6-tons
▪ Temperature Maintenance Storage	400 gallons

Sequence of Operations

The three parts of the Wastewater Heat Pump DHW system include the primary DHW system, the temperature maintenance DHW system, and the sewage management system. They are designed to operate as described below.

Primary DHW System

Primary DHW System

The primary DHW system utilizes three water source heat pump water heaters to provide hot water (140°F) to the primary storage tanks. A closed evaporator loop connects the water source heat pumps to heat exchangers located in the sewage vault. The temperature of liquid in the waste vault is measured and recorded by the controller. When the vault temperature is greater than the minimum temperature allowed by the control programming and there is a demand for heat, the water source heat pumps engage to extract heat from the vault and provide potable DHW to primary storage tanks. Two of the three WWHPs and the associated WWHP source pump engage. The source pumps operate at a constant pressure to circulate water through the heat exchange plates in the vault. The working fluid returns approximately 10°F warmer and then enters the WWHP unit. The WWHP unit removes approximately 10°F of temperature from the source fluid. The WWHP varies the load side flowrate (potable water) to achieve a discharge water temperature of 140°F. Multiple WWHPs work in parallel and are staged ON depending on the building DHW load.

The WWHPs are prevented from functioning until the vault has at least 5' of wastewater in it. Also, if the vault temperature sensor drops below 45°F, the lead pump is turned on to drop the water level in the vault to 2" above the top of the heat exchangers (5'2" above bottom of vault).

If the vault is ever too cold for the WWHPs to extract heat, the backup gas water heaters engage to provide DHW to the primary storage tanks at 140°F. Circulation pumps coupled to the gas water heaters engage to pump water through the heaters and into the primary storage tanks.

Temperature Maintenance System

The temperature maintenance heating system utilizes a building hot water circulation pump, air source heat pump, storage tank, and back up gas water heater with associated pump. HW leaves the electronic tempering valve at 120°F and is circulated throughout the distribution piping with a pump. The returning HW enters the bottom port of the dedicated storage tank or temperature maintenance tank. The tank acts as a buffer volume for the single speed heat pump equipment. This water at around 115°F is drawn into an air source heat pump water heater when the thermostat in the tank calls for heat. The heat pump is set up in a multi pass configuration providing a 10°F lift on the water before discharging it at the top of the temperature maintenance tank. This process repeats 24/7 to keep the water hot throughout the building. If the air source heat pump requires maintenance, cannot meet the hot water circulation load, or is in a fault state, the back-up gas water heat pump engages based on a lower temperature maintenance tank setpoint. This prevents the gas water heater from normally operating yet provides a reliable backup source of heat.

Sewage Management System

Duplex sewage ejector pumps remove effluent from the vault by drawing from the bottom and discharging into the sewer main. Effluent enters at three locations in the top of the vault. The pump controller cycles the lead pump to empty the vault daily at 4 am. Periodically, throughout the day the lead pump operates to remove effluent in the vault if the level rises to a prescribed height, the pump engages to reduce the level by 6”. This process repeats throughout the day to keep the vault within a minimum and maximum during normal daily operation. The controller cycles between the duplex pumps altering which pump is Lead and which is Lag on a 24-hour cycle. If the Lead pump fails, the Lag pump replaces the lead pump and operates per the sequence of operations. A visual and audible alarm is sounded upon pump fault or failure.

The simulation tool concluded that there are strategic ways to control the vault level to maximize the system efficiency. The vault pump-out sequence was linked to the amount of stored hot water available and a vault temperature sensor. When the bank of storage tanks is nearly full of completely hot water, the heat pumps will turn off. At this time, if the vault is cool, the controller would operate the sewage ejector pump to reduce the vault water level. This is an elegant solution because once the storage tanks are filled with hot water, there is no longer a need to heat any more, and emptying the vault will make room for the next inrush of warm waste water. However, implementing this procedure in the field was challenging for multiple reasons. Therefore, the design team implemented a simpler control strategy based only on vault level and not the vault temperature.

A service pump over-ride switch is provided on the pump controller in the Level P2 DHW room. The switch engages the Lead pump to empty the vault down to the pump inlet level or until the operator disengages the over-ride switch.

In the event the building experiences a power outage, the vault is designed to drain normally via gravity out of the overflow to the sewer. Since the vault overflow is higher than the intake sanitary piping feeding the vault, it is assumed that the waste lines will backfill with vault water up to the level of the overflow. This has been approved by Dave Cantrell and Steven Hart, former and present Chief Plumber Inspector for the City of Seattle.

System Alarms

Multiple alarm functions were built into the control systems. This was necessary both from an occupant safety and a building maintenance perspective but also for efficient system performance. The control system sends alarm notifications via email to notify a list of appropriate recipients of an issue. The message includes a brief description of the alarm and a time and date stamp. The alarms include:

- Heat Pump Fault Alarms: Based on alarm outputs from WWHP – 1, 2, 3 and RCC-1. Available alarm outputs from heat pumps to include high pressure, low pressure, voltage fault, or others. “Block11[4] heat pump alarm.”
- Back-up heat: Alarm that emergency heat is being used, based on operation of PMP-G1, G2, or G3. “Block11 back-up gas system is operating.”

[4] Block11 was the name of the project when it was under construction

- Lack of Hot Water: Alarm that water heating system has failed if delivery water is cold, based on sensor T-6. "Block11 water heating supply temperature is low" if T-6 < 115°F.

Water Heating Equipment

The equipment utilized at the project primarily consists of commercially available off the shelf products. However, a custom controller was designed and furnished specifically for the application. The primary system components are listed below.

- Water-to-Water Heat Pumps: Primary heaters, WWHP-1,2,&3
  - Colmac, HPW12, 135,280 Btu/hr nominal
- Wastewater Pumps: Source pumps, PMP-W1,W2,&W3
  - Grundfos, Magna 3-40-180F
- Gas Water Heater: Primary backup heaters, GWH-1,&2
  - Navien, NPE-240S, 183,900 Btu/hr
- Storage Tanks: Primary HW storage, ST-1,2,3,4,5
  - AO Smith, HD60-1000, 1,000 gallons
- Heat Exchangers: Vault heat exchangers, HX-1,2,3,4,5,6,&7
  - AWEB, SJ-08T Slim Jim, 96,000 Btu/hr
- Thermostatic Mixing Valve: Mixing valve, TMV-1
  - Powers, Intellistation, LFIS150DV---
- Air-to-Water Heat pumps: Temperature maintenance heater, RCC-1
  - Colmac, HPA07, 75,000 Btu/hr nominal
- Gas Water Heater: Temperature maintenance backup heater, GWH-3
  - Navien-240S, 183,900 Btu/hr
- Circulation pump: Hot water distribution piping circulation, PMP-1
  - Grundfos, Magna
- Controller: Heating equipment staging controller, C-1
  - Total Controls, Custom controller
- Ejector pumps: ESP-1,2
  - Weil Pump, packaged duplex wastewater pumps
- Various pipe fittings, valves, meters, sensors, and gauges

Photos

This section contains photos of some of the main system components after final installation.

Figure 6. Water-to-Water Heat Pumps: Colmac HPW12 primary heaters with gas water heater back-up equipment mounted on the wall

Figure 7. Mechanical equipment cage in level 2 parking garage. Air-to-water temperature maintenance Colmac, HPA07, in right of frame. Controls and M&V panels on far wall

Figure 8. Primary storage tanks during tank and pipe insulation installation

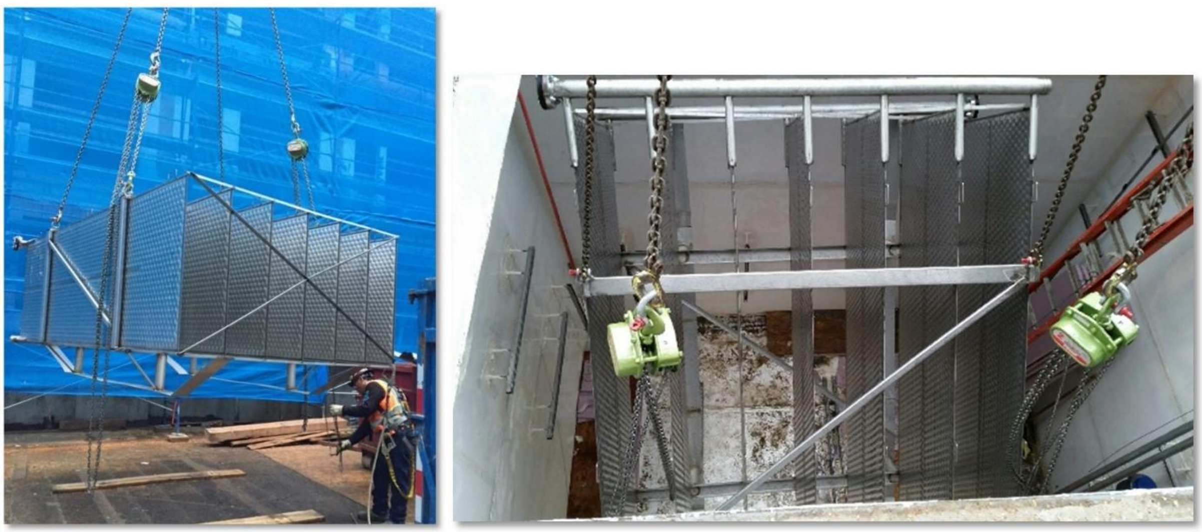

Figure 9. AWEB, SJ-08T Slim Jim Heat Exchangers being lowered into the wastewater vault

Figure 10. Read-out from digital missing station (TMV-1) during system commissioning

First Cost

Construction costs are highly variable and especially hard to predict for nascent technologies. It is difficult to extract a true incremental cost in this case due to the interactive effects of various design decisions and the impact of the system design across trades including architectural, structural, HVAC, plumbing, and electrical. A preliminary estimate places the incremental cost at about $250,000 for this building over comparable baseline systems. Once this system has been piloted and proven, the incremental costs to apply it to more buildings is expected to decline compared to this pilot project. From the consumer side, assuming an electric cost of $0.08/kWh, this system saves about $45,000/yr compared to electric resistance for a simple payback time for this building under 6 years.

Field Installation

The wastewater heat pump system was installed at the Sitka Apartments during construction of the building. The primary components including the water-to-water heat pumps, air-to-water heat pump, HW storage tanks, pumps, and mixing valve were installed shortly after the building was topped off, or the structural framing was completed on the highest level. At this time, the vault walls and floor were poured with concrete, but the waterproof barrier and other components were not installed. The installation of the heat exchangers was dependent on the vault water proofing components being completed. Therefore, the installation of the heat exchangers came after the vault water proofing components were installed and tested for functionality.

The system piping connecting the various components was installed next by the plumbing team. Ecotope performed commissioning site visits to ensure the specifications and design was met. During one of these visits an issue with the storage tank piping connection and temperature sensor was noticed and promptly corrected. After all the piping and valves were installed and verified to be correct, the pipe insulation was furnished.

The heat exchangers were then installed in the vault and connected to the source loop piping. The heat exchangers were engineered on a skid to minimize field work inside the vault. The heat exchanger skid was lowered through the vault lid. The lid is large and made out of concrete, so it requires mechanically powered lifting equipment (crane) to remove. Its use is intended only for first installation and if any major work renovations take place in the distant future. Two access doors were provided for annual inspection and cleaning. Both access hatches are 3’x3’, one is dedicated to ejector pump service and removal and the other for personnel access. After installation and testing of the heat exchangers the structural vault lid was replaced, and the smaller hatches were utilized for installation, commissioning, and maintenance of the system.

Finally, various minor system components were installed, and insulation was furnished for the HW storage tanks and valves. The plumbing, mechanical and general contractors notified Ecotope and the functional testing commissioning activities commenced.

On a parallel track, the monitoring and verification system was designed and integrated into the engineering and then the system installation. This system was set up to determine output capacity and COP of the HPWHs, the effect of the temperature maintenance loop on COP, and the temperature profile of vault water, among other metrics. Full discussion of this system is found below.

Commissioning

Commissioning began in the design phases for this project. This allowed the design team to plan for testing and provide the necessary components to simulate certain conditions. Commissioning site visit reports were provided after each visit and are included in the appendix of this report.

During the field installation of the system, Ecotope visited the project site on multiple occasions to inspect the progression. The site visits were staggered across the project schedule to cover multiple stages of installation prior to functional testing of the system. The site visits included the following:

- Initial site inspection: to get familiar with the project, building layout, and system location.
- Partial completion: to inspect some of the major components that had been partially or fully installed.
- Substantial completion 1: to inspect all major components installed and mechanically fixed to the building structure.
- Substantial completion 2: to inspect piping before covered with insulation.
- Equipment start up: to inspect equipment and startup reports after refrigeration technicians and control contractors site visit.

Functional testing site visits then followed the initial commissioning activities. The functional testing site visits occurred on multiple days over an extended time period. This was necessary because of the system complexity and the need to verify multiple operational sequences. Also, the building occupancy level had to be sufficient to generate enough wastewater to facilitate functional testing. It was possible to complete limited functional testing during construction. These functional tests include:

- Sewage management system functional testing: to verify the ejector pumps operated per the sequence of operations and the alarm signals worked.
- Back up gas water heaters functional testing: to verify that the gas water heaters provided heat to the system upon HPWH fault or failure.
- Temperature maintenance system functional testing including the mixing valve: to verify the temperature maintenance system kept the water in the distribution piping at temperature and the outgoing delivery water temperature was steady at 120°F with varying inlet cool and hot water temperatures.
- Primary heater functional testing: to verify the source loop pumps functioned congruently with the WWHPs to extract heat from the vault and put in potable water and discharge to storage tanks at 135°F.
- 75% occupancy functional testing: to verify system operation and tune sequence of operations to optimize heating cycle of primary WWHPs for larger load conditions.

Maintenance

System maintenance is a critical aspect for reliable and efficient operation of the heating equipment. Preventative maintenance procedures are required for all WWHP subsystems including the primary heating system, temperature maintenance heating system, and the sewage management system. The following list outlines the routine maintenance procedures required for the WWHP system.

- Annual procedures:
  - Inspect the waste vault for sludge buildup around heat exchangers, drain the vault and power wash heat exchangers.
  - Inspect vault lid hatches for vapor seal.
  - Inspect WWHP internal components for visible damage.
  - Review control system data and confirm SOO.
- Quarterly procedures:
  - Inspect and clean inline y-strainers on CW pipe to WWHP-1,2,&3.
  - Inspect and clean inline y-strainers on CW pipe to GWH-1,2,&3.
  - Inspect and clean inline y-strainer on CW pipe to RCC-1.
  - Inspect and clean the air filter on RCC-1 evaporator coil.

Not all of the routine maintenance procedures were addressed in a timely manner during the first 2 years of operation. This resulted in multiple equipment and system issues that are identified below. These issues were identified at multiple times after review of the measurement and verification system data. These issues were then addressed by the maintenance contractor with technical assistance from Ecotope.

- Gas WH water filters: During the initial low occupancy period with little source of heat in the vault, the instantaneous gas water heaters provided as backup were cycled frequently to meet the DHW load. The strainers were not cleaned and became clogged which reduced the heat recovery rate. Cleaning the strainers and verifying the flowrate is now a quarterly check for maintenance personnel.
- Sludge build up in vault: The vault was designed to remove effluent from the vault by pulling from the bottom with entering effluent at the top. This was intended to create a cycling effect to prevent any buildup of sludge on the heat exchangers. This and an annual power wash cleaning of the heat exchanger plates in the vault was intended to reduce fouling of the HXs and reduced system efficiencies. However, the cleaning procedure was not completed until nearly 2 years after occupation. This caused multiple issues with the WWHP heating cycle as they rely on a source of heat. Power washing the HX plates and vault was preformed which alleviated the WWHP heating cycle issue. The sewage ejector pumping sequence has also been tuned to mitigate sludge build up, however, further refinement and techniques to minimize sludge build up on the heat exchangers would benefit the system efficiency.
- Waste plumbing traps became dry in multiple unoccupied apartment units during the first year. This (understandably) resulted in occupant complaints and concern from the building owners that the WWHP system was causing issues. However, it was determined that the regular maintenance procedure of filling unoccupied unit p-traps was not done and that was the sole cause of the issue.
- Temperature Maintenance System: Gas setpoints lowered, RCC-1 set point raised. This turned RCC-1 on earlier and provided better cycle times which resulted in a higher system efficiency.
- Primary System: Setpoints revised to prioritize WWHP heating. Cycles prioritized GWH during periods of WWHP failure, these were changed to prioritize the WWHPs.

Wastewater, although a rich heat source, can require special handling considerations. This building's site elevation provides a useful opportunity for this system. The site is situated such that the low plumbing points in the building are below a large, adjacent city storm sewer pipe. The wastewater must be pumped up and over the storm sewer to connect to the city's sanitary sewer. Such situations are sometimes encountered in large buildings thus it is not a new problem to solve. The traditional solution is to have a detention vault which is periodically emptied by a pump operating on a float switch. If the building plumbing were high enough, the typical drain method is simply by gravity directly to the sewer. The necessity of the site to have a vault, regardless, makes it an even more attractive location for a first pilot project because the incremental changes to make the vault extract heat are relatively smaller than compared to the gravity drained buildings. Nevertheless, those buildings are still candidates for this type of system.

Wastewater handling experts report that the biggest concern in a detention tank is the accumulation of fine grit over time. To mitigate that, the vault floor is sloped towards the location of the ejector pumps. Further, there is an access hatch on the vault in case it needs to be serviced or cleaned.

The ejector pumps are installed on vertical rails so they can be serviced without entering the vault. There are further pressure seals used to facilitate access. The dual set of pumps is set to draw from the very bottom of the vault. Standard practices dictate using two pumps for redundancy. In the case where one falls, the other can provide enough capacity.

In case of total electrical power or pump failure, there is a further backup option to drain the vault. There is an overflow level barely high enough to drain off the top of the vault via gravity alone. This would happen if the vault ever filled completely. At the same time, wastewater would back up into the building pipes but, crucially, it would remain below any traps in the building. This backup is not ideal, which is why the vault and pumps are used but it is an acceptable alternative in a serious situation.

A large unknown of the design remains. That is the long-term interaction of the submerged flat plate heat exchangers with the wastewater. If material builds up on the plates, it is likely to reduce heat transfer effectiveness and performance. Still, these heat exchanges have been used in other challenging conditions like the ocean or freshwater lakes and ponds. In those cases, the plates are exposed to all manner of biological and natural processes and they still function well. Again, should the plates ever need to be cleaned, it will be possible via an access lid.

MEASUREMENT & VERIFICATION

The Measurement & Verification (M&V) system is likely the most extensive that Ecotope has ever installed. The key elements of the metering were designed to address the most important aspects of system performance and also tied back directly to the simulation tool that was discussed earlier.

Measurement points and equipment

The M&V system was built around an Obvius Acquisuite 8812 data logging platform. It incorporated flow and temperature measurements at strategic points as well as true (RMS) power and energy measurements for each piece of water heating equipment (three WWHPs, one RCC, and pumps for three GWHs. (Pump on-time was associated with fossil gas use based on the nominal input usage and combustion efficiency of each gas water heater). See Figure 11 for approximate monitoring equipment locations. Data that were collected and averaged over one-minute intervals are listed in Table 2.

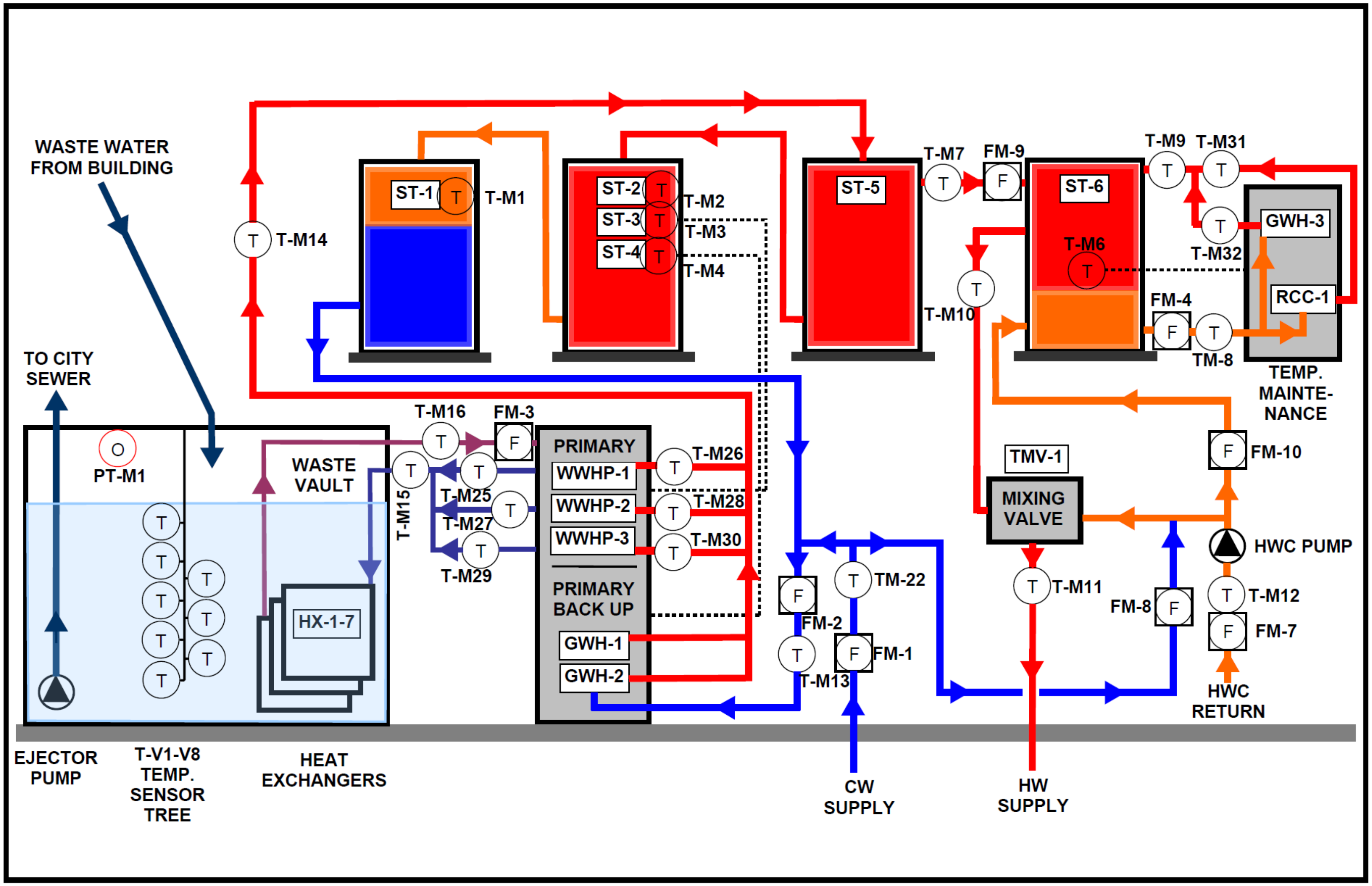

Figure 11. Schematic of WWHP System and M&V monitoring points

Table 2. Measurement & Verification Sensors and Meters

TAG	MANUFACTURER	MODEL	TYPE	SERVES
CT-G1	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	PMP-G1, BACKUP GAS WATER HEATER
CT-G2	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	PMP-G2, BACKUP GAS WATER HEATER
CT-G3	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	PMP-G3, BACKUP GAS WATER HEATER
CT-R1	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	RCC-1 & PMP-R1, AIR SOURCE HEAT PUMP
CT-W1	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	WWHP-1 & PMP-W1, WASTEWATER HEAT PUMP AND SOURCE PUMP
CT-W2	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	WWHP-2 & PMP-W2, WASTEWATER HEAT PUMP AND SOURCE PUMP
CT-W3	DENT INSTRUMENTS	CT-SRL-100-U/B	CURRENT TRANSDUCER	WWHP-3 & PMP-W3, WASTEWATER HEATPUMP AND SOURCE PUMP
FM-1	EKM	SPWM-200-CF	FLOW METER	INCOMING COLD WATER
FM-2	EKM	SPWM-200-CF	FLOW METER	WASTEWATER HEAT PUMP (POTABLE WATER)
FM-3	PUMPS & CONTROLS	PCM-W-300-100G	FLOW METER	VAULT LOOP (NON-POTABLE WATER)
FM-4	EKM	SPWM-150-CF	FLOW METER	RCC-1 & GWH-3 LOOP (RING MAIN)
FM-7[5]	EKM	SPWM-200-CF	FLOW METER	HOT WATER CIRCULATION RETURN LINE
FM-8	EKM	SPWM-150-CF	FLOW METER	COLD WATER LINE TO TMV-1
FM-9	PUMPS & CONTROLS	PCM-H-200-10G	FLOW METER	HOT WATER LINE FROM ST-5 THRU ST-1 TO ST-6
FM-10	EKM	SPWM-200-CF	FLOW METER	HOT WATER CIRCULATION RETURN LINE TO ST-6
OS-M1	Omega	LVU-815	OPTICAL SENSOR	VAULT LEVEL
T-M1	VERIS	TIH-SERIES	TEMPERATURE SENSOR	ST-1 M&V TEMP SENSOR
T-M2	VERIS	TIH-SERIES	TEMPERATURE SENSOR	ST-2 M&V TEMP SENSOR
T-M3	VERIS	TIH-SERIES	TEMPERATURE SENSOR	ST-3 M&V TEMP SENSOR
T-M4	VERIS	TIH-SERIES	TEMPERATURE SENSOR	ST-4 M&V TEMP SENSOR
T-M7	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER SUPPLY LINE FROM ST-1 THRU ST-5 TO ST-6
T-M8	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER SUPPLY LINE FROM ST-6 TO RCC-1 & GWH-3
T-M9	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER SUPPLY LINE FROM RCC-1 & GWH-3 TO ST-6
T-M10	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER SUPPLY LINE TO MIXING VALVE
T-M11	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER SUPPLY LINE TO BUILDING PLUMBING FIXTURES

[5] Original M&V design included several additional flow and temperature sensors that were redundant and were removed to reduce costs: FM-5, FM-6, TM-5, TM-6, TM-23, TM-24

T-M12	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER CIRCULATION RETURN LINE
T-M13	VERIS	TIH-SERIES	TEMPERATURE SENSOR	COLD WATER SUPPLY LINE TO WWHP(s)
T-M14	VERIS	TIH-SERIES	TEMPERATURE SENSOR	HOT WATER SUPPLY LINE FROM WWHP(s) TO ST-1 THRU ST-5
T-M15	VERIS	TIH-SERIES	TEMPERATURE SENSOR	WWHP SOURCE LOOP FLUID, FROM WWHP(s) TO WASTEWATER VAULT
T-M16	VERIS	TIH-SERIES	TEMPERATURE SENSOR	WWHP SOURCE LOOP FLUID, FROM WASTEWATER VAULT TO WWHP(s)
T-V1-V8	CASCADE ENGINEERING	CUSTOM BUILD	TEMPERATURE SENSOR TREE	thermocouple temperature tree (vault) - has 8 thermocouples and signal processors (ProSense XTD-0200F-T)
T-M22	VERIS	TIH-SERIES	TEMPERATURE SENSOR	INCOMING COLD WATER SUPPLY LINE
T-M25	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING SOURCE LINE FROM WWHP-1
T-M26	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING HW LINE FROM WWHP-1
T-M27	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING SOURCE LINE FROM WWHP-2
T-M28	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING HW LINE FROM WWHP-2
T-M29	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING SOURCE LINE FROM WWHP-3
T-M30	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING HW LINE FROM WWHP-3
T-M31	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING HW LINE FROM RCC-1
T-M32	DWYER	S2-4 SERIES	STRAP-ON TEMPERATURE SENSOR	OUTGOING HW LINE FROM GWH-3

Hourly outside air temperature readings were pulled from a nearby National Oceanic and Atmospheric Administration (NOAA) weather station and added to the dataset.

Following is a qualitative overview of the key quantities of interest in each part of the system.

Wastewater Vault

- Wastewater Level (for imputed flow rate). Tracking the level of wastewater in the vault is important for two reasons. First, due to the impracticality of conducting a flow measurement in the wastewater stream, the vault level measurement, combined with the vault geometry, is our only reasonable means of assessing the wastewater flow, and hence the relative amount of hot and cold water in the total water usage. This was a key assumption to the design tool. In addition, the simulation tool suggests theoretical efficiency gains from strategically pumping the vault down before the morning rush. A vault level measurement allows us to verify the pumping strategy and controls.

- Temperature profile of wastewater. The amount of mixing in the wastewater vault represents another key assumption of the simulation tool. We assumed a thermally well-mixed vault for the purposes of design, although it is likely that some temperature stratification develops, with incoming warm wastewater at the top of the vault while heat exchanger plates cool the wastewater at the bottom of the vault. It is possible that temperature layers within the vault could diminish the effectiveness of heat extraction, and this finding could prompt some sort of intervention to assure that the vault mixes (unless thermal stratification occurs that is beneficial to the heating system). To this end, we have a temperature "tree" taking measurements at different levels within the vault.
- Flow and temperature of the working fluid in and out of the vault to the heat pumps. Flow in the line of working fluid from vault heat exchanger plates to the heat pumps as well as supply and return temperature on the line provide a calculation for heat removed from the wastewater vault.

Bank of Heating Sources

- Electricity usage (True RMS) of heat pumps and circulation pumps. This provides the energy use of each individual RCC and will be used for calculating both total energy use and system efficiency.
- Electricity usage of fossil gas backup heater pumps. This measurement will indicate when the gas backup heat operates. When the gas backup heat activates on only the main heating loop (and not the recirculating loop), we can use the utility-grade fossil gas meter to still calculate main heating loop efficiency.
- Flow and temperature – incoming and outgoing – for the entire primary heating source loop. This allows calculation of the total heat added to the domestic hot water, although it does not allow a breakdown by individual heat sources. The heat added here provides the numerator for a COP calculation of the main heating loop.

Bank of Storage Tanks

- Temperature at each tank. These measurements help verify control strategy and assess the amount of available hot water. In addition, the simulation tool assumes perfect stratification of the storage bank; i.e., an "imaginary piston" with hot water on one side and cold water on the other. Severe departures from simulation assumptions would prompt an update.
- Flow in and out of storage tank. The flow through the storage tanks is actually bi-directional: during times of high-water demand before a call for heat is activated, water may flow directly from the city mains into the storage bank. During times of no flow concurrent with a recovery event, water will be pulled from the back end at ST-1. Flow meters will allow calculation of the direction and volume of flow, which is mainly useful for diagnostic and confirmatory purposes.

Recirculation Loop

- Electricity usage (True RMS) of heat pump and associated circulating pump. This provides the energy use of the heat pump by itself and for the COP calculation of the recirculation heating loop.

- Electricity usage of fossil gas water heater backup pump. Similar to the gas backup pumps on the main heating loop, this measurement indicates when the backup gas heat is running. Again, the gas meter will allow us to continue to calculate COP on the recirculation loop in the event that only the recirculation gas backup operates. If gas backup engages on both the recirculation loop and the main heating loop simultaneously then we will only be able to calculate a single, overall system COP for the entire schematic, lumping the main heating loop and the recirculation loop together.

Ecotope set up an online tool to view raw data and hourly and daily averages for each of the monitored points on the WWHP system, as well as calculated values like COP and heat outputs. These data were automatically updated nightly, allowing the engineers and installers commissioning the project to quickly receive feedback on changes they made to the system. Partial data were collected and made available through the online tool since October 2019. Initial data review revealed that several adjustments were needed, including replacement of two flow meters, which took place in January 2020. Full M&V data have been available since January 28, 2020.

M&V & Commissioning Timeline

For now, a brief summary of the M&V component installation is provided here. The M&V system was installed by Ecotope in late 2018, but due to the site not being sufficiently occupied, it was not possible to perform a full system commissioning at the same time the M&V system was able to compile data. (We should note that the data at that point were collected only locally; it took until mid-2019 to get remote data access problems solved). Also, due to changing electrical code requirements imposed by the City of Seattle, some of the M&V system components had to be upgraded in early 2019. The M&V system passed the City's electrical inspection in April 2019.

Figure 12 shows the chronology of the most recent events at the site. It is important to note that M&V data were very useful not just in characterizing system performance, but in providing insight into a variety of problems with system operation.

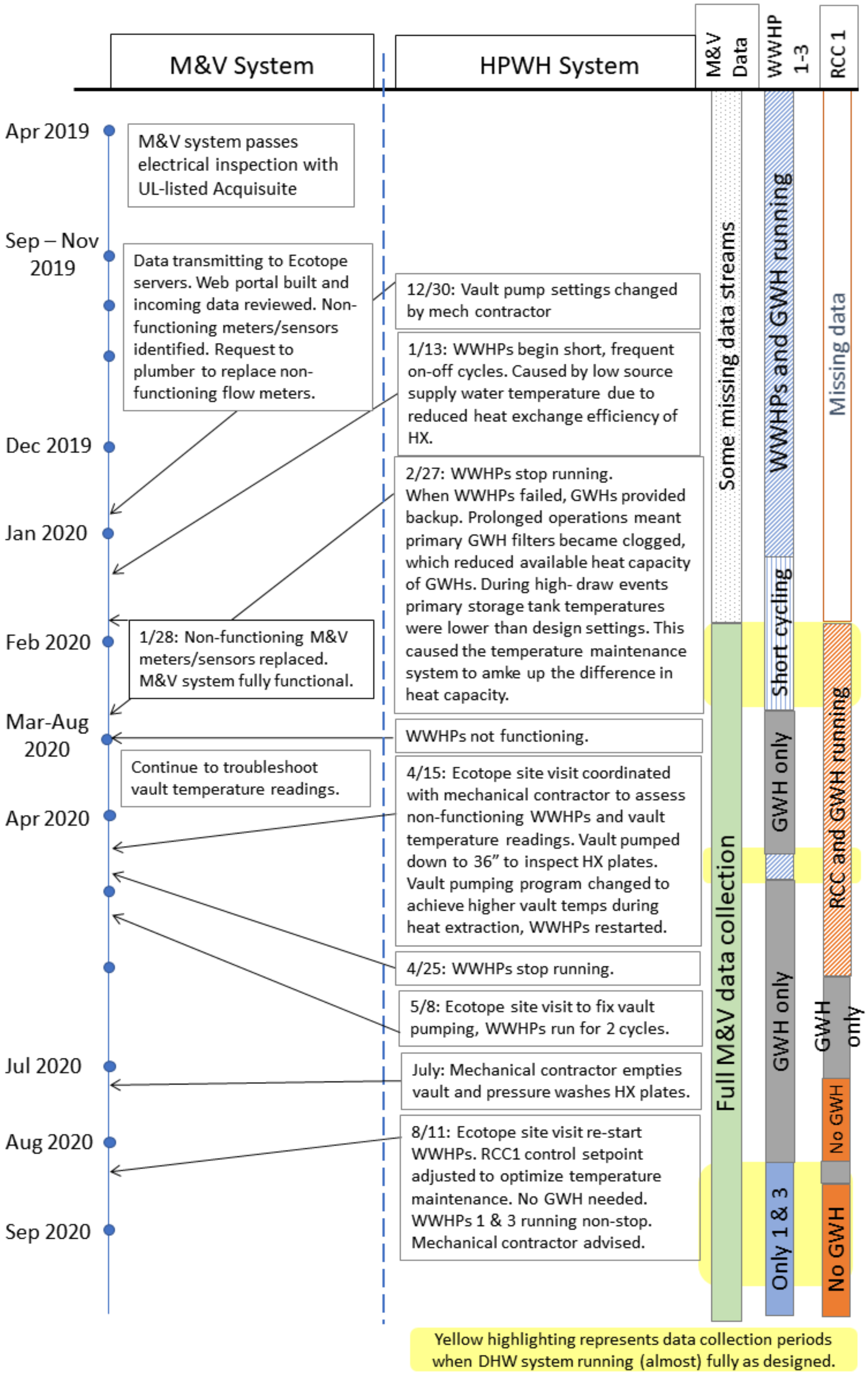

Figure 12. Timeline of M&V and System Commissioning Events

Initial review of the incoming data showed that several data streams were compromised. Importantly these included two flow meters that had to be replaced to have all the needed measurements to calculate performance. New flow meters were ordered, and a plumber hired to replace the non-functioning flow meters in late January 2020. Observations of the functioning M&V data streams showed that the WWHPs began short, frequent on-off cycles in late Fall 2019. This was attributed to low source supply water due to reduced heat exchange efficiency of the heat exchanger plates in the vault. This was later determined to be caused by incomplete emptying of the vault. Basically, the vault was accumulating a layer of sludge that was impeding the heat exchange process in the vault. This meant cooler water was being provided to the WWHPs, which began faulting out on cold incoming water temperatures.

As a result of the events above, the WWHPs stopped functioning approximately a month after full M&V data were being collected. The primary heating load was now being carried by the back-up GWHs. Prolonged operation of these units meant their filters quickly clogged reducing their operating capacity, such that, during high-draw events, the primary storage tank temperatures were lower than design settings. The temperature maintenance system now had to make up the difference in heating capacity and needed both the RCC and the temperature-maintenance GWH to provide the needed load.

Throughout the winter and into spring 2020, Ecotope was in communication with the mechanical contractors to work towards a solution. In April 2020, Ecotope met the mechanical contractors to examine the conditions on-site and to initiate a change in the vault pump settings. While there, the vault was pumped down considerably so that the HX plates could be visually examined. It was clear that the heat exchange process was being hampered by a coating on the HX plates. Pump settings were changed to keep a lower volume in the vault (to keep warm water closer to the HX plates) and to empty the vault more thoroughly overnight (to reduce accumulating sludge). The WWHPs were re-started at this time and the mechanical contractor reserved a pump truck to perform further maintenance activities.

The WWHPs ran for approximately ten days in mid-April and then stopped. Ecotope returned to the site to re-start the equipment, which ran for just a few cycles before stopping again. During this period, a recurring issue with the RCCs control board meant that the RCC became non-operational. In late July, the mechanical contractor’s reservation was fulfilled, and the vault was emptied in order to pressure-wash the HX plates. The RCC control board issue was also addressed, and the RCC re-started. In early August, Ecotope returned to Sitka re-start the WWHPs and adjust the RCC control setpoint for temperature maintenance. At this point, the WWHPs began provided 100% of the primary heating, meaning there was enough thermal resource in the wastewater to be able to provide all of the primary water heating using the wastewater as a source.

These events are summarized in Figure 12. Ecotope continued to monitor the system frequently and soon observed that only two of the three WWHPs were running, and that they were not shutting off per the controls sequence of operations. Additionally, the RCC had a recurrence of the control board issues. Since September, Ecotope has consulted frequently with the mechanical contractor to resolve the ongoing issues with both the primary and temperature maintenance equipment. As of the writing of this report, some of the WWHP control issues have been resolved, but troubleshooting is continuing, and the RCC is providing temperature maintenance with some GWH assistance.

RESULTS

This section summarizes the water usage of building occupants, water temperatures throughout the DHW system, energy usage of the water heating equipment, and recent system performance. Depending on the sensor, data have been available since October 2019, or since late January 2020. Even with partial data, interesting insights are available.

Water Use

Data from October 2019 through October 2020 are included in these summaries. Figure 13 shows average daily gallons of hot water used by apartment.

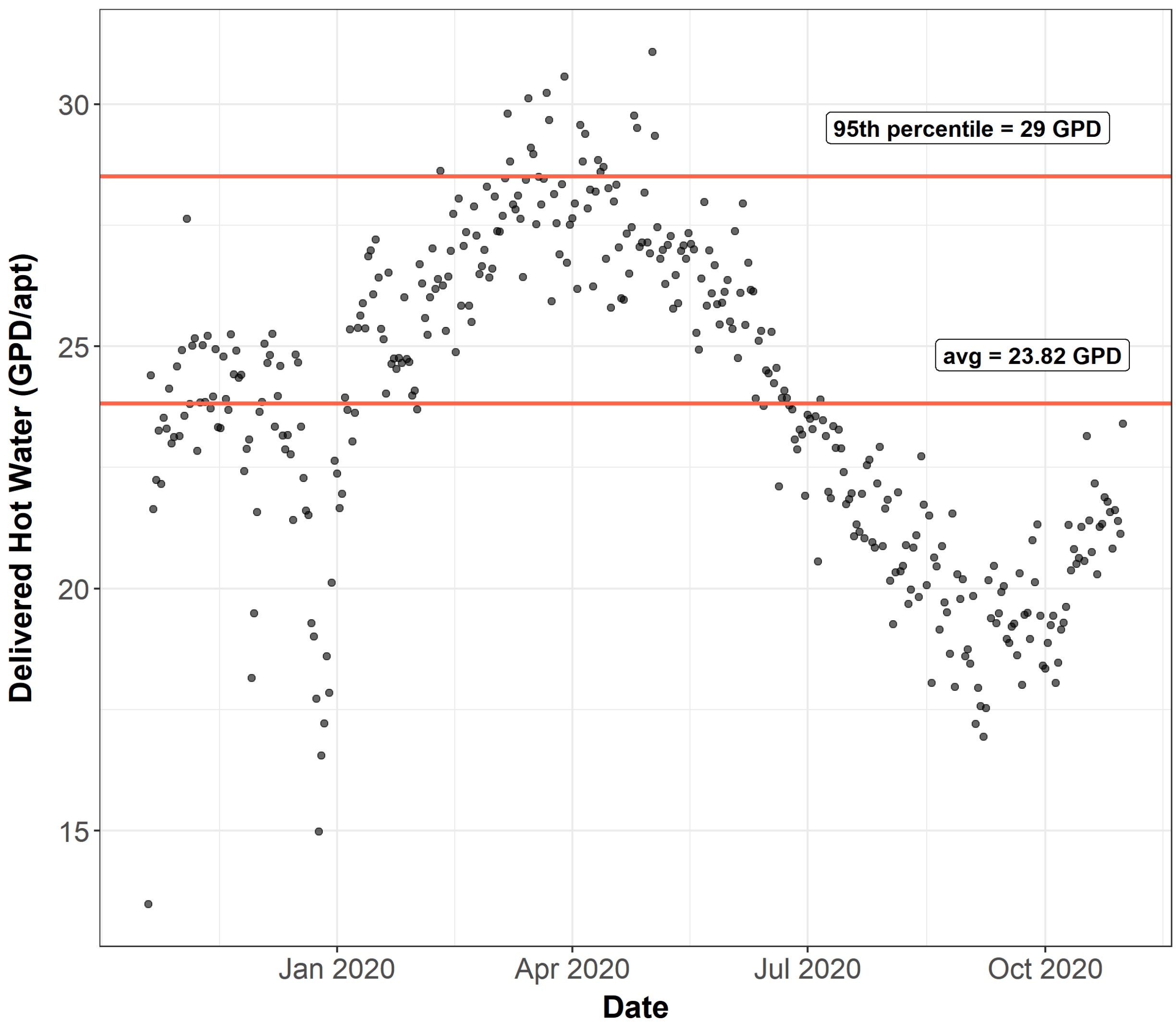

Figure 13. Gallons Hot Water per Day per Apartment

There is a challenge to estimating annual usage (discussed below); nevertheless, this information reveals several informative trends:

- It is likely that the 2019/2020 holiday periods were popular travel times. This is reflected by reduced water usage during those times: end of November 2019, and end of December/beginning of January 2020.
- Recent events in Washington state (and elsewhere in the country and world) have most of the population following COVID-19 “stay at home-stay healthy” orders. This means more people spent time at home beginning in early March 2020. Although water usage typically increases seasonally during the winter months, spring 2020 water usage rates appeared high. This was attributed to Washington state’s initiation of ‘Stay Home-Stay Healthy’ orders. Understanding typical water usage in this building will require additional monitoring given current global circumstances.

The building’s leasing team estimated occupancy in April 2020 to be 547 full-time occupants (over 95% of full occupancy), or 1.5 occupants per apartment. Using this occupancy rate for the monitoring period results in an average of 16.5 gallons per day per person. As discussed earlier, values may change with continued monitoring. (The estimate of occupancy as of early December 2020 is 518 people).

Figure 14 shows daily water profile signatures for weekdays and weekends, for three time periods from October 2019 through September 2020.

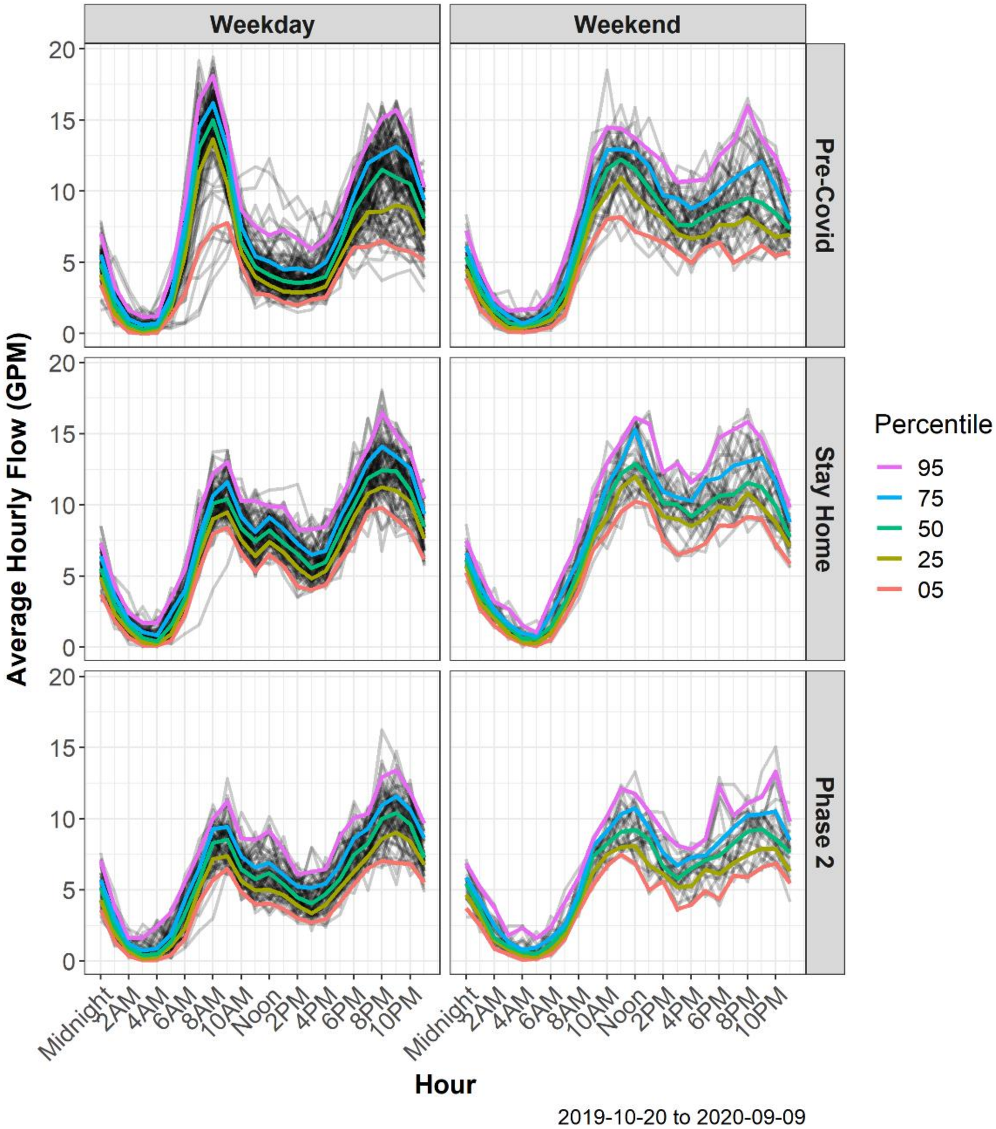

Figure 14. Average Hourly Flow Over Three Periods (2019-2020)

The top panel shows a typical draw profile, similar to what has been seen in other M&V projects in other Seattle multifamily buildings[6], with peak weekday usage occurring between 6-8 a.m. with a second lower peak in the evening. Weekend morning peaks are shifted a little later in the day and show more mid-day usage than during the week. In March of 2020, as with many other locations, Washington state came under "stay at home" orders due to COVID-19. The second panel in Figure 14 shows a shift in peak usage while building occupants are staying at and working from home. The morning peak is substantially smaller and shifts more to 8-9 a.m. As a result, the daily draw profile becomes more evening- dominated.

[6] Heller, J. and S. Oram. 2015. *RCC Pilot Project: Multifamily Heat Pump Water Heaters in Below Grade Parking Garages in the Pacific Northwest*. Submitted to Bonneville Power Administration.

In June of 2020, Seattle entered COVID "Phase 2" status, meaning that additional non-household activities were permitted, and restaurants and other local business re-opened at reduced capacities. It is likely that more people resumed spending additional time away from their homes, especially on weekends. We observed lower usage during weekday evening peaks and weekends than during the "stay home" period. However, this also corresponds with decreases in hot water usage that are normally seen during spring and summer months.

Central heat plant capacity and storage volume were calculated using a 3-hr peak load and a daily estimate of 20 gallons of hot water use per occupant per day. With all systems operating as intended, the WWHPs met the full building DHW load. This was shown to be true in August-September when the hot water load was met without any fossil gas input. The less peaky COVID load profile is further beneficial as peaky loads require more heat pump or storage capacity to meet the load over a day. At Sitka, the system design included sufficient extra storage capacity to provide a safety factor as standard practice in domestic hot water systems. An additional WWHP unit was also provided for system redundancy.

Water Temperatures

Figure 15 shows daily average water temperatures for the primary heating, temperature maintenance, and recirculation loops, as well as incoming city water temperatures and ambient outside air temperatures (OAT) from a nearby National Oceanic and Atmospheric Administration (NOAA) weather station. Three sensors did not begin logging data until December 2019.

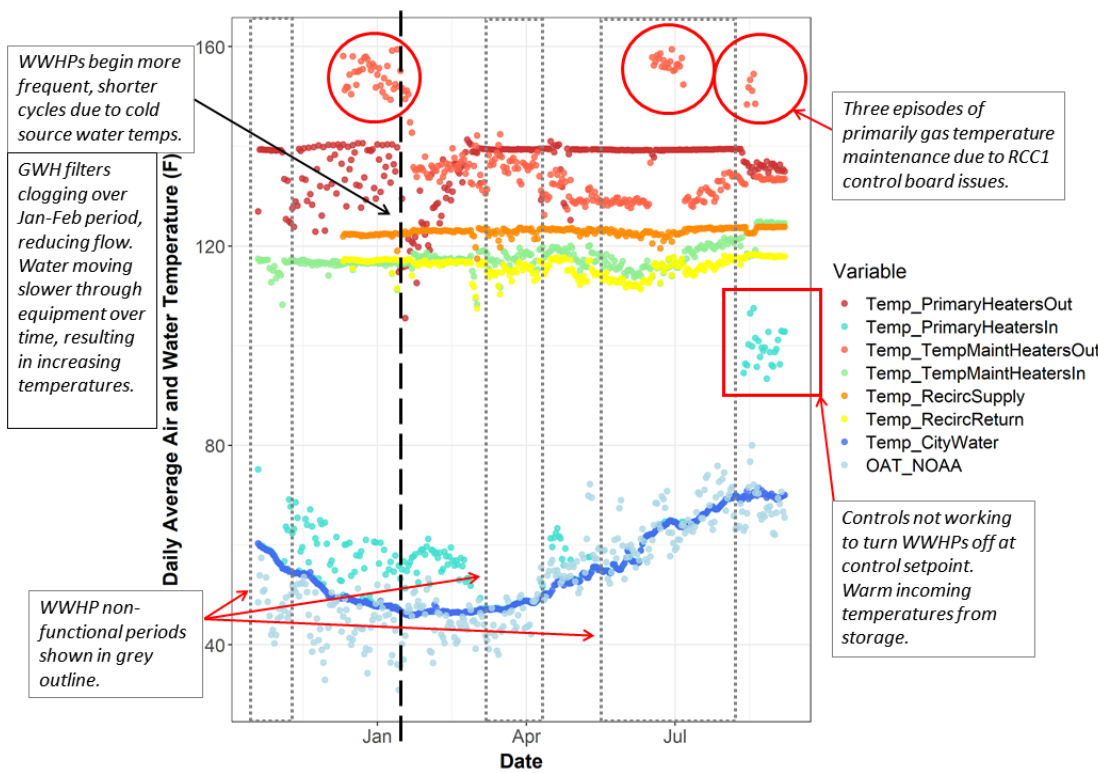

Figure 15. Temperatures entering and leaving primary heaters, temperature maintenance heaters, and recirculation loops

There are several things to notice in Figure 15:

- January through March city water temperatures represent the coldest conditions that will typically be present, ranging from 46 to 49° F.
- Periods when the WWHPs were functioning correspond to higher temperatures through the primary heating loop (until late February 2020, briefly in early April, and again starting in August 2020). Much higher temperatures coming into the Primary Heaters in August and September 2020: the WWHPs were not turning off when the storage temperature reached the control setpoint. This issue was mostly resolved by the mechanical contractor in October 2020, but controls optimization is on-going.
- In January 2020, there was a marked change in the WWHP cycles. In early monitoring, run times could be 12-16 hours in length. Starting in January, run times were substantially shorter. This shift was caused by low source supply water temperature due to reduced heat exchange efficiency of HX plates in the vault.
- Periods with high temperatures (>130° F) leaving the temperature maintenance loop correspond to periods when the temperature maintenance heat pump (RCC1) was either not functioning fully, or not running at all (highest temperatures). During these periods, the gas water heater provided temperature maintenance. RCC1 has had a recurring issue with a faulty solder on the control board over the monitoring period.
- The DHW system began operating without gas water heaters for a sustained period on August 20, 2020.

Figure 16 shows the temperatures entering and leaving the WWHPs and leaving the temperature maintenance RCC. These are the temperatures experienced by individual pieces of equipment, versus the loop temperatures shown in Figure 15. Daily average temperatures are depicted by month over the full M&V period.

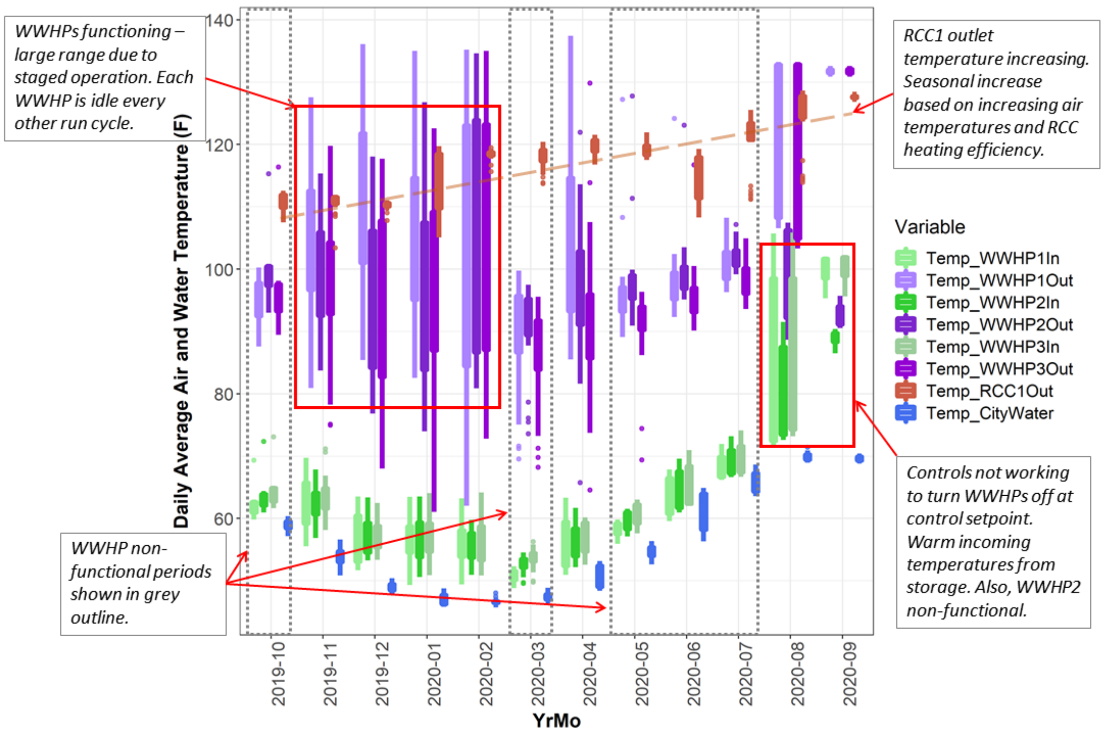

Figure 16. Temperatures entering and leaving WWHP and RCC equipment

Items of note from Figure 16 include:

- Large temperature ranges are seen in water temperatures coming out of WWHP equipment when the WWHPs are running. This is due to the staged operation of the WWHPs, meaning lower temperatures are recorded when that individual WWHP is not running for a given cycle. Water temperatures into and out of the WWHPs are more uniform when the WWHPs are not running over long periods – these periods are outlined in dashed boxes in the figure above.
- In recent months (August and September 2020), incoming water temperature to the WWHPs has been high. This is due to a controls issue. WWHPs 1 and 3 are running constantly, and when the storage tanks are filled with warm water, the warm water from ST-1 is returning to the WWHPs.
- WWHP2 had not turned on once WWHPs were restarted in August 2020; hence the low outgoing water temperature from that unit compared to the other two WWHPs.
- RCC1 outlet temperature increased seasonally over the monitoring period. Also, the RCC set point was adjusted in August 2020 to optimize temperature maintenance function. The thermal on temperature of RCC1 was raised to initial the heating cycle earlier with more stored thermal energy in the temperature maintenance storage tank. This reduced the backup gas water heaters usage as it was cycling on occasionally at the end of the RCC1 cycle.

Equipment Function

Full system operation (heat pumps water heaters as primary heating equipment) was limited to approximately a month in February 2020, and again for several weeks starting August 20, 2020, so annual performance estimates are not possible with the data available as of the writing of this report. The temperature maintenance RCC has also experienced recurring issues with its control board, which made it non-operational for periods over the spring and summer of 2020. This section focuses on the period of M&V data collection from late August-late September 2020 when WWHPs were functioning and the RCC was also operating as intended.

System Performance

Beyond monitoring and providing insights for troubleshooting and system optimization, the M&V data have been collected to address the most important aspects of performance Although there are still system function and controls issues to resolve, Sitka's domestic hot water needs were met with no fossil gas input once the WWHPs were restarted after the vault cleaning and the RCC control board issue resolved. Although this is not sufficient monitoring to estimate annual performance, short-term performance can be calculated at various scales.

- COP WWHP – performance of the WWHP loop. This is the energy out of the WWHP plant, divided by the energy input to the WWHPs.
- COP PrimaryHeaters – performance of the primary heating plant. This includes a small energy input to the back-up gas water heaters even when they are not being used to support the primary heating load.
- COP TempMaintHeaters – performance of the temperature maintenance heating system . As with the WWHP plant, this includes energy input to the RCC and the GWH (if it is being used).
- COP DHWSys – is the overall performance of the domestic hot water system. It includes the primary and temperature maintenance loads.

DHW system COP is calculated as:

$$COP_{DHWSys} = \frac{Delivered_{Energy\ Out} + Recirculation\ Loss_{Energy\ Out}}{PP_{Energy\ In} + TM_{Energy\ In}}$$

Where:

- $Delivered_{Energy\ Out}$ = Heat delivered to the water used in the building
- $Recirculation\ Loss_{Energy\ Out}$ = Heat lost in the circulation loop.
- $PP_{Energy\ In}$ = Primary Plant Energy (sum of all WWHPs and/or Gas WHs)
- $TM_{Energy\ In}$ = Temperature Maintenance Energy (sum of RCC / Gas WHs)

The data summarized below are for this most recent period, and therefore represent short-term performance only. Continued monitoring, optionally paired with seasonal adjustments, would be required to estimate annual COPs. Figure 17 shows the daily COP for the WWHPs, the primary heating plant, the DHW system COP, and that of the temperature maintenance plant with four modes of operation:

- RCC1 not running. WWHPs and GWH3 doing primary and temperature maintenance heating, respectively.
- WWHPs and RCC solely providing DHW at Sitka.
- RCC1 not running. WWHPs and GWH3 doing primary and temperature maintenance heating, respectively.
- WWHPs providing DHW at Sitka with some temperature maintenance gas support.

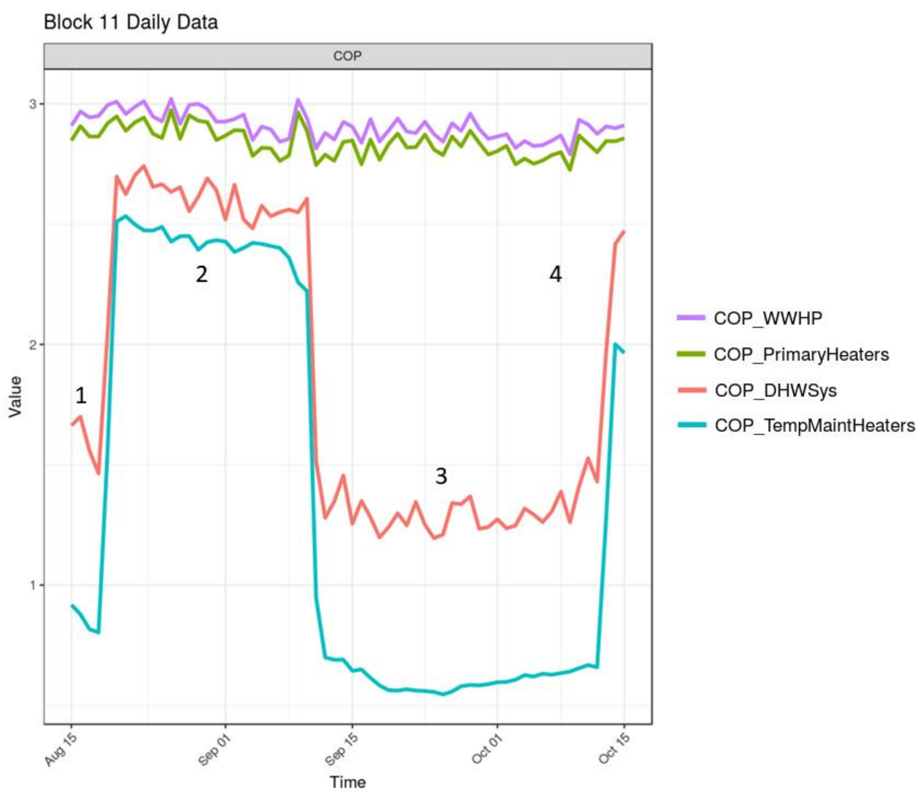

Figure 17. DHW System COP August 15 to October 15

During the period shown in Figure 17, the recurring control board issue with the temperature maintenance RCC can be seen in events 1 and 3. However, periods 2 and 4 show the performance when the system was operating almost as designed.

When the system is fully operable, with all primary and temperature maintenance equipment able to operate, the DHW system was operating without any fossil gas input for several weeks across August and early September (period 2). The average COPs during this period were 2.95 for the WWHP plant and 2.88 for the primary heating plant, which includes a small energy input to the GWHs even when they are not used for producing hot water. The DHW system operated with a performance of 2.6 and the temperature maintenance plant with a COP of 2.4. Of note is the reduction in system COP that occurs when the temperature maintenance load is being supported with fossil gas in period 3. This was due to the RCCs recurring control board issue which has been addressed as of the writing of this report.

From mid-August until recently (including the period in Figure 17), the WWHPs were operating almost continually due to a communication and controls issue. This is creating a parasitic energy draw and inefficient operation when ST-1 is above 100°F. It is likely that this is reducing the WWHP, Primary, and DHW system COPs slightly as more electrical energy is being added to the system than is needed. Resolving the temperature maintenance RCC issue, brought that equipment back to an operable status at event 4. The service contractor is continuing to address the WWHP function and the manufacturer has been notified and is addressing the issues with the service contractor. It is currently assumed the issue should be resolved shortly.

CONCLUSION AND RECOMMENDATIONS

The design and implementation of a wastewater-based heat pump water heating system is complicated, but the underlying physics of the process have proven out at Sitka Apartments. The system was designed as a single-pass system, where the primary heating loop includes R134a water-to-water heat pumps and a heat exchanger system installed inside the wastewater vault. The heated water is stored in several large, well-insulated tanks. The tank and piping layout optimize the primary heat pump efficiency via tank stratification (which means the coolest water is consistently heated by these heat pumps). To keep water consistently at desired service (tap) temperatures, a separate air-to-water heat pump is used rather than passing this warm water back through the primary loop. This design was arrived at after several alternate designs had been engineered and metered by Ecotope. Ecotope also designed and oversaw installation of a measurement and verification systems that allowed remote access to data and calculation of real-time operational efficiency.

When the primary water heating loop and recirculation (temperature maintenance loop) are running as designed, the system meets the demand of the 500-occupancy apartment complex using only heat pump heat transfer; the overall system efficiency in these conditions is about 2.6 (with the primary equipment efficiency alone operating with a COP of about 2.9). Given the cost of the system and the energy savings vs an electric resistance system, the overall simple payback for the added cost of the system (included added engineering) is less than 5 years (using the Northwest's very low commercial electricity rate of $0.08/kWh).

Because of the amount of custom engineering required for this system, and because of ongoing concerns about the condition of the primary heat exchanger and control components, the type of system cannot be regarded (yet) as a turnkey solution for efficient heating of hot water in multifamily buildings. In mild climates like Seattle, wastewater heat pump systems do not yield sufficient efficiency improvement compared to air-source CO_2 systems.

Several additional points deserve mention

- Alarm notifications and feedback loops (M&V) are essential for new technologies and systems like this.

- System sizing is critical for all HPWH systems serving Multifamily buildings with a central heat plant configuration. One such tool, optimized for multifamily buildings, is found at Ecosizer.ecotope.com.
- Wastewater management is a significant challenge in wastewater heat recovery systems like the one at Sitka. More mitigation techniques are likely needed to prevent fouling of the source heat exchanger system. These are needed for turnkey systems. The product manufactured by Sharc industries is likely a viable technology for turnkey applications.
- The technology is more applicable to cold climates since it provides a relatively constant high temperature source of heat on an annual basis. Therefore, the heat pumps do not have to be oversized to meet the DHW load at cool ambient air temperature while operating at a reduced capacity and efficiency.

APPENDIX A: M&V CHRONOLOGY TABLE

Table 3. Measurement & Verification Events Timeline

Event	Year	Month	M&V Observation	Event Cause	Resolution
E1	2019	Apr	M&V system passes City of Seattle electrical inspection with UL-listed Acquisuite and other components. (Flex IOs also had to be housed in rated assemblies and all signal wire within 7' of mech room floors had to be run in conduit.)	M&V system re-wired and re-inspected	N/A
E2	2019	Nov	Begin monitoring. Not all meters are functional. Faulty flow meters are identified and scheduled for replacement.	N/A	N/A
E3	2019	Dec	Vault level increased / pump-out reduced	Vault pump settings changed by mechanical contractor	N/A
E4	2020	Jan	N/A	N/A	Nonfunctioning M&V meters/sensors replaced. M&V system fully functional by the end of the month.
E5	2020	Jan	WWHPs begin a pattern running very short, frequent on-off cycles.		
E6	2020	Feb	WWHPs stop functioning.	Per mechanical contractor, WWHPs were tripping out on cold inlet temperature	See Apr site visit – E7
E7	2020	Apr	Ecotope site visit coordinated with mechanical contractor. Vault pumped down to 36" to inspect HX plates.	Visit to assess non-functioning WWHPs, and vault temperature readings.	Determined that HX no longer functioning as they should, and that pumping schedule should be changed to keep vault level lower throughout the day. Ecotope adjusted vault pump programming. Mechanical contractor applied for waiting list to get access to a pump truck.

Table 3: Measurement & Verification Events Timeline *(continued)*

Event	Year	Month	M&V Observation	Event Cause	Resolution
E8	2020	Apr	WWHPs running continuously.	Relay left on at site visit.	Resolved by follow-up mechanical contractor visit to address relay.
E9	2020	Apr	WWHPs stop functioning. Also vault pump programming reverted to previous settings	N/A	See May site visit – E10.
E10	2020	May	Ecotope site visit to re-start WWHPs, re-initialize new vault pumping programming, and add resistor to vault optical sensor circuit.	N/A	This was to resolve non-functioning WWHPs and reverted programming. WWHPs only ran for a few cycles before falling idle again.
E11	2020	June	RCC1 stopped functioning.	Recurring problem with solder on control board.	Issue fixed July 6. RCC1 running again.
E12	2020	July	Vault pumped and HX plates pressure washed	Follow-up from Apr site visit.	N/A
E13	2020	Aug	Ecotope site visit coordinated with mechanical contractor. WWHPs re-started.	After the vault clean-out, WWHPs had not restarted. This action was to resolve idle WWHPs.	Two of the three WWHPs began doing the primary heating. Primary GWHs no longer running (not needed for water heating).
E14	2020	Aug	RCC1 stopped functioning.	Recurring problem with solder on control board.	Mechanical contractor was able to resolve control board issue. Function resumed a week later.
E15	2020	Aug	Non-stop running and frequent short-cycling of the WWHPs 1 & 3 observed in M&V data. Also, WWHP2 not functional.	Attributed to high incoming water temperatures associated with the WWHPs continuing to run even when storage is full of hot water. Control settings need adjustment	Mechanical contractor notified.
E16	2020	Sept	WWHP functioning addressed, but system flipped from 1 & 3 non-stop operation to 1 & 2. However, RCC control board issues also recur in September.	Mechanical contractor working on WWHP staging, and aware of RCC control board issue.	Mechanical contractor notified.

APPENDIX B: COMMISSIONING REPORTS

ECOTOPE

Runberg: Block 11

Functional Performance Test

Domestic Hot Water – WWHP

Mechanical - Emerald Aire Scope

SYSTEM DESCRIPTION

THE WASTE WATER HEAT PUMP (WWHP) SYSTEM PROVIDES DOMESTIC HOT WATER FOR THE PROJECT. SEWAGE FROM THE BUILDINGS IS ROUTED TO A SEWAGE VAULT IN THE PARKING GARAGE. THE VAULT INCLUDES HEAT EXCHANGERS CONNECTED VIA A CLOSED HYDRONIC LOOP TO A BANK OF WATER-TO-WATER HEAT PUMPS. THE WATER-TO WATER HEAT PUMPS EXTRACT HEAT FROM THE SEWAGE VAULT TO HEAT A BANK OF HOT WATER STORAGE TANKS THAT SUPPLY DOMESTIC HOT WATER TO THE PROJECT. THE WWHP SYSTEM CONSISTS OF THREE INTER-RELATED SYSTEMS WITH TWO CONTROL SYSTEMS THAT COMMUNICATE WITH EACH OTHER. THE THREE SYSTEMS ARE AS FOLLOWS:

1. DOMESTIC WATER HEATING SYSTEM: THIS SYSTEM INCLUDES THE EQUIPMENT ASSOCIATED WITH MAINTAINING HOT WATER IN THE DOMESTIC HOT WATER STORAGE TANKS. A CLOSED LOOP CIRCULATES WATER BETWEEN THE HEAT PUMPS AND THE SEWAGE VAULT HEAT EXCHANGERS. TEMPERATURE SENSORS IN THE STORAGE TANKS ARE USED TO STAGE IN THE HEAT PUMPS. IF THE HOT WATER STORAGE IS DRAWN DOWN TOO FAR, GAS WATER HEATERS WILL KICK IN TO BACK-UP THE HEAT PUMPS.
2. CIRCULATION LOOP HEATING SYSTEM: HOT WATER IS CONTINUOUSLY CIRCULATED THROUGHOUT THE BUILDINGS TO PROVIDE FOR QUICK HOT WATER DELIVERY TO ALL APARTMENTS. THE WATER TEMPERATURE IN THIS LOOP IS MAINTAINED BETWEEN 110-122F BY AN AIR-TO-WATER HEAT PUMP OR REVERSE CYCLE CHILLER (RCC) LOCATED IN THE GARAGE.
3. SEWAGE MANAGEMENT SYSTEM: SEWAGE EJECTOR PUMPS ARE USED TO EMPTY THE SEWAGE VAULT EACH NIGHT INTO THE CITY SEWER SYSTEM.

MODES OF OPERATION

THE COMMISSIONING SHALL BE COMPLETED IN TWO PHASES: GAS WATER HEATING SYSTEM ONLY & FULL WWHP SYSTEM WITH GAS BACK-UP.

FOR THE GAS WATER HEATING SYSTEM COMMISSIONING, THE FOLLOWING OPERATION MODES SHALL BE TESTED: STANDBY, HEATING CALL, AND TEMPERATURE MAINTENANCE.

FOR THE FULL SYSTEM COMMISSIONING, ALL THREE SYSTEMS SHALL BE TESTED. A SERIES OF OPERATION MODES SHALL BE TESTED AGAINST THE SEQUEUNCE OF OPERATION INCLUDING: HEATING CALL, TEMPERATURE MAINTENANCE, OVERFLOW PROTECTION, SEWAGE EJECTION, HEAT PUMP PROTECTION, AND PUMP PROTECTION.

Checks performed by: Colin Grist Signature: Date: 12/07/18

Page 1

ECOTOPE

Runberg: Block 11

Functional Performance Test

Domestic Hot Water – WWHP

SYSTEM: **WWHP - FULL SYSTEM**	DATE: 12/07/18
EQUIPMENT: **WWHP-1,2,3; RCC-1; GWH-1,2,3; PMPS**	AREA SERVED: **ALL**

HEATING EQUIPMENT PARAMETERS							
EQUIPMENT:	**WWHP-1**	**WWHP-2**	**WWHP-3**	**RCC-1**	**GWH-1**	**GWH-2**	**GWH-3**
HEATING CAPACITY	184,800 Btu/hr	184,800 Btu/hr	184,800 Btu/hr	110,300 Btu/hr	183,900 Btu/hr	183,900 Btu/hr	183,900 Btu/hr
REFRIGERANT CHARGE	Pending Equipment start up reports				-	-	-
OUTGOING TEMP SETPOINT DESIGN / MEASURED	135F / 140 F	135F / 140 F	135F / 140 F	8-12F RISE 8 F	140F / 140 F	140F / 140 F	180F / 180 F
INCOMING MAX TEMP DESIGN / MEASURED	110F / 110 F	110F / 110 F	110F / 110 F	130F / 130 F	-	-	-
DESIGN FLOWRATE (POTABLE)	Pending Equipment start up reports				-	-	-
~~TIME DELAY~~ Minimum compressor run time on Colmac equipment	10-min	10-min	10-min	6-min	None	None	None
MINIMUM RUN TIME DESIGN / MEASURED	S1 0-MIN / Stage 1 = 0min	S2 15-MIN / Stage 2 = 15min	N/A N/A	1-MIN / 0-min	NONE None	NONE None	NONE None

NOTES:
-- WWHP-1,2,3 and RCC-1 have a minimum compressor run time to prevent short cycling and compressor longevity. This is internal to the Colmac equipment.
-- Measured across GWH-3 while in operation: Flow 4.4 GPM, Tin=116 F, Tout=180 F, Heat cap. = 140,800 Btu/hr = 11.7 tons

PUMPING EQUIPMENT PARAMETERS						
EQUIPMENT:	**PMP-W1**	**PMP-W2**	**PMP-W3**	**PMP-G1**	**PMP-G2**	**PMP-G3**
DESIGN / MEASURED FLOWRATE (GPM)	35 / Not measured	35 / Not measured	35 / Not measured	3.9 /	3.9 /	4.2 /
DESIGN / MEASURED DELTA T (°F)	7.5 / 6-8 F	7.5 / 6-8 F	7.5 / 6-8 F	90 / 90 F	90 / 90 F	66 / 66 F
TIME DELAY	None	None	None	None	None	None
MINIMUM RUN TIME	None	None	None	None	None	None

NOTES: PMP-G3 AT 66F DELTA T AND 75% CAPACITY AT GWH-3 FLOW RATE SHALL BE 4.2GPM DELIVERING WATER AT 180F FOR A TOTAL CAPACITY OF 11.5 TONS OR 100W/APT LOSS.

SEQUENCE OF OPERATION – STAND BY							
EQUIPMENT:	**WWHP-1**	**WWHP-2**	**WWHP-3**	**RCC-1**	**GWH-1**	**GWH-2**	**GWH-3**
RECORD EQUIPMENT ON/OFF	Off	Off	Off	Off	Off	Off	Off
RECORD TANK TEMPERATURES	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	-
• DESIGN TEMP.	>100F	N/A	>90F	>90F	N/A	>130F	-
• MEASURED TEMP.	101 F	N/A	91 F	91 F	N/A	131 F	-

NOTES:
-- None

Checks performed by: Colin Grist Signature: Date: 12/07/18

Page 2

ECOTOPE

Runberg: Block 11

Functional Performance Test

Domestic Hot Water – WWHP

MV-1 Not included at this project

SEQUENCE OF OPERATION – HEATING CALL					
EQUIPMENT:	**STAGE 1**	**STAGE 2**	**GWH-1,2**	**PMP-G1,2**	**MV-1**
LEAD/LAG CYCLE TIME: 24-hr RECORD EQUIPMENT STAGES:	WWHP-1	WWHP-2	BACKUP	BACKUP	
T-1 LESS THAN 100°F. RECORD T-1:	T-1 = 94 F				
STAGE 1: RECORD SETPOINTS BELOW	-	-	-	-	-
• TURNS ON WHEN T-3 IN ST-3 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	90°F / 89 F	OFF / Off	OFF / Off	OFF / Off	~~CLOSED /~~
• TURNS OFF WHEN T-1 IN ST-1 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	100°F / 101 F	OFF / Off	OFF / Off	OFF / Off	~~CLOSED /~~
NOTES:					
STAGE 2: RECORD SETPOINTS BELOW	-	-	-	-	-
• TURNS ON WHEN T-3 IN ST-3 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	ON / On	90°F / 89 F	OFF / Off	OFF / Off	~~CLOSED /~~
• TURNS OFF WHEN T-1 IN ST-1 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	ON / On	100°F / 101 F	OFF / Off	OFF / Off	~~CLOSED /~~
NOTES: -- Stage-2 has 15 min delay after Stage-1 is called ON.					
GWH BACK-UP: RECORD SETPOINTS BELOW	-	-	-	-	-
• TURNS ON WHEN T-4 IN ST-4 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	ON / On	ON / On	90°F / 89 F	ON / On	~~OPEN /~~
• TURNS OFF WHEN T-1 IN ST-1 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	ON / On	ON / On	100°F / 101 F	ON / On	~~OPEN /~~
NOTES: -- MV-1 not called for on drawings or spec. Not included in scope of this project. -- GWH-1,2 are enabled with a 15 min time delay on second stage of gas water heating. Same as normal Stage-1 and Stage-2 (Normal - WWHP-1,2,3 acting as stage 1 and stage 2).					

SEQUENCE OF OPERATION – CIRCULATION TEMPERATURE MAINTENANCE				
EQUIPMENT:	**RCC-1**	**PMP-R1**	**GWH-3**	**PMP-G3**
DOMESTIC HOT WATER CIRCULATION				
• RCC-1 TURNS ON WHEN T-6 IN ST-6 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	125°F / 125 F	ON / On	OFF / Off	OFF / Off
• RCC-1 TURNS OFF WHEN T-6 IN ST-6 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	130°F / 130 F	OFF / Off	OFF / Off	OFF / Off
DOMESTIC HOT WATER BACKUP				
• GWH-3 TURNS ON WHEN T-6 IN ST-6 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	ON / On	ON / On	122°F / 122 F	ON / On
• GWH-3 TURNS OFF WHEN T-6 IN ST-6 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	ON / On	ON / On	126°F / 126 F	OFF / Off
NOTES: -- PMP-R1 is internal to RCC 1. -- RCC-1 on-site measurements 12/7/18: GAT=49 F; Flowrate (potable)=20.6 GPM; Tin=101.6 F; Tout=106.3 F; **Q=48,410 BTU/HR = 4.03 Tons**, 7 Tons nominal, 57% of nominal capacity. -- Circulation loop losses on-site measurements 12/7/18: Flowrate = 9.1 GPM; Tin=107 F (Recirc return); Tout=122 F (Hot mixed supply temp); **Q=68,250 BTU/HR = 5.69 Tons, approximately 52 W/apt unit**.				

Checks performed by: Colin Grist Signature: [signature] Date: 12/07/18

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Runberg: Block 11

Functional Performance Test

Domestic Hot Water – WWHP

SEQUENCE OF OPERATION – CONTROL SYSTEM ALARMS		
EQUIPMENT:	CONTROLLER	EMAIL
WWHP-1 FAILURE ALARM	Not tested. Pending bacnet points from Carrell for functional testing.	
WWHP-2 FAILURE ALARM	"	
WWHP-3 FAILURE ALARM	"	
GWH-1 ON ALARM	"	
GWH-2 ON ALARM	"	
RCC-1 FAILURE ALARM	"	
GWH-3 ON ALARM	"	
OUTGOING HOT WATER LOW TEMPERATURE ALARM	"	

NOTES:

-- Alarm Functions: Colmac equipment is capable of alarming and currently does when and issue is present. Colmac equipment does NOT send alarms to controller for controller to send out via web interface. Carrell is sending bacnet points to mechanical contractor. Controller alarm functions will be tested at a later date.

REVERT ANY SETTINGS ADJUSTED TO INITIATE A LINE IN CONTROL SEQUENCING BACK TO DEFAULT SETTING.

Checks performed by: Colin Grist Signature: [signature] Date: 12/07/18

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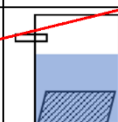
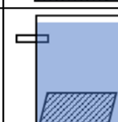
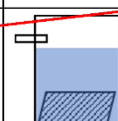
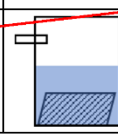
Functional Performance Test

Domestic Hot Water – WWHP

SYSTEM: **WWHP – VAULT LEVEL CONTROL**	DATE:
EQUIPMENT: ESP-1A, ESP-1B, T-7	AREA SERVED: **SEWAGE SYSTEM**

EQUIPMENT PARAMETERS – VAULT LEVEL CONTROL						
EQUIPMENT:	**ESP-1A**	**ESP-1B**	**T-7**	**OVR. SW.**	**PR. TR.**	**TIME CLK.**
~~FLOWRATE (GPM) DESIGN / MEASURED~~	~~450 /~~	~~450 /~~	~~-~~	~~-~~		
~~HEAD PRESSURE (FT) DESIGN / MEASURED~~	~~30 /~~	~~30 /~~	~~-~~	~~-~~		
TEMPERATURE **DISABLE** (F) DESIGN / MEASURED	-	-	<45 F / 45 F	-		
TEMPERATURE **ENABLE** (F) DESIGN / MEASURED	-	-	>50 F / 50 F	-		
~~PRESENT~~						
~~SETTING~~	~~-~~	~~-~~	~~-~~	~~-~~		
NOTES: See Plumbing Cx fuctional test form for crossed out line.						

SEQUENCE OF OPERATION – VAULT LEVEL CONTROL				
SEQUENCE:	**PASS**	**FAIL**	**NOTES**	**VAULT LEVEL**
GRAVITY DRAIN: Not tested under Mechanical - Emerald Aire scope. See Plumbing - Wolfe Cx functional test form				
• DISABLE ESP-1A,B, FILL VAULT WITH HW UNTIL VAULT OVERFLOWS TO CITY SEWAGE LINE.				
• CONFIRM OVERFLOW GRAVITY DRAIN IS FUNCTIONAL AND LEAKS ARE NOT PRESENT IN UPSTREAM PIPING TO VAULT.				
OVERFLOW PUMP-OUT: Not tested under Mechanical - Emerald Aire scope. See Plumbing - Wolfe Cx functional test form				
• ENGAGE ESP-1A,B TO PUMP OUT VAULT TO A LEVEL APPROXIMATELY 1FT BELOW SEWAGE INLET PIPE.				
SEWAGE EJECTION TIMER: Not tested under Mechanical - Emerald Aire scope. See Plumbing - Wolfe Cx functional test form				
• ENGAGE SEWAGE EJECTION TIMER (TYPICALLY 4AM).				

Checks performed by: Colin Grist Signature: [signature] Date: 12/07/18

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Functional Performance Test

Domestic Hot Water – WWHP

• ~~CONFIRM VAULT LEVEL DROPS TO 2" ABOVE HEAT EXCHANGER PLATES~~				
HEAT PUMP PROTECTION:				
• FILL VAULT WITH CW SO THAT PLATES ARE SUBMERGED GREATER THAN 2" FOR HEAT PUMP PROTECTION TEST	PASS		Vault level was 27" at beginning of test. This is 2" above pump down level of 25". Vault temperature at 56 F.	
• ENGAGE HEATPUMP SYSTEM. ALTER VAULT TEMPERATURE DISABLE SETTING TO BE GREATER THAN CURRENT VAULT TEMPERATURE.	PASS		Vault temperature temporarily changed to 44F on programmer so that heatpump temperature protection can be tested. HW drawn at taps to simulate load and call stage 1 ON.	
• CONFIRM HEATPUMPS DISABLE AND GAS WATER HEATERS ENABLE TO SATISFY HEATING CALL.	PASS		Controller prevented Water source heatpumps from running to satisfy heating call. Gas water heaters stage ON with typical stage-1, stage-2 logic.	
• CONFIRM ESP-1A,B ENGAGE TO DRAIN VAULT TO 2" ABOVE HEAT EXCHANGER PLATES.		FAIL	Staging controller sent signal to sewage ejection pumps. Sewage ejection pumps engaged ON to drain vault. Pumps did NOT stop when vault water level dropped to 2" above HX plates. Pumps continued to run to drain vault. Pumps stopped manually to avoid draining vault completely.	
PUMP OVERRIDE SWITCH: Not tested under Mechanical - Emerald Aire scope. See Plumbing - Wolfe Cx functional test form				
• ~~ENGAGE ESP-1A,B OVERRIDE SWITCH TO DRAIN VAULT TO ESP-1A,B INLET LEVEL (MINIMUM VAULT LEVEL).~~				
• ~~CONFIRM VAULT IS PUMPED OUT TO MINIMUM LEVEL. CONFIRM PUMPS DO NOT OPERATE DRY~~				
HEATPUMP VAULT LEVEL PROTECTION:				
• DRAW HW TO CREATE HEATING CALL.	PASS		Vault level approx 4" below HX plates. This level should prevent water source heat pumps from engaging and engage gas water heaters to satisfy heating call.	
• CONFIRM HEATPUMPS ARE DISABLED DUE TO VAULT LEVEL BELOW MINIMUM LEVEL.	PASS		Confirmed. Controller engage gas water heaters to satisfy heating call.	
• CONFIRM GAS WATER HEATERS SATISFY HEATING CALL.	PASS		Confirmed.	
NOTES:				
REVERT ANY SETTINGS ADJUSTED TO INITIATE A LINE IN CONTROL SEQUENCING BACK TO DEFAULT SETTING.				

Checks performed by: Colin Grist Signature: [signature] Date: 12/07/18

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Functional Performance Test

Domestic Hot Water – WWHP

SYSTEM DESCRIPTION

THE WASTE WATER HEAT PUMP (WWHP) SYSTEM PROVIDES DOMESTIC HOT WATER FOR THE PROJECT. SEWAGE FROM THE BUILDINGS IS ROUTED TO A SEWAGE VAULT IN THE PARKING GARAGE. THE VAULT INCLUDES HEAT EXCHANGERS CONNECTED VIA A CLOSED HYDRONIC LOOP TO A BANK OF WATER-TO-WATER HEAT PUMPS. THE WATER-TO WATER HEAT PUMPS EXTRACT HEAT FROM THE SEWAGE VAULT TO HEAT A BANK OF HOT WATER STORAGE TANKS THAT SUPPLY DOMESTIC HOT WATER TO THE PROJECT. THE WWHP SYSTEM CONSISTS OF THREE INTER-RELATED SYSTEMS WITH TWO CONTROL SYSTEMS THAT COMMUNICATE WITH EACH OTHER. THE THREE SYSTEMS ARE AS FOLLOWS:

1. DOMESTIC WATER HEATING SYSTEM: THIS SYSTEM INCLUDES THE EQUIPMENT ASSOCIATED WITH MAINTAINING HOT WATER IN THE DOMESTIC HOT WATER STORAGE TANKS. A CLOSED LOOP CIRCULATES WATER BETWEEN THE HEAT PUMPS AND THE SEWAGE VAULT HEAT EXCHANGERS. TEMPERATURE SENSORS IN THE STORAGE TANKS ARE USED TO STAGE IN THE HEAT PUMPS. IF THE HOT WATER STORAGE IS DRAWN DOWN TOO FAR, GAS WATER HEATERS WILL KICK IN TO BACK-UP THE HEAT PUMPS.
2. CIRCULATION LOOP HEATING SYSTEM: HOT WATER IS CONTINUOUSLY CIRCULATED THROUGHOUT THE BUILDINGS TO PROVIDE FOR QUICK HOT WATER DELIVERY TO ALL APARTMENTS. THE WATER TEMPERATURE IN THIS LOOP IS MAINTAINED BETWEEN 110-122F BY AN AIR-TO-WATER HEAT PUMP OR REVERSE CYCLE CHILLER (RCC) LOCATED IN THE GARAGE.
3. SEWAGE MANAGEMENT SYSTEM: SEWAGE EJECTOR PUMPS ARE USED TO EMPTY THE SEWAGE VAULT EACH NIGHT INTO THE CITY SEWER SYSTEM.

MODES OF OPERATION

THE COMMISSIONING SHALL BE COMPLETED IN TWO PHASES: GAS WATER HEATING SYSTEM ONLY & FULL WWHP SYSTEM WITH GAS BACK-UP.

FOR THE GAS WATER HEATING SYSTEM COMMISSIONING, THE FOLLOWING OPERATION MODES SHALL BE TESTED: STANDBY, HEATING CALL, AND TEMPERATURE MAINTENANCE.

FOR THE FULL SYSTEM COMMISSIONING, ALL THREE SYSTEMS SHALL BE TESTED. A SERIES OF OPERATION MODES SHALL BE TESTED AGAINST THE SEQUEUNCE OF OPERATION INCLUDING: HEATING CALL, TEMPERATURE MAINTENANCE, OVERFLOW PROTECTION, SEWAGE EJECTION, HEAT PUMP PROTECTION, AND PUMP PROTECTION.

Checks performed by: Colin Grist Signature: ________ Date: 11/12/18

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Functional Performance Test

Domestic Hot Water – WWHP

SYSTEM: **WWHP - FULL SYSTEM**	DATE: 11/12/18
EQUIPMENT: **WWHP-1,2,3; RCC-1; GWH-1,2,3; PMPS**	AREA SERVED: **ALL**

HEATING EQUIPMENT PARAMETERS							
EQUIPMENT:	**WWHP-1**	**WWHP-2**	**WWHP-3**	**RCC-1**	**GWH-1**	**GWH-2**	**GWH-3**
HEATING CAPACITY							
REFRIGERANT CHARGE					-	-	-
OUTGOING TEMP SETPOINT DESIGN / MEASURED	135F /	135F /	135F /	8-12F RISE	140F /	140F /	180F /
INCOMING MAX TEMP DESIGN / MEASURED	110F /	110F /	110F /	125F /	-	-	-
DESIGN FLOWRATE (POTABLE)					-	-	-
TIME DELAY							
MINIMUM RUN TIME DESIGN / MEASURED	S1 0-MIN /	S2 15-MIN /	N/A	1-MIN /	NONE	NONE	NONE

NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form

PUMPING EQUIPMENT PARAMETERS						
EQUIPMENT:	**PMP-W1**	**PMP-W2**	**PMP-W3**	**PMP-G1**	**PMP-G2**	**PMP-G3**
DESIGN / MEASURED FLOWRATE (GPM)	35 /	35 /	35 /	3.9 /	3.9 /	4.2 /
DESIGN / MEASURED DELTA T (°F)	7.5 /	7.5 /	7.5 /	90 /	90 /	66 /
TIME DELAY						
MINIMUM RUN TIME						

NOTES: PMP-G3 AT 66F DELTA T AND 75% CAPACITY AT GWH-3 FLOW RATE SHALL BE 4.2GPM DELIVERING WATER AT 180F FOR A TOTAL CAPACITY OF 11.5 TONS OR 100W/APT LOSS.

Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form

SEQUENCE OF OPERATION – STAND BY							
EQUIPMENT:	**WWHP-1**	**WWHP-2**	**WWHP-3**	**RCC-1**	**GWH-1**	**GWH-2**	**GWH-3**
RECORD EQUIPMENT ON/OFF							
RECORD TANK TEMPERATURES	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	-
• DESIGN TEMP.	>100F	N/A	>90F	>90F	N/A	>125F	-
• MEASURED TEMP.							-

NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form

Checks performed by: Colin Grist Signature: [signature] Date: 11/12/18

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Functional Performance Test

Domestic Hot Water – WWHP

SEQUENCE OF OPERATION – HEATING CALL					
EQUIPMENT:	**STAGE 1**	**STAGE 2**	**GWH-1,2**	**PMP-G1,2**	**MV-1**
LEAD/LAG CYCLE TIME: ______________ RECORD EQUIPMENT STAGES:					
T-1 LESS THAN 100°F. RECORD T-1:	T-1 =				
STAGE 1: RECORD SETPOINTS BELOW	-	-	-	-	-
• TURNS ON WHEN T-3 IN ST-3 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	90°F /	OFF /	OFF /	OFF /	CLOSED /
• TURNS OFF WHEN T-1 IN ST-1 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	100°F /	OFF /	OFF /	OFF /	CLOSED /
NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form					
STAGE 2: RECORD SETPOINTS BELOW	-	-	-	-	-
• TURNS ON WHEN T-3 IN ST-3 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	ON /	90°F /	OFF /	OFF /	CLOSED /
• TURNS OFF WHEN T-1 IN ST-1 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	ON /	100°F /	OFF /	OFF /	CLOSED /
NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form					
GWH BACK-UP: RECORD SETPOINTS BELOW	-	-	-	-	
• TURNS ON WHEN T-4 IN ST-4 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	ON /	ON /	90°F /	ON /	OPEN /
• TURNS OFF WHEN T-1 IN ST-1 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	ON /	ON /	100°F /	ON /	OPEN /
NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form					

SEQUENCE OF OPERATION – CIRCULATION TEMPERATURE MAINTENANCE				
EQUIPMENT:	**RCC-1**	**PMP-R1**	**GWH-3**	**PMP-G3**
DOMESTIC HOT WATER CIRCULATION				
• RCC-1 TURNS ON WHEN T-6 IN ST-6 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	125°F /	ON /	OFF /	OFF /
• RCC-1 TURNS OFF WHEN T-6 IN ST-6 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	130°F /	OFF /	OFF /	OFF /
DOMESTIC HOT WATER BACKUP				
• GWH-3 TURNS ON WHEN T-6 IN ST-6 DROPS BELOW SETPOINT: **DESIGN / MEASURED**	ON /	ON /	122°F /	ON /
• GWH-3 TURNS OFF WHEN T-6 IN ST-6 RISES ABOVE SETPOINT: **DESIGN / MEASURED**	ON /	ON /	126°F /	OFF /
NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form				

Checks performed by: Colin Grist Signature: ______________ Date: 11/12/18

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Runberg: Block 11

Functional Performance Test

Domestic Hot Water – WWHP

SEQUENCE OF OPERATION – CONTROL SYSTEM ALARMS		
EQUIPMENT:	CONTROLLER	EMAIL
WWHP-1 FAILURE ALARM		
WWHP-2 FAILURE ALARM		
WWHP-3 FAILURE ALARM		
GWH-1 ON ALARM		
GWH-2 ON ALARM		
RCC-1 FAILURE ALARM		
GWH-3 ON ALARM		
OUTGOING HOT WATER LOW TEMPERATURE ALARM		

NOTES: Not tested under Plumbing - Wolfe scope. See Mechanical - Emerald Aire Cx functional test form

REVERT ANY SETTINGS ADJUSTED TO INITIATE A LINE IN CONTROL SEQUENCING BACK TO DEFAULT SETTING.

Checks performed by: Colin Grist Signature: Date: 11/12/18

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Functional Performance Test

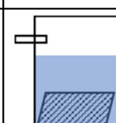
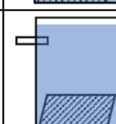
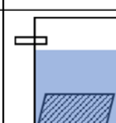
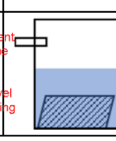
Domestic Hot Water – WWHP

SYSTEM: **WWHP – VAULT LEVEL CONTROL**	DATE: 11/12/18
EQUIPMENT: ESP-1A, ESP-1B, T-7	AREA SERVED: **SEWAGE SYSTEM**

EQUIPMENT PARAMETERS – VAULT LEVEL CONTROL

EQUIPMENT:	ESP-1A	ESP-1B	T-7	OVR. SW.	PR. TR.	TIME CLK.
FLOWRATE (GPM) DESIGN / MEASURED	450 / 394 GPM	450 / 394 GPM	-	-	–	–
HEAD PRESSURE (FT) DESIGN / MEASURED	30 / Not recorded	30 / Not recorded	-	-	–	–
TEMPERATURE **DISABLE** (F) DESIGN / MEASURED	-	-	<45 F /	-	–	–
TEMPERATURE **ENABLE** (F) DESIGN / MEASURED	-	-	>50 F /	-	–	–
PRESENT	yes	yes	yes	yes	yes	yes
SETTING	-	-	-	-	see notes	3am
NOTES: -- Thickness of vault liner not accounted for in ESP-1A and ESP-1B flowrate measurement. -- Pump inlet = 0" -- HX level = 23" -- Daily Pump = 25" -- Tank inlet = 156"						

SEQUENCE OF OPERATION – VAULT LEVEL CONTROL

SEQUENCE:	PASS	FAIL	NOTES	VAULT LEVEL
GRAVITY DRAIN:				
• DISABLE ESP-1A,B, FILL VAULT WITH HW UNTIL VAULT OVERFLOWS TO CITY SEWAGE LINE.	PASS		System functioned 1-2 weeks in overflow mode at end of September. Testing was extensive. No issues observed	
• CONFIRM OVERFLOW GRAVITY DRAIN IS FUNCTIONAL AND LEAKS ARE NOT PRESENT IN UPSTREAM PIPING TO VAULT.	PASS		Confirmed	
OVERFLOW PUMP-OUT:				
• ENGAGE ESP-1A,B TO PUMP OUT VAULT TO A LEVEL APPROXIMATELY 1FT BELOW SEWAGE INLET PIPE.	PASS		Vault level was 6" above waste inlet when system was turned ON. Alarm on sewage ejection pump controller illuminated. PMP was engaged on for 5min. A visible countdown timer was observed on the controller display. Tank was pumped down to 130".	
SEWAGE EJECTION TIMER:				
• ENGAGE SEWAGE EJECTION TIMER (TYPICALLY 4AM).	PASS		Time setting was initially 4am. Time setting adjusted to 5min later then current time to allow Cx team to commission the system. Pumps engaged ON when current time and time setting (8:30am) aligned. Pumps operated until vault level was reduced to pump down level. Setting reverted to 4am.	

Checks performed by: Colin Grist Signature: [signature] Date: 11/12/18

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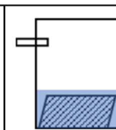
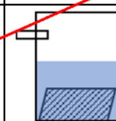
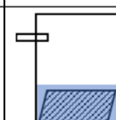
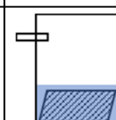
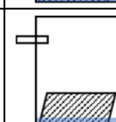
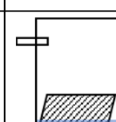
Runberg: Block 11

Functional Performance Test

Domestic Hot Water – WWHP

• CONFIRM VAULT LEVEL DROPS TO 2" ABOVE HEAT EXCHANGER PLATES	PASS		Confirmed	
HEAT PUMP PROTECTION: Not tested pending Emerald Aire staging controller to start up				
• FILL VAULT WITH CW SO THAT PLATES ARE SUBMERGED GREATER THAN 2" FOR HEAT PUMP PROTECTION TEST				
• ENGAGE HEATPUMP SYSTEM. ALTER VAULT TEMPERATURE DISABLE SETTING TO BE GREATER THAN CURRENT VAULT TEMPERATURE.				
• CONFIRM HEATPUMPS DISABLE AND GAS WATER HEATERS ENABLE TO SATISFY HEATING CALL.				
• CONFIRM ESP-1A,B ENGAGE TO DRAIN VAULT TO 2" ABOVE HEAT EXCHANGER PLATES.				
PUMP OVERRIDE SWITCH:				
• ENGAGE ESP-1A,B OVERRIDE SWITCH TO DRAIN VAULT TO ESP-1A,B INLET LEVEL (MINIMUM VAULT LEVEL).	PASS		Confirmed. Pump over ride switch was engaged to empty vault to minimum level.	
• CONFIRM VAULT IS PUMPED OUT TO MINIMUM LEVEL. CONFIRM PUMPS DO NOT OPERATE DRY.	PASS		Confirmed. Pressure transducer disengaged pump when vault level dropped to pump inlet level.	
HEATPUMP VAULT LEVEL PROTECTION: Not tested pending Emerald Aire staging controller to start up				
• DRAW HW TO CREATE HEATING CALL.				
• CONFIRM HEATPUMPS ARE DISABLED DUE TO VAULT LEVEL BELOW MINIMUM LEVEL.				
• CONFIRM GAS WATER HEATERS SATISFY HEATING CALL.				
NOTES:				
REVERT ANY SETTINGS ADJUSTED TO INITIATE A LINE IN CONTROL SEQUENCING BACK TO DEFAULT SETTING.				

Checks performed by: Colin Grist Signature: [signature] Date: 11/12/18

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APPENDIX C: ECOSIZER REPORT

Ecosizer – Central Heat Pump Water Heating Sizing Tool

ECOTOPE

Manual

Prepared for:

Charles Kim, Southern California Edison

Alex Chase, 2050 Partners

Yanda Zhang, ZYD Energy

Brett Korven, Sacramento Municipal Utility District

Prepared by:

Ecotope: Paul Kintner, Adria Banks, Scott Spielman, Colin Grist, Jonathan Heller

October 1, 2020

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1. INTRODUCTION

This report details the need and methodology for a best-practice sizing tool for central heat pump water heater systems (CHPWH) in multifamily buildings. This will be a generic sizing tool that gives basic sizing information for any piece of equipment with a known heating output capacity. The tool is called the Ecosizer.

Overall, the Ecosizer will assist designers to optimize the selection of heat pump water heating (HPWH) equipment and hot water storage volume for multifamily buildings. This tool is intended to support the market for CHPWHs and the following goals:

- to rapidly increase the adoption of this technology
- to reduce the perceived risk of this new technology
- to reduce maintenance issues
- and to reduce system cost by standardizing and simplifying the approach

Existing common water heater sizing methodologies for central water heating equipment tend to be very conservative and favor quick recovery capacity over large storage volumes. These approaches can deliver reliable and cost-effective gas water heating systems, but if CHPWH systems are sized in the same way they often result in very expensive, and sometimes unreliable, systems. In general, sizing for CHPWHs should take a different approach, which utilizes large storage volumes to provide for peak hot water demand periods and smaller output capacity, which results in long, slow recovery periods with compressors operating up to 16-20 hours per day. These systems will be the most cost effective and result in fewer maintenance issues.

CHPWH systems following this sizing strategy to minimize heating capacity are already in use in multifamily buildings. In 2018 Ecotope completed the design of a central Sanden CO2 HPWH system as a retrofit DHW system in a 60-unit low income multifamily building. Both the existing electric resistance water heating system and the retrofit heat pump water heating system were monitored to quantify how well the heat pump water heating system functioned. That retrofit resulted in a 63% reduction in energy needed for the domestic hot water system[1].

The case study also demonstrated that an extremely small amount of heat pump capacity, coupled with a relatively large amount of storage volume, can provide reliable hot water for a multifamily building. At the case study noted above, 60 people were supplied with hot water with only the equivalent of 20kW of heat pump capacity. This is much less capacity than has traditionally been provided in the marketplace when sizing gas or resistance water heating equipment. The building was previously served by 120kW of

[1] Banks, A., Grist, C., and J. Heller. 2020. CO2 Heat Pump Water Heater Multifamily Retrofit: Elizabeth James House, Seattle WA. Prepared for Washington State University Energy Program, under contract to Bonneville Power Administration

electric resistance heating capacity. Therefore, to drive the price of these systems down to make them cost effective, the marketplace needs support in the form of a sizing tool that will enable confident sizing of smaller systems to serve the load.

This report is laid out as follows: Section 2 provides brief insight into HPWH and why HPWH systems need specialized design. Section 3 details how the specialized design of HPWH systems accounts for the temperature maintenance load. Section 4 provides the methodology employed in the Ecosizer CHPWH sizing tool for normal operation and load shift scenarios. Section 5 discusses future work for the Ecosizer design tool.

2. EQUIPMENT OVERVIEW

The heat pump equipment currently directly addressed by this tool employ “Single-Pass” heat exchangers, as opposed to the “Multi-Pass” approach employed in most hydronic space heating applications. This means that the flow of water through the heat pump is regulated to maintain a constant target output temperature. Most single-pass heat pumps can output hot water at the target setpoint of 135-160°F with incoming water temperatures ranging from 40-110°F. The advantage of the “Single Pass” arrangement is that a usable water temperature is always delivered to the top of the storage reservoir.

Most refrigeration cycles used in HPWHs do not operate well at warm incoming water temperatures (above approximately 110°F). Building hot water circulation pumps provide hot water throughout the distribution system, with typical supply water at 120-125°F and return water at 105-115°F. 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. A critical design feature of CHPWH systems with hot water circulation systems is to separate these two distinct building DHW loads: primary water heating and temperature maintenance. In doing so the DHW system design can prioritize delivering cool water to the HPWHs for peak performance 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.

3. TEMPERATURE MAINTENANCE SYSTEM OVERVIEW

Single-pass HPWHs provide high-efficiency performance but cannot be used to heat warm water returning from recirculation systems. A key innovation that can be implemented to overcome this limitation of single-pass HPWHs is to use a temperature maintenance system separated from the thermally stratified primary storage volume. A temperature maintenance system consists of a recirculation pump, a storage tank (the “loop tank”), and a temperature maintenance heat source. (The Ecosizer considers two characteristically different types of temperature maintenance systems: “swing tank” design uses a loop tank piped in series with the primary storage (**Figure 1**) and parallel loop tank design uses a loop tank piped in parallel with the primary storage (**Figure 2**).

Important design commonalities between the two types of temperature maintenance system are:

- Multiple Storage Tanks: The primary storage volume may be provided with one large vertical storage tank or multiple smaller tanks.

- High Primary Storage Tank Temperature: HPWHs can heat water to a relatively high temperature (135-160°F). Doing so increases the effective stored hot water volume of the plant and mitigates legionella related risks. It also supports the ability of the primary heat pump plant to offset temperature maintenance heat losses.
- Thermostatic Mixing Valve: To prevent scalding, outgoing water shall be tempered with recirculation return water and incoming city water down to approximately 120°F before delivery to the occupants. A high-quality electronic mixing valve is recommended. The distribution system return water should be piped to the mixing valve and the temperature maintenance tank.

Swing Tank

In the swing tank approach, the primary system uses a temperature setting in the range of 140-160°F, which is higher than the water temperature supplied to occupants. The temperature maintenance system is in series with the primary storage such that the high temperature water from the primary system is supplied to the bottom of the temperature maintenance tank, or swing tank. A backup electric water heater is necessary in the temperature maintenance tank to account for the temperature maintenance load during periods of low DHW demand. The backup electric heater is controlled to keep the temperature maintenance tank from dropping below the supply water temperature.

During a DHW draw event, water is supplied from the swing tank to the thermostatic mixing valve to mix with warm return water from the hot water distribution system. The water volume removed from the swing tank is replaced by hot water from the primary system, effectively using the primary DHW system to heat the temperature maintenance system. The temperature in the temperature maintenance tank then "swings" between the supply water temperature and the setpoint of the primary HPWHs to reduce the use of the resistance element.

Piping the output of the primary storage to the bottom of the swing tank is to ensure complete mixing of the swing tank. When the swing tank is fully mixed, the outlet temperature of the tank will be lower than if it was stratified. When mixed, any given hot water draw at the taps removes a greater volume from the swing tank and more energy is added to the swing tank from the primary system, making the swing tank concept more effective. This swing tank approach works well in buildings with efficient distribution piping designs and well-insulated distribution systems that keep temperature maintenance losses low, and in buildings that utilize CHPWH equipment which is able to produce relatively high temperature water (>150°F) at relatively high efficiencies, such as CO_2 HPWH equipment.

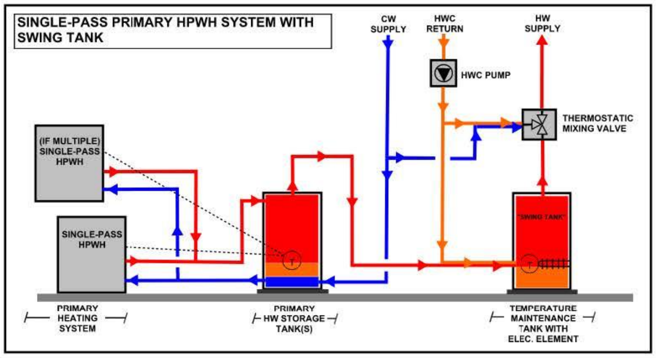

Figure 1. Example of centralized domestic hot water HPWH plant with a swing tank.

Parallel Loop Tank

The parallel loop tank approach completely removes the temperature maintenance load from the primary system by piping the primary system directly to the mixing valve and bringing the recirculation return to the bottom of the temperature maintenance tank, which is plumbed in parallel with the primary storage. This parallel loop tank is then heated with an electric resistance element, or ideally with a separate multi-pass HPWH. For optimal multi-pass HPWH operation, the parallel loop tank should be maintained to have as much thermal stratification as possible. During operation, the multi-pass HPWH raises the tank temperature 5-10°F to account for the temperature maintenance load.

This parallel loop tank using a multi-pass HPWH approach is recommended in buildings with relatively high distribution losses due to long inefficient or poorly insulated distribution system, resulting in relatively high temperature maintenance losses. This system will also work well with systems designed to use lower primary water storage temperatures.

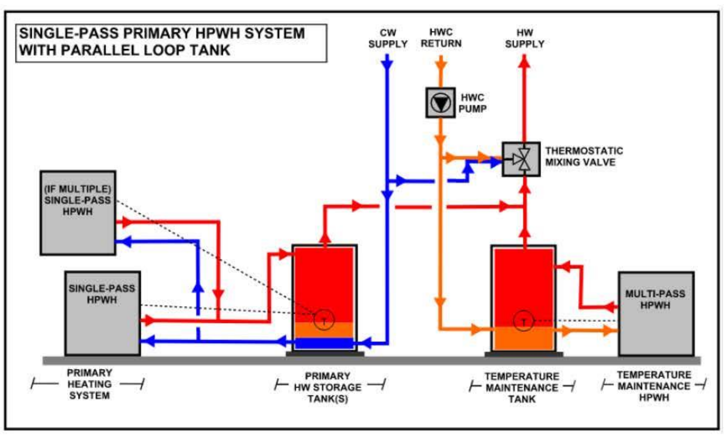

Figure 2. Example of a CHPWH plant with a parallel loop tank.

4. SIZING TOOL METHODOLOGY

This section covers the methodology used in the Ecosizer CHPWH sizing tool for the primary system and the temperature maintenance system. The size of the primary system is determined by the daily hot water demand on the design day, which is calculated based on the user input for Input Method, Number of People, Number of Apartments, and Peak Gallons per Day per Person. Sizing for the temperature maintenance system depends on the user input for Recirculation Loop Heat Loss (W/Apartment), in the Advanced Schematic Options. Guidance for this load is provided in the Temperature Maintenance Sizing section of this report and in the Ecosizer. The data and code for the calculation methods described below is publicly available[2].

Hot Water Demand Calculation

The first step in sizing CHPWH plants is estimating the hot water demand in the building. Hot water demand is specified by daily hot water demand (in gallons) and load shape. The daily hot water demand, $V_{HW,Day}$, is calculated as:

$$V_{HW,Day} = N_{people} \cdot V_{gpdpp}$$

Where N_{people} is the total number of people in the building and V_{gpdpp} is the peak hot water demand in gallons per day per person. In the sizing tool users must specify the number of people and the peak hot water demand or use estimates defined by ASHRAE or California code standards.

Number of People

To estimate people, the sizing tool needs inputs for the number of people and/or number of apartments. There are two input methods for these:

1. If the designer knows how many people will occupy the building they can simply enter the number of people into the tool.
2. If the designer does not know how many people will occupy the building, there is an option to use available data sources for occupancy estimates. This will be based on the number of bedrooms and the occupancy rate (number of people per unit by the number of bedrooms).

For the later input method, the tool provides three options for the number of people per apartment size/type, presented in Table 1. The California ratios used in CBECC-Res are based on the 2009 Residential Appliance Saturation Study[3]. For California low income groups ratios are sources from the CA Tax Credit Allocation Committee (CTCAC)[4]. An ASHRAE publication[5] provides two sets of national data for multi-family and low-income multi-family buildings developed from the 2009 Residential Energy Consumption

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[2] https://github.com/EcotopeResearch/HPWHulator

[3] Palmgren, C., N. Stevens, M. Goldberg, R. Bames, and K. Rothkin (2010). 2009 California Residential Appliance Saturation Survey. Technical report, KEEMA, Inc., Oakland, California.

[4] California Tax Credit Allocation Committee (CTCAC) (June 2020). Compliance Online Reference Manual Low Income Housing Tax Credit Program (LIHTC). Part 3.3 B. https://www.treasurer.ca.gov/CTCAC/compliance/manual/manual.pdf

[5] Florida Solar Energy Center. *Estimating Daily Domestic Hot-Water Use in North American Homes*. FSEC-PF-464-15. June 30, 2015. www.fsec.ucf.edu/en/publications/pdf/FSEC-PF-464-15.pdf

Survey. The ASHRAE low-income multifamily occupancy ratios are higher than the ASHRAE market rate multifamily occupancy ratios.

Table 1. Occupants per bedroom for three different Multi-family data sets.

Apartment Size	Occupants/Bedroom			
	CBECC-Res	CTCAC	ASHRAE Market Rate	ASHRAE Low Income
Studio	1.37	1	1.49	1.69
1 BR	1.74	1.5	1.93	2.26
2 BR	2.57	3	2.39	2.83
3 BR	3.11	4.5	2.84	3.40
4 BR	4.23	6	3.29	3.97
5+ BR	3.77	7.5	3.74	4.54

Peak Demand Per Person

To estimate the peak hot water demand per person, the sizing tool provides a few options. First, the tool provides estimates for V_{gpdpp} from 2015 ASHRAE HVAC Applications handbook pages 50.15 - 50.16. These options are ASHRAE Low at 20 gallons per day per person (gpdpp) at 120°F and ASHRAE Medium at 49 gpdpp at 120°F. The ASHRAE Medium number is likely an overestimate of any modern multifamily building due to the outdated data used. To provide a modern[6] estimate, we evaluated hot water usage in three market-rate multi-family buildings with low flow fixtures in Seattle, WA, to determine peak hot water usage.

From a design perspective, one building stands out from the others as having higher hot water use and a higher peaking load. The 118-unit building is in a family-oriented neighborhood, while the others are in more night-life oriented neighborhoods. Data for the building was collected between January 2014 and November 2018.

To find the design peak hot water use we use the 98th percentile of daily hot water demand, the empirical cumulative density function is given in **Figure 3**, which evaluates to 25 gpdpp[7].

[6] Note that our modern hot water usage data is pre-COVID. We have found that average water usage increased in monitored Seattle buildings by 20% during the stay-at-home orders. It is not clear how that may have impacted the peak daily use.

[7] We find the best fit distribution to the ECDF is a normal distribution which is used to scale the user input for percentage of days load shifted in the load shift section of the report.

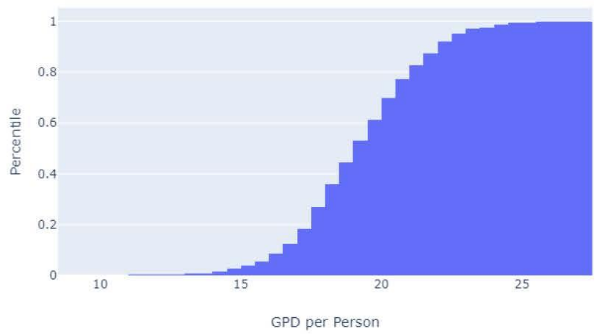

Figure 3. The empirical cumulative density function for the design building.

California Demand Per Person

The Ecosizer tool also provides an option for hot water demand derived from CBECC-Res 2019[8]. The hot water use profiles are divided into ten distinct profiles for studios, 1-bedroom units, 2-bedroom units, 3-bedroom units, 4-bedroom units, and 5-bedroom units[9]. When a CBECC-Res user constructs a multi-family building in the software, the software uses the appropriate number units of each size. If there are more than ten units in the building of a bedroom size, the CBECC-Res will repeat hot water draw profiles.

To adapt this data to the Ecosizer, one-minute timestep output was captured for the HPWH system in a 10-unit building of just one-bedroom size. The resulting hot water draws were aggregated to the daily level and divided by the number of people in the building to get an expected value of DHW in gallons per day per person for each unit size for each day of the year. The results of this process are shown in Figure 4 for each unit size for hot water supplied at 120°F. The dashed red lines represent the 98th percentile days. The dashed blue line represents the median daily use. By sourcing this data directly from CBECC-Res, the data captures assumed hot water waste associated with distribution piping in the unit and with waiting for the hot water to heat up. For details on the losses see Kruis et al. (2019)[9].

To maintain the variation present in the daily DHW demand, the methodology in the Ecosizer multiplies the daily expected values for each unit size by the user input for number of apartments of a given size to get an expected value in the building for each unit size. The expected values by unit size are summed together to build a yearly DHW profile for the building. The Ecosizer finds the 98th percentile DHW day from the yearly profile to calculate the peak demand.

[8] http://www.bwilcox.com/BEES/cbecc2019.html

[9] Kruis, N, Wilcox, B., Lutz, J. and Banaby, C. (2019) Development of Realistic Water Draw Profiles for California Residential Water Heating Energy Estimation – Revised (March, 2019). http://www.bwilcox.com/BEES/docs/dhw-profiles-revised3.pdf

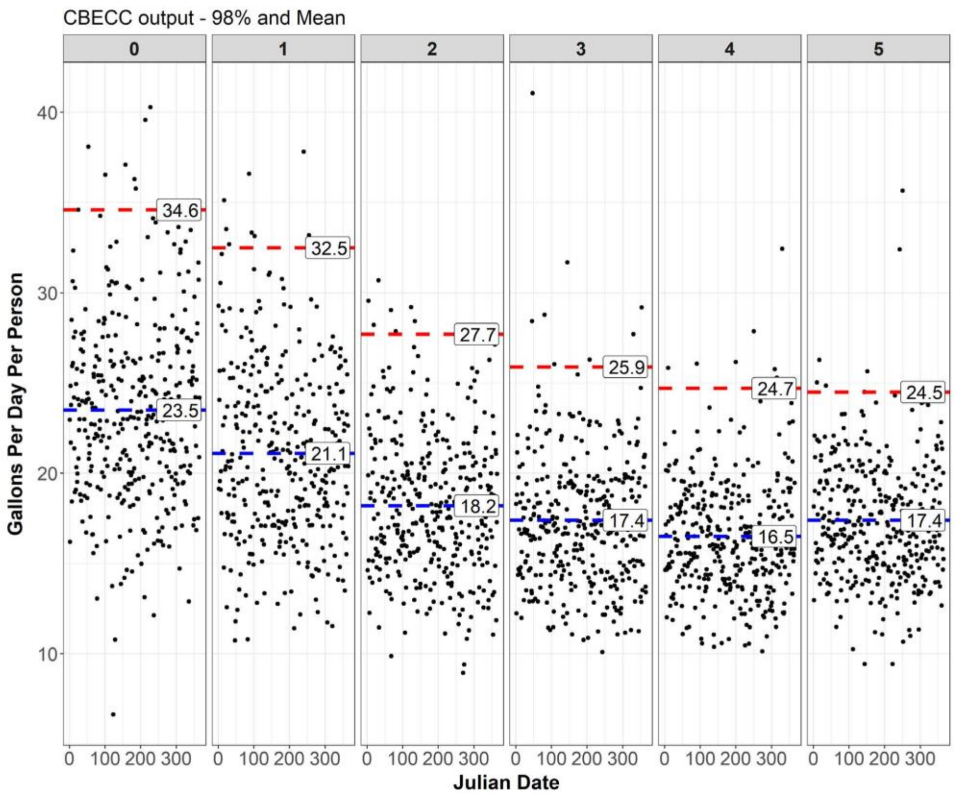

Figure 4. Expected daily DHW per person for each of the CBECC-Res apartment types.

Load Shape

The load shape is found from an analysis on the hourly demand for each day in the dataset for the 118-unit multifamily building. A selection of potential days is chosen from days that are in between the 98th and 95th percentile of daily hot water use and in the upper percentile of 3- and 4-hour peak loads. Most days satisfying the first criteria also satisfy criteria for a high peak load, indicating a correlation between the volume of hot water used during the day and the peak hot water use during the same day. The design day chosen is one that maximizes the cross-correlation between itself and the average day, both shown in Figure 5. This means the design day has a similar use pattern to the average day load shape but has the peaking hot water loads that are important for sizing a HPWH system and is useful for predicting the timing of peaking loads in a load shifting scenario.

The peak design day load shape represents a likely worst-case multifamily load shape with a very high morning peak driven by morning showers and cooking, very low mid-day usage which indicates most occupants at work or school, and a second slightly smaller evening peak representing after work showers and dinner prep. Building occupancy types with fewer workforce occupants (ie. senior or supportive housing) will likely exhibit a somewhat flatter curve with hot water usage spread out more even over the day. Those load shapes will not need as much storage volume to get through the peak periods. Note that this worst-case load shape assumes some diversity of occupants in a multifamily building with some high users and some low users distributing their demand over the day. It is possible in small multifamily buildings with less diversity that usage patterns could align in ways that produce higher peaks or higher total demand. Care should therefore be taken when using the Ecosizer for buildings with fewer than about 20-30 occupants.

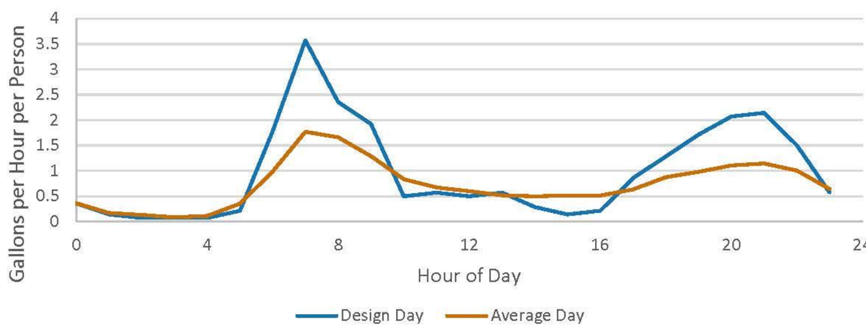

Figure 5. Measured Load Shapes from Ecotope Buildings.

In the sizing tool, the load shape is used for any input of N_{people} or V_{gpdpp}. The design day load shape in Figure 5 is normalized by the total daily use per person such that each hour represents a fraction of the daily use. For use in the sizing tool, the load shape is scaled by the total daily hot water demand for a user's specific case.

Sizing Methodology for Primary Plant

This section discusses sizing of the primary plant when using no recirculation loop or a parallel loop tank. The method is altered when using a swing tank design as the primary plant must provide a portion of the heating capacity to support temperature maintenance of the distribution system, as discussed in the next section on sizing for swing tank systems. The sizing method presented in this section is the next logical step forward from the "More Accurate Method" referred to in the 2015 ASHRAE HVAC Applications handbook pages 50.15 - 50.16. Here it is modified to better represent lower capacity systems producing hot water during occupant use. In lieu of calling the method here the More "More Accurate Method" we call this method the Ecosizer Method.

Sizing the primary plant of a CHPWH system is done to meet the peak hot water usage period (when HPWHs cannot generate enough hot water to keep up with demand) on the design day. This ensures that hot water will be continuously supplied year-round. Sizing of the systems depends on the design and operation of the storage volume. The design of storage volume is summarized into one idealized storage tank in Figure 6, which represents storage tanks in parallel or series. The user input for the aquastat fraction is the percentage of hot water volume removed from the tank before the HPWH's turn on due to cold water at the sensor. The user input for storage efficiency represents what percentage of the total hot water storage volume is at the storage temperature when full, the red section in Figure 6, since the storage volume can be degraded by mixing and that HPWH's will turn off when the incoming water is below setpoint.

The recommended minimum sizing options are found by:

1. The minimum capacity for the water heater is determined first based on the user input value for "maximum daily runtime for the HPWH compressor", $h_{max,hr}$., which is recommended and defaulted to 16 hours. The corresponding hot water generation rate, $\dot{G}(t)$, is calculated following:

$$\dot{G}(t) = \frac{V_{HW,Day}}{h_{max,hr}}$$

2. Storage volume is found by considering the worst-case scenario, when entering a peak hot water usage period the HPWH has not heated up the whole volume of the tank and the HW level is just below the aquastat. A peak hot water usage period is defined as any period where the hot water draw rate exceeds the hot water generation rate, i.e. $\dot{V}_{HW}(t) > \dot{G}(t)$. The storage volume that remains at the start of the peak hot water usage is the running volume, shown in Figure 6. This must be equal to the volume of hot water used during the peak event that the HPWH cannot generate. To find this volume the running integral of the difference between the hot water draws and generation rate is found by:

$$V^i_{supply}(t) = \int_{t^i_{peak}}^{t} \left(V_{HW,Day} * \dot{V}_{HW}(t') - \dot{G}(t')\right) dt'$$

Where $V^i_{supply}(t)$is the running difference, $\dot{V}_{HW}(t)$ is the normalized load shape, and t^i_{peak} is the start of the i^{th} peak hot water usage period. The design day could have multiple peak periods, each is used to evaluate a running volume and only the max running volume should be used for sizing. The running volume is the absolute minimum of the all the supply values $V_{running} = \min\left(V^i_{supply}(t)\right)$.

3. The running volume is just what is above the aquastat, the total storage for DHW at the supply temperature is then found by the user input for the aquastat fraction, AF, defined as the ratio between the total storage volume and the useable fraction of storage, the red section in Figure 6.

$$V_{total,T_{supply}} = \frac{V_{running}}{(1 - AF)}$$

4. Lastly, offsets are used for the differences in the user inputs for storage temperature and supply temperature.

$$V_{total,T_{storage}} = \frac{T_{supply} - T_{CW}}{T_{storage} - T_{CW}} V_{total,T_{supply}}$$

5. The sizing curve (storage vs. capacity) is created by varying $h_{max,hr}$ from 24 hours to the minimum value defined as $\frac{1}{h_{max,hr}} > \max\left(\dot{V}_{HW}(t)\right)$, which would lead to a scenario where the hot water generation rate is greater the DHW usage.

Given the methodology, the load shape chosen will have large effects for the recommend sizing. Load shapes with higher peaking loads will require more storage than load shapes with a more distributed hot water load. This is the reason careful consideration for the peaking hot water load was given in the load shape section.

Lastly, the required heating capacity, $\dot{Q}_{primary}$, on the design day can be found from:

$$\dot{Q}_{primary} = \rho c_p \frac{V_{HW,Day}}{h_{max,hr}} (T_{supply} - T_{CW})$$

where ρ is the density of water, c_p is the heat capacity of water.

The Ecosizer also checks that the cycling volume, Figure 6, the primary storage volume between the aquastat and the bottom of the effective storage volume, has a large enough volume that the primary HPWHs can run for at least ten minutes in the absence of hot water draws, per manufacturer recommendation. The cycling volume found from user inputs is compared to a minimum cycling volume:

$$V_{cycling,min} = 10 \text{ minutes} * \dot{G}(t)$$

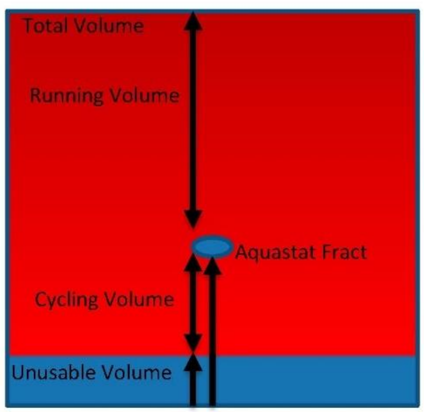

Figure 6. An illustration of the parts of the storage volume.

An example of this is worked through in Figure 7 and Figure 8, for a building using 2000 gallons of DHW per day and a maximum daily runtime for the compressor of 16 hours. In Figure 7, the blue bars represent the daily hot water load shape, $V_{HW,Day} * \dot{V}_{HW}(t)$, and the hot water generation rate is shown in green. The difference between the hot water use and the hot water generation rate is shown in orange. In this case, there are two instances of peak hot water use, t_{peak} at 0600 and 1900.

The cumulative difference between DHW generation and DHW use starting at the beginning of peak events is shown in Figure 8, the minimum value of both curves represents the running volume. In this instance the running volume is 270 gallons. If the aquastat fraction is 0.4, then the total storage volume is 450 gallons (V=270/(1-0.4)=450).

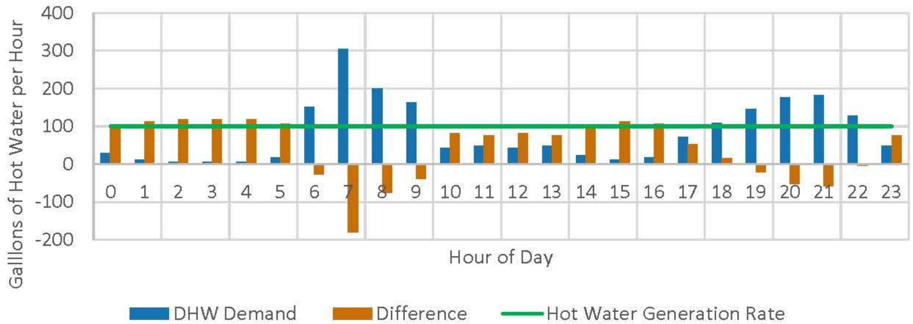

Figure 7. Hot water (HW) use, heating rate and difference throughout the day.

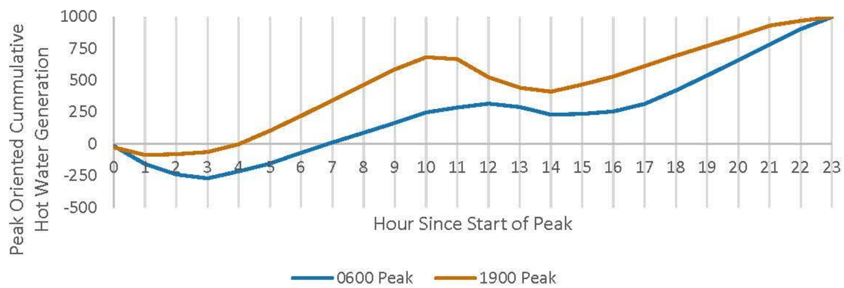

Figure 8. Cumulative supply after peak event.

HPWHs can run longer than the design minimum runtime on occasion, for example all day, and this creates a built-in safety factor for days where the total GPDPP may be greater than the max used in the sizing tool. However, this safety factor does not increase the heating rate and does not provide safety against a greater than predicted peak. For an increase in the peak event, the aquastat fraction serves as a safety factor. It will typically be unusual for the storage volume to be sitting at just the running volume at the start of the peak draw period. Therefore, this extra typical fraction of the cycling volume provides an increase in the total available storage.

To give an idea about the storage and the heating capacity, a simple model is run for the primary heat pump water heater plant on the design day and plotted in the Ecosizer. More information on the simulation is available in Appendix A.

Temperature Maintenance Sizing

The temperature maintenance module will size the temperature maintenance storage and heat capacity using the inputs for the time-dependent load shape, primary storage temperature, and supply temperature to the occupants from the primary sizing tool. Additionally, the optimization of the temperature maintenance tank will depend on user input for the number of apartments and temperature maintenance heat loss rate.

Based on the schematic chosen, the temperature maintenance system will either be designed as a parallel loop tank or as a swing tank. A parallel loop tank has an electric resistance element or a multi-pass HPWH that is piped in parallel with the primary system. On the other hand, the swing tank has an electric resistance element and is designed to use the hot water from the primary HPWH to account for the majority of the distribution losses.

Calculation of the Temperature Maintenance Load

Sizing for temperature maintenance is difficult because the recirculation load is unknown a priori. This load is unknown for new construction and relatively hard for the designer to predict as it is determined by many factors that may be outside of their control, including the pipe sizing, the length of circulated piping, the insulation levels, the quality of the insulation and thermal bridging at pipe supports, and the location of the piping inside or outside of the heated envelope of the building.

The temperature maintenance load has a user input value for the recirculation loop loss. For advising and setting a default for what this should be, we can only base our assumptions of this load on data from previously studied buildings. These data show a median of ~100 watts per apartment (W/apt), with a 25th percentile of ~66 W/apt and a 75th percentile of ~175 W/apt[10]. This upper bound of 175% of the median value is recommended for sizing the heating elements in the temperature maintenance systems for new construction.

In a retrofit, a measurement of the recirculation loop heat loss rate is possible and highly recommended. This is a poorly researched load and it will ultimately require the designer to estimate the loss rate and provide back-up heating capacity as a safety factor. An engineer may be more familiar with the recirculation loop-flow rate and return temperature which can be used to find the heat loss rate from:

$$N_{apt}\dot{Q}_{loop} = \rho c_p \, f_{loop}(T_{supply} - T_{return})$$

Where N_{apt} is the number of apartments, $\dot{Q}_{loop}$ is the recirculation loop losses per apartment unit, f_{loop} is the flow rate of the recirculation loop, T_{return} is the recirculation loop return temperature, and T_{supply} is the supply temperature to the occupants or the temperature entering the recirculation loop. The tool offers users inputs for the recirculation loop losses per unit, or the recirculation loop flow rate and return temperature. Using the later inputs, the tool will calculate the recirculation loop losses per apartment unit based on the inputs for flow rate, return temperature, and supply temperature.

Swing Tank

The swing tank heating capacity is sized to meet the recirculation loop load during periods without hot water input from the primary system. The minimum heating capacity for the swing tank, $\dot{Q}_{TM}$, is:

$$\dot{Q}_{TM} = SF \;\; N_{apt} \, \dot{Q}_{loop}$$

[10] Kintner P., and Larson, B. (2019). Literature Review of Multifamily Central Domestic Hot Water Distribution Losses. Prepared for NEAA.

Where SF is the user input for safety factor applied so that the swing tank heating capacity will exceed the temperature maintenance load. The resistance element in the swing tank is recommended to be sized to meet the 75th percentile of temperature maintenance loads. In a study of 45 multifamily buildings in CA, WA, and NY, the 75th percentile was approximately 1.75 times the expected input for the temperature maintenance load following the available data, which is used to set the default safety factor.

The swing tank gains energy from the primary system during DHW draws to meet a fraction of the temperature maintenance losses. In an ideal situation, the energy gained by the swing tank could coast through long periods of time, i.e. overnight, without using the resistance elements. For typical multifamily buildings with primary storage temperature at 150°F, the primary storage can supply up to 50W/Apt of heat to the swing tank on average. Since the industry has not prioritized reduction of distribution losses, the reality of most systems is that the temperature maintenance losses are greater than the energy gained in the swing tank from hot water draws.

To understand the effects of swing tank storage volume on energy use of the resistance element, we performed a simulation to model just the swing tank in the open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[11]. In this analysis, we assume the primary system always supplies hot water at 150°F and vary the temperature maintenance load and the swing tank volume. More details of the simulation are available in Appendix B. The goal of modeling the systems is to develop simplified recommendations that can be used to size the system. The results of the study suggested that the sizing of the swing tank volume does not effectively reduce energy use at typical temperature maintenance values. If care is taken to reduce the temperature maintenance load below about 50 W/apt, a system can benefit from increased swing tank volume. An increased volume can store energy from peak hot water events for longer periods of time, allowing the swing tank to coast through periods of low hot water draws without using backup electric resistance elements.

CA Title 24 prescriptive sizing requirements for the swing tank volume were developed before this more thorough analysis was completed. Therefore, the Title24 prescriptive sizing requires tank sizes that are likely larger than necessary in most cases with high temperature maintenance loads[12]. In cases where meeting the CA prescriptive sizing is not necessary, the sizing recommendations are in Table 2. The sizing of the swing tank was done to minimize the size of the tank and thus the cost of adopting this new technology.

Table 2. Recommend swing tank volume following MASHRAE and CA Title 24

	Swing Tank Volume (Gallons)	
Number of Apartments	EMASHRAE	Title 24
0 - 12	80	80
13 - 24	80	96
24 - 48	80	168
49 - 96	120 - 300	288
> 96	120 - 300	480

[11] https://github.com/EcotopeResearch/HPWHsim
[12] This is likely to change following future code development.

Because the swing tank is in series with the primary system, the swing tank requires the size of the primary system be increased to account for the temperature maintenance load. To find the increase in the volume and heating capacity of the primary system, the swing tank is simulated by tracking changes in the tank temperature due to hot water draws and temperature maintenance losses, according to Appendix A.

In the simulation the resistance element is sized based on the user inputs for the recirculation loop losses and the temperature maintenance safety factor. The swing tank volume in the simulation is sized at the upper bounds of the recommended values. This represents a safety factor as the higher volume swing tank will have a smaller temperature change during the peak hot water draws and result in a greater daily hot water load on the primary system. Lastly, the simulation assumes the resistance element turns on at the supply temperature and has an 8°F dead band, which is typical of resistance hot water tanks.

The simulation for the swing tank is run assuming a worst-case scenario, where the swing tank temperature is the coldest possible before the resistance elements turn on, which is when the largest demand on the primary system will occur. In this scenario, the swing tank is marginally above the supply temperature at the start of the peak hot water usage period, defined in the primary plant sizing section.

Example results of the swing tank simulation are shown in Figure 9, for an example with 2000 gallons of hot water used per day, 6 kW of temperature maintenance losses, a supply temperature of 120°F, and a storage temperature of 150 °F. The blue bars are the hot water demand at the supply temperature which is the same curve as Figure 7; this is what occupants are using at the taps. The grey bars are the volume of hot water drawn from the swing tank and primary system at the swing tank temperature, calculated using a mixing ratio. The greater the swing tank temperature the greater the percent difference is between the two bars.

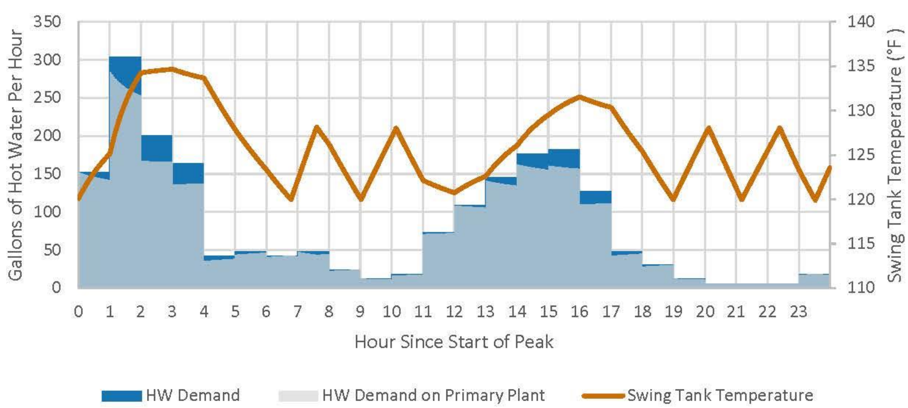

Figure 9. Swing tank simulation plot.

Cumulatively, for the 24 hours after the peak event, the HW demand on the primary plant is 86% of the total volume of daily hot water demand. This is relatively invariant, ±1%, to the initial conditions and reasonable changes to the volume of the swing tank.

Importantly for sizing the primary plant, the volume of hot water drawn from the primary plant to the swing tank is at the storage temperature, not the supply temperature. The sizing methodology for the primary plant with a swing tank factors this in by using the hot water demand on the primary plant, in Figure 9 as the hot water load. The ratio between the total daily hot water demand, $V_{HW,Day}$, and the total daily hot water demand on the primary plant from the swing tank, $V_{HW,Swing}$, is found from:

$$f_{swing} = \frac{V_{HW,Day}}{V_{HW,Swing}}$$

This represents the average mixing ratio of hot water supplied by the swing tank for the peak day. The daily hot water demand on the primary plant is the volume of hot water that the primary plant must supply at the storage temperature to the swing tank.

Beyond the change in load calculation there are two important changes for sizing the primary plant:

1. This method accounts for the mixing of hot water down to the supply temperature. Thus the storage volume is already sized at the storage temperature, so step 5 in the primary plant methodology is skipped.
2. The primary heating capacity is adjusted to meet the demand on the primary plant, $V_{HW,Swing}$ at the storage temperature:

$$\dot{Q}_{primary} = \rho c_p \frac{V_{HW,Swing}}{h_{max,hr}} (T_{storage} - T_{CW})$$

Parallel Loop Tank

A parallel loop tank sees only the constant temperature maintenance load. The design of a parallel loop tank system must balance the expected load with the volume of the loop tank and the capacity of the temperature maintenance heating system. Too little capacity will lead to cold water being circulated. Too large of a capacity could lead to short-cycling of equipment.

The first control on sizing the parallel loop tank is the minimum time the HPWH is expected to be off, t_{off}. This controls the loop tank volume, which is designed to cool off from the setpoint of the temperature maintenance HPWH to the minimum temperature in t_{off}. This is represented graphically for an example case in Figure 10, where, during the first time period t_{off} the tank loses energy equal to $N_{apt}\dot{Q}_{loop}t_{off}$. When the temperature change in the tank is known, the tank volume, V_{TM}, can be found from

$$V_{TM} = \frac{N_{apt}\dot{Q}_{loop}}{\rho c_p} \frac{t_{off}}{T_{setpointTM} - T_{turnOn}}$$

Where ρ is the density of water, c_p is the heat capacity of water, $T_{setpointTM}$ is the temperature maintenance multi-pass HPWH setpoint, and T_{turnOn} is the temperature at which the multi-pass HPWH turns on.

The sizing of the heating capacity for a parallel loop tank follows that of the swing tank heating capacity, in that the heating capacity is designed to exceed the recirculation loop losses using the user input for the temperature maintenance safety factor. Again, the default temperature maintenance safety factor is 1.75.

$$\dot{Q}_{TM} = SF \ N_{apt}\dot{Q}_{loop}$$

The expected runtime of the temperature maintenance multi-pass heat pump can be found from the volume and the heating capacity to ensure the system does not short cycle. The tool compares the expected runtime to a threshold of 20 minutes. The heat capacity for the temperature maintenance heat pump, is equal to the energy that is added to the tank over the expected runtime, t_{run}, plus the continuous temperature maintenance load. This is shown graphically in Figure 10, and can be written as

$$\dot{Q}_{TM} = \frac{\rho c_p V_{TM}}{t_{run}}\left(T_{setpointTM} - T_{turnOn}\right) + \ N_{apt}\dot{Q}_{loop}$$

Then substituting in the equation for V_{TM} and $\dot{Q}_{TM}$:

$$Saftey \ N_{apt}\dot{Q}_{loop} = \ N_{apt}\dot{Q}_{loop}\left(1 + \frac{t_{off}}{t_{run}}\right)$$

Lastly solving for t_{run}:

$$t_{run} = \ t_{off}/(Saftey - 1)$$

The Ecosizer checks that t_{run} meets a minimum runtime of 20 minutes to prevent short cycling the multi-pass HPWH.

Figure 10 gives an example operation where the temperature maintenance tank has a setpoint of 135°F and a 10°F temperature lift. A typical operation for the temperature maintenance HPWH will run for 20 minutes then turn off for 20 minutes, and cycle repeatedly.

Note that due to the uncertainty in the distribution loss rate, it will often be advisable to size the temperature maintenance HPWH to cover a typical loss rate of about 100 Watts per apartment and then to include some electric resistance as back-up in case of higher than normal losses.

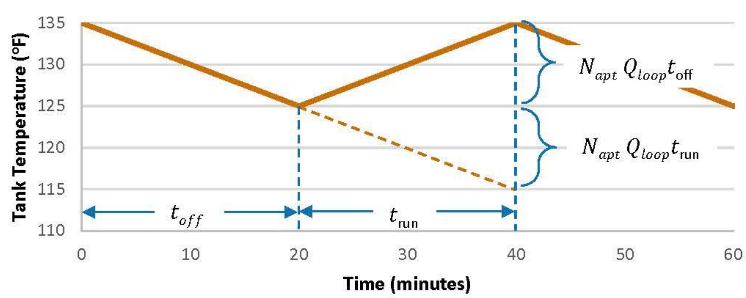

Figure 10. Parallel loop tank average temperature over time in orange.

Load Shift Sizing

The load shift module allows users to block out part of the day when the HPWHs may be prevented from running as a response to utility signals or to avoid peak electricity pricing periods. The storage volume and heating capacity necessary to meet the load may need to be increased depending on the time and extent of these peak power periods. The sizing methodology for load shift follows the same methodology as the minimum sizing for the primary system, except the time-dependent hot water generation rate, $\dot{G}(t)$, is set to 0 during hours when operation of the HPWH is excluded.

To ensure that a system can achieve load shifting during every peak period of the year would require significant increases in storage volume and/or heating capacity. Therefore, there is also a modifier for the percent of load shift captured. The user input for percent of load shift captured calculates a derated gallons per person per day according to a normal function fitted to the empirical cumulative density function given in Figure 3.

When sizing a load shifted CHPWH plant the system is sized against both the load shift and the non-load shift scenarios, to ensure that the load shift scenario is a more conservative design than the non-load shift scenario.

For example, in a situation similar to the example worked in Figure 7 and Figure 8, if a user sets the load shift period to be between 5PM and 8PM, the assumption is that hot water generation rate goes to 0 during this time period, shown as the yellow line in Figure 11. This also shifts the start of the 2nd peak period to 17:00 from 19:00 in Figure 7.

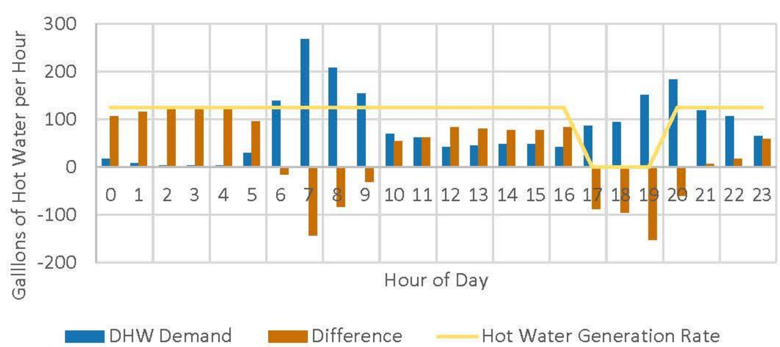

Figure 11. A load shift scenario where the systems is HPWH is excluded from 1700 to 2000.

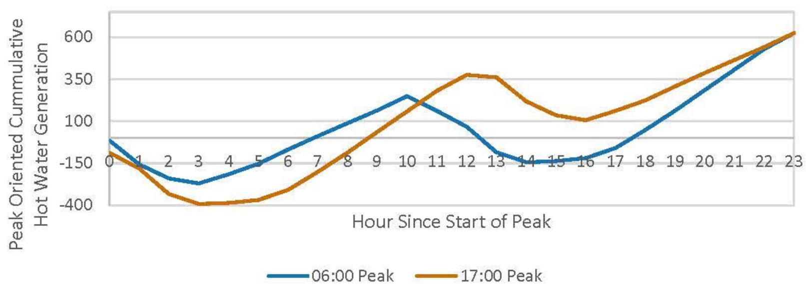

Figure 12. The cumulative supply after peak events for a load shift scenario.

In Figure 11, the load shifted hot water heating rate is given in yellow, noticeably dipping to zero during the hours from 17 – 20, just as an example. The difference between the heating rate in yellow and the hot water load shape is shown in orange. Note that in this case, when heating returns at hour 20:00, the heating rate is lower than the hot water load during that hour. This is factored into the sizing of the running volume in Figure 12 because the method looks at the accumulation of the difference between the generation rate and the demand over the 24 hours after the peak not just the peak period.

The cumulative supply curves after the start of the peak events are shown in Figure 12 for both peak events. The absolute minimum of both curves in Figure 12 is the running volume. In this case the load shifted peak period starting at 17:00 provides a larger running volume than the peak period starting at 06:00.

In this instance the load shift scenario needs a greater volume of storage than the non-load shifting scenario, which is sized by the 06:00 peak in Figure 8. However, cases with shorter load shifting periods may size the system smaller than the non-load shifting scenario. The methodology used here is to check both scenarios and return the larger running volume.

There are scenarios where increasing the hot water generation rate can reduce the primary storage volume. For example, in Figure 11, if the hot water generation rate is increased to 200 gallons of hot water per hour the required load shifted storage volume would decrease because the DHW demand at 20:00 can be met. But the running volume during this load shift scenario cannot be less than the volume of DHW demand during the hours from 17:00 – 20:00.

A similar scenario could be envisioned if two load shift periods were used. If the hot water generation rate were not large enough to fully recover the storage volume between the two periods, the running volume would have to store the storage volume from the first load shift period and some from the second. Again, increasing the hot water generation rate to a point where the tank could fully recover would decrease the storage volume.

When designing for load shift, the default aquastat fraction, 0.40, of the storage volume can become pointlessly large. The aquastat fraction provides some safety based on the total storage volume, which can grow quickly when sizing for load shift. When doing load shifting, it is recommended users reduce the aquastat fraction by lowering the aquastat in the primary storage volume to reduce the total stored volume. (Note: if it is turned down too low the user is notified of the minimum value for the aquastat fraction to prevent short cycling). However, this is a parameter of CHPWH plant design, so users should be aware of where the aquastat port is on the storage tanks used in their design and can use the sizing curve and aquastat fraction to match the volume of their designed system to a minimum heating capacity.

For most cases, sizing for load shift will require an increase in primary storage volume over a non-load shift scenario. This is true even in cases with an increased temperature storage temperature. The tool will not directly tell users what temperature to increase their storage volume to for load shifting through their input periods, but users can increase the storage temperature to see the decrease in storage volume for their load shift scenario. Users should check that their load shift scenario with increased storage temperature does not have a lower storage volume than the system sized without load shifting with increased storage temperatures.

If users are interested in finding out how much load shift can be achieved with a non-load shift sized system and an increased primary storage temperature setting, users will have to first find out how big their storage volume is for the no load shift scenario with a low storage temperature. Noting the primary system size for the non-load shift case, users can set their load shift hours and elevated storage temperature, then iteratively adjust the user input for percent of load shift captured to find the effectiveness of their non-load shifted system.

Temperature Maintenance Load Shift

The Ecosizer tool allows for load shifting of the parallel loop tank, but the swing tank design is inherently load shift capable during periods of high DHW demand compared to the temperature maintenance load. See the swing tank temperatures in Figure 9. In practice, to accomplish load shift of the swing tank it should be heated above setpoint by the electrical resistance elements prior to the load shift period.

Users interested in load shifting a parallel loop tank can increase the number of hours the multi-pass HPWH is turned off. The results will end up increasing the required volume and the heating capacity. The expected run time could be set to the expected time between a load shifting signal and the load shifted period.

5. FUTURE MODULES

The Ecosizer CHPWH sizing tool is needed to support designers to incorporate CHPWHs in a way that helps ensure optimally-sized systems. To help the industry in this transition, this sizing tool should be combined with an annual performance model so that designers could see the energy use impacts of the range of possible design choices. The annual performance model will be based around typical use conditions as opposed to the peak design conditions used in the sizing tool. The energy performance tool will use the premier open-sourced HPWH simulation software used in CBECC-Res, HPWHsim[13], and will be based on:

- Location-based weather from TMY3 files, including a model for predicting entering water temperature.

[13] https://github.com/EcotopeResearch/HPWHsim

- Equipment specific sizing for specific manufacturers (i.e. 15-ton stages), using performance maps for specific equipment to calculate design temperature minimum output capacity. These performance maps have been collected for a wide range of CHPWH equipment by the CEC for use in the CBECC-Res software.

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APPENDIX A – SIMPLIFIED SIMULATION

The simulation plots used in the Ecosizer tool were provided to instill confidence in the method and help users understand the methodology. The simulation is run for three days, with minute timesteps, to initialize the CHPWH system but only the last day is provided for the user in the Ecosizer.

Primary Plant

The simulation of the primary system works by tracking the volume of hot water remaining in the primary system. This assumes the system is perfectly stratified and all the hot water above the cold temperature line is at the storage temperature, this also ignores thermal losses to the environment. The simulation balances the hot water demand according to the hot water load shape and the volume added according to the calculated hot water generation rate from the recommend compressor runtime of 16 hours a day. This is:

$$V_{primary,T_{storage}}(t+1) - V_{primary,T_{storage}}(t) = \Delta t\left(\dot{G}_{T_{storage}}\ (t) - \dot{V}_{draw,T_{storage}}(t)\right)$$

Where $V_{primary,T_{storage}}$ is the effective storage volume, Δt is the time step of one minute, $\dot{G}_{T_{storage}}(t)$ is the time variant hot water generation rate for water at the storage temperature, and $\dot{V}_{draw,T_{storage}}$ is the hot water demand rate at the storage temperature. The hot water demand rate is assumed to be constant across every hour, an assumption that is acceptable for demonstration purposes but not for evaluating an annual energy estimate where real hot water draws are necessary. The demand on the primary system is mixed down from the storage temperature to the supply temperature.

During each time step of one minute, the simulation evaluates if the system is heating or should be heating based on the user input for the aquastat fraction. If it is, the hot water level is adjusted by the difference between the hot water generation rate and the hot water demand rate. If not, heating the hot water level is decreased by the hot water demand rate. Conveniently, the hot water generation rate is assumed to be constant so the simulation will check if the heating condition happens during in the middle of a minute or if the volume at the end of a timestep exceeds the total storage volume, and adjust the time hot water is generated to a fraction of minute.

Swing Tank

Since the swing tank is in series with the primary system the temperature needs to be tracked to inform inputs for primary step, unlike the parallel loop tank which is separated from the primary system, see Figure 1 and Figure 2. The simulation on the swing tank tracks the average temperature of the swing tank every minute, assuming the swing tank is well mixed. Any hot water demand from the swing tank is mixed at the swing tank temperature and the volume removed from the swing tank is replaced from hot water from the primary system.

The change in temperature is contributed to by three factors: the recirculation loop losses, the heating of the resistance elements, and the contribution of hot water from the primary system. The change in temperature of the swing tank, $T_{swing}(t)$, from one time t to time $t + \Delta t$, can be found from a sum of these heat sources, $\dot{Q}_i(t)$:

$$T_{swing}(t+\Delta t) - T_{swing}(t) = \frac{\Delta t}{\rho c_p V_{TM}} \sum_i \dot{Q}_i(t)$$

The simulation assumes the recirculation loop losses are a constant wattage loss given the user input; then the change in swing tank temperature from one timestep to the next is also a constant. The total recirculation loop losses can then simply be written by:

$$\dot{Q}_{total\ loop}(t) = N_{apt}\dot{Q}_{loop}$$

The resistance heating element is also a constant heat source if the elements are running. The size of the elements is calculated from:

$$\dot{Q}_{TM}(t) = SFN_{apt}\dot{Q}_{loop}$$

The last source of heat in the swing tank comes from the primary system during hot water draws. Where it is assumed the swing tank outlet is mixed with the cold incoming water, and the mixed down draw is replaced with water from the primary system. The change in energy can be described as the difference between the energy in and energy out:

$$\dot{Q}_{Primary}(t) = \rho c_p V_{mixed}(t)\left(T_{storage} - T_{CW}\right) - \rho c_p \dot{V}_{draw,T_{swing}}(t)\left(T_{swing}(t) - T_{CW}\right)$$

$$\dot{Q}_{Primary}(t) = \rho c_p \dot{V}_{draw,T_{swing}}(t)\left(T_{storage} - T_{swing}(t)\right)$$

Where $\dot{V}_{draw,T_{swing}}$ is the hot water draw, $\dot{V}_{draw,T_{supply}}$, mixed down from the supply temperature to the swing tank temperature found from:

$$\dot{V}_{draw,T_{swing}}(t) = \frac{T_{supply} - T_{CW}}{T_{swing}(t) - T_{CW}} \dot{V}_{draw,T_{supply}}(t)$$

The mixed hot water draw is important for finding what the total demand is on the primary system and as such the system sizing.

Each timestep, these three heat sources are summed together to find the swing tank temperature for the next timestep. Like with the primary system simulation, the swing tank simulation also checks if the heating elements should be turned on or off at the sub-minute level.

APPENDIX B – SWING TANK SIMULATION

To develop rules around the appropriate storage volume for a swing tank, we performed a simplified model of a swing tank using the open-sourced HPWH simulation tool, HPWHsim[14], which is used in Title 24 CBECC-Res compliance software. The simulation uses minute-long timesteps to track temperatures and heat flows with a HPWH or electrical resistance tank. The inclusion of HPWHsim for this study, is to simulate a swing tank for a year to make annual estimates of energy use in the swing tank and to determine how much of the temperature maintenance load is covered by the swing tank versus the primary system.

[14] https://github.com/EcotopeResearch/HPWHsim

The parameter space for modeling a HPWH system is vast. Here we can only test a limited number of inputs due to computational and time constraints. We reduce the varied input parameters to:

- The temperature maintenance load, ranging from 25 W/apt to 200 W/apt, for a building with 118 apartment units.
- The swing tank electric resistance elements were controlled to be 1.5 times the temperature maintenance load.
- The swing tank storage volume, ranging from 80 Gallons to 700 Gallons.
- The annual hot water draws, which was taken from a year of data from a building with 118 apartment units monitored at 10-minute intervals. We assume the hot water draws are averaged across each 10-minute period. This also included data for the cold incoming water supply.

Input parameters that were kept constant across all model runs are:

- The primary storage temperature, at 150°F, which implies that the primary HPWH system can always meet the load.
- The hot water supply temperature was kept constant at 120°F.
- The recirculation pump flow rate was kept constant, which means the hot water recirculation return temperature was calculated from the recirculation loop losses.
- The air temperature around the tank is assumed to be a constant 70°F, which controls the small UA heat losses from the swing tank.

The mixing valve is an important piece of the model because it controls the volume of water removed from the swing tank. During a hot water draw for recirculation, the water from the swing tank is mixed down with the water from the recirculation loop return. This action mixes hot water from the swing tank with warm water (~115°F). As a result, to reach the supply temperature, only a small fraction of the volume comes from the swing tank. On the other hand, DHW drawn by occupants at the tap introduces cold water to the system. At the mixing valve, DHW draws are mixed with swing tank water and the cold-water temperature and thus requires much larger volume to be taken from the swing tank to meet the supply temperature. This action also draws water from the primary system and heats up the swing tank. During this simulation we also assume the swing tank is well mixed during every time step.

The results of the model runs are shown in Figure 13, where annual resistance element energy use in the swing tank is plotted against swing volume for different temperature maintenance loads. As expected, increasing the temperature maintenance load increases the annual resistance energy use. Surprisingly though, increasing swing tank volume has a small effect on the annual energy use at higher (>100 W/apt) temperature maintenance loads. This is attributable to the dominance of the constant temperature maintenance load.

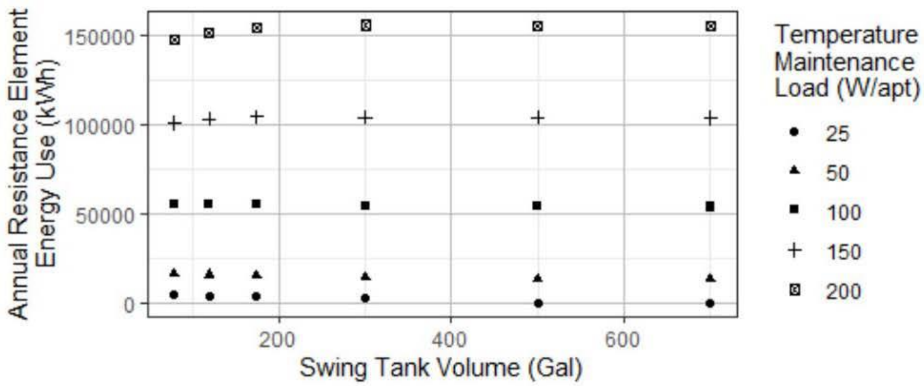

Figure 13. Annual energy use in the swing tank with swing tank volume for different temperature maintenance loads.

For the hot water draws to match the energy lost due to temperature maintenance load at any hour, the hourly hot water draw can be found from:

$$N_{apt}\dot{Q}_{loop} = \rho c_p f_{draw}(T_{primary} - T_{supply})$$

$$f_{draw} = \frac{N_{apt}\dot{Q}_{loop}}{\rho c_p(T_{primary} - T_{supply})}$$

For this case, assuming 100 W/apt, we can then calculate the draw per person:

$$f_{draw} = \frac{118[\text{apt}]}{140[people]} * 100\left[\frac{W}{apt}\right] * 3.412\left[\frac{BTU}{hr}\right] / (8.314\ [\text{lb/gal}] * 1\ [\text{Btu/lb} - {}^\circ\text{F}] * (150\ [{}^\circ\text{F}] - 120\ [{}^\circ\text{F}])$$

$$f_{draw} = 1.15 \text{ gphpp}$$

The data shown in Figure 5 suggests this only occurs for 1 hour of the day during the morning peak on average. For most hours of the year, the temperature maintenance heat losses are dominating the system, meaning the tank rarely has a chance to increase its stored energy and coast through periods of low use and the swing tank serves as a resistance water heater for most of the year. Comparatively, if the system has a reduced temperature maintenance load of 50 W/apt, $f_{draw} = 0.574$ gphpp, which is well below the morning and evening peak on average in Figure 5. Following this logic, buildings that have more diversity of DHW draws may have a higher average draw and see less resistance element use in the swing tank.

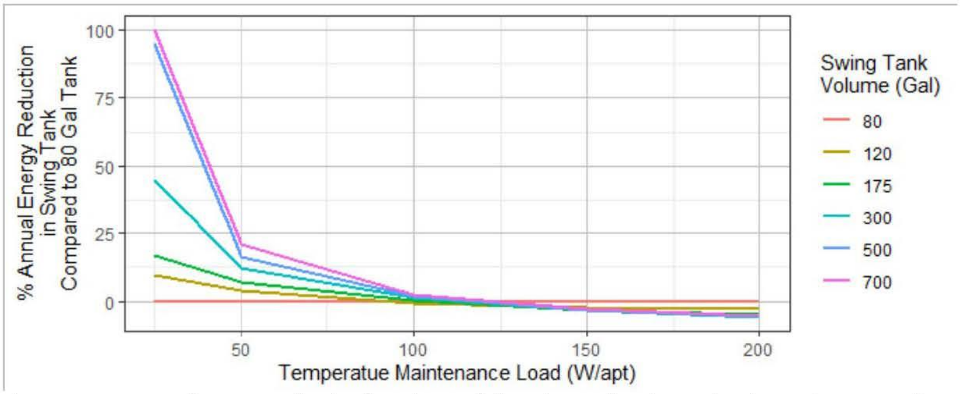

Figure 14. Percent of energy reduction in swing tank from increasing the tank volume above 80 gallons as a function of the temperature maintenance load (For a building with 118 dwelling units).

If the swing tank cannot store hot water to make it through periods of low DHW demand relative to the temperature maintenance load, increases in the swing tank volume cannot save energy. This is shown in Figure 14, where the annual resistance element energy use is shown as a percent savings of an 80-gallon swing tank with varying temperature maintenance loads. At a temperature maintenance load of 100 W/apt, increasing the volume of the swing tank from 80 to 700 gallons only reduces annual energy use 2.6%. However, at a temperature maintenance load of 50 W/apt, this same increase in tank volume sees a 21% energy savings, and at 25 W/apt a 700-gallon tank reduces the annual resistance element energy use to 0 kWh.

A priori, the best estimate for the temperature maintenance load is 100 W/apt, where increases in tank size see a minimal energy savings. Consequently, our recommendation for sizing the swing tank volume would be getting a minimally sized tank that can handle the peak flows. Recommended tank sizes are given in Table 2 by number of apartment units. If designers are able to push for a reduction in recirculation losses through use of insulated pipe hangers or other measures, there are benefits to increasing the swing tank volume. A 300-gallon swing tank could reduce energy use by the resistance elements by 12% over an 80-gallon swing tank.

The swing tank does not cover the entire temperature maintenance load. In an ideal design with a low temperature maintenance load, the primary system will cover the load; but in most use cases the primary system will only cover a fraction. In the simulation we know exactly what the temperature maintenance load is and how much energy is created by the resistance elements to cover this load. The difference between these loads is the energy added by the primary system to cover the temperature maintenance load.

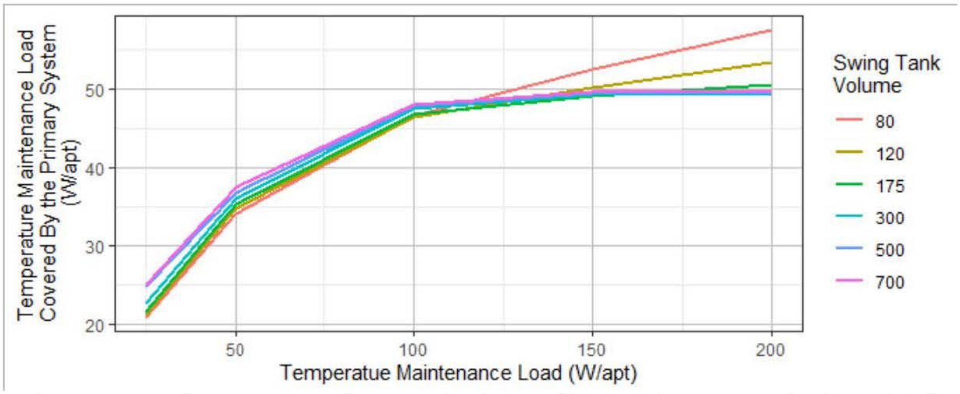

Figure 15. Annual temperature maintenance load covered by the primary system for the modeled temperature maintenance loads.

Figure 15 shows the annual average of the temperature maintenance load covered by the primary system in watts per apartment. The figure shows an asymptotic approach towards 50 W/apt; however, the temperature maintenance load covered by the primary system could likely be greater than this for different draw profiles or greater temperature maintenance loads, with the latter being strongly discouraged.

Overall difficulty in sizing the swing tank comes from being able to predict the temperature maintenance load. More research should be done in this field to constrain the problem. More research also needs to be done on sizing of swing tanks, which should include variation in hot water draws, resistance element sizing, and primary setpoint.