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Emerging Technologies

Colmac Cx-Series Heat Pump Water Heating System: Jackson Apartments, Seattle WA

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Colmac Cx-Series Heat Pump Water Heating System: Jackson Apartments, Seattle WA

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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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ABSTRACT

Domestic water heating in multifamily buildings represents a substantial energy load, which can be significantly reduced with properly designed heat pump water heater (HPWH) systems. Early projects using Colmac HPWH products in Technology Innovation Model (TIM) Demonstration Projects resulted in feedback to the manufacturer for additional product development. This case study highlights the latest product technology developments of Colmac's HPWH equipment with third-party controls; it also represents one of the first deployments of Cx-series equipment in the nation. Findings from almost a year of monitoring confirm that many of the TIM product development recommendations were addressed, including defrost controls, improved staging and controls logic, improved alarming, and an overall more integrated approach to HPWH systems (e.g., accommodating staging of backup equipment). Cx-equipment efficiencies (2.4-2.5) were found to be similar to field efficiencies with previous-generation HPA-series equipment. Average annual System COP was approximately 1.98, which was degraded by electric resistance function for a period when the temperature maintenance HPWH equipment was inoperable. Equipment efficiency represents an area for possible continued improvement for Colmac products, as well as development of low-global warming potential products. As the HPWH market expands, sustained product evolution will ensure continued market competitiveness and the potential for increased savings. Nevertheless, this project demonstrated that these HPWH systems can cut domestic water heating energy use by approximately half and be a valuable efficiency tool for Bonneville Power Administration's energy reduction goals.

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Acronyms

BAS	Building Automation System
BPA	Bonneville Power Administration
BTU	British Thermal Unit
CHPWH	Commercial Heat Pump Water Heater
COP	Coefficient of Performance
DHW	Domestic Hot Water
F	Fahrenheit
GPD	Gallon per Day
GPM	Gallon per Minute
HPWH	Heat Pump Water Heater
HVAC	Heating Ventilation and Conditioning
kW	Kilowatt(s)
M&V	Measurement and Verification
NOAA	National Oceanic and Atmospheric Administration
OAT	Outside Air Temperature
SQL	Structured Query Language
ST	Storage Tank
TIM	Technology Innovation Model
TMV	Temperature Mixing Valve
WH	Water Heater

Executive Summary

Heat pump water heater (HPWH) systems have the potential for increased efficiencies in the two main domestic water heating processes: primary water heating and temperature maintenance. In multifamily buildings, these combined loads represent a quarter of the overall building energy use. Therefore, efficiency improvements in multi-family sector water-heating loads, in particular, can help Bonneville Power Administration reach its energy use and demand reduction goals.

The objective of this case study was to document the equipment operation and field performance of Colmac's latest generation of HPWH equipment – the Cx series. The Cx-series equipment was developed based on findings from previous Technology Innovation Model (TIM) demonstration projects using Colmac's HPA-series equipment installed in underground parking garages in the Pacific Northwest. This report outlines the findings from almost a year of monitoring and provides insights into equipment function and performance.

Many of the product development recommendations were addressed with the Cx-series equipment, including defrost controls, improved staging, controls logic and alarming function (provided by a third-party controller), and an overall more integrated approach to HPWH systems (i.e., accommodating backup equipment into system staging logic). Although some Cx-equipment issues were encountered within the first year, it is worth noting that Jackson Apartments was among the product's first deployments, and Colmac serviced the equipment quickly and integrated findings into subsequent installations. Equipment efficiencies[1] were found to be similar to field efficiencies with HPA-series equipment: 2.4-2.5, with annual system performance estimated at 1.98. Overall average system COP was lower due in part to the operation of electric resistance heat to handle the temperature maintenance load for a period when the temperature maintenance HPWH was inoperable.

Colmac's Cx-series products provide substantial efficiency improvements over conventional electric resistance and gas water heating systems. Even so, to ensure continued competitiveness as the HPWH market expands, Colmac should focus on continuous improvement of its current offering. This should progress toward a plug-and-play model, improved equipment efficiencies, and development of low global warming refrigerant products.

Background

Ecotope began designing domestic hot water (DHW) systems with commercial heat pump water heater (CHPWH) equipment in 2009 after feasibility studies[i] provided proof of concept for DHW production using Colmac HPA-series HPWHs. Initial demonstration projects were designed in

[1] Equipment performance only assesses the energy inputs / outputs at the HPWH equipment; whereas system performance accounts for tank and temperature maintenance losses, as well as backup equipment operation.

conjunction with Colmac Industries, based on the manufacturer's prior experience deploying the equipment in hot, humid climates. Applications in the Pacific Northwest required equipment to be installed in thermally buffered areas, such as subterranean parking garages. As heat pumps function by moving heat from a source to a sink – air to water in this case – the warmer air in the parking garage (compared to winter outdoor installations) provided a better heat source and minimized the occurrence of defrost cycles, which degrade performance.

There have been three previous studies which culminated in design guidelines and best practices for DHW systems with this class of HPWH equipment. Study results and design recommendations are summarized in a 2018 persistence study report to Bonneville Power Administration (BPA)[ii]. The initial demonstration projects also uncovered several issues with the product itself. The main concerns were with compressor longevity, defrost controls, fan

The demonstration project at Jackson Apartments represents the latest product technology developments of Colmac's HPWH equipment with integrated third-party controls, based on improvements identified through the TIM.

operation controls, and creation of a 'packaged' product to reduce the need for tailored engineering for each installation and to allow broader implementation of the technology. A "version 3" design was installed at Batik Apartments, a seven-story, 195-unit mixed-use building in Seattle, WA (which was also included in the persistence study). That project implemented many design refinements and minimal controls. A similar system was installed at Cypress Apartments, a nearby building with over 200 units and street-level retail. The Cypress project used similar design criteria as Batik, had improved controls (with logging capability and data collection on tank

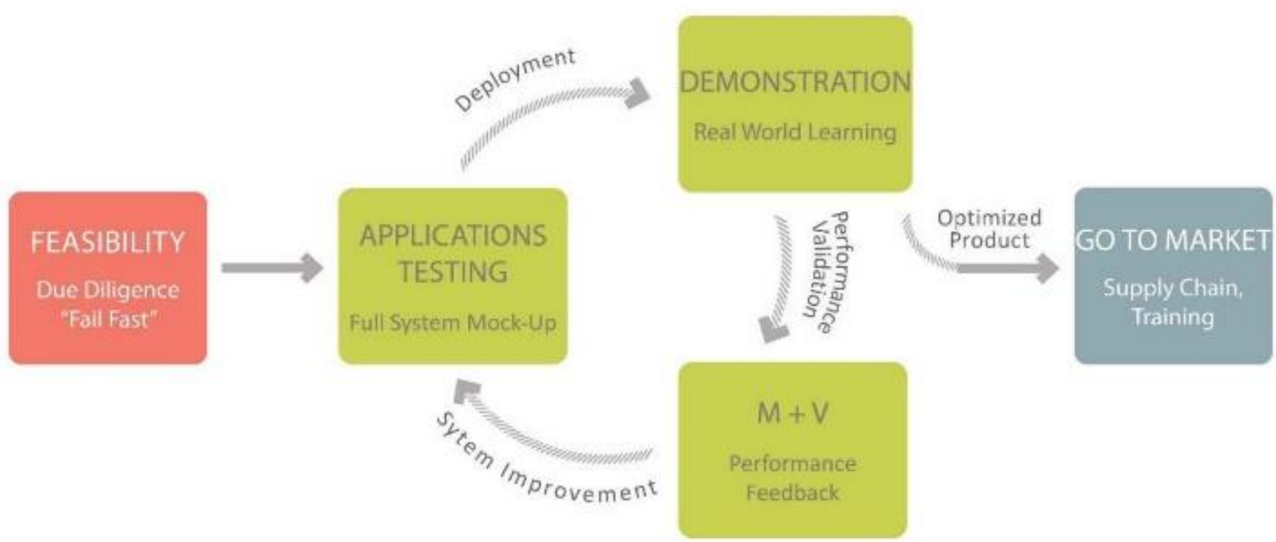

Figure 1. Technology Innovation Model with feedback loop for further product development

temperatures and heating calls, and remote viewing/setpoint access), but did not include Measurement & Verification (M&V) support.

The demonstration project at Jackson Apartments represents the latest product technology developments of Colmac's HPWH equipment with integrated third-party controls, based on improvements identified through the TIM. Figure 1 shows the TIM and the product development feedback mechanism.

As a result, this new demonstration project:

- assessed how the newly developed Cx-series products operated and ensured that the previous operational issues observed with HPA-series equipment have been resolved,
- documented all aspects of system performance, as well as any challenges to the design, installation, and commissioning, and
- helped diagnose and correct any problems that were detected.

Additionally, results from this field study will be used to shape potential future projects.

System Design

There are two HPWH systems at Jackson Apartments (Figure 2), one in the West Building and one in the East Building.

This report covers only the design and monitoring of the East plant, which serves 166 apartments. The primary water heating is accomplished by two CxA units (HPWH-5

Figure 2. Jackson Apartments in Seattle, WA (Source: Apartments.com)

and HPWH-6) that deliver hot water into a series of three 500-gallon storage tanks (ST-8-10). These single-pass HPWHs use refrigerant R-134a. A backup primary heating solution is provided through a 50-gallon electric-resistance tank (WH-4).

Temperature maintenance is provided by a separate CxV HPWH (HPWH-7), using R-410a. HPWH-7 provides temperature maintenance through a 500-gallon Durawatt (WH-3) tank with integral electric resistance heater. The system is designed to have the load fully served through the HPWH capacity, and the electric-resistance heater is there to provide backup in the event of HPWH equipment malfunction. Figure 3 shows a simplified schematic of the DHW system components and M&V measurement points.

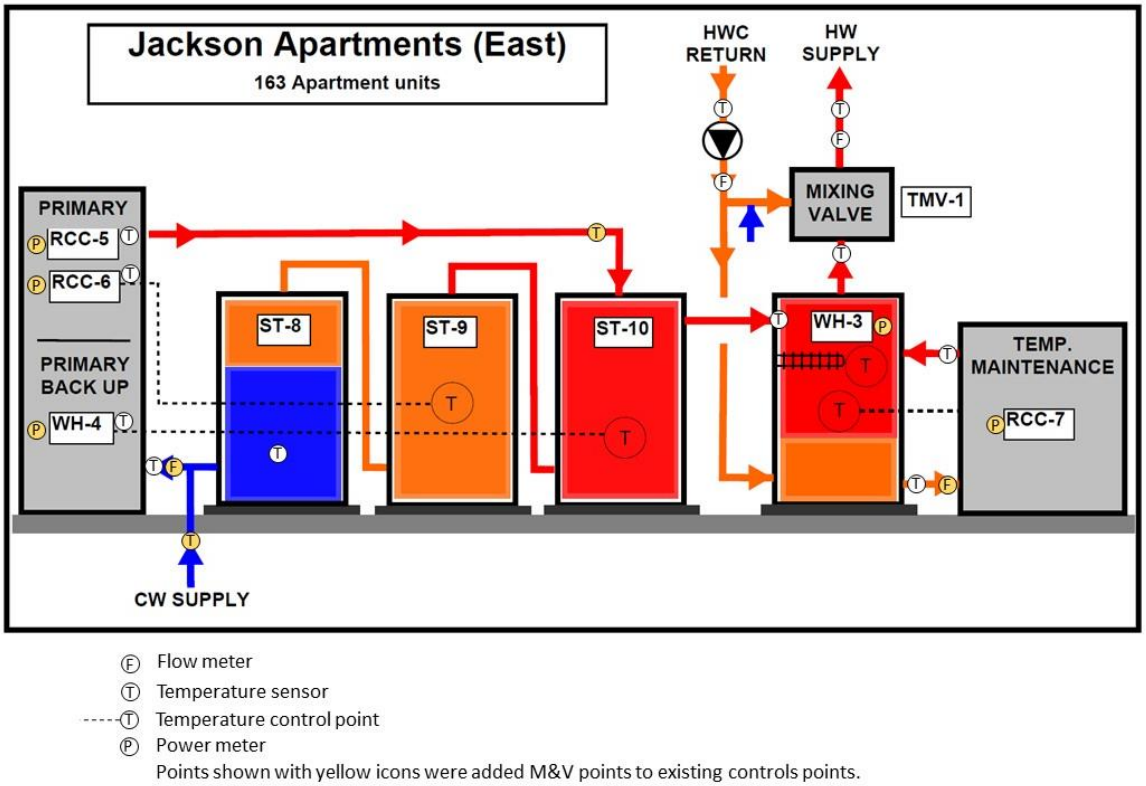

Figure 3. Schematic of water heating system at Jackson Apartments

The following bullets outline the main elements of the DHW system design. Photographs of many of these components are provided in the following Photographs section of this report.

- *Single Pass:* The primary plant design is based around a single-pass heat exchange strategy. 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 135°F delivered to storage tanks ST-8 through ST-10. The HPWHs are configured to handle entering water temperatures from 50-110°F. The advantage of the single-pass arrangement is that a usable water temperature is always delivered to the top of the storage reservoir. The primary HPWHs are configured to operate in staged lead/lag cycles. The lead HPWH turns on when ST-9 drops below the adjustable 90°F setpoint, and the lag will initiate if the same tank drops below 85°F. Both HPWHs are controlled to turn off when ST-8 rises above 100°F.

- *Multiple Storage Tanks:* Multiple primary storage tanks are plumbed in series. The series plumbing arrangement enables a high degree of temperature stratification throughout the system, with the hottest water at the end of the primary storage system (ST-10).

- *Temperature Maintenance:* The temperature maintenance task is performed by a dedicated HPWH. This strategy isolates the temperature maintenance load and serves it with equipment that is dedicated to the warmer temperatures of return recirculation water. Heating can be accomplished in a multi-pass configuration whereby heating is incremental, with the water passing multiple times through the HPWH to reach the target temperature. However, this heating mode has higher flow rates and is prone to mixing the temperature maintenance tank, which results in higher incoming temperatures to the HPWH. Equipment checks partway through the monitoring period revealed that the temperature maintenance HPWH-7 had been set in single-pass mode, likely since project inception. Single-pass mode is typically characterized by a lower flow rate and larger temperature lift, which can allow stratified storage and cooler incoming water to the temperature maintenance HPWH. This is discussed more in the System Operation section. HPWH-7 was configured to provide a 20-30°F lift when the temperature maintenance tank (WH-3) drops to 125°F, bringing the temperature back to the 130°F set-point.

- *Backup Electric Water Heaters:* This design utilizes two electric resistance tanks as backup. For the primary water heating task, WH-4 is a 50-gallon tank that is only enabled when ST-10 drops below 125°F. At that point it will turn on to maintain a 135°F tank temperature. When ST-10 rises above 130°F, WH-4 will stop operation. The temperature maintenance tank (WH-3) is a 500-gallon tank containing an electric resistance element. If the temperature maintenance HPWH-7 does not run or cannot meet the load, WH-3 is programmed to maintain the setpoint. The temperature maintenance tank was originally designed for a 122°F setpoint; however, during commission the tank dead band required programming to a slightly higher setpoint of 125°F – see HPWH System section for commissioning details.

- *Electronic mixing station:* To provide high-accuracy temperature delivery, a digital mixing station is used to deliver ~124°F water to the building's recirculation loop. The installed unit (Figure 8) uses a dual-mixing valve strategy to allow precise +/- 2°F control over delivery water temperatures

- *Controls:* The systems at Jackson Apartments include a third-party integrated cloud-based monitoring and reporting system (Figure 9). Building maintenance personnel can view and change settings online.

Additionally, alerts can be sent via email or text in the event of equipment alarms or low delivery temperatures. Six alarm points are specified in the control logic for this Building Automation System (BAS) – three for failure alarms on HPWH equipment, two for element-on alarms for the electric resistance equipment, and a low temperature alarm when outgoing hot water from the tempering valve is below 120°F. Note that additional alarms are configurable in the online control portal, including for storage tank temperatures and for the pump that is engaged when the primary electric resistance tank is called on. Additionally, trend logs are available for all points, which allows for easy viewing of the historical operation of the system over time. Colmac also provides a cloud-based monitoring and reporting system, which was not assessed in this project.

Figure 4. HPWH-5, one of two primary CxA HPWHs

Figure 5. Left to right - primary storage tanks ST8-10 and WH-3 (trim tank)

Photographs

The following photographs show details of the DHW system, including the HPWH units and piping, and details of the storage tanks, mixers, controls, temperature sensors, and flow meters.

Figure 6. Backup primary electric resistance tank, WH-4

Figure 8. BAS-enabled digital mixing station, yellow thermistor visible in left front pipe

Figure 7. Wall-mounted temperature maintenance HPWH-7 (CxV)

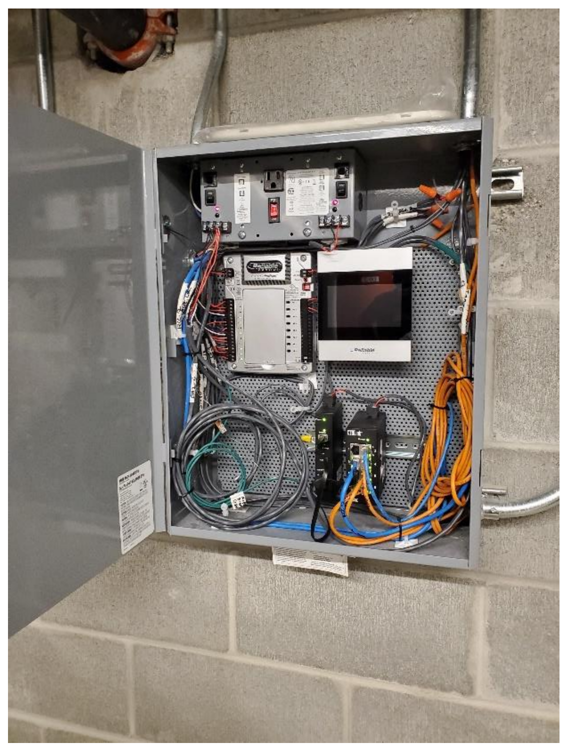

Figure 9. Jackson East control panel

Figure 10. Ultrasonic flow meter

Methods

Jackson Apartments' M&V system leveraged the existing controls monitoring and reporting interface. Johnson Barrow, a Heating Ventilation and Conditioning (HVAC) equipment representative organization and controls installer, outfits Colmac installations with a Reliable Controls system which provides real-time operations, remote access to data and configurable control point settings, and automated alarming. Working with Johnson Barrow, the project team was able to add several temperature sensors, and flow and power meters, to the existing suite of control points. These added points allow calculation of performance metrics. Additionally, secure access to the Azure Structured Query Language (SQL) database for both the controls monitoring points and M&V sensors was provided so that the project team could compile a longitudinal dataset and assess system operation and performance over time.

Figure 3 is a simplified schematic of the East Plant showing controls and added M&V monitoring points. This study was intended to focus on the performance of the DHW system as a whole rather than the efficiency of each piece of equipment. However, sensor placement allowed calculation of the coefficient of performance (COP) of the temperature maintenance CxV heat pump and primary (CxA) heaters. Equipment-level COPs for Cx HPWHs will be verified by coordinated product testing at the PG&E lab, while data from this project showed the field operation and performance of the DHW system, and the primary and temperature maintenance heaters.

Data from the cloud-based controls interface were collected nightly from Johnson Barrow's Azure SQL database and compiled on the project team's servers each day. The project team set up an online tool[2] to view raw data and both hourly and daily averages for each of the monitored points on the HPWH system, as well as calculated values like COP and heat output. This data was automatically updated nightly, allowing the engineers and installers commissioning the project to quickly receive feedback on changes they made to the system.

[2] https://ecotope.shinyapps.io/HPWHViewer/

Beginning in September 2020, partial data was collected and available through the online tool, with the full suite of data points initiated in October 2020.

Findings

This section contains findings from the HPWH system commissioning process as well as the M&V commissioning and timeline. Summaries from M&V findings on system operation, hot water load, and system performance are also provided.

Commissioning Process

This section reviews the commissioning process (for both the HPWH and the M&V system), summarizes the findings, and describes how topics were resolved.

HPWH System

The project team commissioned the DHW system at Jackson Apartments' East Building with major testing occurring on both August 14, 2020, and September 24, 2020. The project team's evaluation resulted in several issues, which were resolved by January 2021. The following points summarize the commissioning findings and resolution of noted items.

- Confirmed presence of plumbing hot water circulation line insulation, continuous insulation, and pipe hangers sufficient to accommodate insulation around piping at attachment points. This reduced hot water circulation losses in the building. No corrective action needed.
- Initial testing showed the alarm functionality was not complete at the time of the first commissioning site visit. Subsequent functional testing and sequence of operation procedures were completed and showed the alarm system to be properly functioning. Building maintenance personnel, the installing and controls plumbing contractors, and the design engineers all receive an email alarm upon detection of one or more system faults. These include low temperature of outgoing hot water, equipment fault or failure, low temperature of outgoing HW to the building, and engagement of backup systems.
- A measurement and verification (M&V) system was designed and installed on the HPWH system to verify the long-term system efficiency and overall trends. This system was used for commissioning purposes as well. During commissioning it was observed that a few sensors, such as the WH-3 and HPWH-7 current transducers and the TMV-2 flowmeter, were installed incorrectly. The electrical and controls contractors were notified and able to resolve the issues, which were primarily due to polarity of the electrical connections of low voltage metering equipment and mislabeling of control sequencing.
- The temperature maintenance heater (HPWH-7) for the East building was not functioning during the first functional testing site visit. The fan

was running, but the compressor was not. As a result, the unit was not providing heat to the system and was not in a defrost-operation state. Initial repairs were unsuccessful. Ultimately, multiple components, such as the heat exchanger, had to be replaced due to manufacturing defects. This was completed in October 2020.

- The control dead band for WH-3 was found to be wider than anticipated. A dead band in this context is the range which fails to trigger the electric resistance water heater to come on. WH-3 was initially set at 122°F and providing backup for HPWH-7. The water heater dead band was found to be approximately 4°F, with WH-3 maintaining the water temperature at approximately 118-122°F. The low end of this range is less than the target discharge water temperature of 120°F and resulted in an alarm signal from the controller. When the backup system called to engage it was not able to maintain the 120°F, so the overall temperature was lifted to maintain the bottom of the dead band at 120°F. Controls were adjusted so the dead band remained at 4°F with a raised setpoint of 125°F for WH-3. This assured a discharge temperature of 120°F.
- The backdraft dampers on the garage exhaust fans were closed while the fans were operating in low speed. These fans are critical for a functional HPWH system as they are used to remove cool exhaust air from the multiple HPWH units. Backdraft damper weights were rebalanced for both high flow and continuous low flow fan speeds. The system was also adjusted so one fan runs to maintain the continuous ventilation rates, while the other three are off until called on by CO2 sensors.
- During initial visits it was noted that the temperature maintenance HPWH in the neighboring West plant was set in single-pass configuration, and it was reconfigured in the field by the installing contractor. This topic was not highlighted during commissioning of the East plant temperature maintenance HPWH; however, during later system checks, HPWH-7 was also found to be in a single-pass mode – see the M&V Timeline section of this report for further discussion.
- The circulation loop temperature loss was measured at 1.5°F, with the pump faster than anticipated (at approximately 22 gallons per minute (GPM)). This higher flow found during commissioning would result in more frequent cycles of the heating equipment. The plumber was tasked with adjusting the flow rate to target a 5-10°F drop in temperature between the supply and return water temperatures. Subsequent M&V monitoring suggest the temperature delta across the recirculation loop is now closer to 4.2°F, and the flow rate approximately 14 GPM.

- It was noted that each of the HPWHs entered a 10-minute fan cycle after each heating call. The manufacturer communicated that those fans run after each heating run to ensure moisture is removed from the coil and filter any ice buildup is cleared. Although the 10-minute duration is adjustable, this corresponds to the minimum time between compressor starts. The fan-cycle occurs regardless of ambient conditions (i.e., is not limited to defrost conditions) so it leads to unnecessary energy use during warmer periods. No corrective action needed.

M&V System

Commissioning of the M&V system was an iterative process as observations from the collected data frequently required repeated site visits to verify connections or settings or to resolve data quality concerns. One of the initial observations was that the flow meters integrated into the mixing station package, being leveraged for M&V, were providing questionable flow values. Additionally, the flow meters were repeatedly losing their communications with the controls platform, meaning data would not be collected. Numerous fixes were attempted, but eventually new control boards needed to be provided by the mixing station manufacturer and installed (which occurred in March 2021). Parallel to those efforts, the project team purchased a portable ultrasonic flow meter to be used in lieu of the mixing station in-pipe meters. The portable meters were installed approximately at the same time as the control boards were replaced. There were some intermittent data stoppages with the portable meters, which were resolved in June.

Other anomalous readings were observed in the primary heating loop, in the temperature, power, and flow readings. Access to the temperature readings in the HPWH units themselves was available via the control points, and M&V monitoring added separate thermistors to the pipes routing water into and out of the primary heaters. While the thermistors in the HPWH showed similar exiting water temperatures (~141°F) during heating calls, the M&V temperature sensor showed elevated temperatures (>150°F) only when HPWH-6 was running. There were similar trends with different flow and power readings depending on which HPWH was running (see Figure 11). The project team suggested that the thermistor in HPWH-6 could be giving an artificially low reading, and Johnson Barrow verified conditions on-site. It was found that the HPWH-6 thermistor was loose in the thermowell. Thermal paste was applied, and the probe was properly secured in March 2021. This resolved the temperature and power disparities between the two units; however, the flow readings were unresolved.

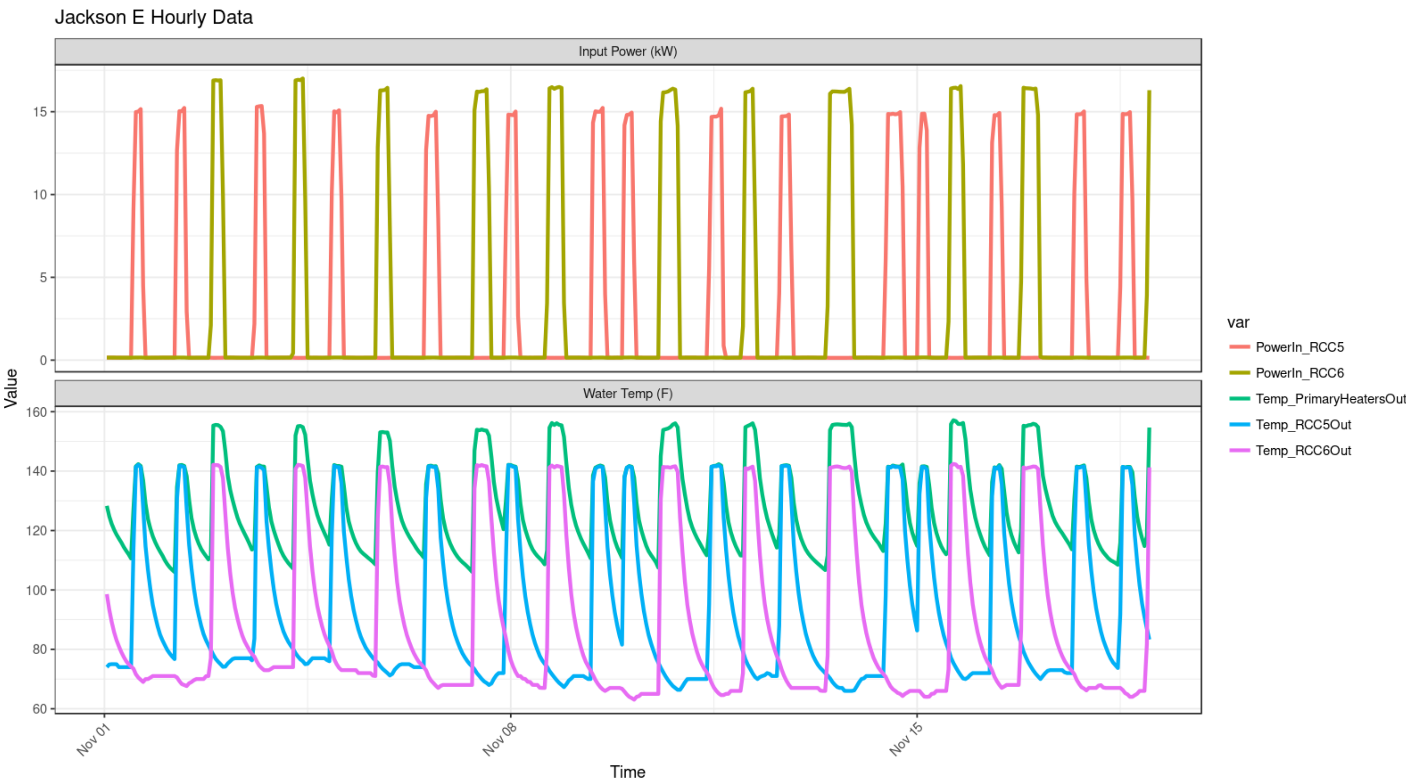

Figure 11. Fall 2020 data showing different exiting temperatures and power readings when individual HPWHs were engaged

In March 2021, both HPWHs were frequently staging simultaneously to meet the load. During short periods, individual HPWHs would be engaged and the flow disparity between the two units continued. Additionally, flow readings simply seemed too high. In April 2021, the project team further examined the flow meter installation and found that the meter was in alarm and confirmed that the readings were not coinciding with the in-unit flow calculated by the primary HPWHs. It was determined that the meter had been installed incorrectly, and needed to be rotated 45°, so that the sensor port was located on top of the horizontal pipe. The plumber was able to make a site visit and rotate the meter in mid-July 2021. The flow disparity continued, and the project team made a follow-up visit the following week, finding the flow meter still in alarm. Following our site visit, a technical assistance case was opened with Onicon, the flow meter manufacturer, and an Onicon representative scheduled to make a site visit. Review of the power and installation appeared normal, but intermittent no flow, reverse flow, and output alarms continued on the display, while diagnostic information and the sensors seemed to be working. After further consult, Onicon technical support suggested trying something that had worked recently at a different project. There they had found electrical noise being conducted through the copper pipes; this noise was just enough to cause the processor to incorrectly read the sensors in the meter. A ground wire from the meter body to a ground input on the circuit card was added to the Jackson flow meter and that immediately eliminated the noise, and the meter began reading very consistently without any alarms. The flow meter on HPWH-7 was also grounded at this time as a precaution. Since finding the prior instance of electrical noise running through a buildings' pipes, Onicon has made the grounding procedure a factory modification on their F-4600 flow meters.

M&V Timeline

Commissioning of the M&V system took some time. Nevertheless, valuable information about system operation and performance was collected throughout. As has been seen in other M&V projects[iii,iv], these insights can be extremely useful on new technology installations, as M&V allows for early diagnosis of problems *before* expensive equipment replacement is needed. Independent monitoring identified the dislodged temperature sensor in HPWH-6. Addressing this issue meant the equipment was returned to its intended operating state.

> *M&V allows for early diagnosis of problems before expensive equipment replacement is needed.*

Table 1 outlines the timeline for major monitoring and maintenance events, and their resolution, at the field site. This year of monitoring also coincided with extreme winter and summer weather events in the Pacific Northwest, which are mentioned in this timeline as they are apparent in the other Findings sections.

Table 1. Major measurement and verification events

Event	Year	Month	M&V Observation	Event Cause	Resolution
1	2020	Oct	Colmac onsite to start HPWH-7 and to replace heat exchangers in all HPWHs		
2	2020	Oct	Temperature and flow differences observed between primary heaters HPWH-5 and 6 after Colmac site visit. Power readings reduced from initial weeks, but difference in signature between HPWH-5 and -6 still observed.	Thermistor likely dislodged during heat exchanger replacement, explaining temperature and power disparities. Flow reading issues tracked to a different cause.	Thermistor re-inserted in temperature well in Mar 2021
3	2020	Nov	Mixing station 1 lost communication	Identified to be control board issues	

4	2019	Dec	Mixing station 2 lost communication. No flow information available through mixing station flow meters.	See above	Manufacturer provided replacement control boards for all mixing stations. Installed in Mar 2021
5	2021	Feb 13-27	Primary heaters operating non-stop. WH-4 providing primary back-up. Only very minimal back-up from WH-3 (on temperature maintenance side).	Extreme cold weather.	
6	2021	Feb 25	Ecotope installs portable ultrasonic flow meter to replace mixing station flow meters	See Event 2	
7	2021	Feb-Mar	Equipment power readings are no longer being recorded for approximately a week.	Communication for the portable flow meter was assigned on top of the power meters	Issue detected and worked with controls representative to resolve.
8	2021	Mar 17-Apr 28	WH-3 (back-up ER WH for the temperature maintenance) operating steadily.	Possible start to issues with HPWH-7	Ecotope notified building maintenance. Eventually, Ecotope visited site and reduced set-point.
9	2021	May 11	Ecotope determined HPWH-7 had been set in single-pass mode, likely since October 2020.		
10	2021	Jun 27-29	Garage temperatures reach 90°F	Regional extreme heat event.	
11	2021	Jul 4	HPWH-7 system leaked refrigerant and stopped functioning. Temperature maintenance provided by electric resistance.	Refrigerant leak.	See event 13
12	2021	Aug 7-9	Temporary data outage		Resolved by controls contractor.
13	2021	Aug 24	Colmac repairs HWPH-7. WH-3 no longer engaged for temperature maintenance.		

As mentioned previously in this report, the temperature maintenance HPWH (HPWH-7) at the East plant was determined to be in single-pass mode during a May site visit (Event 9). As this was not observed during initial system commissioning, it is likely that the single-pass configuration was set in October 2020 when the unit was serviced early in the monitoring period. Although the original design specified this HPWH operate in multi-pass, it was determined that the lower flow rate and higher temperature lift of single-pass mode may keep the tank more stratified and, therefore, allow HPWH-7 to process cooler incoming water and HPWH-7 was left in single-pass mode.

Ambient Conditions

This HPWH system was monitored for just under a year and operated under several extreme weather events in 2021. Even in the buffered conditions of a subterranean garage, these events are obvious in Figure 12 which shows the incoming air temperatures for each of the three HPWHs at Jackson Apartments alongside the outside air temperature from a nearby National Oceanic and Atmospheric Administration (NOAA) weather station. Beyond the temperature extremes, the air inside the garage is typically warmer than environmental conditions outside the garage. This has been reported previously at other subterranean garage HPWH installations[iii]. At this site, the air inside the garage was typically 5.5°F warmer than outside.

Also of note, during the Fall and Winter (October 2020 – March 2021), HPWH-7 is subject to slightly cooler air temperatures as it is located outside the mechanical cage. HPWH-5 and HPWH-6 are installed inside a mechanical cage, where the storage tanks are also located. Although insulated to minimum R-25 to minimize losses, there may still be some temperature increase proximate to the primary HPWHs, while HPWH-7 is subject to the larger (cooler) garage area.

System Operation

One aim of M&V monitoring was to report on system function and how the different parts (primary heaters, temperature maintenance heaters, recirculation loop) worked together to serve the domestic hot water needs in this multi-family building. The following sections generally serve as a review of the setpoints and system operation but also capture anomalous events recorded during data collection.

The primary backup electric resistance equipment only engaged fully during the coldest conditions.

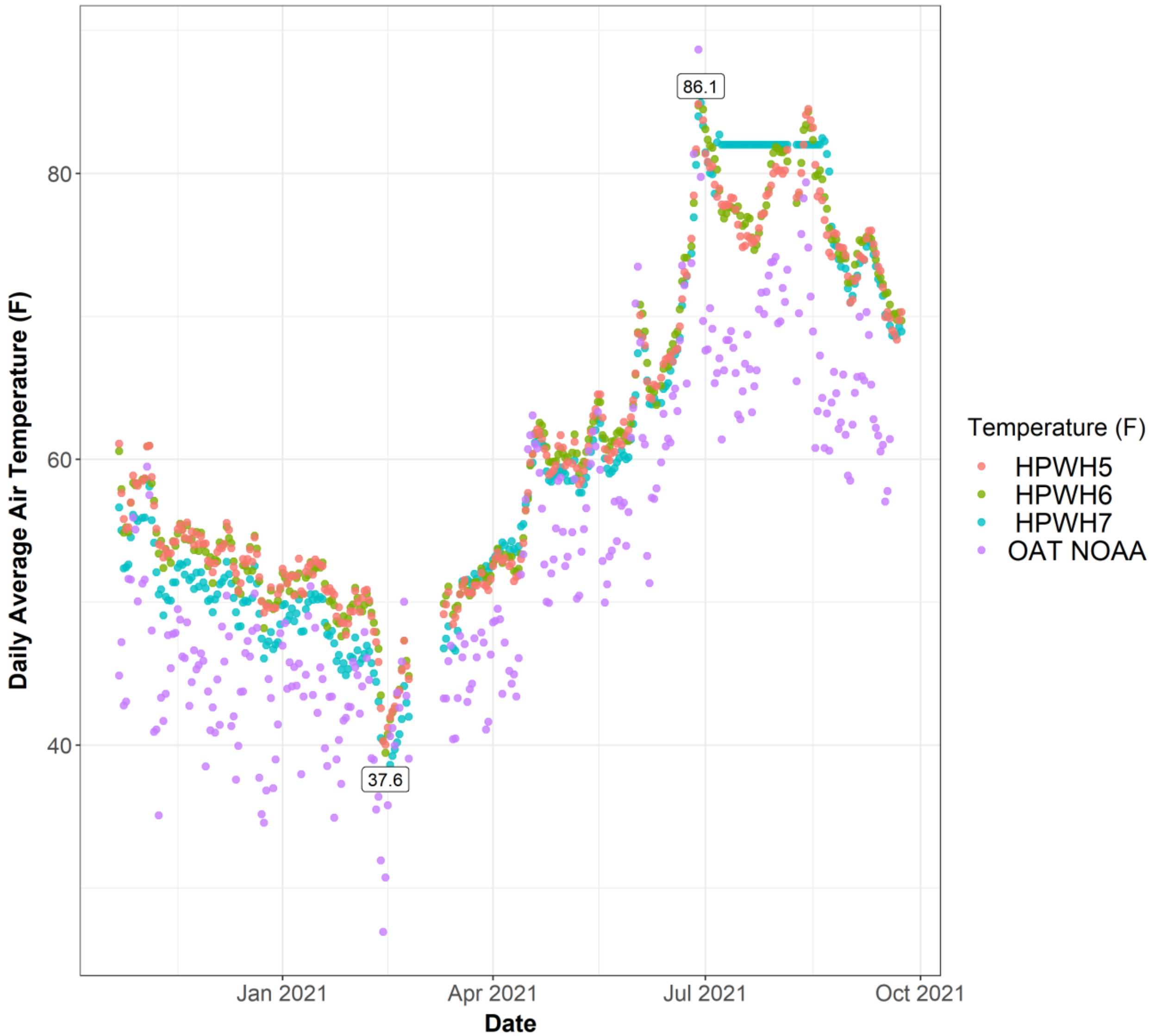

Figure 12. Average daily incoming air temperatures at HPWHs installed in a parking garage with average outside air temperature

Primary Heaters

The HPWH system was designed to serve the anticipated load with HPWHs, but electric resistance tanks were incorporated to serve as backup in the event the HPWH equipment needed to be serviced. Figure 13 shows that the HPWHs (5 and 6) in the primary heating loop provided an approximate 70°F lift over the monitoring period. The required lift was larger over the colder winter and spring months, when city water temperatures are lower.

As described in the Commissioning Process and M&V Timeline sections, there are several interesting occurrences visible in the primary loop water temperatures. Initially, a thermistor in HPWH-6 was not well-seated, causing the HPWH to move more heat than intended into the water delivered to storage. Because the HPWHs alternated their staging approximately daily and ran

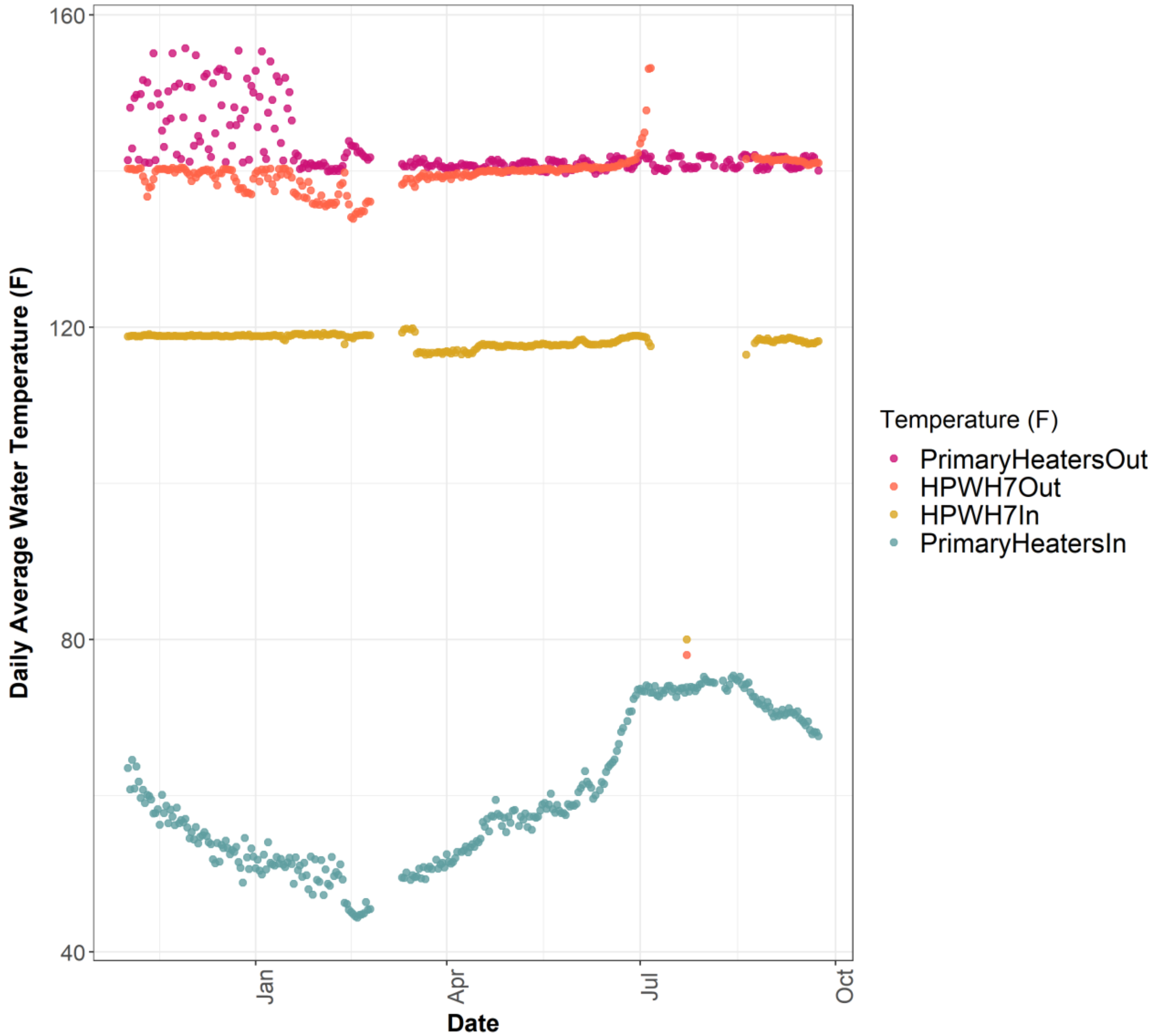

Figure 13. Daily average water temperatures across the primary heating loop and in/out of HPWH-7

one to two heating cycles per day, there were days when only one or the other of the HPWHs were operating. This can be seen as a fairly large spread in the Primary Heaters Out values in early monitoring. When the thermistor was adjusted, both HPWHs had similar heat outputs (data in 2021).

The other two interesting phenomena are the very cold incoming water temperatures in early February, and the steep rise in incoming water temperatures in late June. Both of these occurrences correspond to extreme weather events, which influenced city mains water temperature and the ambient temperatures in the garage (visible in the daily air temperature averages - Figure 12).

The cold weather event is also visible in Figure 14 as the period with highest power usage from the primary equipment, including the backup electric resistance water heater. During this period with extreme cold air (~40°F) and incoming

Figure 14. Daily power use (kW) of primary and temperature maintenance equipment

water temperatures (~45°F) the HPWHs could not quite meet the load. The primary backup electric resistance equipment only engaged fully during the coldest conditions.

Otherwise, the backup electric resistance for primary heat was not used substantially. Low level usage was observed during summer months, but the elements were only engaged for short ~5-minute periods on occasional days when ST-10 temps dipped briefly below 125°F.

Temperature Maintenance Heaters

M&V events discussed earlier are also apparent in the temperature maintenance power use (Figure 14). During the coldest weather period, the backup electric only came on intermittently – for the longest period (~3 hours) when air temperatures were 37-38°F. This demonstrates that the CxV supported the temperature maintenance load (largely without assistance) even during very low ambient temperatures.

In March, the project team notified building maintenance that the electric resistance WH-3 was on, while HPWH-7 was also active. In April, the project team visited the site, and adjusted the WH-3 set-point. Reducing the set-point slightly (to 122°F) allowed HPWH-7 to fully support the temperature maintenance load once again (WH-3 turned off). Supply temperatures were monitored during this period and occasionally dipped to 120°F. In July, HPWH-7 became inoperable, and WH-3 solely supported the temperature maintenance load until HPWH-7 was repaired.

Referring to Figure 13 shows the temperature lift provided by the CxV HPWH-7. In early monitoring the temperature delta was 15-20°F. Since March the provided lift has been just over 20°F.

Winter Operations

HPA-series equipment defrost control strategies were limited to timer- and temperature-based approaches stemming from these systems commonly being used in warmer climates, with less likelihood of frost buildup. In the Pacific Northwest over-winter conditions are conducive to ice build-up on evaporator coils even in underground garages. These events were observed in several previous field studies with HPA-series equipment and had consequences for compressor longevity.

Cx-series equipment incorporate a 'defrost-detection logic' based on coil performance and ambient air conditions. Defrost detection will trigger the heat pump to use hot refrigerant gas bypass to melt potential frost on the evaporator coil. Additional logic then triggers the compressor to turn off and the fan to run to clear any condensate. For CxA equipment, the fan is variable speed and will ramp up and down to clear the coil, while CxV equipment does not have a variable-speed fan and will run the fan at a constant speed.

This demonstrates that the CxV supported the temperature maintenance load (largely without assistance) even during very low ambient temperatures.

Cold-weather operation was observed over prolonged periods at Jackson Apartments with daily average garage air temperatures frequently below 50°F from late December through February. The defrost-detection and condensate-clearing operation described above was observed through M&V monitoring and no indication of high refrigerant pressure faults (as was seen in previous field studies) was detected.

As an additional strategy to ensure coils stay free of moisture, there is a 10-minute (adjustable duration) post-heating-cycle fan-operation period that will run regardless of ambient temperatures. Although fan power draws are a small proportion of the overall equipment draw, these short fan cycles can add up cumulatively especially for temperature maintenance equipment which runs frequently (one or more times every hour) over the course of a day. Additional ambient condition logic on these per-heating-cycle fan runs may offer some energy savings over long-term operation.

Primary Storage Temperatures

The aim of primary storage tanks in series is to create a stratified volume of water such that the water closest to delivery to the building is warmest, and the water closest to the HPWHs is coolest. We can see that stratification in Figure 15. The outlier values for ST-8 and ST-9 occurred in mid-February when the HPWHs were not able to sustain the primary heating load while operating in defrost mode.

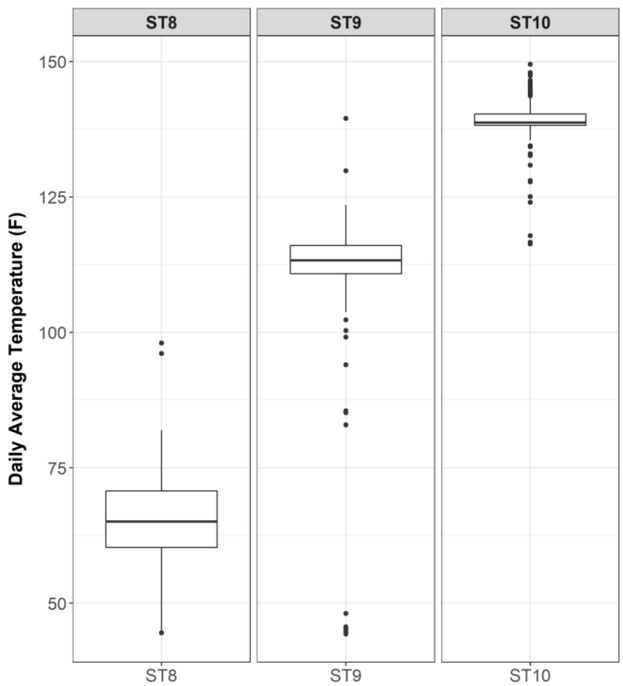

Figure 15. Daily average temperatures in storage tanks 8-10

Recirculation Losses

Typical ranges for multifamily building recirculation losses are between 55 and 90 watts per apartment[v,vi]. Measured losses in the Jackson East building were approximately 51 watts/apartment. Initial measurements showed a very low drop in temperature across the recirculation loop.

On-site observations of the in-pipe temperature gauges and deployment of surface-mounted temperature sensors were used to correct low in-pipe readings from the recirculation supply sensor.

Duty Cycle

Manufacturer guidance recommends that HPWH designs aim for the equipment to operate with a 16-hour duty cycle, or cumulative hours of operation per day. This balances equipment wear-and-tear with the possibility of a moderate capacity buffer for peak conditions. Figure 16 shows the duty cycle for each of the primary HPWHs (HPWH-5 and -6) and the temperature maintenance HPWH-7.

This building was reaching full occupancy over the duration of the study period, so the primary HPWHs were not seeing the design load until only recently. Occupancy reports provided by the leasing office show that 75% occupancy was obtained in spring (May – June) 2021. Since the building is currently 95% occupied (as of September 2021), the designed primary heating capacity is likely to be more in line with the hot water load, and the duty cycle for the primary equipment is anticipated to increase slightly but still well within the design criteria.

By contrast, the temperature maintenance HPWH is operating a bit more than it would ideally. This was mostly due to fall/winter operation when the temperature maintenance HPWH consistently ran > 20 hours/day. Currently (in September), the temperature maintenance HPWH is operating 13-14 hours/day. With increased occupancy in the building, more hot water from the primary storage will enter the temperature maintenance tank, likely offsetting some of the heat output required from HPWH-7 in the winter of 2020/2021.

Equipment Maintenance

The key maintenance activities observed during the almost one-year of monitoring at the Jackson East plant were primarily on HPWH-7, although HPWHs 5 & 6 were also serviced very soon after system start-up. On initial equipment start-up:

- HPWH-7 was initially provided with an incorrect electrical label. During startup, the breaker (sized per the electrical label) tripped because the unit drew more current than the breaker allowed. Colmac re-tested components and performed a field Underwriters Laboratories (UL) test for a new certification. The electrical breaker was replaced with a larger appropriately sized breaker. The startup procedure was then completed without issue.

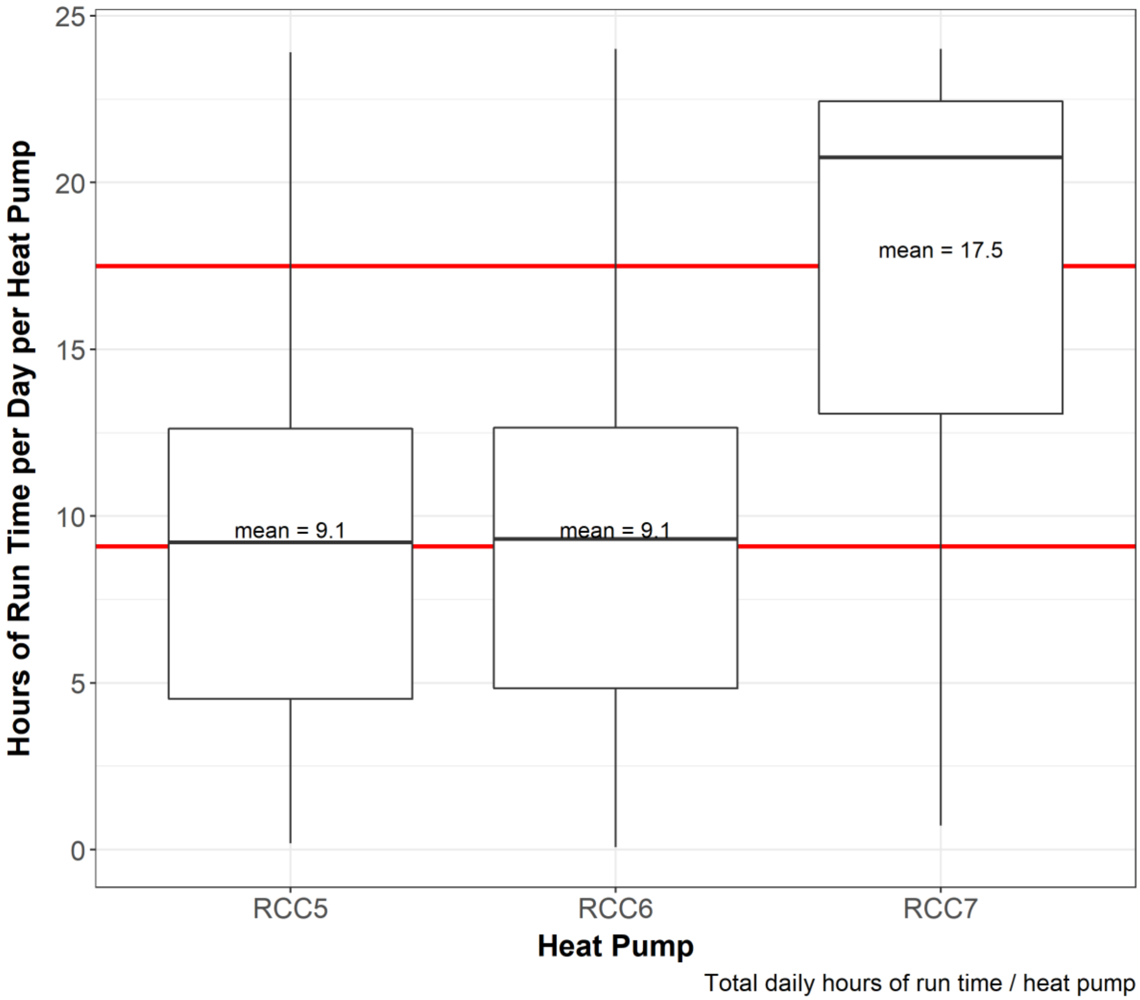

Figure 16. Duty cycle of each HPWH overall averages shown as red lines

During commissioning site visits, HPWH-7 was found to be inoperable again. This required immediate service and parts replacement (to all three HPWHs). Service activities performed in October 2020 included:

- HPWH-7's refrigerant-to-refrigerant heat exchanger had failed causing a refrigerant leak. Colmac and the installing contractor replaced the heat exchanger with a larger plate frame HX, performed an extended vacuum test, and repaired the unit to working order.
- Compressor and pump re-wiring for CxV HPWH-7.
- Condenser replacements for CxA HPWHs 5 and 6. This included heat exchanger replacements similar to HPWH-7 as there had been a production issue with the original components.

Since the Colmac service visit in October 2020, there were approximately eight months of full function. However, in late June/early July, HPWH-7 experienced a refrigerant leak that resulted in the loss of all its refrigerant, which required repair.

Water Use

Due to communications issues (as well as a minimum flow level that was too high) from the flow meters integrated into the mixing-station, accurate flow readings were not available until alternative instrumentation was installed in March 2021. Figure 17

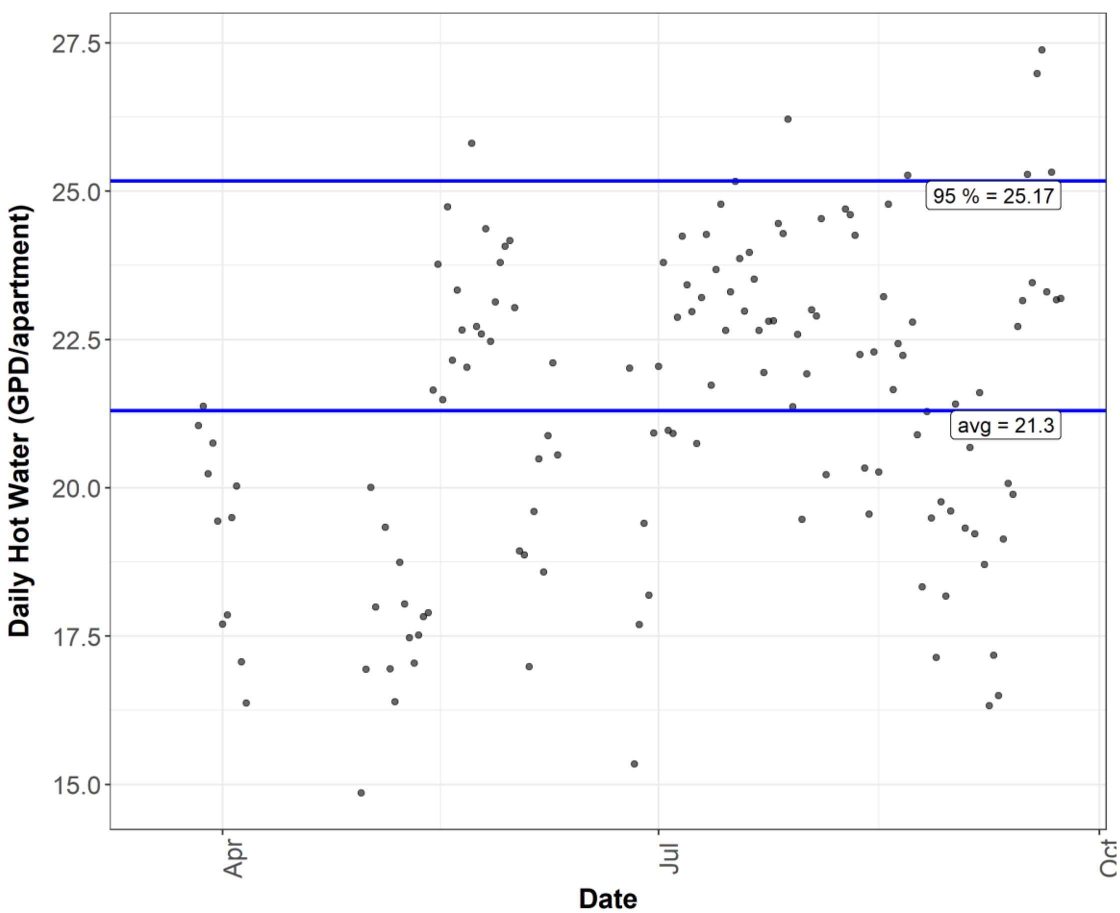

Figure 17. Daily gallon per apartment hot water usage

summarizes the subsequent monitoring from spring until fall 2021.

Occupancy increased over the early monitoring period, and the building was at about 75% occupancy by the end of May, when consistent flow readings were available. Hot water usage was approximately 21.3 gallons per apartment/day or (given an average occupancy of 240 occupants from May to September) 14.7 gallons/day/person. This is a little low for per-person hot water usage, compared to previous multi-family studies in the region[vii,viii], but this estimate also represents a time of year when there is typically lower DHW use, and annual averages will likely be a little higher as water use increases over the cooler months.

Performance

Monitoring points allowed the coefficient of performance (COP) to be assessed for the CxV (HPWH-7), the primary heater loop (which is essentially the primary equipment performance), and the entire DHW system. Due to overlapping issues with flow monitoring, the temperature maintenance equipment offered the most observations, while the primary heaters' flow readings were resolved in August. Metrics for calculating system performance became available in the spring, However, over the study period, the building only became over 75% occupied as of June 1, 2021. Thus, system performance is assessed from June1 through September.

Performance at each level is understood by capturing the energy output divided by the energy inputs:

$$COP = \frac{Energy\ Out}{Energy\ In}$$

Which energy components are assessed in the performance calculation is determined by the metric of interest, and how the M&V was designed (refer to Figure 3).

The performance for HPWH-7 has the following energy terms:

- Energy Out = $Flow_{HPWH7}$ * ($Tout_{HPWH7}$ - Tin_{HPWH7})* 8.3lbs/gal * 1 Btu/lb * 60mins/hr
- Energy In = energy used by HPWH7

The primary heaters' performance requires flow through the primary water heating equipment and the temperature change from water entering the primary heating equipment to the water leaving the primary water heating equipment, with energy inputs including both primary HPWHs.

System performance is more complicated as it incorporates all the hot water energy delivered to the building (as well as the distribution losses) as energy outputs, and all water heating equipment energy use (all HPWHs and electric resistance elements) as energy inputs.

Analysis was constrained to the period when the building had reached > 75% occupancy (June 1, 2021) until the end of the study period. Figure 18 shows the calculated performances from June 1, 2021, until Sept 30, 2021.

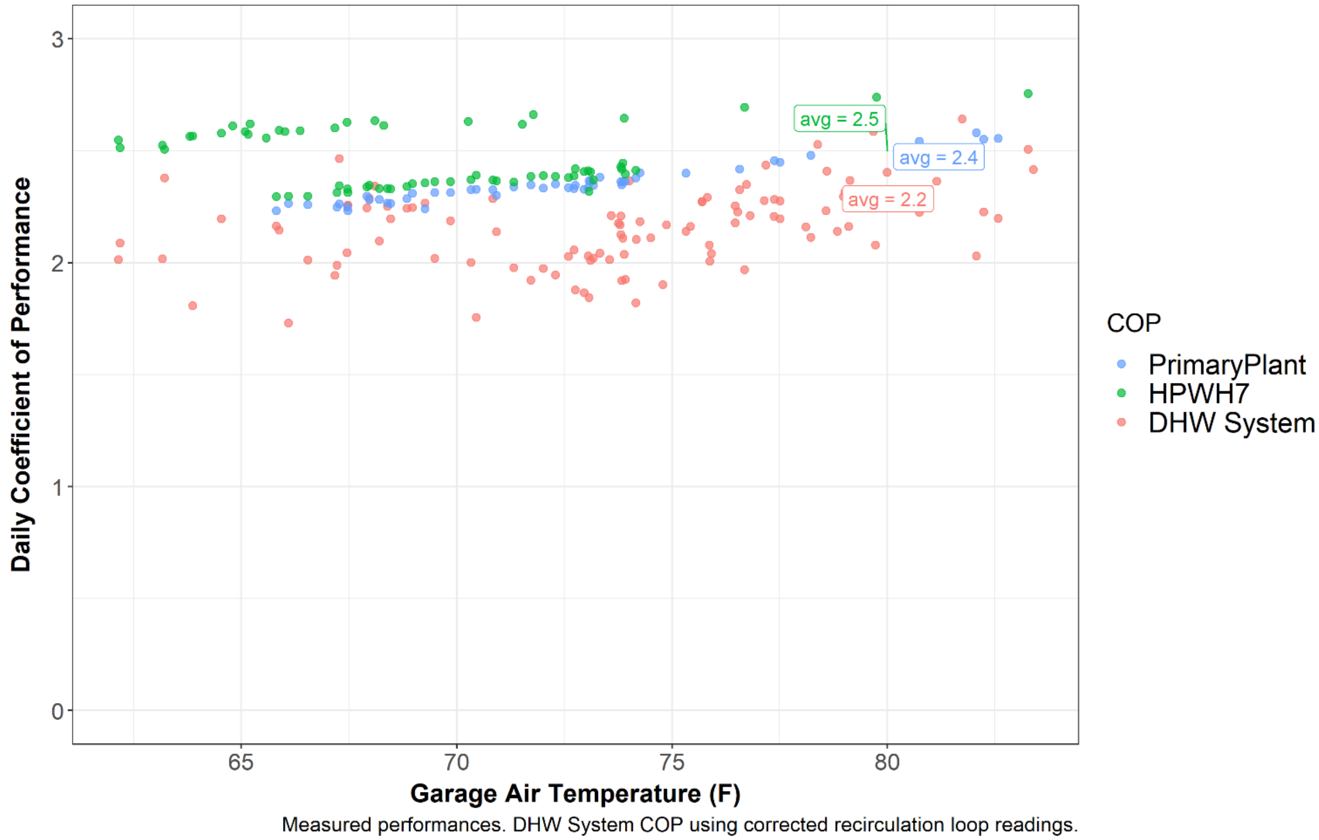

Figure 18. Coefficient of performance for HPWH-7, the Primary Heaters, and the DHW system.

The CxA (Primary Heaters) and CxV (HPWH-7/Temperature Maintenance) equipment performed similarly to HPA equipment, where previous studies[ix,x] found average equipment COPs of 2.4 to 3.0. System COP at the study site for the June 1 to Sept 30 period was 2.2.

Because the monitoring period for system performance was constrained, an annual value was estimated based on the relationship of COP to garage air temperature (as it is related to outside air temperature (OAT) at this site). Mean daily outside air temperatures over a five-year period were used to predict the OAT for days where system COP could not be calculated, and the 101 days of monitoring (and relationship between measured OAT and garage air temperature) used to predict the remainder of the "average temperature" year.

Projected annual system performance was calculated as 1.98. Actual future system performance may improve slightly at this site as the monitoring period included an interval when the temperature maintenance HPWH was inoperable, and the temperature maintenance task was fulfilled by the backup electric resistance equipment.

Conclusions and Recommendations

This project demonstrated that the new generation of Colmac Cx equipment has addressed many of the primary concerns from previous field installations of earlier-generation (HPA) HPWH equipment.

Specifically:

- HPA defrost controls were inadequate, leading to high limit failures when ice formed on evaporator coils. The original equipment operation also had consequences for HPA compressor longevity. Despite prolonged cold conditions in February 2021, no high limit failures were observed at Jackson Apartments. And HPWH equipment required minimal electric resistance backup during cold winter conditions.
- The Cx equipment incorporates 'defrost detection logic' which was observed during M&V monitoring. When ambient conditions fell below 45°F, heating cycles were interspersed with fan operation, and hot gas bypass frost-handling. This kept HPWH equipment operational during cold-weather conditions and no indication of high-pressure refrigerant faults was detected.
- Operations at Batik Apartments ("version 3" design) showed that power outages and over-voltage sensitivity could cause equipment to enter an idle status until it was manually re-started. No such events were observed during monitoring at Jackson Apartments.
- Third-party alarm notifications are easily configurable with the Cx-equipment and include failure alarms on HPWH equipment, element-on alarms for the electric resistance equipment, and a low temperature alarm when outgoing hot water from the tempering valve is below 120°F. These were tested during commissioning and would prevent the system from operating for long periods on backup electric resistance. However, repeated alarms for electric resistance elements caused these alarms to be disabled. It's critical that potential 'nuisance alarms' are investigated and resolved to ensure repeated false alarms don't prevent the system from being serviced or checked as it should be.
- TIM feedback outlined the need for a 'packaged' product to reduce the need for tailored engineering for each installation and to allow broader implementation of the technology. Jackson Apartments was a custom engineered design. The current iteration of staging logic has made significant progress towards including backup heaters into the system logic, but a full HPWH system as configured at Jackson Apartments still requires customized engineering.
- CxV-5 and CxA-15 field-measured equipment performances were in line with previous studies of HPA-series equipment [xi] (COP > 2). Based on manufacturer performance data,

slightly higher performances may be obtainable with other CxA models (e.g., CxA 10, 20, 25, 30).

Additional recommended improvements include:

- Equipment reliability - manufacturing deficits have been addressed swiftly but have resulted in short periods of non-operation for the CxV HPWH. It is worth noting that this project represented one of the earliest installations of this equipment. Subsequent installations incorporated findings from initial Colmac site visits to Jackson Apartments. Additionally, a design that includes backup water heating capacity ensured that hot water continued to be provided without interruption to building occupants.
- During all ambient conditions post-heating-call fan cycles were observed on each HPWH. This means a small amount of fan energy is used at the close of every heating cycle. Additional ambient condition logic on these per-heating-cycle fan runs may offer some energy savings over long-term operation.
- Alarming – electric resistance element-on alarms were disabled as a nuisance alarm. The operation of electric resistance equipment is still observable through the on-line third-party controls portal; however, it is likely that disabling the alarm will allow electric resistance to operate beyond a purely backup function.
- From an operation's perspective it is also recommended that system commissioning ensure electric resistance backup heaters have labels with the appropriate set points affixed to the equipment as a reference.
- The HPWH system at Jackson Apartments is still a custom-engineered solution. Further development of a fully packaged product is warranted. Additionally, this project assessed a controller provided by a third-party. Colmac's native controls and alarms system should be assessed in the field.
- Continued development towards low-GWP refrigerant solutions will maintain Colmac's market-competitiveness as R-134a and R-410a approach phase out.
- Continued refinements to improve equipment efficiencies will also contribute to increased competitiveness in an expanding HPWH market. Nevertheless, these products currently provide marked equipment efficiency improvements over conventional electric resistance and gas water heating systems.

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