



Emerging
Technologies

CO2 Heat Pump Water Heater Multifamily Retrofit: Elizabeth James House Seattle WA

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CO2 Heat Pump Water Heater Multifamily Retrofit: Seattle WA

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A Report for the BPA Emerging Technologies Initiative

The following report was funded by the Bonneville Power Administration (BPA) to assess emerging technology topics that have the potential to increase energy efficiency. BPA is committed to identify, assess and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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Acronyms

aCOP _{DHWSys}	Annual Coefficient of Performance of the Domestic Hot Water System
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BUH	Backup Heater
BtuH	British Thermal Unit-hours
BTU/Hr	British Thermal Unit per Hour
CO ₂	Carbon Dioxide
COP	Coefficient of Performance
CW	City Water
DHW	Domestic Hot Water
EB	Electric Boiler
ERWH	Electric Resistance Water Heater
F	Fahrenheit
GPD	Gallons per Day
Gal/yr	Gallons per Year

GPM	Gallon per Minute
GWP	Global Warming Potential
HPWH	Heat Pump Water Heater
HW	Hot Water
kBTU	Thousand British Thermal Units
kW	Kilowatt(s)
kWh	Kilowatt-hour(s)
kWh/yr	Kilowatt-hour(s) per Year
M&V	Measurement and Verification
NOAA	National Oceanic and Atmospheric Administration
OAT	Outside Air Temperature
PHPWH	Primary Heat Pump Water Heater
ST	Storage Tank
TMV	Temperature Mixing Valve

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Abstract

Heating water for occupant use in existing multifamily buildings represents a substantial energy load. This load is made up of the energy required to heat the water, and also energy to maintain the water temperature within a building’s distribution piping. Properly designed heat pump water heater (HPWH) systems have the potential for increased efficiencies in both primary water heating and temperature maintenance. Additionally, new CO2 heat pumps represent a shift from traditional refrigerants to low global warming potential (GWP) refrigerants.

This case study demonstrated that multiple Sanden (CO2) heat pump water heaters (typically used in single-family residential applications), together with a novel “swing tank” design, can collectively serve the water heating and recirculation loop temperature maintenance needs of a 60-unit low-rise multifamily building in the Pacific Northwest. Field-collected data showed that



the system delivered a coefficient of performance (COP) in excess of 3 and provided an average of 20 gallons of hot water per day per apartment.

Over the monitoring period there were periodic equipment issues. Even so, system efficiency was maintained during these instances. This demonstrated that domestic hot water for a large building can be supplied by a remarkably small heat pump plant - just 5-tons of nominal capacity, which sometimes functioned for long periods with less than 4-tons of capacity and minimal backup system contribution. These events also highlighted the value of Measurement & Verification monitoring in emerging technology installations, and the need for automatic remote alarm capability for these systems.

Heat pump water heaters are an emerging technology in the domestic water heating market, especially in multifamily building applications. Because of this, installation costs have been high. However, with market growth, established design and installation practices and increased competition costs will come down. The Sanden CO2 HPWH is a versatile product and is very efficient. The novel "swing tank" design and applications require additional research but have demonstrated results for reducing water heating and temperature maintenance loads in multifamily buildings across Pacific Northwest climate zone



Executive Summary

Domestic hot water heating in multifamily buildings represents a substantial energy load. This load includes heating water from city water supply for use by building occupants, as well as maintaining the water temperature in building distribution piping – a strategy used to make hot water quickly available to occupants throughout the building. Properly designed heat pump water heater (HPWH) systems have the potential for increased efficiencies in both primary water heating and temperature maintenance processes. Carbon dioxide (CO₂) heat pump water heaters in particular offer a low global warming potential solution to water heating energy loads.

This case study demonstrated that multiple Sanden (CO₂) HPWHs (typically used in single-family residential applications), together with a novel “swing tank” design, can collectively serve the water heating and temperature maintenance needs of a 60-unit multifamily building in the Northwest. Annual monitoring demonstrated that the system provided an average of 20 gallons per day per apartment and had an average system coefficient of performance of 3.3 with minimal contribution from the backup electric resistance water heating (ERWH) system.

This report outlines the findings from a year of monitoring and provides valuable insights into equipment performance and function; proofing of a novel “swing tank” design; and installation costs analysis. The HPWH system offered substantial savings over the original electric resistance water

heating system, performing with over three times the efficiency. Despite periodic equipment errors and the occasional use of the backup ERWH, the HPWH system worked very efficiently. Although HPWH equipment is still relatively novel to the installation community in Seattle, there are local indications that costs are becoming more affordable amongst experienced contractors. Additionally, the energy savings of these systems can offset the initial installation cost over conventional equipment.

Based on the findings from this project, with proper design, domestic hot water heating and temperature maintenance for mid-sized multifamily buildings can be efficiently served by residential-scale CO₂ HPWH equipment and a “swing tank” design. Further study of recirculation losses is needed for developing additional HPWH and “swing tank” designs and sizing. Additionally, development of alarm notification and control capabilities for this equipment will ensure that optimum operation can be maintained. CO₂ HPWHs are a valuable energy efficiency tool across the multifamily sector for both new and existing buildings.

Designed properly, a residential scale CO₂ HPWH along with a swing tank, can serve a mid-sized multifamily building.

Readiness: The Sanden CO2 HPWH product readiness rating is shown below.

- **Market/Commercial Readiness – Level 5.** This scale of HPWH is widely available through standard distribution channels.
- **Product Performance – Level 5.** This heat pump has been field tested in single-family and small multi-family applications and has a developed performance map. The current study expands the application possibilities to multifamily buildings with 100 units or less.
- **Program Readiness – Level 3.** This technology shows a pathway to cost-effectiveness with future market growth, established design guidelines, and competition among contractors.

Background

This pilot demonstrated the use of carbon dioxide (CO₂) heat pump water heaters (HPWHs) in a central plant configuration to produce domestic hot water (DHW) for a multi-unit apartment building. The study site, Elizabeth James House, hereinafter referred to as the Site, is an existing 4-story, 60-unit, low-income senior apartment building located in Seattle, Washington. Built in 1968, it is an “all-electric” building with a pre-existing electric resistance water heating. The focus of this case study was to retrofit the electric resistance DHW system to a HPWH system and assess the long-term field performance evaluation.

The existing system was comprised of three relatively new 39 kW instantaneous electric water heaters, three 120-gallon hot water storage tanks, a primary water heater pump, a building hot water circulation pump, and an expansion tank. The three instantaneous electric water heaters were connected in parallel to three storage tanks piped in series. A thermostat in the middle tank controlled the primary water heater pump ON or OFF based on the tank temperature. The three instantaneous electric water heaters engaged on flow and modulated the heating capacity to output 135°F water to the serial bank of storage tanks. This system functioned and delivered hot water to the apartments as designed. However, significant opportunity for energy and cost

savings existed by retrofitting the system with a high efficiency CO₂ HPWH.

HPWHs transfer heat energy from one source (typically air) to potable water. This is three to four times more efficient than a fossil-gas or electric-resistance water heater. BPA selected a CO₂ HPWH for its low global warming potential, its ability to function outdoors in cool climates, and the high efficiency. CO₂ delivers a high coefficient of performance (COP). Although the HPWH product selected was originally designed for the single-family residential market, by ganging multiple HPWHs together the product met the DHW needs for a larger multi-unit building.

Ecotope designed a central plant using

- Four 15,000 BtuH Sanden HPWH (Model GUS-A45HPA¹);
- Three existing storage tanks;
- Three existing instantaneous electric water heaters and pump;
- The existing building hot water circulation pump;
- A new 175-gallon storage tank; and
- A new thermostatic tempering valve.

Using the existing Site equipment reduced upfront costs and provided emergency backup. The retrofit was completed in 2018, monitoring began in March 2019, and results demonstrated that the HPWH system is three times more efficient than the previous ERWH boiler system.

¹ The model currently on the market is the “Gen3” product line (GS3-45HPA-US), with a new product offering likely available in summer 2020. The Gen3 product offers more flexibility in the

water temperature settings, which can be controlled from 130° to 175°F.



System Design

The Sanden HPWHs used contain R-744 refrigerant commonly referred to as CO₂. This refrigeration cycle does not function well with warm incoming water (above about 100°F). Building hot water circulation pumps typically return water at 115°F to the storage tanks. DHW systems that use electricity or gas work well with warm water entering the primary storage tanks or primary heaters. However, with HPWHs this warm incoming recirculation water decreases performance. A critical design feature of HPWH systems with hot water circulation systems is to separate the two distinct building DHW loads. Therefore, DHW system design prioritized delivering cool water to the HPWHs while maintaining thermal stratification in the primary tanks. This resulted in optimal equipment efficiency, less cycling of the heating equipment, and better reliability of the system. However, this design required a dedicated system to maintain hot water in the distribution system (“temperature maintenance”).

A critical design feature of HPWH systems is to separate the primary heating and temperature maintenance loads

A key innovation implemented for the Site was a temperature maintenance tank designed as a “swing tank”. This approach supplied high temperature water (~150°F) to the temperature maintenance tank from the primary storage tanks. This water mixed

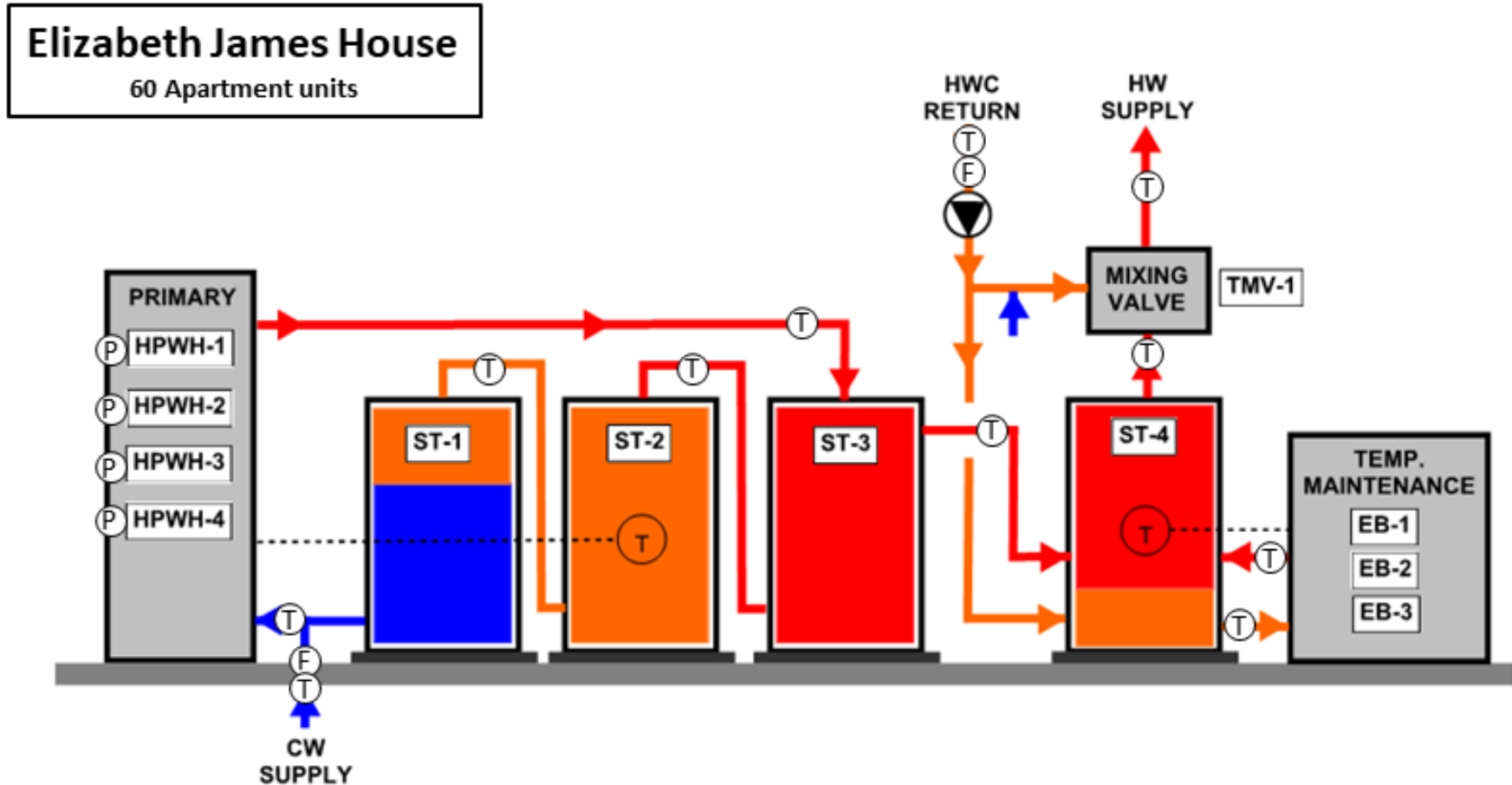
with warm return water from the building distribution system. The tank temperature then “swings” from about 120-150°F to supply a consistent 120°F water to the building without additional heating.

The system used the existing instantaneous electric water heaters to provide backup water heating capacity. An aquastat in the fourth storage tank (the temperature maintenance tank) controls the existing primary pump ON or OFF based on the tank temperature. This water is pumped through the three existing instantaneous electric water heaters and returned to the top of the fourth tank. This results in a robust backup system for both the primary heating system (HPWHs) and the temperature maintenance heating system.

The HPWHs produce hot water at temperatures near 150°F, which is delivered to the top of the third storage tank. Adding hot water to that tank creates a useful temperature stratification in the storage tanks. Cold municipal water enters the bottom of the first storage tank, closer to the HPWHs, ensuring cooler incoming water temperatures and better performance. Due to the high temperature water produced by the HPWHs, a thermostatic mixing valve was added to prevent scalding and conserve energy.

Refer to the schematic diagram (Figure 1) for a simplified visual representation of the plant and locations of monitoring equipment. The narrative that follows explains the critical features central to the HPWH DHW plant design.

Figure 1. HPWH Plant Schematic and Monitoring Equipment Locations



ⓕ Flow meter

Ⓣ Temperature sensor

---Ⓣ Temperature control point

Ⓟ Power meter. EB power for the boiler bank is calculated as the full panel power less the sum of the heat pumps.

- *Single Pass:* The design is based around a “Single Pass” heat exchange strategy as opposed to the typical “Multi Pass” strategy employed in most hydronic space heating applications. This means that the flow of water through the heat pump is regulated by a control valve or variable speed pump to maintain a target output temperature of 149°F. This results in a variable flow rate and variable temperature rise across the heat pump, as opposed to the typical fixed flow rate and fixed 10-20°F temperature rise on the water. The heat pump can therefore output 149°F water with incoming water temperatures ranging from 40-122°F². The advantage of the “Single Pass” is that a usable water temperature is always delivered to the top of the storage reservoir.
- *Multiple Storage Tanks:* This design used multiple storage tanks plumbed in series. The arrangement enabled a high degree of temperature stratification throughout the system, with the hottest water at the end of the primary storage system (ST-3). It also used of smaller, less expensive tanks that were easier to install and fit through doorways. The three existing tanks were reused for the primary storage tanks. A fourth tank, ST-4, was added to act as a dedicated temperature maintenance tank (“swing tank”). This fourth tank is in series with the three primary tanks. See Figure 1.
- *Storage Temperature:* The water was heated to a relatively high temperature (149°F) to effectively increase the stored heating capacity of the plant. This controls possible legionella bacteria, and increases the effectiveness of the “swing tank” (ST-4). To prevent scalding, outgoing water is tempered with recirculation water and/or incoming municipal water down to approximately 120°F before delivery to the apartments.
- *Backup Electric Water Heaters:* This design used the three existing instantaneous electric water heaters for backup. Configured in parallel and operating in unison to deliver 135°F water to ST-4. The backup instantaneous electric water heaters operated any time the final storage tank dropped below 120°F either due to inadequate capacity coming from the HPWHs or due to extended periods of time with no hot water draws and continuous cooling from the recirculation system.
- *Temperature Maintenance Swing Tank:* This tank (ST-4) was designed to swing in temperature between 120°F and 150°F. During periods with hot water use, over-heated (~149°F) water moves from the primary storage tank to the “swing tank”. These periodic draws keep the “swing tank” primed above 120°F. If the “swing tank” drops below 120°F the backup electric water heaters raised the temperature above 125°F.
- *Serial Primary and Temperature Maintenance Tank Arrangement:* The series configuration enables a “swing tank” concept, which is defined as providing over-heated water from the primary tanks to be mixed with cooler

² Heat pumps can continue to function at incoming water temperatures below 40°F.

recirculation water in the “swing tank”. If there is enough over-heated water from the primary tanks, the mixed temperature in the “swing tank” will be greater than or equal to the needed use temperature. This strategy works effectively with heat pump cycles that require a large temperature lift to the water, like CO2 heat pumps. If there is enough hot water use to balance out the circulation loop losses, no additional heat is needed in the “swing tank”. If additional heat is needed, it can be supplied by resistance heat or a dedicated heat pump. The existing instantaneous ERWH were reused to provide backup.

- *Controls:* The Site’s HPWH system does not have a central plant control, each HPWH operates in parallel with stand-

alone controls. Each HPWH also has built-in control logic to cycle the units ON or OFF based on a thermocouple reading. The middle primary tank (ST-2) contains four thermocouples that are connected to the HPWHs. The HPWHs are turned ON when the thermocouple readings drop below 113°F. Heating continues until the water entering the HPWHs reaches 122°F.

Photographs

The following photographs illustrate the DHW system, including the HPWHs, piping, storage tanks, mixers, controls, backup boiler equipment, temperature sensors and flow meters.



Figure 2. Sanden HPWHs After Pipe Insulation (CU-1, 2, 3 and 4)

**Figure 3. Temperature Maintenance
DHW Storage Tank Before Pipe
Insulation (New Tank ST-4)**



**Figure 4. Primary DHW Storage Tanks Before Pipe Insulation
(ST1, 2, and 3)**



Figure 5. Electronic Mixing Valve and Valve Controller (TMV-1)



**Figure 6. Instantaneous Electric Water Heater
(Existing EB-1)**



Figure 7. M&V Temperature Sensor and Flow



Figure 8. Snowstorm and Tree Damage to CU-3.

Methods

The Site Measurement & Verification (M&V) system was built around an Obvius Acquisuite 8812 data logging platform, with concurrent eGauge monitoring of electrical energy use. It incorporated flow and temperature measurements at strategic points as well as electricity usage for each HPWH and the electric resistance water heaters (Figure 1 illustrates monitoring equipment locations). Data that were collected and averaged over one-minute intervals included:

- The flow of incoming city water;
- Water temperatures into and out of the HPWH heaters;
- Water temperatures exiting each storage tank;
- Water temperatures into and out of the electric boilers;
- Water temperatures into and out of the recirculation loop;
- Temperature of (cold) city water entering the system;
- Electricity to heat water (by each HPWH and the bank of three boilers);
- Flow in the recirculation loop; and

- Outside air temperature readings from a nearby National Oceanic and Atmospheric Administration (NOAA) weather station.

Ecotope set up an online M&V portal to view raw data and hourly and daily averages for each of the monitored points on the HPWH system, as well as calculated values like COP and heat output. This data was automatically updated nightly, allowing engineers and installers commissioning the project to quickly receive feedback on changes. Data have been collected and available through the online tool since spring 2019.

Additional information about equipment operation, system installation costs, and Sanden equipment development were gathered from project partners.

Findings

Summary Findings

High-level data summaries from annual monitoring are provided in **Table 1** below. The gallons per day reported are the total average hot water used by the building occupants. Each of these summaries are discussed in greater detail below.

Maintenance Timeline

This section highlights the importance of M&V equipment on new technology installations. M&V allows for early diagnosis of problems, potentially before expensive equipment replacement is needed. Analysis of M&V data also leads to learning that can be used to improve system performance or make changes in future designs. Additionally, long-term monitoring can be valuable for informing persistence studies.

M&V data has been invaluable and allowed for viewing system operation remotely. Early in the commissioning process, HPWH3 stopped operating and entered an “idle” status several times. The M&V data identified the issues. As a result the team visited the Site and addressed the idle equipment. Frequently, the equipment could be re-started by cycling the unit, after which time it would operate normally for a period before falling idle again. In February 2019, while HPWH3 was already idle, a snowstorm caused a tree limb to fall on it. Ecotope was able to use the M&V data to determine that the damaged unit was also the unit that had been idle since

Table 1. Summary Measurements

Gal Per Day (GPD) Total	Gal Per Day Per Apartment	HPWH Energy (kWh/day) †	Annual System COP	Avg Outdoor Air Temp (F)	Avg Inlet H2O Temp (F)	Avg H2O Temp Output (F)	Days Monitored*
1,198	20	68	3.3	54.5	59.4	147	331

* A leak event and short energy monitoring outages required few days be dropped from the analysis dataset. Presented values represent annual estimates, using regression estimation to fill missing data periods.

† Sum of all HPWHs

January. The storm-damaged unit was replaced in March 2019.

Several weeks later the team reviewed the M&V online portal and detected a different unit (HPWH1) in idle status. Initially, the error code was believed to indicate a faulty control board; the manufacturer suggested replacing it. Later, it was determined that the error code was misinterpreted based on error codes from a prior generation model. The error codes received to date were eventually attributed to a low-flow/high entering-water temperature warning. With this new information, action was taken to resolve idle HPWH1 in July.

In late May, a water leak was detected at the site. This was addressed in June, and the repair required shutting off the water. As the water was turned back on, a single valve was overlooked, causing water to flow backward through the system. This registered as extremely high flow rates visible via the M&V portal. In mid-June, the valve issue was addressed, but there were still only three operational HPWHs.

In mid-July, with new information on the error codes, the team discovered that HPWH1 was shutting off to avoid operating at high temperatures. The incoming water filter (strainer) was clogged, leading to the high-water temperature warning. Once the strainer was cleaned, and the unit power cycled, HPWH1 resumed proper function.

After mid-July, there were few equipment issues until September 2019, when the same unit (HPWH1) again experienced idle periods. A service visit identified a clogged strainer and the same strainer cleaning and cycling of power procedure brought the HPWH back

online. In September, the mechanical contractor instructed the facilities staff in this process.

Additional idle events were detected between November 2019 and February 2020. The error code was not always recorded by building maintenance staff, but rinsing the filters and power cycling the units returned the idle unit to operations. In late January – early February 2020 two of the HPWHs became idle. The error on both units indicated the condenser fan revolution had initiated the alarm. In March, the error history on HPWH1 revealed that the November through February events were also due to the condenser fan revolution error. Appendix A provides a summary of the events at this site to date.

The January/February event also suggested that the electric boiler backup system was not fully operational because the temperature of the water delivered to the recirculation loop fell below the backup system set point. Maintenance staff conducted an onsite investigation to verify backup system operation settings. In March, staff determined that the set-point for the back-up boiler operation was changed to a higher

M&V site data was critical to detect and troubleshoot HPWHs; facilitated communications with stakeholders and maintenance staff; and ensured that the system operated as designed.

temperature (~135°F). This may have caused the boilers to only provide shorter than needed operation, because the signal to ON and signal to OFF were approximately the same. The set-point was reduced back to 120°F. In April 2020, after the monitoring period included in this report, a mechanical contractor serviced the boilers and found failed flow sensors for all boilers due to clogged impellers.

Error codes included both condenser fan operation and clogged incoming water filters. In the latter case, water quality may need to be considered with this generation of equipment. Additionally, preventative monitoring and cleaning of equipment filters after repair events is recommended. However, the current generation Sanden product available on the market today has a different heat exchanger configuration that no longer has filters on the incoming water line³. Additionally, Gen3 equipment allows for remote start/stop capability.

The M&V data was critical to detect and troubleshoot issues with HPWHs, and facilitate communications. M&V data verified hot water service to the building occupants and facilitated actions to resolve idle equipment. Through all of the above, the M&V data ensured that the system operated as designed for as much time as possible. The M&V data alerted staff to equipment outages or other issues.

The M&V data portal was especially useful for systems that lack controls or notification systems. Without M&V data the periods when one or more HPWHs were inoperable would

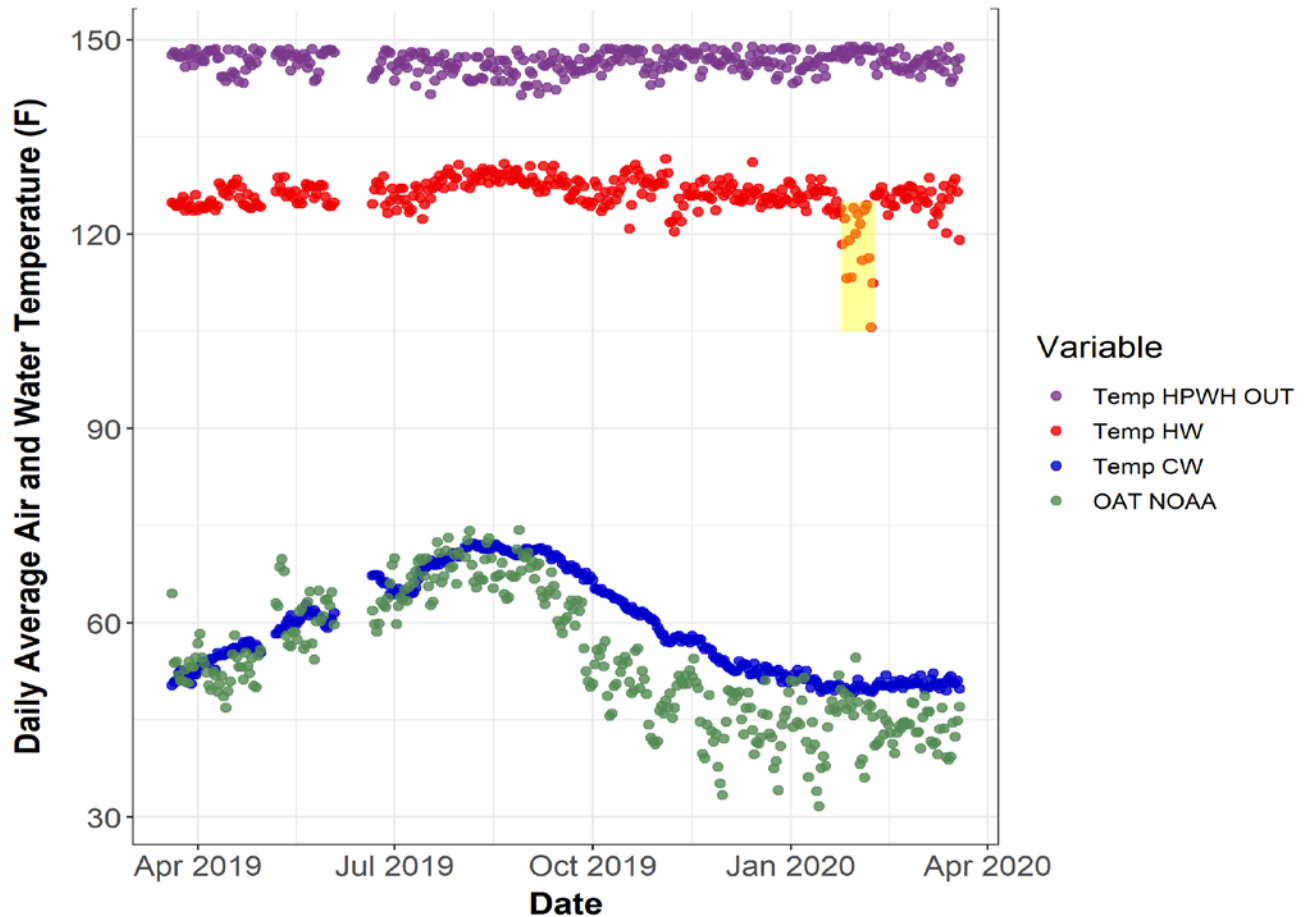
have been much longer in duration. The HPWHs are extremely quiet and it is difficult to detect if they are functioning without checking directly. Furthermore, the back-up electric system is designed to ensure hot water continues to be delivered. Without built-in alarm notifications, maintenance personnel will not be aware that the HPWH DHW system is not operating as designed and inefficient backup DHW systems will likely operate for extended periods.

Water Temperatures

M&V data from March 20, 2019 through March 20, 2020 were used in this analysis. Figure 9 shows the water and air temperatures for M&V monitoring (excluding the leak event in June 2019). Collected M&V data show incoming (50-72°F) city water being heated to 147°F (even during periods when only three HPWHs were operable) and delivered to the recirculation loop at approximately 125°F. The dip in the delivered water temperatures in late January 2020 to early February 2020 corresponds with a time when multiple HPWHs were inoperable. Simultaneously, the backup electric boilers were not operating normally because of an inadvertent setpoint adjustment that compromised the flow sensors – these equipment issues were resolved in March-April 2020.

³ John Miles, General Manager, Eco Products, Sanden International. Phone interview. 2020-02-24.

Figure 9. Daily Average Air and Water Temperatures



Leak event removed.
Yellow highlight shows period with < 4 operable HPWHs and back-up not functioning properly.

Variables are defined as:

Temp HPWH OUT: Temperature of water leaving the HPWH bank and entering ST-3.

Temp HW: Temperature of the hot water delivered to the recirculation loop.

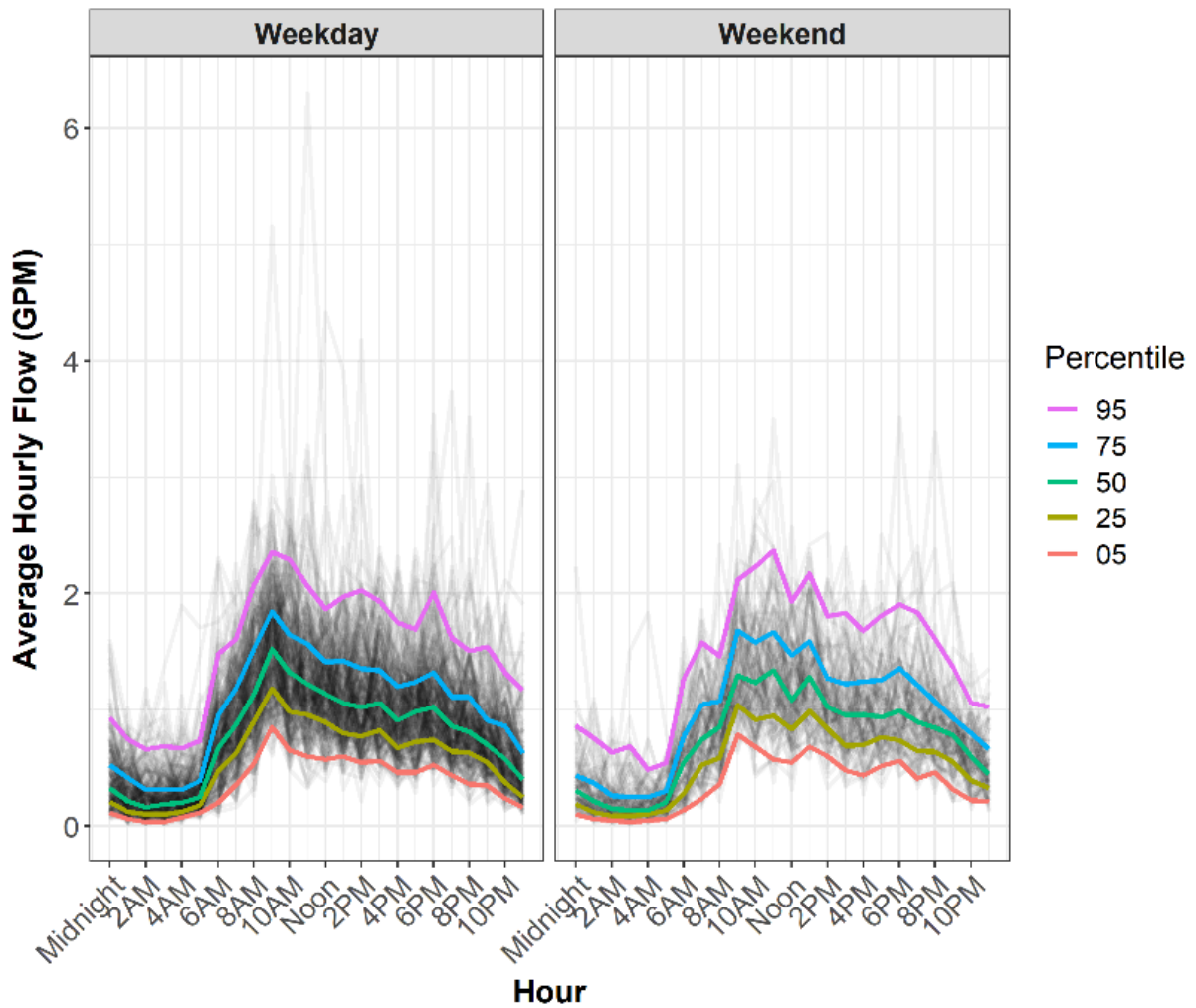
Temp CW: Incoming municipal water temperature, which shows a seasonal pattern of a high of ~70°F in August. Lowest temperatures are typically measured between January and February.

OAT NOAA: Outside Air Temperature (OAT) as recorded by NOAA weather station. OAT shows a similar seasonal trend as Temp CW.

Water Use

Collected data included hot water use by building occupants' over the course of the project. Several interesting metrics are quantifiable through measured flow data. Figure 10 shows hourly average demand in gallons per minute (GPM) by the hour of the day, and by weekend or weekday. Individual days are shown in light gray. Colored lines indicate percentile of all data, with the middle green line (50%) being the median.

Figure 10. Average Water Use (GPM) by Hour of Day (Leak event removed)



Overall, there is little difference between weekday and weekend use patterns. Both weekdays and weekends show higher 8-10am, and 6pm usage. Weekday and weekend as well as daily and hourly differences are less pronounced at the Site compared to other multifamily buildings. Multifamily buildings with working occupants typically have low mid-day usage on weekdays when occupants are at work, and weekend morning peaks may be shifted later in the day (Heller 2015). This is likely due to the senior demographic at Site.

Recorded flow data also demonstrated annual water usage at the Site. Much as inlet water and outside air temperatures show seasonal cycles, so does occupant water usage. Typically, water use is higher during cooler months and lower in warmer months. Regression analysis was used to estimate, daily delivered hot water for missing periods (approximately a week when the leak and repair resulted in inaccurate flow). With average daily temperatures for these periods, regression analyses were also used to predict a gallons per apartment unit metric, which was then included with measured data to calculate annual estimates.

Based on this analysis, the hot water delivered averages approximately 20 gallons per unit per day (Figure 11). The occupancy of Site is reported by the owner to be one person per apartment unit. Based on this, the water usage is a little higher than measured in previous multifamily studies from larger market-rate workforce buildings which reported 13-19 GPD per person (Heller 2015). This may be due to the building's senior demographic, resulting in the occupants spending more time at home compared to multifamily buildings with working occupants who spend more time away from the building.

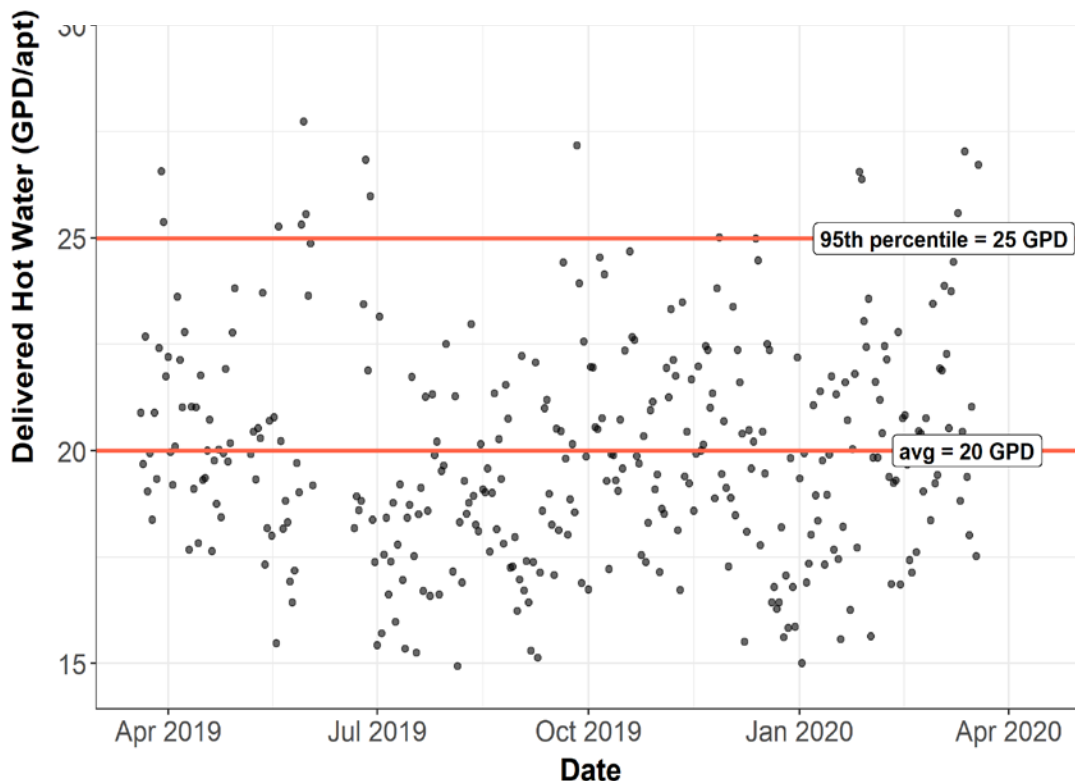
The ninety-fifth percentile of daily flow volumes, indicate that, on occasion, an average of more than 25 gallons per unit per day can be used by occupants. The highest average daily usage was 35 gallons per unit per day – almost double the average for this building.

This highlights the importance of including some amount of back-up heat capacity for HPWH systems. Without back-up heat capacity the HPWH system would need to be sized to provide nearly double the typical demand to ensure that occupants have unlimited hot water throughout the year.

DHW System Performance

The main performance metric of interest for this field study is the DHW system performance. This includes the primary water heating and the temperature maintenance heating equipment (as well as any backup heating equipment) and is intended to capture all energy inputs and outputs of the water heating and distribution (recirculation) system.

Figure 11. Daily Hot Water Used by Occupants (GPD/apartment)



The annual DHW system performance at Site can be calculated as:

$$aCOP_{DHW_Sys} = \frac{Delivered_{Energy\ Out} + Recirculation\ Loss_{Energy\ Out}}{PHPWH_{Energy\ In} + BUH_{Energy\ In}}$$

Where:

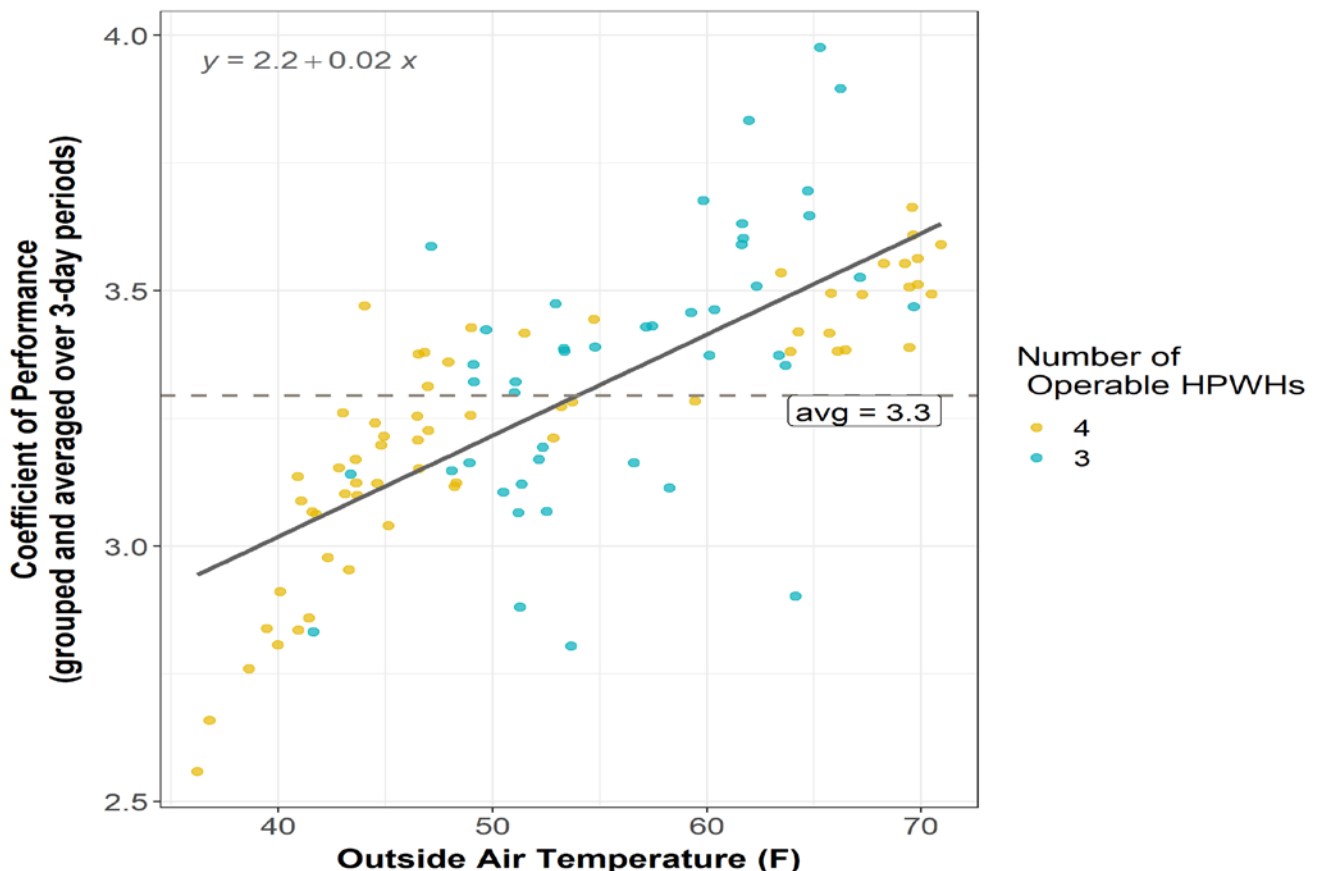
- $Delivered_{Energy\ Out}$ = Heat delivered to the water used in the building
- $Recirculation\ Loss_{Energy\ Out}$ = Heat lost in the circulation loop.
- $PHPWH$ = Primary HPWH
- BUH = Backup Heater

Figure 12 shows the DHW system COP over the monitoring period. It is divided into periods when all four heat pumps were functioning and periods when only three were functioning. As can be seen, the system efficiency was maintained with only three operable heat pumps.

HPWH Duty Cycle

The equipment manufacturer has recommended that systems should be designed so that equipment does not run for more than 16 hours per day. **Figure 13** shows that the equipment typically ran for approximately fifteen hours when all HPWHs were operable. Fewer functioning HPWHs led to longer run times of approximately twenty hours per day.

Figure 12. DHW System COP by Outside Air Temperature



Ninety percent of the time, the heat pumps ran for less than twenty-four hours (whether there were three or four operable units). In the most extreme cases the HPWHs ran for several days consecutively. This was observed in late May 2019 as a leak was detected at the site and again in February 2020, when two HPWHs were inoperable, and the backup system not responding. At that time, the operable equipment ran for five days.

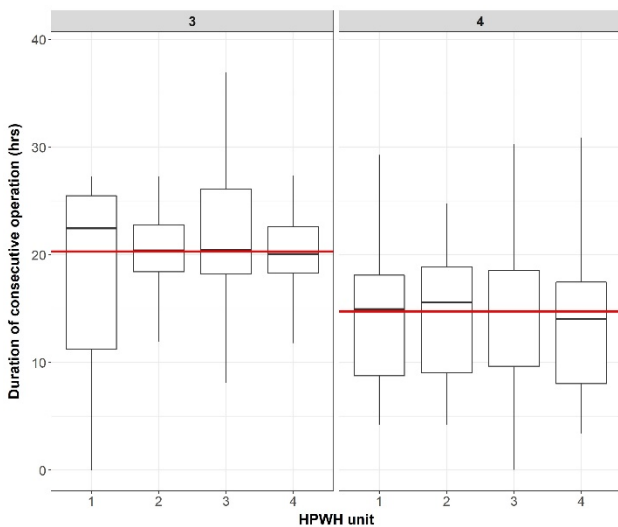


Figure 13. HPWH Run Times

One consideration in future designs would be to include an additional heat pump beyond what is strictly needed to serve the design load. The costs of additional equipment should be balanced against the contribution of the added heat pump: reduced run times when operating normally, further reducing the contribution of a backup system, and resiliency during periods when one or more heat pumps may be inoperable.

Temperature Maintenance and Swing Tank Operation

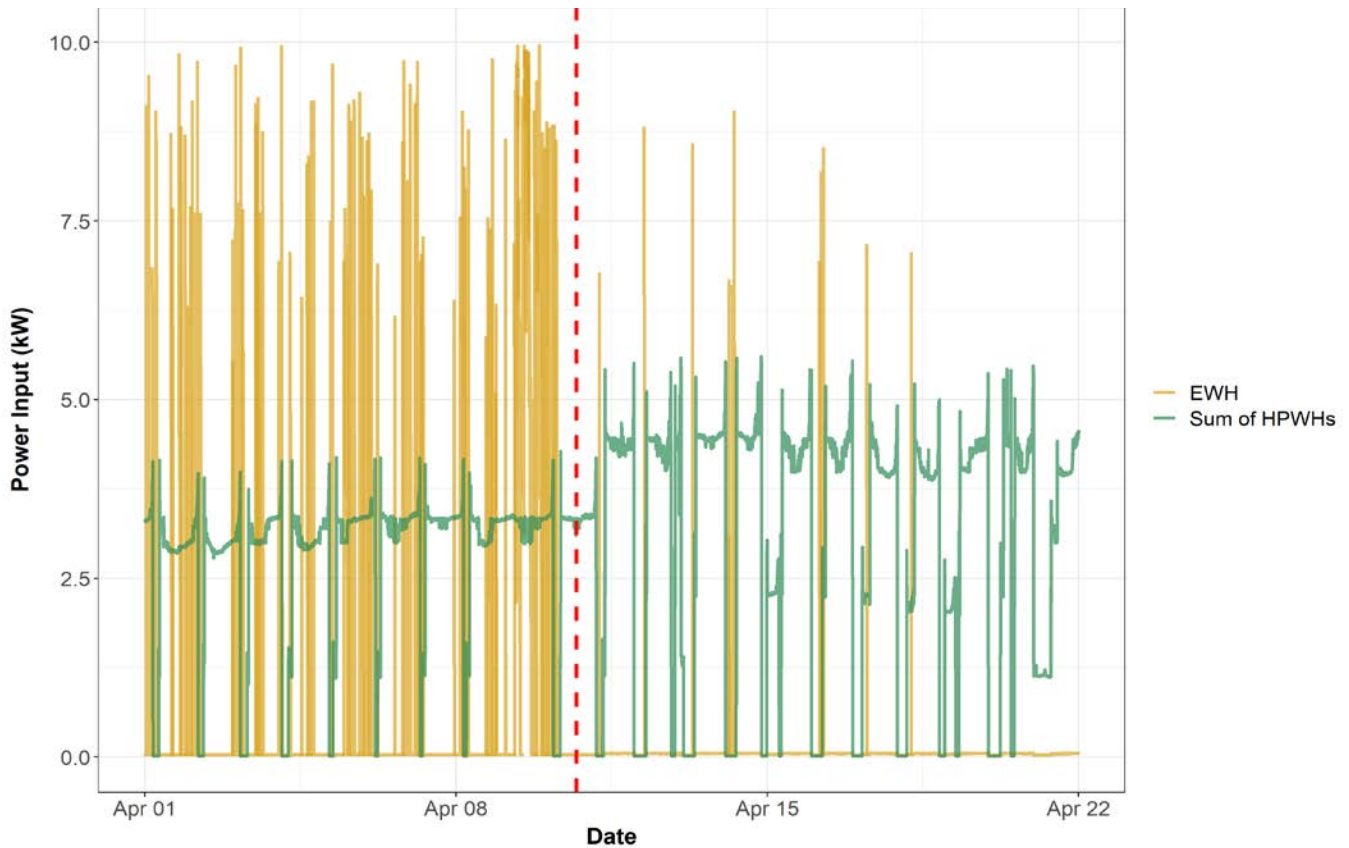
The “swing tank” at the Site is “minimum-sized” in that a larger storage tank could not fit through the mechanical room door.

However, due to the low recirculation loop losses at this Site, the tank sizing is almost perfect. Intended to minimize the use of backup electric water heaters to maintain the recirculation loop delivery temperature, the “swing tank” does this most effectively when all HPWHs are operable (and the design capacity of 150°F water is provided), the occupant draw pattern is approximately 20 gallons per apartment per day, and occupant usage keeps the “swing tank” primed and above the 125°F delivery temperature. When the environment, or draw pattern, differ from the design standards, the electric resistance water heaters initiate to keep the recirculation temperatures within setpoint parameters. Additionally, if the HPWHs are not operating as intended or draw patterns exceed the design load, the ERWH boilers can serve the building’s hot water needs.

Although the majority of the HPWHs operated flawlessly during the monitoring period, occasionally, one or more HPWHs have been inoperable. The red line in **Figure 14** demarcates the ERWH usage during a period with three operable HPWHs (before April 11, 2019) and with four operable HPWHs (until April 22). With the HPWH equipment operating as designed (to the right of the red line) only minimal operation of the backup boiler equipment was observed.

Additionally, the “swing tank” is kept at a more stable temperature when all HPWHs are available. Periods when only three HPWHs were operable show lower temperatures and a greater variability in average daily temperatures of water leaving the “swing tank”. This is as expected as it would take longer for three HPWHs to recharge the

Figure 14. Redline Demarcating Power Input (kW) 3 vs 4 Operable HPWH



storage tanks with 150°F water, and the electric boilers are set to maintain recirculation loop temperatures (not the super-heated water provided by the HPWHs).

Backup System

The electric resistance water heating equipment provided backup for temperature maintenance handled by the “swing tank” and assisted in the event of reduced HPWH function. Over the course of monitoring the ERWH were needed for both these tasks, as can be seen in **Figure 14**. Overall, however, the boilers only contributed approximately three percent of the total heat⁴ to the water.

⁴ Calculation based on the first half of monitoring, as the electric boilers were compromised and not fully functional by the end of the monitoring period.

In this project, where the electric boilers were already present, it worked well to use as a backup system. At future projects, the need for full backup could be avoided by installing additional, redundant stages of heat pumps and a larger “swing tank.”

Installing additional, redundant stages of heat pumps and a larger “swing tank” will minimize the need for ERWH back up.

Financial Analysis

The costs and business case of installing a central heat pump water heating system as a retrofit to the existing electric water heating system is shown in Table 2. It outlines the baseline pre-existing electric water heater case for water heating and hot water circulation reheat, and the resulting retrofit HPWH system serving both the water heating and temperature maintenance loads. The total installation cost includes added equipment (HPWH units, added storage tank, and a thermostatic mixing valve), engineering costs, and added plumbing labor. The total project costs were relatively high because there is not a well-established market.

The retrofit HPWH system has a simple payback of 18.3 years with no utility incentives. For typical projects, the local utility offers an incentive of \$500/apartment for this type of equipment which would have reduced the payback time to 13.6 years. Based on more recent installations of smaller HPWH systems in the Seattle area (described in the next section), the retrofit system cost at the Site was significantly more. Even with original installation costs and potential incentives, this system is cost effective with the payback period being within the expected 15-year lifetime of the equipment.

For this particular project, the installation and engineering/design costs were fully incentivized by City of Seattle's Office of Housing HomeWise Weatherization Program⁵. Potential retrofit and new-construction projects may have different incentive

⁵ Charlie Rogers, City of Seattle, Office of Housing, HomeWise Program. Personal email. 2020-04-09.

programs available to offset payback timelines, making heat pump water heaters an attractive, effective option.

Additional insights from local HPWH installations

City of Seattle Office of Housing shared installation costs for additional CO2 heat pump water heater retrofits at other local sites⁶. These projects represent multiple HPWHs installed at four complexes to replace existing electric resistance equipment, with 1-2 HPWHs per townhome. Provided costs included materials, tax, permitting, labor (at State prevailing wage residential rates), etc. Aggregate costs for Sanden installation give a weighted average of \$5,668 per installed Sanden heat pump. Extrapolating this rate to Site, where four Sandens were installed, HPWH equipment installation costs could be estimated at less than \$23,000 or \$378/apartment.

A more robust market, established design guidelines, and competition among contractors, will lower installation costs.

Central DHW systems, such as the one at this site, require additional equipment (an added storage tank and a thermostatic mixing valve) and involve potentially more plumbing / trades labor. The added estimated costs totaled an additional \$2,000 each for the tank, the mixing valve, and additional components, and approximately double that sum in

⁶ Charlie Rogers, City of Seattle, Office of Housing, HomeWise Program. Personal email. 2019-01-15.

additional labor (\$12,000). Although these are rough estimates, they are estimates for central DHW installations where contractors are more familiar with the equipment and installation process. Additionally, these estimates suggest that existing utility incentives could substantially offset installation costs (estimated total at \$41,000). Based on these estimates, the installation costs (and therefore

the payback period) at the Site were perhaps three times what they could be. To support reduced design costs for future projects, Ecotope is working to develop system configuration and sizing guidelines that should minimize required engineering⁷.

Table 2. HPWH Retrofit Installation Cost Calculations

Site Energy Use & Cost Calculations		
Building and Site Characteristics		
Annual Water Usage	438,000	Gal/yr.
Annual ERWH Electric Use	76,083	kWh/yr.
Electricity cost	0.11*	\$/kWh
Equipment Efficiency		
HPWH DHW System	3.3	COP
ERWH	0.98	COP
Hot Water Circulation System		
Annual HWC losses	7,700	kWh/yr.
Baseline Electric Water Heating (ERWH) System		
Annual ERWH Electric Use	76,083	kWh/yr.
Annual HWC ERWH temperature maintenance	7,857	kWh/yr.
Proposed Heat Pump Water Heating (HPWH) System		
Annual HPWH Electric Use	23,055	kWh/yr.
Annual HWC HPWH reheat	2,333	kWh/yr.
Proposed HPWH System Savings		
Electric Savings	58,511	kWh/yr.
Bill Savings (@ \$0.11/kWh)	\$6,441	\$/yr.
Proposed HPWH System Savings		
Retrofit Installation Costs	\$117,840	\$
Potential Incentive	\$30,000	\$
Net Cost (w/ Incentives)	\$87,840	\$
Simple Payback	13.6	yr.
Simple Payback w/o Incentives	18.3	yr.

*https://www.bls.gov/regions/west/news-release/averageenergyprices_seattle.htm

Key Design Principles

Some of the key design principles that emerged from the HPWH retrofit design at the Site include:

- Storage and HPWHs should be sized per ASHRAE 2015 “Low water usage” methodology. This project demonstrated that domestic hot water for a large building can be supplied by a remarkably small central heat pump plant. Hot water for 60 apartments is supplied by just 5-tons of nominal capacity and functioned for long periods with less than 4-tons of capacity. Industry standard design practices lead to oversized systems. This is evidenced by the 120KW of electric resistance capacity designed for the existing system; over five times the output capacity.
- Storage and controls must be configured to allow a large volume of cold water to be stored before turning on heat pumps. This allows for a longer cycle length⁸ without having too-hot water enter the heat pump and potentially decrease efficiency and possible high head pressure. Aquastat location is important. Locate Aquastat far enough away from incoming water to avoid triggering Aquastat every time water is used.
- Building hot water temperature maintenance recirculation systems represent a significant energy usage. Using electric resistance will significantly decrease efficiency. However, a large volume of warm water from the recirculation loop returning to the primary

storage and HPWHs also results in lower performance. An effective strategy is to separate the temperature maintenance load from the primary load, allowing the primary HPWH system to run at peak efficiency.

- Typical non-electric tempering valves do not function well with varying inlet water temperatures. Consider use of electronic tempering valves.
- Heat lost from the circulation loop and distribution piping can account for 25 to 50 percent of the heat needed for the water heating system. Insulate the circulation and distribution piping. Eliminate all areas of thermal bridging.
- The “swing tank” design philosophy is a proven concept and will minimize the electric resistance temperature maintenance recirculation loop load.
- Repurposing existing equipment in retrofit projects, (storage tanks, the original system for backup, or recirculation reheat) saves upfront costs.
- Include robust measurement, verification, monitoring with automatic alerts to building to assist in diagnosing issues and improving future designs.

Conclusion and Recommendations

This project demonstrated that HPWHs can yield significant energy savings for multifamily buildings in the Pacific Northwest climate. This demonstration also showed that Sanden

⁸ Minimum run times of one hour are recommended per John Miles, General Manager, Eco Products, Sanden International.

equipment can be successfully adapted to serve multifamily applications, and that the “swing tank” concept was an efficient way to treat the building hot water circulation loop heat losses. Although this demonstration was a 60-unit building, this same approach could be extended to serve larger buildings.

Annual measurement and verification at Site provided the following insights:

- Based on annual monitoring, the average DHW system coefficient of performance was 3.3. Annual operation showed that the HPWHs used an average of 68kWh/day. The DHW System COP is defined as the heat energy required to heat the incoming water to delivery temperature plus the heat energy required to make-up the losses in the recirculation loop divided by all of the electrical energy needed to power the heat pumps and back-up electric boilers.
- The average water usage at this site is 20 GPD/apt, or 20 GPD/person. This is a little higher than usages measured in previous multifamily studies from larger market-rate buildings which reported 13-19 GPD per person (Heller 2015). Additionally, this site has less dramatic peak demand periods and almost no difference between weekend and weekday usage. Increased usage and shifted daily patterns maybe because the Site is a senior facility versus workforce demographic at the other sites.
- The M&V metering equipment was installed primarily to evaluate equipment performance. However, the M&V served as a diagnostic tool for identifying and solving operational problems. Without the M&V equipment, it would not have been possible to detect and address system issues swiftly. Future central heat pump water heating system designs should incorporate some means for automatic remote alarms to be sent to building owners and maintenance personnel to maintain operations and avoid inefficient back up system operations.
- The “swing tank” concept was a successful method to isolate the warm recirculation water from the HPWHs. The dedicated temperature maintenance tank was designed and sized to be a “swing tank”, utilizing over-heated water in the primary storage tanks to mix with the cooler water returning from the recirculation loop. The periodic draw of the over-heated water into the temperature maintenance “swing tank” kept the tank primed above the temperature at which the backup electrical boiler system will engage. This design minimized the electric resistance reheat of the hot water circulation system, and was a successful strategy at this site, due to the building’s low recirculation losses.
- The existing electric system was preserved during the HPWH retrofit to provide support for the “swing tank” operation, and backup for water heating in the event of equipment outages. Over the course of monitoring at this site, the electric boilers were needed for both these tasks; however, the boilers only contributed approximately three percent of the total heat to the water. At future installations, the need for full backup could be avoided by installing additional, redundant stages of heat pumps and a larger “swing tank”.
- Median run times with four operable heat pumps were 15 hours per day or a 63% duty cycle. This includes summer and winter periods representing the warmest and coldest ambient conditions. Fewer operable units resulted in longer median duty cycles (83% or

20-hours). In extreme cases, during a leak event and when multiple heat pumps were inoperable, run times could exceed 24-hours.

- Incremental costs for HPWH systems are still higher than conventional equipment; however, it is expected that the cost for heat pump water heating systems will drop significantly as the products make their way into the mainstream market. Until that time, utility and other incentive programs can reduce the payback period for early adoption. Even without incentives, however, HPWH systems demonstrate substantial cost-effective energy savings making them an attractive water heating option in retrofits and new construction.
- The average hot water use on the peak day was nearly double the average daily use. This indicates that designers of HPWH systems should consider incorporation of less expensive back-up electric resistance capacity for the few peak days to allow for a more cost-effective system designed for the majority of days without sacrificing hot water delivery to the occupants.

Recommendations for future research projects and product development include:

- Additional pilot studies in low- and mid-rise buildings to expand multifamily applications for this water heating technology and contribute to utility program design. Future pilots should incorporate an automatic alarm capability and redundant heat pump stages.
- Expanded “swing tank” designs and applications require a tested method for predicting recirculation losses so that temperature maintenance systems can be sized reliably. This will require additional research on temperature maintenance systems and recirculation losses.

- This project included the minimum heat pump capacity needed to serve the project. During the course of the study this site experienced intermittent periods when one or more HPWHs were inoperable. Frequently this could be addressed swiftly by mechanical contractors or experienced maintenance staff. However, including an additional Sanden unit in system designs would allow for some measure of elasticity in output capacity. This could decrease overall HWPB run times, and further reduce backup system operation, and provide adequate heat pump capacity for periods when one of the units is off-line. Future study into the cost and performance impact of this “safety factor” approach to HPWH system design would be needed.
- Some level of M&V equipment for the purpose of troubleshooting should be included in all emerging technology installations.
- Based on M&V data collected in this study, we recommend two changes to the Sanden product for multifamily applications: a control system capable of turning on multiple units from a single temperature sensor, and an automatic remote alarm capability. These additional features will ensure that systems are operating as designed over the long-term and that utility programs that incentivize these installations are realizing the anticipated savings. Ideally, this is a manufacturer-provided feature; however, interim third-party solutions could be useful and should be included in demonstration project testing.

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Appendix A – Major Monitoring and Maintenance Events

This appendix provides a table (Table 3) outlining the timeline for major monitoring and maintenance events, and their resolution, at the field site.

Table 3. Major Measurement and Verification Events

Event	Year	Month	M&V Observation	Event Cause	Resolution
1	2018	Dec	Ongoing M&V Equipment trouble shooting; active energy monitoring	A faulty flow meter was identified and scheduled for replacement	Eventual flow meter replacement in March 2019
2	2019	Jan 2019	HPWH3* entered idle status (this had happened several times previously)	Error code indicated possible control board issues†	
3	2019	Feb	Tree branch fell on inoperable HPWH3	Storm damage	New HPWH ordered to replace damaged equipment
4	2019	Mar 7	Faulty flow meter and damaged Sanden replaced	See Events 1 and 3 above	Resolution to Events 1 and 3 above
5	2019	Mar 20	HPWH1 entered idle status	Error code indicated possible control board issues†	Issue detected and building maintenance alerted
6	2019	Apr 11	HPWH1 operable again	See Event 5	Building maintenance staff power cycled the equipment so it resumed operation – resolution to Event 5
7	2019	Apr 22	HPWH1 entered idle status	Error code indicated possible control board issues†	Issue detected and building maintenance alerted. Because of second failure for this unit, factory recommended control board replacement. Part was ordered.
8	2019	May 1	Energy monitoring data outage	Remote connection to data communication protocols interrupted.	Resolved connection issues, and data began logging again within 5 days

Event	Year	Month	M&V Observation	Event Cause	Resolution
9	2019	Jun 4	System drained to facilitate pipe leak repair	Pipe leak	Pipe repaired
10	2019	Jun 18	Site visit to address non-stop flow through the system	A valve was overlooked when the water was turned back on after the leak repair	Adjusted valve, so that normal flow resumed
11	2019	Jun 28	Maintenance visit.	Visit to address history of repeated idle periods for HPWH1.	Control board replaced on HPWH1. HPWH1 operated for a few hours and then was idle again.
12	2019	Jul 17	HPWH1 operable again	See Event 7	Building maintenance staff power cycled the equipment so it resumed operation – resolution to Event 7
13	2019	Aug 1	Energy monitoring data outage	Remote connection to data communication protocols interrupted	Resolved connection issues, and data began logging again within 1 day
14	2019	Sep 19	HPWH1 entered idle status	Error code - low flow / high entering water temperature	Issue detected and mechanical contractor alerted
15	2019	Oct 14	HPWH1 operable again	See Event 14	Mechanical contractor cleaned strainer and power cycled equipment – resolution to Event 14
16	2019	Nov 6	HPWH1 entered idle status	Unknown error code [‡] – see Event 17	Issue detected and building maintenance alerted
17	2019	Nov 18	HPWH1 operable again	See Event 16	Building maintenance staff cleaned strainer and power cycled equipment – resolution to Event 16
18	2019	Dec 6	HPWH1 entered idle status	Unknown error code [‡] – see Event 19	Issue detected and building maintenance alerted
19	2019	Dec 9	HPWH1 operable again	See Event 18	Building maintenance staff cleaned strainer and power cycled equipment – resolution to Event 18

Event	Year	Month	M&V Observation	Event Cause	Resolution
20	2019	Dec 20	No issue		Building maintenance staff performed preventative cleaning on all HPWH strainers.
21	2019	Dec 27-28	HPWH3§ entered idle status	Unknown – possible tank stratification keeping the aquastat above the temperature which would have engaged the HPWH	HPWH resumed normal operation on 12/29. No action was taken.
22	2020	Jan 23 2020	HPWH1 entered idle status	See Event 24	Issue detected and building maintenance alerted
23	2020	Feb 6	HPWH2 entered idle status	See Event 24	
24	2020	Feb 8	HPWHs operable	Error code on both units (E071) indicated condenser fan motor revolution error. Upon re-start contractor observed normal fan operation.	Mechanical contractor serviced the idle units. Resolution to Events (22 & 23)
25	2020	Mar 18	Abnormal back-up system operation observed during February HPWH idle period.	Possible cause identified as a set-point, adjusted since commissioning.	Lowered final storage tanks set point back to 120°F threshold.

*Numbering corresponds to eGauge labelling.

† Initial error codes were mis-diagnosed and early equipment shut-offs were attributable to low-flow / high entering-water temperatures.

‡ HPWH1 error history was accessed 2020-03-18. Stored records indicated these errors were due to a condenser fan motor revolution error.

§This is HPWH4 via the online web portal.

Assumptions

This table summarizes criteria used in assessing the product readiness for this project.

<p>Market/Commercial</p>	<p>Level 1: Not commercially available or limited, pre-commercial availability Level 2: Commercially available outside of Pacific Northwest (PNW). Requires special order in NW. Level 3: Commercially available in PNW from one manufacturer through standard channels. Level 4: Commercially available in PNW from with at least one competitor. Stocked throughout region. Level 5: Commercially available with 2+ competitors, well developed supply chain. Widely and easily available.</p>
<p>Technology</p>	<p>Level 1: Concept not yet validated Level 2: Concept validated: Product with similar technology has been installed and operated successfully. Level 3: Limited Assessment: Product has been installed and operated successfully. Level 4: Extensive Assessment: Product has been installed in PNW climate and shown to operate successfully. Level 5: Comprehensive Analysis: Performance Map has been developed. Level 6: Approved for Implementation</p>
<p>Program</p>	<p>Level 1: No program design. No risk assessment. Level 2: Not cost effective (CE), but preliminary analysis shows a pathway to CE. Limited program design and risk assessment. Level 3: Not cost effective but shows pathway to CE with higher volumes, more competition, improved technology. Small scale pilots. Level 4: Marginally at cost effective levels. Program design complete, larger scale pilots underway. Well-developed risk assessment. Level 5: Cost effective. Ready for full-scale programs. Periodic risk assessment process in place.</p>