Waste Water Heat Pump Design and Feasibility Study

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Prepared for
Mira Vowles, Project Manager
Bonneville Power Administration
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Prepared by
Ben Larson, Michael Logsdon, and Jonathan Heller
Ecotope, Inc.

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A Technology Innovation Project Report

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Ben Larson is Director of Research and Technology at Ecotope. He has a multifaceted background in physics, alternative energy, climate change, and energy efficiency. Among his work at Ecotope is a key role maintaining and developing the SEEM energy simulation program, which is used to model energy efficiency improvements in the residential sector. Mr. Larson also manages projects at Ecotope including Pacific Northwest regional efforts to investigate heat pump water heater performance.

Jonathan Heller, P.E. is President of Ecotope. He has over 25 years of experience providing design, research, and consulting on energy and resource efficiency in the built environment. Mr. Heller's research has provided the technical basis for the development of regional energy codes and energy conservation programs. He provides consulting services to local developers, architects, universities, and housing authorities, as well as regional utilities and municipalities.

Michael Logsdon is a statistician and research scientist at Ecotope. He has a meandering background in engineering, biotech, and mathematics. Mr. Logsdon generates web dashboards for datasets, proposes novel methodologies for analyzing measured energy use, and generally helps people understand their data.

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Abstract

Glossary of Acronyms and Abbreviations

ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BPA	Bonneville Power Administration
Btu	British thermal unit
C	Celsius
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
kW	kilowatt
kWh	kilowatt hours
R-22	Refrigerant 22
R-134a	Refrigerant 134a
RCC	Reverse cycle chiller
WWHP	Waste water heat pump

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Executive Summary

Under contract to the Bonneville Power Administration (BPA), and in partnership with Vulcan Real Estate and Seattle City Light, Ecotope is researching, designing, piloting, verifying and documenting a heat pump water heating system for large, multifamily buildings using the building waste water as the heat source. The waste water heat pump (WWHP) will recover waste heat streams from the building and heat water for domestic use at extremely high efficiency levels.

This project follows directly from a previous Ecotope project pioneering the use of air-source heat pump water heaters, or reverse cycle chillers (RCC), located in below-grade parking garages of mid-rise multifamily buildings in Seattle (Heller 2015). That project effectively delivered systems with annual coefficients of performance (COPs) of 2.6-2.8 using 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 will produce hot water from a much warmer reservoir (~70°F) potentially yielding overall COPs of 4-5. Much like the RCC project 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.

Vulcan Real Estate is developing the pilot building in the Seattle South Lake Union neighborhood. It will have 385 units, consist of two floors of concrete construction topped by five wood-framed stories. It will sit above a below-grade, two-level concrete parking garage.

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.

Using the WWHP simulation and informed by lessons learned from the previous RCC projects, the proposed design includes eight 500 gallon hot water tanks plumbed in series, three 15-ton Colmac water-to-water reverse cycle chillers operating in parallel, a 15,000 gallon wastewater vault, and 50-tons of flat-plate heat exchanger capacity submerged in the vault. Satisfying heating demand for continually recirculating hot water will be met by a separate, air-source heat pump system optimized for the task.

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 allows 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.

Considerable analysis of equipment specification sheets and use of the simulation suggests the system could perform with a COP of 4-5 on an annual basis. Using the lower-end of 4 for estimation purposes, this WWHP system is projected to save 500,000 kWh/yr at this building compared to a baseline system of in-unit electric resistance tanks. The high variability in construction costs, especially for nascent technologies, make cost projects challenging. We will only know the final incremental cost once construction is complete but we estimate it is $100,000 to $200,000. For a retial electricity cost of 0.08 $/kWh, that gives a simple payback in under 2.5-5 years depending on the incremental capital cost.

Based on preliminary research, design, and optimization, Ecotope believes the wastewater heat pump design to be feasible and cost-effective, and advises proceeding.

1 Introduction

The largest single energy use in new mid- and high-rise multifamily buildings in the Pacific Northwest is domestic water heating. This accounts for approximately ¼ of the total building energy use (Heller 2009). With the regional shift towards growing residential urban centers, the Northwest is seeing a boom in new apartment construction. The draft 7th Northwest Power Plan predicts the construction of 4,750 new mid- and high-rise units per year over the next 20 years, 78% of which will have electric water heating systems (NW Council 2015). The typical electric system is an in-unit resistance tank with an annual efficiency of 80%. To address this growing electric load, Ecotope is pursuing research on centralized water heating systems operating with heat pumps that can achieve efficiencies far greater than typical systems.

Under contract to the Bonneville Power Administration (BPA), and in partnership with Vulcan Real Estate and Seattle City Light, Ecotope is researching, designing, piloting, verifying and documenting a heat pump water heating system for large multifamily buildings using the building waste water as the heat source. The waste water heat pump (WWHP) will recover waste heat streams from the building and heat water for domestic use at extremely high efficiency levels. The system will be built in a multifamily building with nearly 400 apartment units.

This project follows directly from a previous Ecotope project pioneering the use of air-source heat pump water heaters, or reverse cycle chillers (RCC), located in below-grade parking garages of mid-rise multifamily buildings in Seattle (Heller 2015). That project effectively delivered systems with annual coefficients of performance (COPs) of 2.6-2.8 using 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 will produce hot water from a much warmer reservoir (~70°F) potentially yielding overall COPs of 4-5. Much like the RCC project 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.

The concept is to locate a waste water holding vault on the ground floor or first level of parking in the building. All waste water from the multifamily units will be directed to the vault which will provide the heat source for a heat pump water heater. The vault will house stainless steel heat exchanger plates, used by the heat pump, to extract heat from the vault and heat a bank of domestic water storage tanks.

In the first phase of the project, Ecotope is assessing the viability and cost-effectiveness of the system. The assessment is contained in this feasibility study. Pending the successful outcome shown by this study, the project team will move on to system design and documentation for a new building. If the systems can be designed so that it fits well with the overall goals of the project, the team will proceed with the construction, installation, and verification (M&V) of the system. A measurement protocol will be created and deployed to monitor the system performance so it can be optimized and fully quantified. After system performance verification, the design details will be documented in design guidelines that can guide future installations.

The feasibility study consists of three main components: background research, simulating the waste water heat pump system, and schematic design. The background research assembles information from previous studies, collects materials and products available for the system and assesses waste water handling concerns. A critical component to the overall study is the numerical model of water-heat flows in the building over the course of a day and year to optimize component sizes. The last part of the feasibility study is the schematic design to verify final feasibility whereby producing a rough cost estimate for implementation. All three components are considered, in turn, in the following report.

2 Background Research

In order to determine the viability of a waste water heat pump, Ecotope conducted background research consisting of general research in to waste water heat extraction, existing, similar projects, waste water handling concerns and best protocols, and products available for system components. Section 2 of this report details those findings.

2.1 Extracting Heat from Waste Water

Optimizing the energy efficiency of a building involves tracking and minimizing sources of heat loss. Typically this implies a consideration of heat transfer through the building envelope, but energy also leaves the building in the form of heated water, exiting down the drain.

People have thought about and implemented systems to extract heat from waste water for decades. The simplest design is known as drain water heat recovery, and is basically a coil of piping either wrapped around a drain pipe, or immersed in a greywater holding tank (CCHT 2006, DOE 2016). These are passive energy transfer systems where heat from the warm, outgoing waste water transfers to fluid circling in the coil. The effectiveness of the systems vary based on design and installation configuration. All are limited by the passive heat transfer characteristics. Studies suggest that drain water heat recovery on a shower/tub pipe can save 40-60% of the water heating energy for a shower (CMHC 2013). That is effectively a COP of 2 but only applies to the shower use.

Alternately, rather than a simple heat exchanger affixed to drain pipes or immersed in holding tanks, a more ambitious design extracts heat from wastewater with heat pumps, which utilize compressor work to move heat from one reservoir to another. Although they require external energy to operate, active heat transfer systems have the advantage of being able to extract more heat from the source reservoir than passive systems whereby making use of more of the available energy. Essentially, they are able to make “higher quality” energy by heating water to higher, more useful temperatures.

Vancouver, British Columbia deployed the first sewage heat recovery system in North America (Dodge 2013). It is a large-scale system mining the heat in sewage from multiple buildings to supply 3.2 MW of heat to 12 buildings in the neighborhood. This district heating system is of a much larger scale than the single-building waste water system our study proposes. Further the system provides energy for space heating buildings while the WWHP will provide energy specifically for water heating.

Also near Vancouver, British Columbia, there are several building-scale sewage heat recovery systems.[1] Those systems differ significantly from the proposed WWHP in that they tap in to the city mains sewage line for a heat source. That heat source is the collected total waste from numerous buildings. Essentially, it is the energy input of many buildings used to heat one building. The WWHP system is an energy balance within a single building. Further, most of those existing projects are providing space heating as opposed to the water heating that the WWHP will provide.

2.2 Related Work by Ecotope

Ecotope has recently engineered several buildings which lay the groundwork for this project. They include centralized water heating systems for multifamily buildings using air-source heat pumps and flat plat, “ocean-source” heat pumps for building space heating.

2.2.1 Central Heat Pump Water Heating in Multi-Family Parking Garages

The most similar work currently undertaken in the research and development community is being conducted by Ecotope and funded by BPA through their Energy Efficiency Emerging Technology program. In that work, Ecotope pioneered the use of air-source heat pump water heaters, or reverse cycle chillers (RCC), located in

[1] For an example see http://www.sewageheatrecovery.com/projects-and-installations/industrial/gateway-theatre/

below-grade parking garages of mid-rise multifamily buildings in Seattle (Heller 2015). That project effectively delivered systems with annual coefficients of performance (COPs) of 2.6-2.8 using the underground garage as a heat source. The RCC pilot projects developed a detailed picture of the water usage characteristics in modern multifamily buildings. Among others, these characteristics indicate existing hot water system sizing methodologies are significantly oversized for today's lower flow plumbing fixtures and current urban demographics and lifestyles in Seattle. The RCC pilot projects provided valuable lessons which we can apply to the WWHP system including hot water storage design, recirculation loop management, and heat pump control. Those lessons, as the apply to this project, are presented in section 4.

2.2.2 Flat Plat Heat Exchangers

Another project which has provided relevant experience for Ecotope is the Northwest Maritime Center in Port Townsend, WA.[2] For that project Ecotope used heat exchangers similar to those proposed for the WWHP system. The heat exchangers are fastened to a pier in deep water in the Puget Sound and are connected to a water-source heat pump system used to heat the building. The heat exchangers are subject to harsh ocean environments and are still operating well years in to the building's life. This is a similar concept to that being proposed here; instead of extracting water from 45 °F ocean water we will be extracting heat from 70-80 °F waste water.

2.3 Waste Water Handling Concerns and Best Protocols

Waste water, although a rich heat source, can require special handling considerations. This particular 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 waste water 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 isn't 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.

Waste water 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 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. Typically the pumps alternate in running. In the case of high flow situations, both can run. In the case where one falls, the other can typically 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, waste water would back up in to 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 waste water. 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

[2] See more project details at http://www.ecotope.com/projects/detail/northwest-maritime-center/ and http://www.millerhull.com/html/nonresidential/nwmaritime.htm.

natural processes and they still function well. Again, should the plates ever need to be cleaned, it will be possible via an access lid.

2.4 Materials and Products Available for System Components

There are a few products and materials, special to a waste water heat pump system that are discussed in this section. This is not an exhaustive list of components, rather it focuses on items potentially unique to the WWHP.

2.4.1 Vault Lining

The concrete vault must be lined with a liquid-tight material that can last the life of the building. Ecotope selected HYDROclick by AgruAmerica.[3] The concrete protective lining is installed in several steps. First, HYDROclick sheets (similar in size to plywood) are incorporated directly in to the concrete form. The seams are joined and backed by the "click" rails. Next, the seams are welded together to fully seal the liner. The backing rails are slightly conductive which allows a meter to pass over the seams and return a warning signal if there are any gaps in the weld. This ensures a proper seal. The lining will also be placed on the lid of the tank to form a liquid- and air-tight seal. Last, pipe penetrations can be molded in to the system ahead of time or they can be cut in and welded smooth later.

2.4.2 Pump Control – Pressure Transducer

The typical pump control is done by float switches but this system will use an additional pressure transducer at the bottom of the vault. The pressure measurement will be used to accurately determine the height of water in the vault. It will be tied in to a centralized computer control system which will allow the control system to pump out the vault to optimize the heat source temperatures. Still, the design retains float on/off switches for emergency backup in case the pressure transducer control fails. There is no special product requirement but the general concept is worth noting here due to the deviation from standard design practice.

2.4.3 Heat Exchanger

Ecotope has identified a flat plate heat exchanger to site submersed in the vault. The working fluid runs through this heat exchanger, picking up energy from the vault and transferring it to the heat pumps which extract it. Ecotope selected a Slim Jim model exchanger from AWEB Supply which is commonly used in pond, lake, and ocean water applications.[4] The heat exchange plates are made from 304 stainless steel to resist corrosion over the life of the building.

2.4.4 Heat Pump Equipment: Conventional vs Transcritical

Ecotope identified two candidate heat pumps: a traditional, subcritical R-134a cycle with Colmac[5], or a transcritical CO_2 cycle with Mayekawa[6]. An air-source version of the Colmac equipment was used in the previous RCC pilot projects. The version for this product will be a water-source unit. CO_2 heat pumps offer intriguing possibilities

Carbon dioxide has seen increasing usage as a refrigerant, especially in heat pump water heating applications. This is at least somewhat due to CO_2's environmentally-friendly properties as a refrigerant. It is "not toxic, flammable or corrosive, and it has no impact on the ozone layer. It is inexpensive and readily available." (Austin and Sumathy 2011) By definition carbon dioxide has a GWP of one, as compared to 1430 for R-134a or 2100 for R-410a (US EPA 2015). There are essentially no fears of CO_2 being regulated out of existence for heat pump applications. Where CO_2 can be utilized to provide comparable efficiency to an HFC-based heat pump it is an ideal refrigerant to use.

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[3] http://agruamerica.com/products/concrete-protective-liners/hydroclick/
[4] http://www.awebgeo.com/slim_jim_geo_lake_plate_home.html
[5] http://www.colmacind.com/heatpumps/watersource/
[6] http://www.mayekawa.com/products/heat_pumps/

However, the critical point of CO_2 – the temperature and pressure beyond which distinct gas and liquid phases do not exist – occurs at roughly 88°F, a temperature too low for a traditional vapor-compression cycle. Instead, heat pump water heating with CO_2 refrigerant uses a so-called “transcritical” cycle, where, rather than condensing the refrigerant to eject energy to the incoming domestic water, a “gas cooler” transfers heat through sensible cooling of supercritical CO_2. This cycle is so named for operating in both sub and supercritical zones.

The nature of the single phase sensible cooling – rather than refrigerant condensation – lends a transcritical CO_2 cycle heat pump well to inducing a large temperature lift. An exergy analysis by Cavallini compared a traditional, R-22 vapor compression cycle to a transcritical CO_2 cycle operated under similar conditions, and suggested that the greatest thermodynamic losses of the CO_2 cycle occur during the isenthalpic expansion process (2004). Physically, this step corresponds to gas expansion occurring at the expansion valve between the gas cooler and the air-to-refrigerant heat exchanger. These throttling losses can be minimized with colder CO_2 temperature exiting the gas cooler, which would correspond to a greater temperature lift of the secondary fluid (the water to heat). The temperature profile of the sensibly-cooled CO2 along the heat exchanger more closely matches the temperature profile of domestic water, rather than the condensing temperature of the R-134a system.

Heat pump water heating is an ideal application for large temperature lifts, as maintaining tank stratification is paramount to an efficient HPWH. In a stratified tank, hot water is available on top, and cold water is heated most efficiently on bottom. Drawing cold water from the bottom of the tank, heating it to setpoint in a single pass, and injecting at the top of the tank maximizes the utility of a HPWH by maximizing tank stratification, and also plays to the strengths of the transcritical CO_2 cycle. These features suggest promise for transcritical CO_2 heat pump water heating and possible applications to space heating as well.

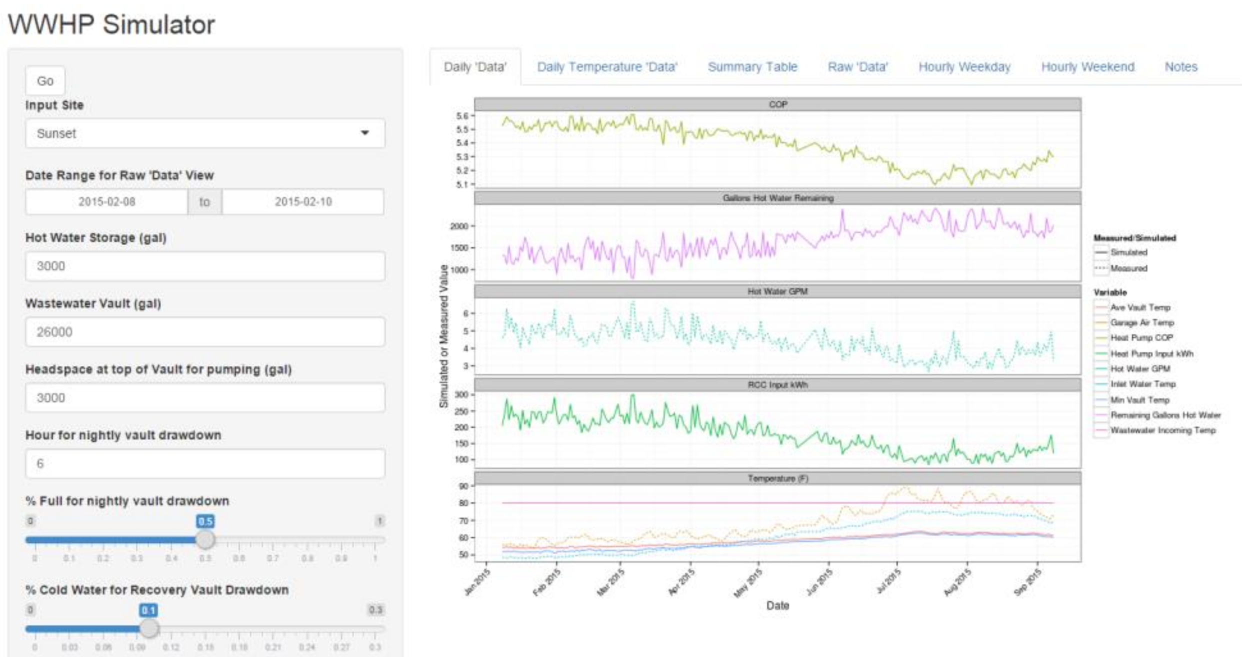
Nevertheless, the Ecotope team decided to pursue the Colmac reverse cycle chiller equipment. The Mayekawa CO_2 heat pump requires an additional heat exchanger, since potable water is not allowed through the unit. In addition, TCHPs are optimized for high temperature water heating, 150°F and above. Temperatures this high are unnecessary to meet domestic hot water demands in a multi-family building. Further, due to the novelty of this equipment at this time in America, there are some questions about the availability of technicians and support. CO_2 heat pumps should still be considered for future applications.

3 Waste Water Heat Pump Simulation

A critical piece to the feasibility study is the numerical model of energy and water flows in the proposed system. The physics-based simulation allows us to predict what will happen to the building water heating system under various conditions. Further, it allows designers to size system components to see how changing them may, or may not, meet differing water use patterns. This simulator was written with the statistical software R, RStudio add-ons, and customized C++ modules. The simulation is hosted on a website here: https://ecotope.shinyapps.io/WWHP_Simulator/. It is accessible to anyone with the link and will be further publicized if the entire pilot project proves viable. The idea is to make it available to engineers and designers to help them in building and sizing future buildings. Section 3 presents an overview of simulation concepts, embedded assumptions, and examples of output applicable to this project.

Figure 1 shows a sample screen shot of the simulation interface although it is best experienced by following the link and viewing in a web browser. The left side of the simulator contains fields for user-settable inputs. Here, the designer can select different water draw patterns and experiment with different hot water storage tank sizes, vault sizes, and heat pump staging controls. The right side of the screen shows both graphical and tabular data outputs.

Figure 1. WWHP Simulator Interface



Simulation Inputs

The following are a list and description of all user adjustable inputs to the simulation:

- Input Site – Ecotope collected detailed hot water usage data from two similar buildings for Reverse Cycle Chiller projects, Stream Uptown and Sunset Electric. This input selects which building's water draw profile to use for the simulation.
- Hot Water Storage – The volume of hot water storage to simulate.
- Wastewater Vault Gallons – The volume of the wastewater vault.
- Headspace at top of vault – The volume of the vault to pump down when the vault fills with wastewater. For example, selecting this input at 3000 gallons implies that, once the simulated vault fills with wastewater, the top 3000 gallons will be pumped out.

- Hour for nightly drawdown – One potential control strategy for optimizing efficiency is to pump the vault down every night, to best take advantage of the warm incoming wastewater from the morning rush. This input specifies at which hour that drawdown takes place, for example 6am.
- Percent full for nightly drawdown – The volume of wastewater in the vault at the end of the optional nightly drawdown. For example, selecting 30% for this input and 6am for the previous input causes, every morning at 6am, the vault to be pumped down to 30% full.
- Percent cold water for recovery drawdown – Another vault pumping strategy for optimizing efficiency is to, rather than pump the vault down at the same time every morning, do so in response to the storage tanks refilling with hot water. The idea is that, with the completion of hot water recovery, it may be advantageous to pump out the vault to best take advantage of incoming warm wastewater during the next peak period. This input specifies the amount of cold water remaining in the storage tanks to trigger a hot water recovery drawdown. For example, setting this at 10% would cause vault pumping once no more than 10% of the storage tanks are occupied by cold water.
- Percent full for recovery drawdown – The volume of wastewater in the vault at the end of the optional recovery drawdown.
- Number of heat pump stages – The heat pump design involves stages to minimize the number of heat pump on/off cycles. This input sets the number of stages to use.
- Tons per Stage – The nominal capacity of tons of each heat pump stage.
- Stage X Activation (Percent Cold) – For each stage X, this specifies the amount of cold water in the hot water tanks sufficient to trigger the stage. For example, with 4 stages, an obvious set of inputs would be to fire stage 1 at 20% cold water, stage 2 at 40% cold water, stage 3 at 60% cold water, and stage 4 at 80% cold water. As the stored hot water amount decreases, the idea is that more heat pumps activate to meet the load.
- Recirc Losses Extracted from Vault – This input, in tons, specifies an assumed amount of heat extracted from the wastewater vault in order to satisfy the load on the recirculating hot water loop. This can be set to zero to assess the impact of separating the recirculating water load from the primary load.
- Hot Water Storage UA – The total heat loss rate of the bank of hot water storage tanks.
- Wastewater Temperature Override – An optional input. If set to zero, then the assumed incoming wastewater temperature to the vault is a weighted average of hot water setpoint and inlet mains water temperature. If set non-zero, then the incoming wastewater temperature assumes the entered value.
- Hot Water Fraction – Specifies the weights for the weighted average of hot water setpoint and incoming city mains tap water temperature, used to compute the incoming wastewater temperature. For example, setting this at 45% will use 45% of the setpoint temperature and 55% of the city mains temperature to estimate incoming wastewater temperature.
- Number of Units in Building – The number of apartment units assumed in the completed building. This is used to scale the hot water usage data from Stream Uptown and Sunset Electric, the two building for which we have detailed hot water use measurements, but that have a different number of units and occupants.
- Occupants Per Unit – The number of occupants per apartment assumed in the completed building. This input is also used to scale the hot water use data from our two differently sized reference buildings, Sunset Electric and Stream Uptown.
- Equipment – Specify either using the Colmac R-134a heat pumps or the Mayekawa CO_2 heat pumps, the two models for which we translated performance maps into the simulation.

Simulation Outputs
The following are a list of the tabular outputs from the simulation. In addition, the simulation graphically displays many other values in a time-series over the time period of interest.

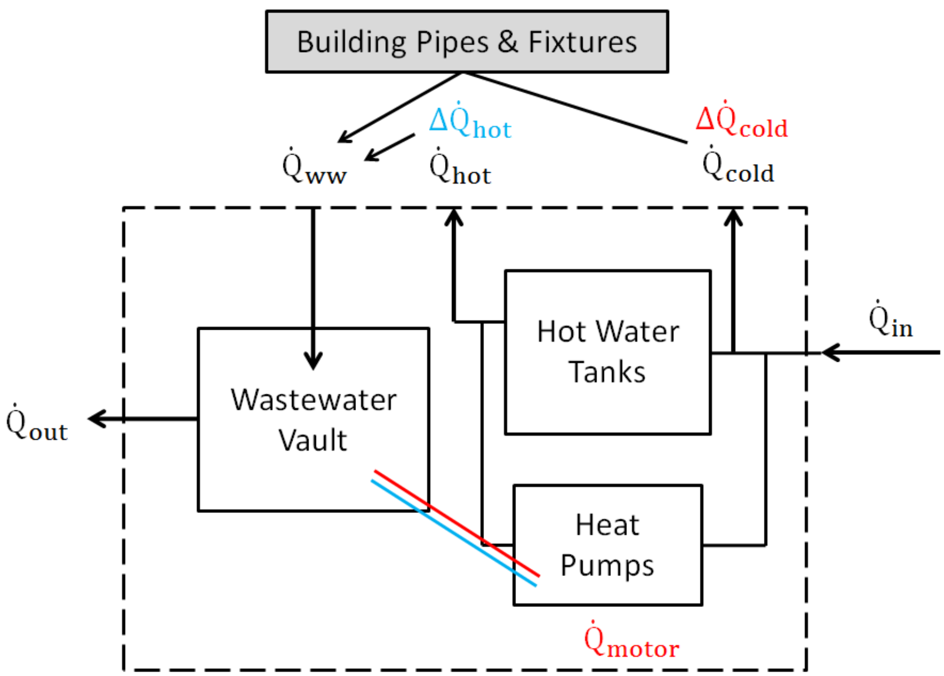
- Vault Temperature – The average temperature of the assumed well-mixed vault.
- Vault Level – The amount of wastewater currently occupying the vault.
- Hot Water Storage Remaining – The amount of deliverable hot water remaining in the storage tanks.
- Heat Pump kWh – The energy consumed by the RCCs.
- COP – The rated efficiency of the RCCs operating under the simulated conditions.

3.1 Energy Balance

Figure 2 shows the energy balance of the basic concept, considering a reference frame of the hot water storage tanks, heat pumps, and wastewater vault. The energy contained in the city mains water flowing into the system is represented as $\dot{Q}_{in}$, and the energy contained in the spent wastewater flowing out of the system is represented as $\dot{Q}_{out}$. Three external heat flows to the reference frame exist: input energy in the form of compressor and pump motors, $\dot{Q}_{motor}$, heat gained by the cold mains water on its journey through the building, $\Delta\dot{Q}_{cold}$, and heat lost by the domestic hot water on its journey through the building, $\Delta\dot{Q}_{hot}$. Put another way, after the journey, what is left is, $\dot{Q}_{ww}$, the energy entering the vault. This quantity depends on much heat the cold water gained and how much heat the hot water lost.

The limiting case for this concept occurs in wintertime, when incoming mains water may be 45 °F or below. Due to low temperature constraints on the system we would prefer the vault stay above 45 °F to avoid problems with freezing. This implies that the net heat transfer between cold water, hot water, and the building must equal the input heat from the motors. In turn, this implies that the feasibility of wintertime operation depends very crucially on the heat transfer between water streams and the building. Unfortunately, this quantity is not well known and has been studied little, if at all.

Figure 2. Waste Water Heat Pump Energy Balance



$$\dot{Q}_{out} - \dot{Q}_{in} = \dot{Q}_{motor} + \Delta\dot{Q}_{cold} - \Delta\dot{Q}_{hot}$$

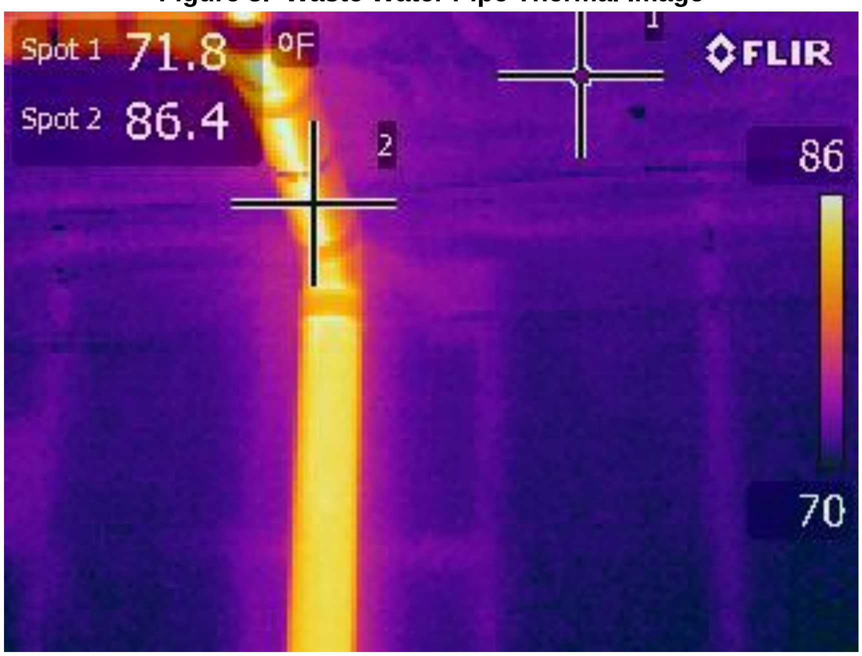
3.2 Model Simplifications and Assumptions

As with all models, it is necessary to make simplifications and assumptions. The simplifications are shortcuts largely made in the name of calculation or programming expediency and generally have little impact on output accuracy. The assumptions, on the other hand, are necessary when we possess incomplete information and, therefore, have to guess at the workings of a physical process or value. Those have greater risk to impact the output accuracy. Both are discussed in this section.

3.2.1 How Warm Will the Wastewater Be?

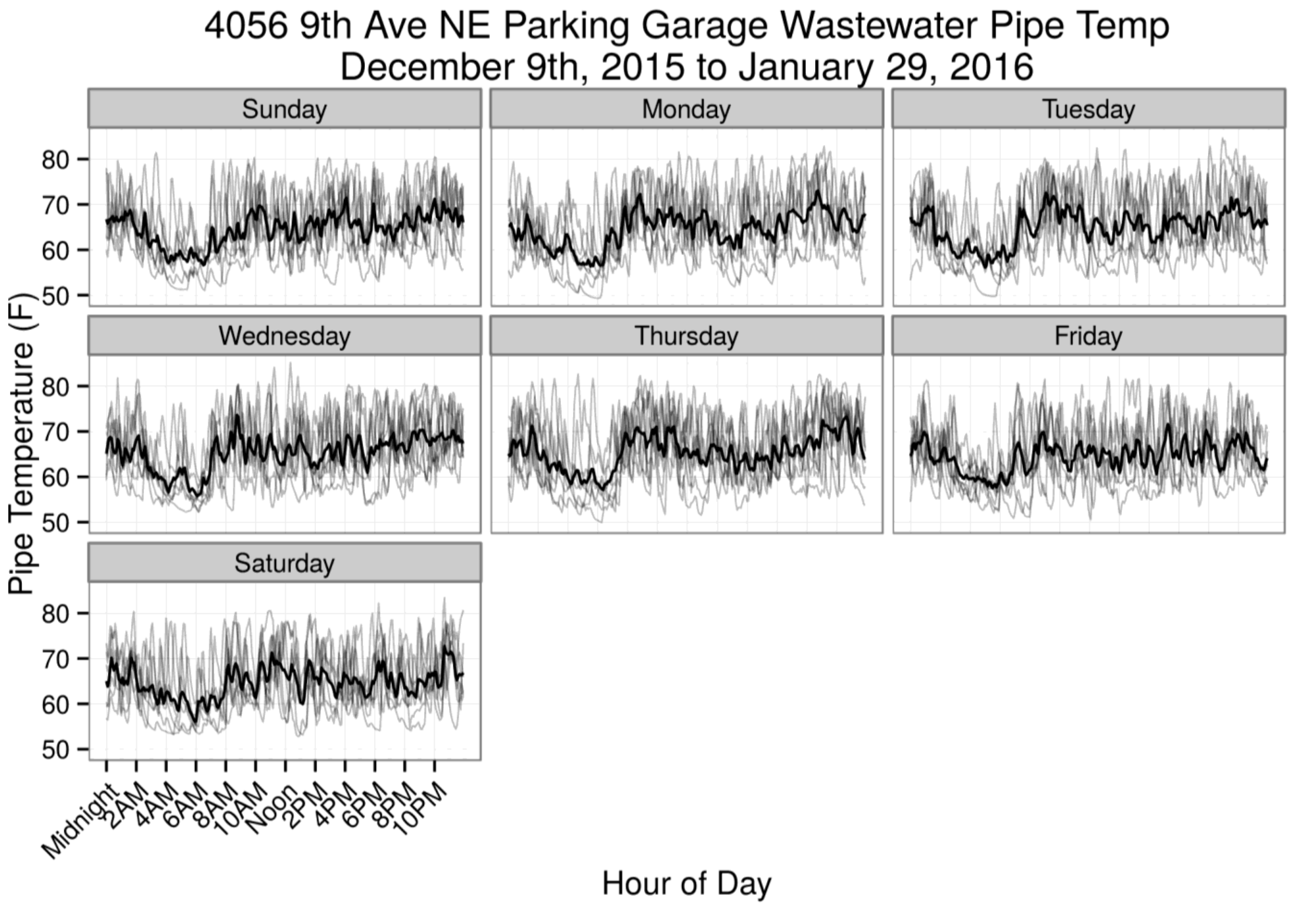
As posed in 3.1, this is a crucial question. The overall viability of the system – as well as somewhat more subtle changes in overall efficiency – depends on the incoming wastewater temperature to the vault. For sure, that temperature has to be between the cold water mains temperature and the hot water set point. To at least get a "ballpark" verification the temperature, Ecotope conducted spot measurements of a multifamily building waste water pipe. This pipe is in the parking garage adjacent to Ecotope's Seattle office. Figure 3 is a thermal camera image of the pipe around 10am on a weekday morning in September 2015. The pipe is PVC, which is somewhat insulating so the actual fluid temperature is certainly warmer than the pipe surface temperature of 86 °F. Based on the sound emanating from the pipe, it was clear water was flowing. Given the time of day, one or more units were showering providing hot drain water. At other times of the day, the drain water will be different temperatures because the water end use will be different. For example, a cold-wash cycle in a clothes washer may only produce cool fluid temperatures.

Figure 3. Waste Water Pipe Thermal Image



In addition to the spot measurements, Ecotope measured and logged the temperatures on the same pipe for nearly two months in the coldest part of the year. Figure 4 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 don't definitively know when the water was flowing and the corresponding temperature. That limits the conclusions we can draw from Figure 4, 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 waste water is likely to be warm enough for an effective system.

Figure 4. Waste Water Pipe Temperatures – Winter Time



Ultimately, within the simulation, we don't need to directly input the waste water temperature. Instead, a simplification is to know how much of the waste water was once hot and how much was once cold. From water meter data at one of the RCC pilot project buildings, the Stream Uptown, we estimated 45% of the water was hot while 55% was cold. This 9:11 ratio is what the simulation uses for the hot water ratio.

3.2.2 Occupancy and Assumed Hot Water Demand

The simulation uses measured hot water flow from the RCC pilot project Sunset Electric and Stream Uptown buildings, scaled appropriately based on the relative unit counts of those buildings to the proposed building. This has the advantage of capturing seasonal patterns, daily patterns, and the full spectrum of usage rather than simply an overall average. Note that it is important to consider the variance of water draws – in addition to merely mean water usage – when interested in nonlinear outcomes, such as running out of hot water or experiencing freeze problems with the wastewater vault or working fluid. To do so, the raw data from the RCC project buildings is used, scaled by the ratio of total occupancy, and stepping through the 10-minute observations one row at a time throughout the entire 1-2 years of monitoring. In practice, other draw patterns could be created and added as inputs to the simulation as well.

As an example, Figure 5 shows seasonal and daily variation in the average daily flow at the two RCC buildings. This directly feeds into the simulation. It also allows a look at the consequences of two different usage patterns. The residents of the Sunset Electric building on Capitol Hill seem to be home less-often and use less hot water than the residents of the Stream Uptown building in Lower Queen Anne. During the summer months, residents of Sunset Electric sometimes used as little as ten gallons per person per day of hot water. Having each of these different patterns to select from is useful to explore simulation output under a higher or lower load scenario.

Figure 5. Daily Flow Timeline in 2015 for RCC Sites

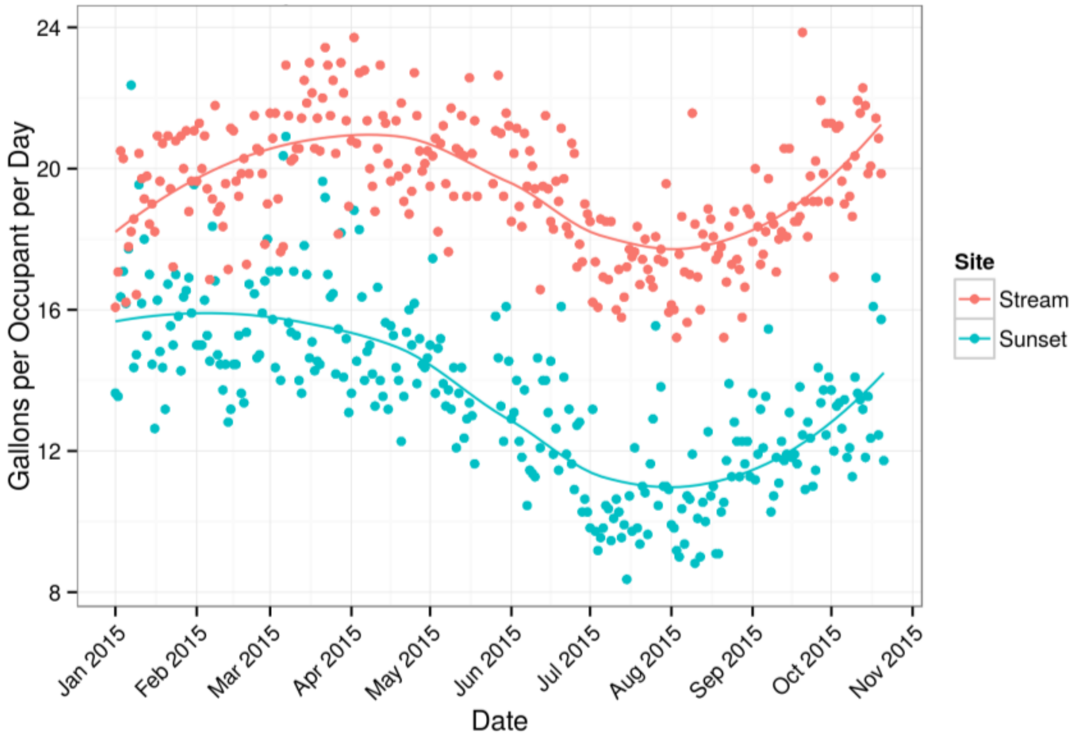
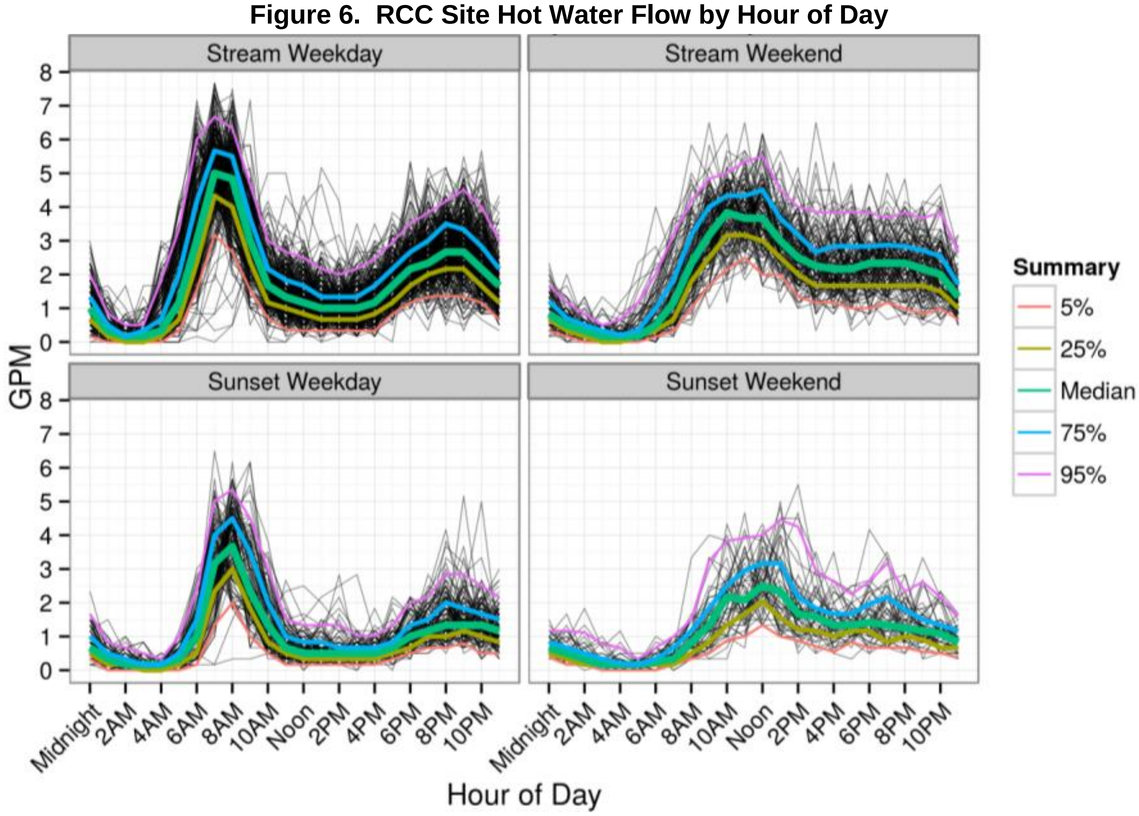


Figure 6 shows the variation of measured flow at the RCC buildings by hour of day. The importance of the weekday morning shower is evident, as well as the stark difference between weekday and weekend use patterns. The WWHP simulation, using this data as input, encounters the full range of water heating demand scenarios.

Figure 6. RCC Site Hot Water Flow by Hour of Day



3.2.3 Further Simulation Assumptions

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 doesn’t exchange heat with its surroundings. In reality, 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 supplementad 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.

3.3 Simulation Outputs

Figure 7 illustrates some of the graphical output from the simulator. It presents 24 hours of output for an example day in April. This simulation used the Stream Uptown (higher use) draw patterns, a 25,000 gallon vault size, and three heat pumps. Beginning at 4AM, the vault is strategically pumped down to prepare for the peak morning use. At 6AM, significant hot water usage begins. In response, the heat pumps turn on in sequence to recover the temperature in the bank of storage tanks. By 8AM, even though the heat pumps are removing energy from the vault, enough new, hot waste water has entered to raise the temperature to 62 °F. This is just one of many possible outputs and analyses from the simulation.

Figure 7. WWHP Simulator Raw Output – Example 1

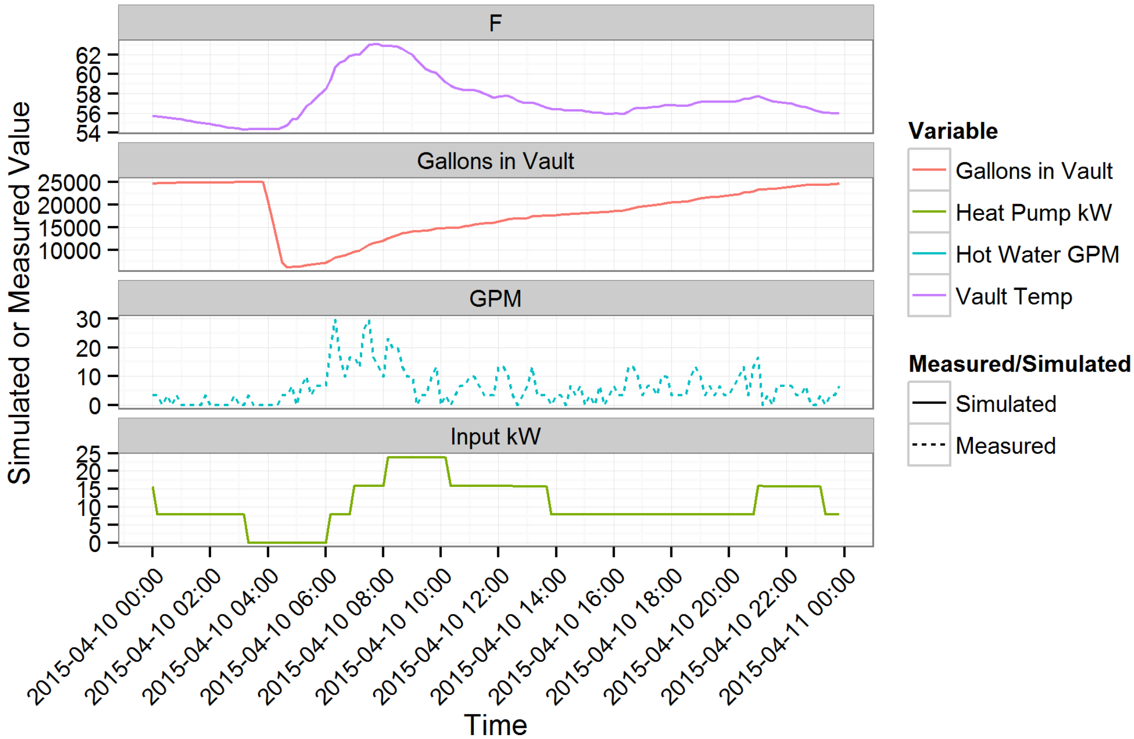
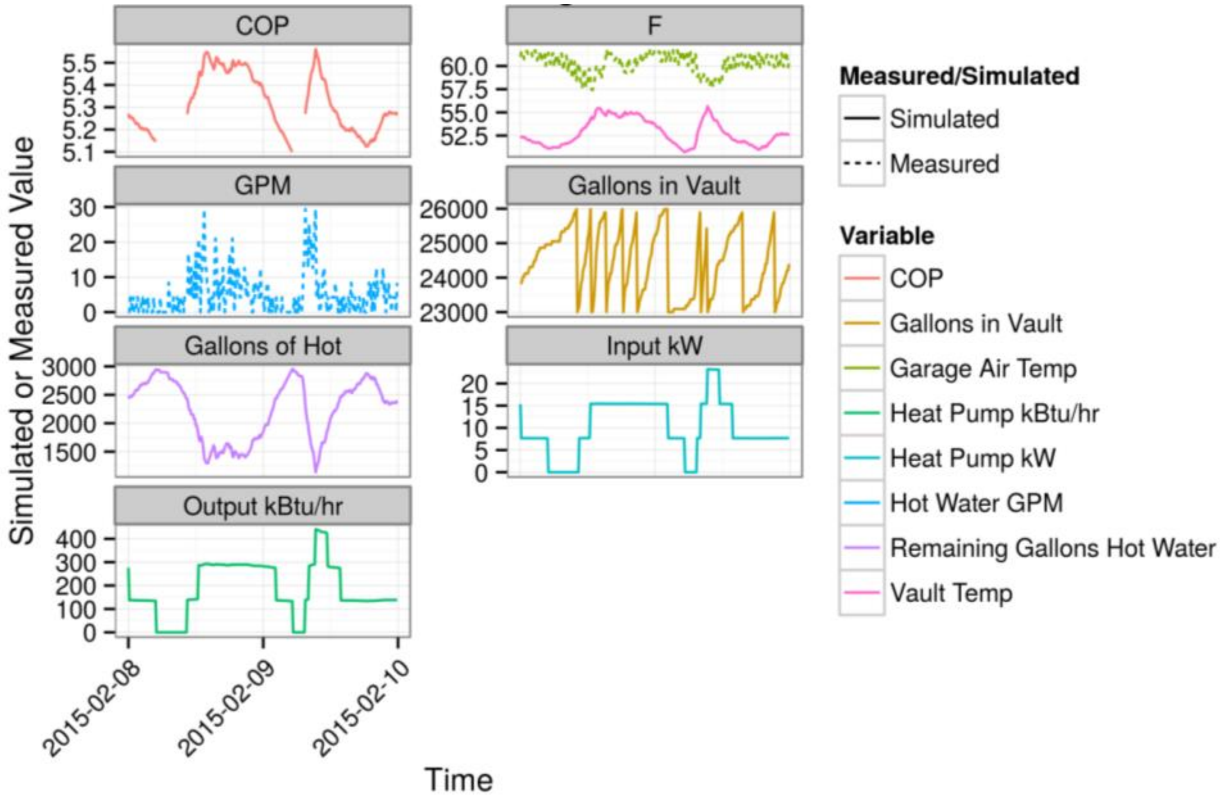


Figure 8 provides a second example of the simulation output. This one shows eight total variables, six of which are outputs. The graphs span two days to demonstrate different draw patterns. This simulation was run with the Sunset Electric (low usage) draw profile. Of particular interest on the graph is the Gallons of Hot water available. This simulation used a 3,000 gallon storage capacity. In the middle of the night, all of it is hot. The morning peak uses over half of the stored volume. This helps in system sizing as it indicates that on these two days, the system could get away with 1,000 gallons less storage capacity and still meet the load.

Figure 8. WWHP Simulator Raw Output – Example 2



With the simulation operational using the assumptions and simplifications described in the earlier section, we used it to answer several critical research and design questions. The detailed simulation allows us to make better design decisions before construction and without building many buildings while making incremental improvements to each. The questions and suggested solutions are posed below.

3.3.1 Recirculation Loop Heat Losses

As demonstrated in the RCC projects, the heat required to offset losses from continually recirculating hot water throughout the building (a standard practice in mid- and high-rise multifamily buildings) can prove large and costly. We can decompose the necessary heat from the system into two regimes: heat added to cold city mains water, and heat added to warm (reheat) recirculated water. By design, the cold city mains water will be heated through the wastewater heat pump system. The question is whether to additionally heat the recirc water with the WWHP, or whether to employ a separate heating system optimized for recirc conditions.

Given the energy balance diagram, and the practical constraints on cooling the wastewater vault, it would appear at first glance unlikely that the vault could provide enough heat year-round to meet the recirculation load. The WWHP Simulator also provides insight, by simulating the removal of heat from the vault to satisfy recirculating water heat requirements. The simulation suggests that, in the absence of specific information on wastewater entering temperatures, it is not feasible to remove recirc heat from the vault.

Figure 9. Simulated Daily Minimum Wastewater Vault Temperature

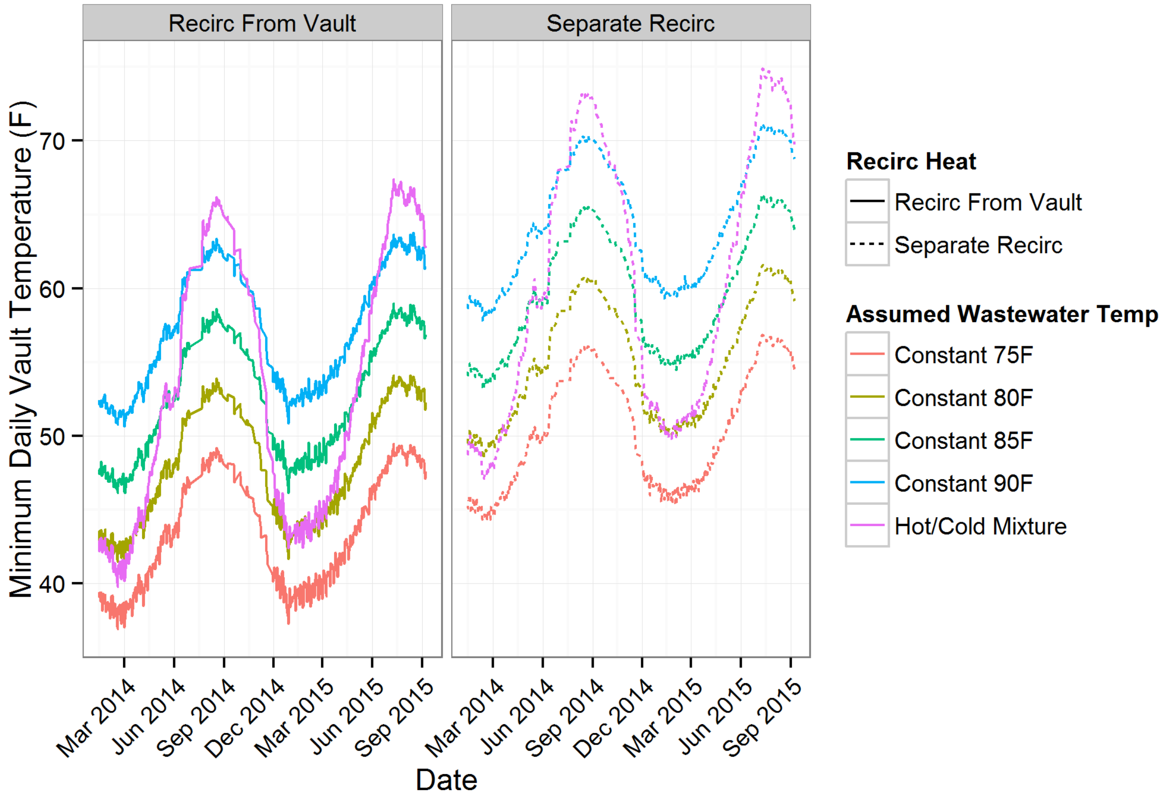


Figure 9 shows the consequences of pulling recirc heat from the vault for a range of assumptions as to the temperature of the incoming wastewater. These assumptions include constant incoming wastewater temperatures from 75 °F to 90 °F, as well as a hot/cold mixture that take a weighted average of the mains water temperature and the hot water setpoint temperature, assuming a 9:11 hot water to cold water split. The recirculation loop heat loss rate in the figure was taken to be 48,000 Btu/hr which we estimated based on a 400 unit building. Proving the assumed four ton recirculating load with heat from the vault appears to lower the minimum vault temperature by around five degrees according to the simulation. Depending on the ultimate incoming wastewater temperatures, this may prove infeasible for wintertime water heating. In none of the examples in Figure 9 does the vault freeze but anytime the predicted temperature approaches 40°F or colder, we begin to be concerned that local temperatures in the vault, especially adjacent to the heat exchanges could freeze. In the absence of compelling wastewater temperature data, we think the prudent course is to decouple the recirculated water heating requirement from the wastewater vault system.

3.3.2 Strategic Vault-Pumping

One question ideal to be answered by the physics simulation is whether strategic vault pumping can increase efficiency. We see in the Sunset Electric and Stream Uptown measured hot water usage that the largest volume of warm wastewater flows during the morning peak interval. It would seem logical that emptying the vault of thermally spent (cold) wastewater in preparation for the morning rush could better utilize the large inflow of warm wastewater.

Table 1 shows estimated annual efficiencies using the Stream Uptown-based hot water demand for a variety of nightly pumping scenarios. In each, the vault is pumped down to some percent full at a time between 3AM and 7AM. For example, the case of "30%" full represents pumping wastewater out of the vault until it is only 30% full. The case of "100%" full represents no nightly drawdown at all and is included for reference. The simulated efficiencies suggest a possible COP boost of approximately two tenths by pumping the vault down as far as possible (while keeping the heat exchangers submerged), sometime between 4AM and 6AM. The table is color coded by COP with the highest in green and lowest in red. Table 2 complements the efficiency table by illustrating the average vault temperature associated with each draw-down scenario. This is the average over the course of the entire simulation. Again, the highest levels are in green with the lowest in red.

Table 1. Strategic Vault-Pumping Efficiencies

Drawdown Time	Nightly Vault Drawdown Level - Percent Full						
	20%	30%	40%	50%	60%	80%	100%
2:00 AM	5.51	5.48	5.44	5.41	5.39	5.33	5.32
3:00 AM	5.55	5.51	5.47	5.44	5.41	5.34	5.32
4:00 AM	5.57	5.53	5.49	5.45	5.42	5.35	5.32
5:00 AM	5.56	5.52	5.48	5.45	5.42	5.35	5.32
6:00 AM	5.49	5.46	5.44	5.42	5.4	5.35	5.32

Table 2. Strategic Vault-Pumping Temperatures

Drawdown Time	Nightly Vault Drawdown Level - Percent Full						
	20%	30%	40%	50%	60%	80%	100%
2:00 AM	57.8	57.6	57.32	57.06	56.88	56.28	56.17
3:00 AM	58.4	58.07	57.7	57.37	57.12	56.38	56.17
4:00 AM	58.64	58.28	57.9	57.54	57.25	56.44	56.17
5:00 AM	58.4	58.1	57.81	57.49	57.23	56.46	56.17
6:00 AM	57.57	57.45	57.35	57.18	57.02	56.46	56.17

We continued the investigation by looking at the same metrics for the "recovery draw-down" scenarios: when the water tanks are almost completely full of hot water then we assume that demand has for the time ceased and that the vault should be pumped down to prepare for the next period of higher demand. Table 3 shows that the maximum draw-down, to 20% when the stored cold water fraction is the smallest gives the greatest efficiency increase. Overall, it has the potential to boost COP by one quarter point. Table 4 is the complementary table showing the average vault temperatures for each scenario.

Table 3. Strategic Vault-Pumping – Recovery Draw-Down Efficiencies

Cold Water Fraction	Recovery Vault Drawdown - Percent Full						
	20%	30%	40%	50%	60%	80%	100%
5%	5.59	5.54	5.5	5.46	5.43	5.35	5.32
10%	5.57	5.53	5.49	5.45	5.43	5.35	5.32
15%	5.54	5.5	5.47	5.44	5.42	5.35	5.32
20%	5.51	5.48	5.45	5.43	5.41	5.36	5.32

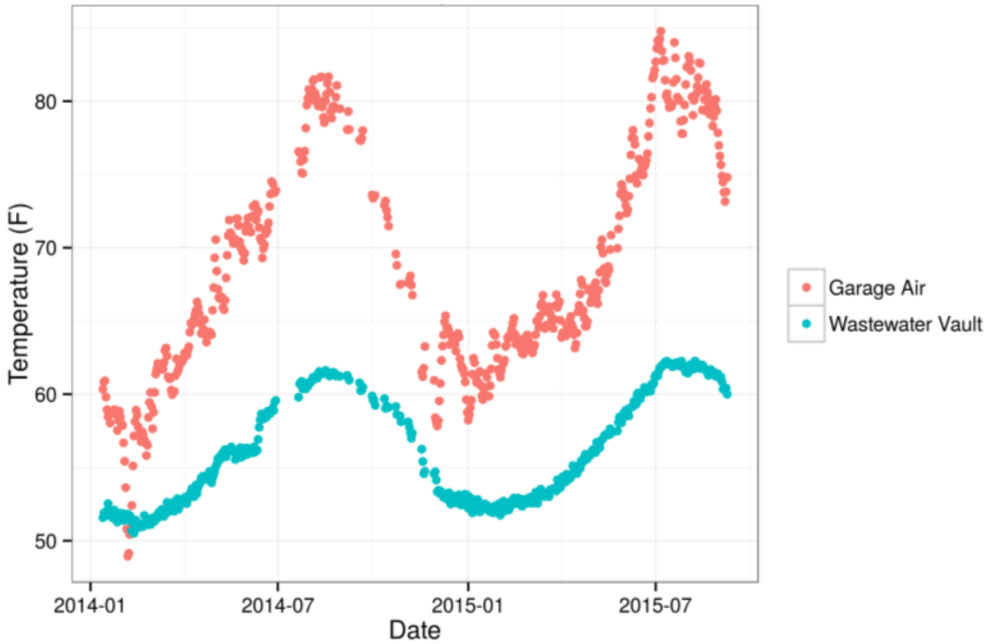
Table 4. Strategic Vault-Pumping – Recovery Draw-Down Temperatures

Cold Water Fraction	Recovery Vault Drawdown - Percent Full						
	20%	30%	40%	50%	60%	80%	100%
5%	58.88	58.43	58.02	57.65	57.35	56.5	56.17
10%	58.49	58.14	57.82	57.52	57.27	56.51	56.17
15%	57.94	57.72	57.52	57.32	57.16	56.52	56.17
20%	57.43	57.33	57.22	57.12	57.03	56.54	56.17

3.3.3 Vault Insulation

The simulation outputs can also help to answer whether or not it is advantageous to insulate the vault from the parking garage or the ground or both. Figure 10 shows measured garage air temperature from the Stream Uptown building, along with simulated wastewater vault average daily temperature using the Stream Uptown demand as simulation input. Under these conditions, the wastewater vault stays mostly between 50 and 60 °F, whereas the Stream Uptown parking garage was measured mostly between 60 and 80 °F. Given that the garage is usually warmer than the vault it doesn't make sense to insulate those boundaries. Further, given that ground temperatures range from 50-60°F, it also doesn't make sense to insulate between the vault and the ground. Of note, this graph shows daily averages in the vault so misses the peak temperatures following the morning rush when the vault is hot and the heat pumps are running. In that case, the heat pumps will extract heat from the water more quickly than it will lose heat to the environment.

Figure 10. Vault and Garage Air Average Daily Temperatures Compared



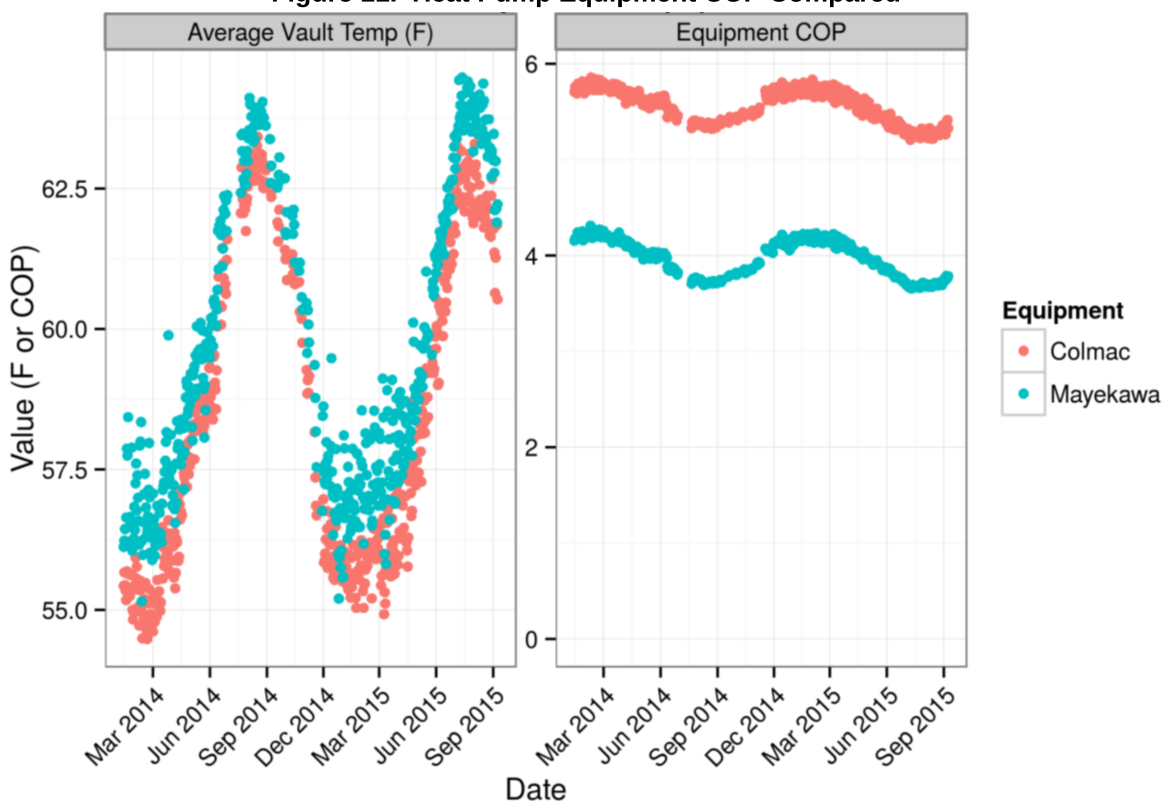
3.3.4 Heat Pump Equipment Compared

With the simulation, we also compared estimates of annual operating efficiency for the two different heat pumps considered in section 2.4.4. Using manufacturer's literature, we encoded, input power and output capacity for the two equipment types. The Colmac equipment specifications show a much higher COP. Projecting performance from cutsheets to the WWHP concept suggests a COP around 5.5 for the Colmac heat pumps and 4.0 for the Mayekawa. Figure 11 shows the daily average COP and vault temperatures over a 1.5 year period. Note though that, based on our understanding of comparable R-134a refrigerant cycles, there is some skepticism surrounding the projected Colmac efficiency: it would not be surprising for the Colmac equipment to ultimately deliver a COP around four, rather than over five. Consequently, we suggest proceeding with the notion that the annual COP will be more like four and another more than that will be a bonus.

One interesting consequence of the supposed lower efficiency of the Mayekawa equipment is actually more leeway with the vault temperature during cold, wintertime inlet mains temperatures. Because of the peculiar nature of the WWHP – ideally cannibalizing the same heat over and over – the energy of the heat pump compressor actually provides a valuable source of heat added to the system, and greater system efficiency actually makes it more crucial to recover a large proportion of heat.

Consider the month of February, when Seattle mains water temperatures are around 45°F. For operational and freezing concerns, we don't want the temperature of the wastewater in the vault to drop below 45°F, i.e. in the worst case water comes in at 45°F and leaves to the sewer at 45°F. Now consider a hypothetical (yet physically impossible) heat pump that moves heat with no compressor work at all. This heat pump would have to recover 100% of the heat added to the water. For every unit of heat added to the water and sent up to the building, the heat pump would have to recover that unit before ejecting spent wastewater to the sewer. Obviously recovering 100% of the energy is impossible, due to heat transfer between the water and wastewater pipes and the building. Basically, the more efficient the heat pump, the more heat it needs to recover, because the heat from the compressor motor makes up a smaller fraction of the heating requirement. Now, this is not to say that we should intentionally look for less efficient equipment, but merely to note the apparently strange interrelationships in this system.

Figure 11. Heat Pump Equipment COP Compared



4 Design

Vulcan Real Estate is developing the building in the Seattle South Lake Union neighborhood. It will have 385 units, consist of two floors of concrete construction topped by five wood-framed stories. It will sit above a below-grade, two-level concrete parking garage. Using the WWHP simulation, lessons learned from the RCC projects, and the criteria for this building, we have created the following system and submitted the design drawings to the project team.

The RCC pilot project provided clear design guidance including the following: 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 recirculation loop losses can be huge. While it is straight-forward enough to satisfy the first three guidelines in a design, providing an efficient solution to dealing with recirc losses is challenging.

Engineering calculations showed that this building could have recirc 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 luke-warm 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) 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 for each purpose.

Using the 48,000 Btu/hr load as an input to the WWHP simulator showed that it had the potential to catastrophically tax the system. Constantly removing that much heat from the vault may cause it to freeze. The recirc loop, however, is a curious item in the building energy flow. Any heat that is lost by the loop, goes directly in to the building. During winter, this is useful heating energy so it is not all lost. Ultimately, we decided the best option was to separate the recirc loop heating from the WWHP. Our design choice is to use an air-source RCC for that load. Essentially, the recirc loop heating energy will come from the below-grade parking garage air. This leaves the WWHP, at its projected higher COPs, to do the majority of the water heating. At the project outset, we anticipated doing all the water heating with the WWHP but the numerical simulation has proven its value already by guiding this design decision.

The simulator has also shown strategic ways to control the vault level to maximize the system efficiency. For relatively little incremental controls cost, the design concept is to link the vault pump-out to the amount of stored hot water available. When the bank of storage tanks is nearly full of completely hot water, the heat pumps will turn off and then the pump will draw-down the vault. This is an elegant solution because once the tanks are filled with hot water, there is no longer a need to heat any more. Emptying the vault then will make room for the next inrush of hot waste water which will concomitantly trigger a demand to heat up the storage bank.

4.1 Schematic and Sizing

4.1.1 Component 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 can assume 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. Multiple simulation runs resulted in us selecting the following equipment sizes:

- **Detention Vault**: 15,000 gallons
- **Heat Exchangers** (submerged in vault): 5 nominal 10-ton plates
- **Water Source Heat Pumps**: 3 nominal 15-ton water-to-water units
- **Hot Water Storage**: bank of 8, 500-gallon tanks (4,000 gallons total)
- **Air-Source Heat Pumps** for recirculation loop heating: 2 nominal 4-ton air-to-water units

4.1.2 Schematics

Drawings in this section are excerpts from design documents and not intended for construction.

Figure 12 and Figure 13 show the vault schematics.

Figure 12. Vault Schematic Profile

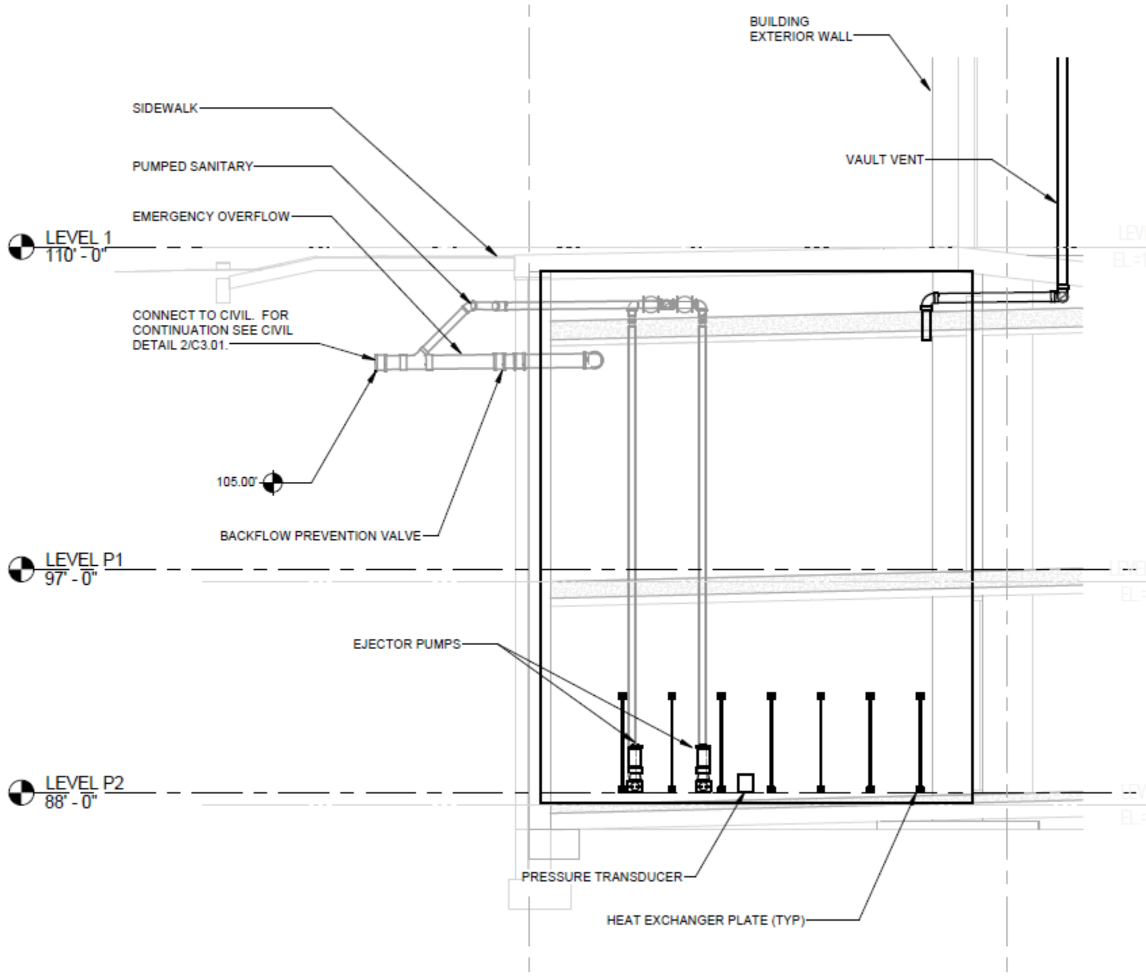


Figure 13. Vault Schematic Section

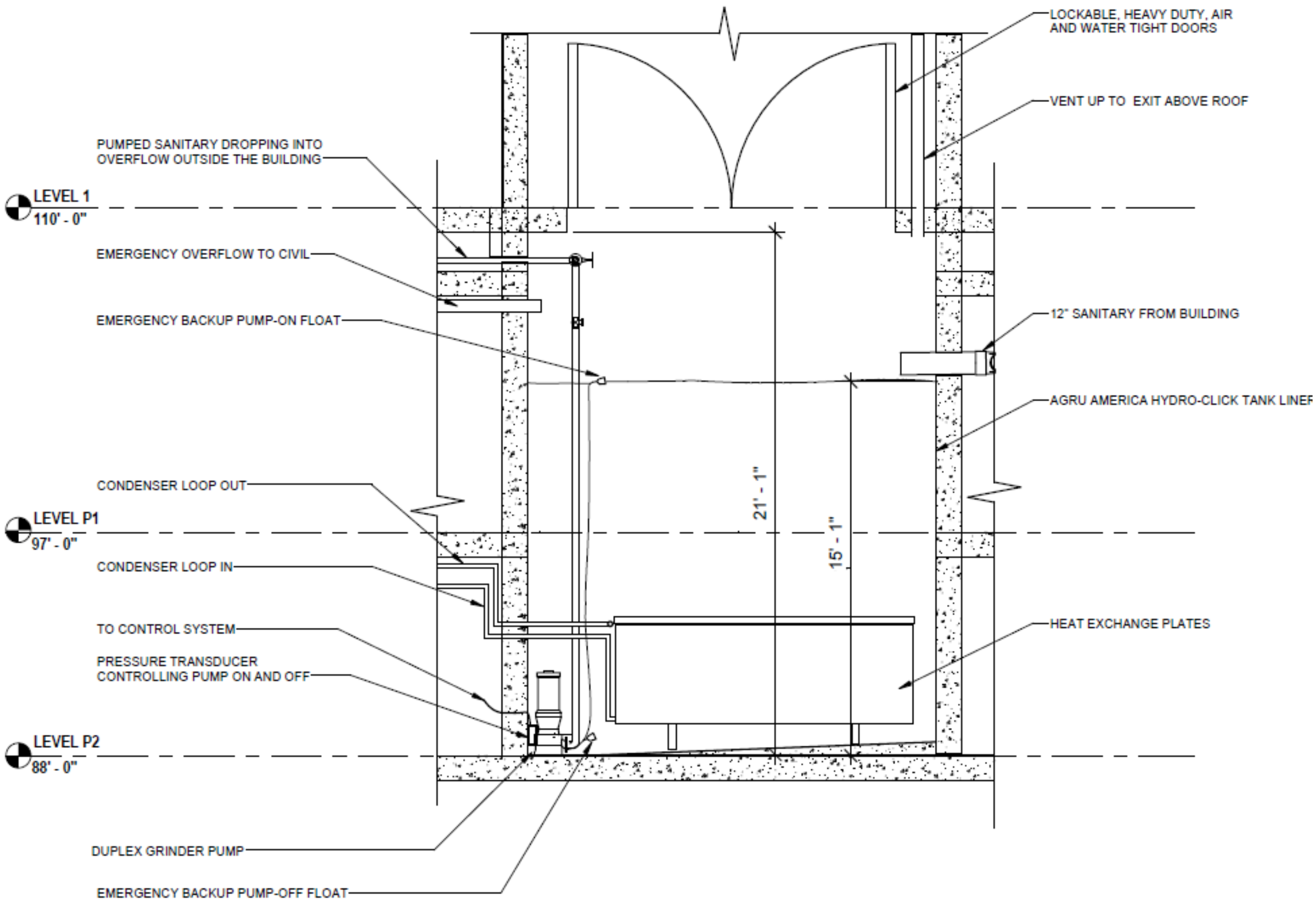
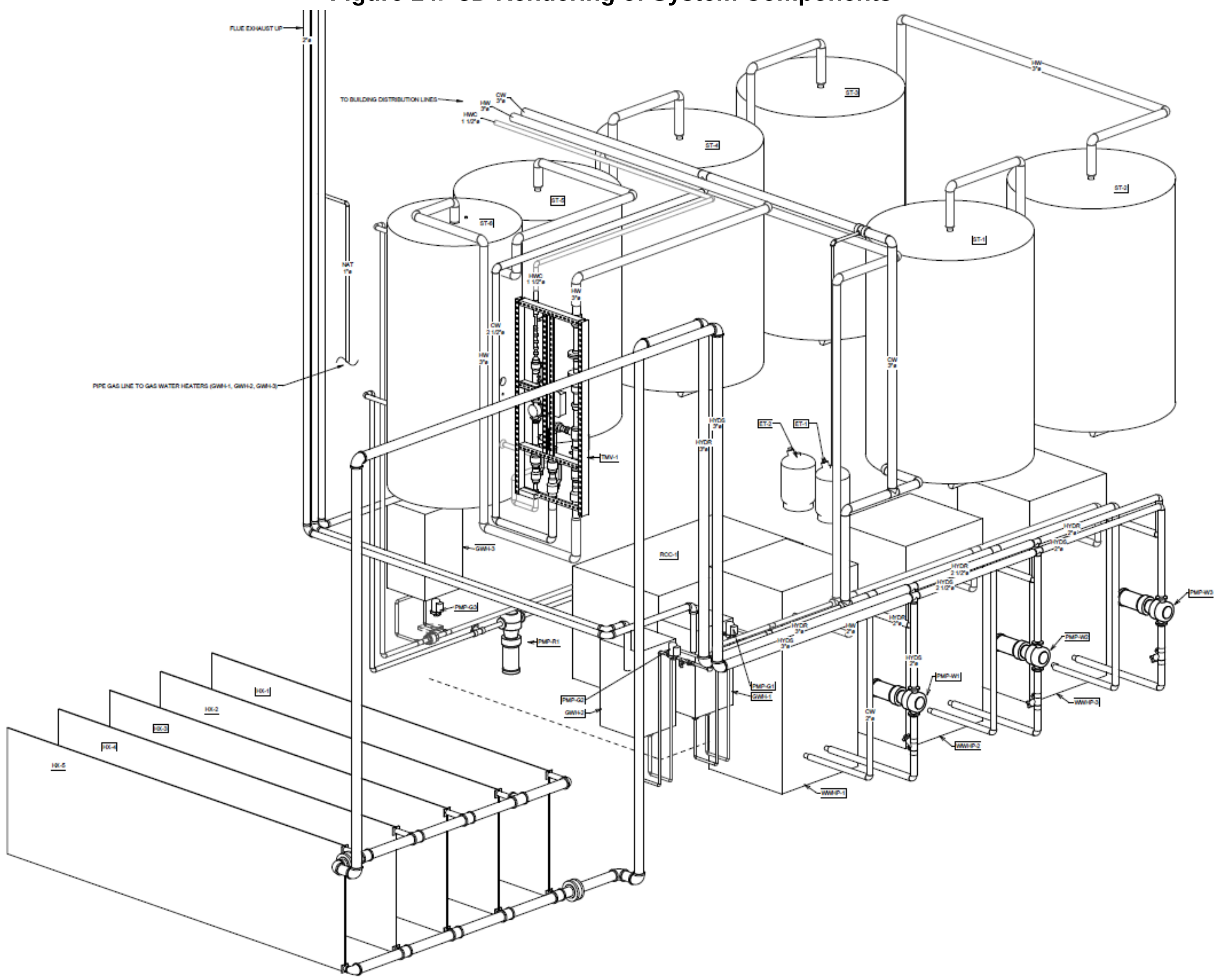


Figure 14 presents a 3-dimensional rendering of all the major system components. The building walls are removed for clarity. The heat exchangers (bottom left) sit at the bottom of the vault which rises across both levels of the parking garage. The heat pumps themselves and the hot water storage tanks are on separate levels. The heat pumps (large boxes, bottom right) are on the lower level. The bank of storage tanks are placed above.

Figure 14. 3D Rendering of System Components



4.2 Energy Savings and Costs

4.2.1 Energy Savings Estimates

The values we used to determine energy savings are presented in Table 5. 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 70F (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 0.8. All other values are documented elsewhere in this report. Overall, this building is projected to save in excess of 500,000 kWh/yr.

Table 5. Energy Savings Calculations

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 = 0.8	653,065
kWh/Year at COP = 4	130,613
kWh/Year Savings	522,452

4.2.2 Cost Estimates and Cost/Benefit Analysis

Construction costs are highly variable and especially hard to predict for nascent technologies, we won't have a fully accounting of costs until the project is complete. A preliminary estimate places the incremental cost at $100,000 for a building this size 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, the simple payback time is under 3 years. Even if the incremental costs double, the simple payback time is under 5 years.

5 Conclusions

Based on preliminary research, design, and optimization, Ecotope believes the wastewater heat pump design to be feasible and cost-effective, and advises proceeding. First, the background research found appropriate components. Second, the numerical simulation showed the heat balance within the system could lead to high efficiencies. Third, the design drawings proved components could be sized and assembled in a workable way. Finally, the energy savings and cost estimates suggest the full system will be cost effective and a true benefit to the building operation, the local utility, and BPA.

Research in to the equipment required for the system found the following components, special to a WWHP design, were appropriate:

- Vault lining – Agru America’s HYDROclick
- Pressure transducer – submerged in vault for precise volume control
- Heat exchanger – Flat plate Slim Jim from AWEB Supply
- Heat pumps – R-134a water-to-water equipment from Colmac

The simulation tool helped to inform and optimize design decisions. It proved especially useful in the following 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 allows 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. Should the entire project prove viable, the simulation tool will be further publicized for future construction projects to use.

Using the WWHP simulation and informed by lessons learned from the previous RCC projects, the proposed design includes eight 500 gallon hot water tanks plumbed in series, three 15-ton Colmac water-to-water reverse cycle chillers operating in parallel, a 15,000 gallon wastewater vault, and 50-tons of flat-plate heat exchanger capacity submerged in the vault. Satisfying heating demand for continually recirculating hot water will be met by a separate, air-source heat pump system optimized for the task.

Considerable analysis of equipment specification sheets and use of the simulation suggests the system could perform with a COP of 4-5 on an annual basis. Using the lower-end of 4 for estimation purposes, this WWHP system is projected to save 500,000 kWh/yr at this building compared to a baseline system of in-unit electric resistance tanks. The high variability in construction costs, especially for nascent technologies, make cost projects challenging. We will only know the final incremental cost once construction is complete but we estimate it is $100,000 to $200,000. For a retail electricity cost of 0.08 $/kWh, that gives a simple payback in under 2.5-5 years depending on the incremental capital cost.

Based on the positive outlook of the conclusions set fourth, Ecotope recommends proceeding with the system design as proposed. The next phase will be to assess incoming contractor price bids, provide a detailed energy savings estimate to Seattle City Light to receive a capital cost incentive for the equipment, and finalize construction documents.

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