Eliminating the Swing Tank and Other Design Considerations in Large-Capacity CO2 Heat Pump Water Heating

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ABSTRACT

Central heat pump water heating (CHPWH) has emerged as a key technology to decarbonize domestic hot water systems in new and existing multifamily and commercial buildings, necessitating novel design strategies to optimize efficiency, ease of installation, first costs, and operational costs. Furthermore, CHPWH systems that use carbon dioxide (CO2) refrigerant offer advantages, while also posing design and operational challenges.

This paper showcases five projects led by the Association for Energy Affordability, in partnership with Ecotope, the Electric Power Research Institute, and New Buildings Institute, in which we demonstrate multiple configurations of large capacity CO2 CHPWH systems in existing low-income multifamily buildings located in disadvantaged communities across California. Four of the sites received the Mitsubishi Heat2O systems, while one site received the WaterDrop system. All systems were heavily instrumented and monitored, with significant pre-retrofit data, as well as post-retrofit data. Design options tested include industry-standard design, re-use of existing tanks, and a novel swing tank design using an external tankless electric water heater. In this paper, we share:

- Product design changes made by Mitsubishi based on data from these pilot sites
- Utility cost impacts and mitigation strategies when fuel switching to a CHPWH system in the most expensive electric utility in the country
- The potential to perform load shifting with CHPWH systems that weren’t designed with extra storage capacity for this purpose
- Impacts and opportunities for recirculation heating, including eliminating the swing tank
- Addressing equipment noise at an urban retrofit
- Recommendations for scaling large capacity CHPWH retrofits

Introduction

Electrification is a fundamental strategy to decarbonize buildings, and many jurisdictions have passed regulations requiring or incentivizing electrification to meet their goals for climate pollution reduction (Hazboun 2023). According to the 2020 Residential Energy Consumption Survey, water heating comprises 17.3% of the total residential combustion fuel consumption (EIA 2023). Water heating is an even larger proportion of combustion fuel use in multifamily buildings, due to lower space conditioning loads per unit than single-family homes.

While a small selection of CHPWHs has been available in the US for a long time, utilizing large capacity CHPWHs for entire buildings is a relatively new design strategy to most of the multifamily and commercial market. The building industry is still learning which CHPWH designs are the best fit for the wide variety of multifamily buildings.

The California Energy Commission’s (CEC) Electric Program Investment Charge (EPIC) Program provided a grant to Association for Energy Affordability (AEA) starting in 2020 to demonstrate large capacity low global warming potential (low-GWP) CHPWH systems in multifamily buildings. The grant also funded instrumentation and monitoring of systems, as well as operational testing, to better understand how these systems perform in a variety of configurations and under different circumstances. As of the publication of this paper, three sites have completed construction, testing, and data collection, while two are still in construction.

State of Central Heat Pump Water Heating

CHPWHs are a crucial technology for decarbonizing multifamily buildings. When AEA first began deploying CHPWH plants in 2016, there were relatively few heat pump (HP) product options for integration with storage tanks, and design guidelines were just starting to emerge. Since then, designs have developed and new products have come to market.

Products

This paper focuses on split-system air-source CHPWHs and excludes multipurpose or combi heat pump systems. As of the publication of this paper (early 2024) the following manufacturers are offering CHPWH equipment in the US: AO Smith/Lochinvar[1], Colmac, ECO2 Systems, Intellihot, Laars, Lync, Mitsubishi, Nyle, Rheem, and Transom. Available CHPWH products range in output capacity from 15.4 MBH (ECO2 Systems 2021) to 640 MBH (Transom 2024).

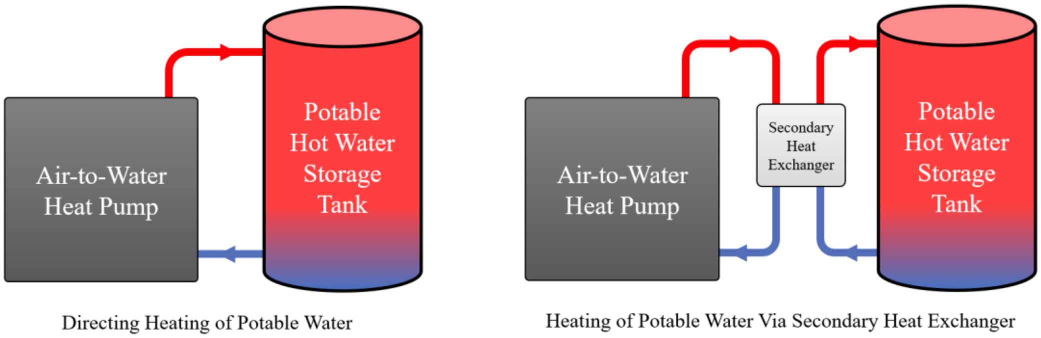

Figure 1. Direct heating vs. use of secondary heat exchanger. *Source:* Association for Energy Affordability, Inc.

CHPWH products are designed to heat a tank of hot water in one of two ways: multi-pass or single-pass. Multi-pass units heat water in a relatively mixed temperature tank gradually, with water making multiple passes through the HP with each pass adding around 10 °F of heat to the water. Single-pass HPWHs are designed to heat the water in a stratified tank from top to bottom. Both CHPWH systems included in this study are single-pass. Most CHPWH products, including those from AO Smith/Lochinvar, Colmac, ECO2 Systems, Laars, Nyle, Rheem, and Transom,

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[1] AO Smith and Lochinvar co-brand the same CHPWH equipment

are designed to directly heat potable water and deliver it to a pressurized storage tank for distribution throughout a building. HPs available from Lync and Mitsubishi, on the other hand, require a secondary heat exchanger (Hx) between the HP loop and the DHW storage tank (see Figure 1). This study includes equipment of both configurations.

Another defining characteristic that drives other aspects of any HP (including HPWHs) is the type of refrigerant. Large-capacity HPWH systems available today in the US use a variety of refrigerants that have different performance characteristics and global warming potential (GWP). This study focuses exclusively on systems that use CO2 (sometimes referred to as R-744) as the refrigerant or working fluid, in part because it has a very low GWP of 1, and also because it is well-suited for domestic water heating applications due to its high output temperature and higher COP at low ambient temperatures than R-134a and R513a .

Design

The primary design considerations that affect CHPWH system configurations include building size, space constraints, electrical constraints, and hot water distribution configuration (EPRI 2022). This paper focuses on the design considerations expected to have the greatest impact on system performance, namely: equipment location (e.g., space constraints, air temperature, sound level), hot water load (both peak and daily), heat pump capacity, storage volume, and recirculation reheat strategy.

In multifamily CHPWH retrofits, equipment location is a significant driver of design decisions. The first aspect of location is the climate zone and associated outdoor temperatures of the building location. When designing a CHPWH system, inlet air temperature is accounted for in sizing calculations for meeting peak load under design conditions. For CHPWHs located in unconditioned spaces or intaking unconditioned/outside air, the worst-case condition is the coldest expected winter day for that location, based on available weather data for the site, often from ASHRAE (*ASHRAE Climatic Design Conditions* 2024). Existing sites with compact gas DHW systems may have little room for larger storage tanks optimized for HPs, as well as few viable locations for HP units that generate sound and need to move large volumes of air. It is within the constraints of each unique building that a CHPWH system must be sized and designed.

Sizing of CHPWH systems is different from sizing of gas water heating systems. Because HPWHs rely primarily on storage to meet peak loads, using a one-hour delivery capability or first-hour rating, common for gas systems, is inappropriate. Since its introduction in 2020, the Ecosizer tool has quickly become established as the default sizing tool for CHPWH systems (Ecotope 2024). This free online tool allows designers to dynamically trade off different design aspects of a CHPWH system to arrive at a design tailored to a particular project.

One of the primary considerations for any CHPWH system is the balance of HP capacity (how much heat it can generate per hour) and storage volume. To meet a particular building’s peak load with less storage volume requires greater HP capacity, and vice versa. For example, an electrically constrained building may need to maximize hot water storage volume to minimize HP capacity (and associated electrical power draw). Conversely, a space-constrained site may be limited to less hot water storage, requiring more HP capacity. Many existing buildings face both electrical and space constraints, requiring creative problem solving or, in some cases, electrical service upgrades.

Recirculation Design and Central Heat Pump Water Heating

An important design parameter for CHPWH systems is the building's recirculation design. DHW recirculation systems reduce wait times for hot water and reduce water wasted. On the other hand, DHW recirculation also uses energy, through pumping energy and increased thermal losses of hot pipes but reduces water waste and improves resident satisfaction. DHW recirculation systems can have many different piping configurations, but all rely on one, or in most cases, many hot water return lines that come together to return to the DHW system for reheating. The balancing and heat loss from the recirculation system can be a significant contributor to the overall DHW system energy consumption. There are three locations to which recirculation return water can be piped for reheating: the primary storage tank(s), a swing tank, or a parallel tank.

Return to the primary tank is how conventional gas water heating systems are piped. The recirculation water is connected to the cold water makeup to the storage tank, where it mixes with incoming water to be heated. This approach is common for multi-pass CHPWH, but uncommon for single-pass CHPWH. Figure 3 (below) shows this approach, with a dotted line to the storage tank, indicating that there is currently no industry standard location to return recirculation water in a single-pass HPWH system. This study tested the impact of using different return locations.

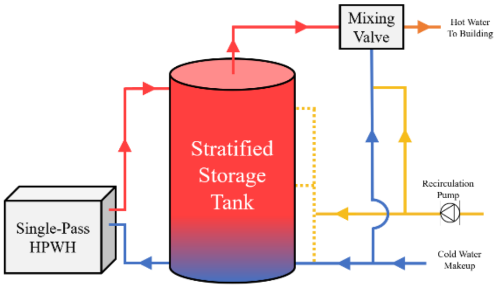

Figure 3. Direct return of recirculation water to storage tank. *Source:* Association for Energy Affordability, Inc.

More common in single-pass CHPWH systems is to return the recirculation water to a separate tank. The most common way to do this is via a "swing" tank, as shown in Figure 4 (left). In this setup, first introduced by Ecotope, recirculation water is returned to a separate tank with its own heat source, piped in series with the primary heat pump-heated tank. In this configuration, when there is hot water demand, water from the primary tank flows into the swing tank, charging it with very hot water. The temperature of the swing tank will drop during times of low or no DHW consumption in the building. The advantage of a swing tank is that it ensures the single-pass heat pump always has the coldest possible inlet water, maximizing heat pump efficiency. Additionally, it allows the super-heated water heated by the heat pump to meet some or all of the recirculation load, depending on regularity of demand. The disadvantage of a swing tank setup is that long periods of low demand mean recirculation loads must be met with the (usually electric resistance) heating element in the swing tank, which is lower efficiency than the single-pass heat pump.

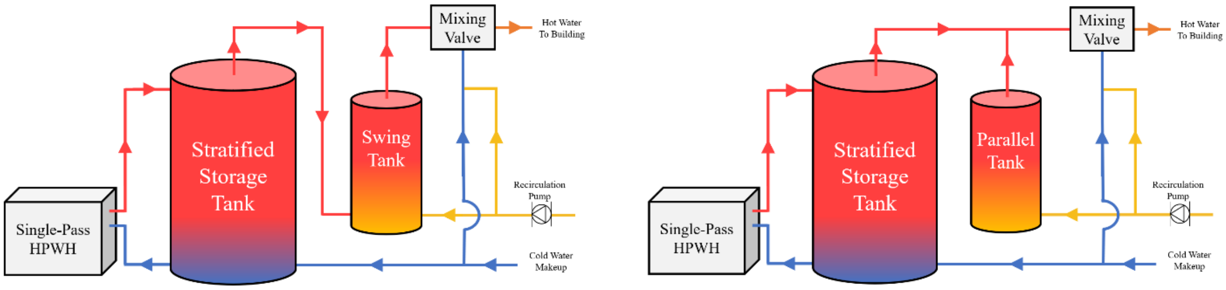

Figure 4: Swing Tank (left) vs. Parallel Tank (right) for reheating of recirculation return water. *Source*: Association for Energy Affordability, Inc.

Another approach to reheating recirculation return water is a parallel tank, illustrated in Figure 4 (right). This design is piped in parallel with the primary tank, rather than in series. Water from the primary tank cannot enter the parallel tank, so all recirculation heat loss is met with the heating element for the parallel tank. The authors are aware of few examples of parallel tank systems, and all use a heat pump to reheat the parallel tank water.

Equipment and Designs for Demonstration Sites

This section describes equipment and designs for the five demonstration sites included in this project. Four of the demonstration sites received the Mitsubishi Heat2O system, while one site received the WaterDrop system.

Equipment - Mitsubishi Heat2O

The Mitsubishi Heat2O, sold in the U.S. by Mitsubishi Electric Trane US HVAC LLC (METUS), is a large-capacity CO2 refrigerant HPWH manufactured in Japan. Asia, Europe, and Oceania have had this product in the market for many years before it was introduced to the U.S.

The Heat2O is a single-pass HPWH that utilizes a secondary Hx to heat potable water in a separate storage tank. The heat pump delivers 176 °F water to the Hx, but due to losses, the hottest water delivered to the potable storage tank is typically around 165 °F. The water between the heat pump and Hx is a closed loop and referred to as the “primary” loop. The water in the primary loop is circulated by a pump built into the Heat2O unit. The water between the storage tank and the Hx, referred to as the “secondary” loop, is circulated by an inline pump, which is controlled by a flow switch on the primary loop. The Heat2O unit does not directly control the secondary loop pump. Rather, the secondary loop pump turns on when it detects flow in the primary loop.

The heat pump determines when to run by monitoring one or more temperature sensors in the storage tank(s). When the Heat2O sees that the water temperature at a particular sensor, referred to as the “On sensor”, has reached a pre-determined minimum temperature, the unit will start operating, pulling cold water from the bottom of the tank(s), and delivering hot water to the top of the tank(s). The Heat2O does not vary its capacity based on water temperature. It delivers the full heat capacity based on its current operating mode. While running, the Heat2O will monitor the water temperature at another temperature sensor, referred to as the “Off sensor.”[2] When the temperature at the Off sensor rises to its setpoint, the unit will turn off. The most basic controls for the Heat2O are built into the unit itself, but METUS requires a separate controller for all installations in the U.S. This controller is comprised of a wall-mounted box connected to the HPs and other components of the system, with a color display on the outside of the box showing basic heat pump performance data. This controller allows some aspects of the system to be monitored and changed remotely by either the owner or METUS, if desired. In the US, the Heat2O is currently recommended by METUS to be designed with a swing tank to cover recirculation losses. In other markets, including Europe and Asia, Heat2O units have been installed without a swing tank.

Equipment – WaterDrop

Waterdrop is a factory-built skid system that utilizes multiple residential-sized SANCO2 HPWHs connected in parallel to serve larger loads. The skid includes all components of the CHPWH plant, including heat pumps, controls, primary storage tanks, swing tank, mixing valve, and recirculation pump. The skid is built by WaterDrop Systems, in Tumwater Washington, and SANCO2 heat pumps are manufactured in Japan.

The Waterdrop skid packages the SANCO2 heat pumps (typically 2-9 heat pumps) with a pre-designed and factory-built set of components for a complete CHPWH plant in an insulated outdoor-rated box that can be dropped onto a building site to minimize on-site labor. This skid-based approach has the potential to reduce system installation errors due to contractor unfamiliarity with CHPWH systems, as well as reduce installation time and associated labor costs.

Demonstration Sites

This project includes five demonstration sites, with the following basic characteristics. Due to their locations in coastal and central California, as well as the timing of the installations relative to the publishing of this paper, none of the sites have experienced significant cold ambient air conditions. The only site likely to experience such conditions in the future is Kings View Manor.

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[2] For at least one demonstration site, due to site constraints, a single sensor was used as both the On and Off sensor. This is not the ideal configuration, and was only done to accommodate challenging existing conditions, including reuse of existing storage tanks.

Table 3. Demonstration Site CHPWH Designs

Name	City	Dwelling Units	CHPWH Product	Recovery (MBH)	Storage Volume (gal)	Storage Ratio (gal/MBH)
Lassen Apartments	San Francisco	81	Mitsubishi Heat2O	273	357	1.3
Light Tree Apartments	East Palo Alto	28	Mitsubishi Heat2O	273	300	1.1
Kings View Manor	Fresno	53	WaterDrop	139	505	3.6
Plaza at Sierra	Fontana	90	Mitsubishi Heat2O	136 136	300 600	2.2 4.4
Lillian Place	San Diego	74	Mitsubishi Heat2O	273	785	2.9

The CHPWH systems were each designed in response to the unique challenges and limitations of each demonstration site. The storage ratio listed in the final column of the above table allows for comparison of how much hot water storage a CHPWH plant has relative to HP capacity. For reference, the Ecosizer tool allows for sizing of plants with storage ratios between 1 (minimum storage) and 12 (maximum storage), with a default storage ratio of 5.2 (Ecotope 2024). Lower storage ratios, like those for the demonstration sites, are typical for retrofit CHPWH plants that are unlikely to have space to accommodate very large storage volumes.

Figure 5. Two Heat2O units at Lassen Apartments, (left), and Waterdrop skid at Kings View Manor (right). *Source*: Association for Energy Affordability

Advancements Toward a Replicable Approach to CHPWH Retrofits

The lessons learned by the project teams at these demonstration projects have led to several advancements toward a more replicable approach to CHPWH retrofits, including the Hx and controls package, recirculation return options, parallel electric tankless swing design, noise mitigation, and utility cost mitigation.

Heat Exchanger and Controls Package

The Mitsubishi external Hx components (see shaded area in Figure 6) were required to be site-built and consist of a brazed plate Hx, secondary variable speed pump, buffer tank, temperature and flow sensors, and associated fittings and gauges. In addition to careful execution by the installing contractor, this initial design relied on in-pipe temperature sensors which were intended to control the secondary pump's speed to maximize the change in water temperature across the Hx to maintain high machine COPs. Various piping errors were corrected during installation. During commissioning, two secondary pumps (one per each heat pump) were repeatedly ramping up and down, struggling to maintain the correct speed because the leaving temp from one pump was influencing the other. Ultimately the team had to move to a surface-mount, thermistor-based control which was more responsive and stabilized pump operation.

In addition, demonstration sites struggled with purging air from the closed loop side of the Hx, both during startup and continually while in operation. Ultimately, the research team installed either a prepackaged feed tank system on the closed loop (i.e., small reservoir that automatically adds water to the system based on pressure) or an automatic pressure reducing fill valve. The former solution is not connected to a water source, and requires maintenance staff to observe and refill the reservoir if needed. The latter automatically fills the system using a connection to a water supply. In both cases these devices helped maintain adequate pressure on the closed loop side of the system which prevented equipment from turning off on a low water pressure error. Mitsubishi favored the feed tank solution as it allowed the user to both control water quality used to fill the system and to monitor the system for leaks.

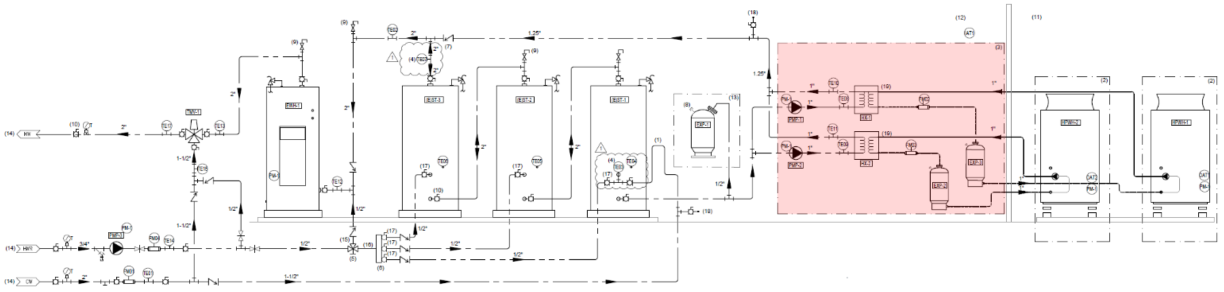

Figure 6: Lassen plumbing drawing. *Source*: Ecotope

Initial installations (two under the grant, and four additional sites developed in parallel with the grant team) all experienced similar installation difficulties to ensure proper Hx piping and commissioning, and filling and maintaining pressure in the closed loop. As a result of this, the Mitsubishi product team elected to design a factory-built Hx assembly that removes this complexity from field installations. The assembly contains the and reduces the installation requirement to four water connections, one power connection, and one communications cable. As of January 2024, the Mitsubishi team has indicated that they plan to release this product in Q3 2024 after initial testing is completed.

Returning Recirculation Water to Primary Storage

As of the writing of this paper, standard design practice for single-pass HPWH systems relies on a swing tank design, and all five demonstration sites were designed and built this way. The project team and Mitsubishi were interested in investigating alternatives to these standard designs to reduce installation complexity, project cost, electrical load, and space requirements. Three demonstration sites included additional variations on swing tank design to test different approaches to manage recirculation reheat.

At the Lassen project, a recirculation flow manifold was included to allow the research team to temporarily redirect return water flow away from the swing tank and directly into any one of the three primary storage tanks (shown in Figure 6). After initial M&V was completed and baseline system efficiencies were documented, the project team ran week-long consecutive tests for which recirculation return water flow was turned off at the swing tank and opened into one of the primary storage tanks, forcing the HPs to heat recirculation water. The swing tank remained on as a means of providing some backup water heating capacity in the event of a system malfunction. Prior testing by Mitsubishi in Europe of this approach yielded "positive results" but no data were available to validate it, so the team was eager to perform the testing in a fully instrumented system to measure impacts. The Mitsubishi team's expectation was that sending return water to the hottest tank would produce the best and sending to the coldest tank would dramatically reduce the HP's COP. They were concerned that sending water to the middle tank could create a scenario where the HP would operate longer than desired since the "off" temperature command was based on a temperature increase at the middle tank thermistor, and constantly bathing this thermistor in mid-temperature return water would prevent this.

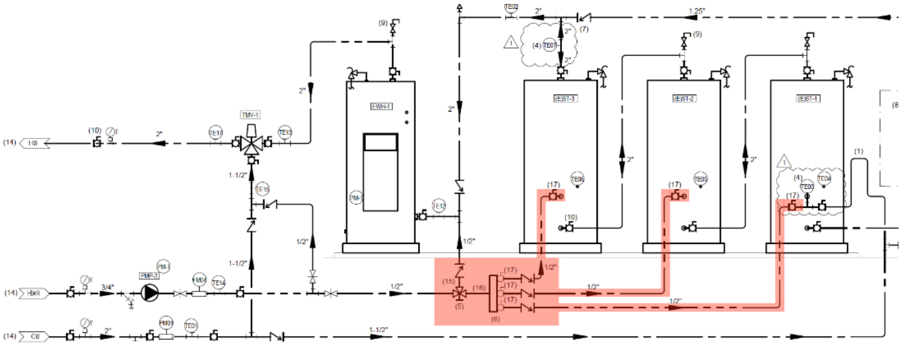

Figure 6: Lassen recirculation manifold drawing. *Source*: Ecotope

Initial test results for each return pathway, however, revealed that the HP operation remained stable (it neither excessively short cycled nor remained in a constant call for heat). In all tests, swing tank operation was eliminated, HP machine COP decreased, and overall system COP increased. Unexpectedly, piping recirculation back to the "cold" tank resulted in the highest system COP of 2.7, compared to a baseline of 2.3 for this site, equating to a 15% reduction in energy consumption. Results from this first experiment are currently being validated with a longer two-week test for each recirculation strategy at the site. Further analysis may determine that the COP improvement for the Lassen site was a result of poor existing tank stratification, wherein the HPs were already seeing relatively warm incoming water before the recirculation test was performed. Given this hypothesis, the project team is looking for opportunities to test recirculation to primary storage strategy at a final demonstration site which is expected to have a more stratified primary storage tank compared to Lassen.

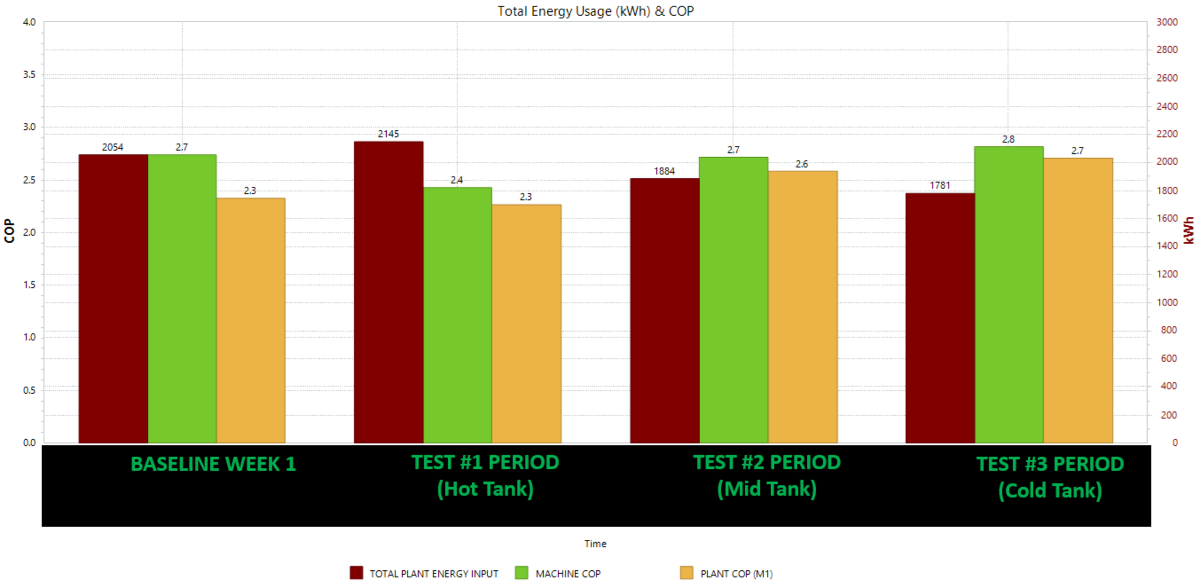

Figure 7: Lassen recirculation test results. *Source*: Association for Energy Affordability, Inc.

Parallel Electric Tankless Swing Tank Design

The Plaza and Lillian demonstration sites (which are mid-construction during time of report writing) were designed with a novel swing tank. The design relies on heating the swing tank with a 22 kW electric-resistance tankless water heater that's piped similarly to how a boiler heats an indirect storage tank, instead of a traditional immersed electric element array in the swing tank. Two sets of motor control valves allow the tankless water heater to heat just the swing tank (standard operation). If manually placed in back-up mode at the control panel, these motor control valves allow for the heating of the primary storage tank volume as well. This strategy adds complexity compared to the default swing tank approach, but presents an opportunity to provide more back-up capacity than if the swing tank could only heat its own volume of hot water. Potential applications for this design include sites like Plaza which only needs one Heat2O HP to meet the building load, but calls for an additional HP for redundancy/resiliency in the event of HP equipment downtime. Additionally, in very cold climates, the reduced performance of the Heat20 for the coldest days of the year may result in needing an additional HPs at winter design conditions, and this alternative design could allow automatic operation of the supplemental heater to cover this winter peak load with less equipment.

Noise Mitigation

Of the five demonstration sites, Lassen (San Francisco, CA) and Lillian (San Diego, CA) are the most urban, with adjacent buildings built on property lines. Lillian's equipment will be installed in a subterranean parking garage whereas Lassen's equipment was installed in a courtyard adjacent to a neighboring building and beneath resident's apartment windows. During the design phase of the project, an acoustical consulting engineer was hired to evaluate the installation location, local codes, and equipment specifications to determine if the location would comply with code. The results of the analysis (shown in Figure 8) indicated that the equipment would *just* meet noise requirements. The design team discussed various additional interventions to reduce noise levels, all of which were either too expensive to implement on this project (e.g., locate equipment on roof) or were impractical (e.g., build sound deadening enclosure for HP). A low cost, sound deflecting exhaust hood was considered as a solution to reduce apartment noise levels, but would have increased noise levels at the property plane and would have likely exceeded the noise criterion for this location. Upon further consultation with the acoustician, the design team elected to move forward with the project with the knowledge that the equipment noise levels could be further reduced, if needed, either by turning off one HP, or adjusting the HP output during nighttime hours (when the noise ordinance criterion was more stringent).

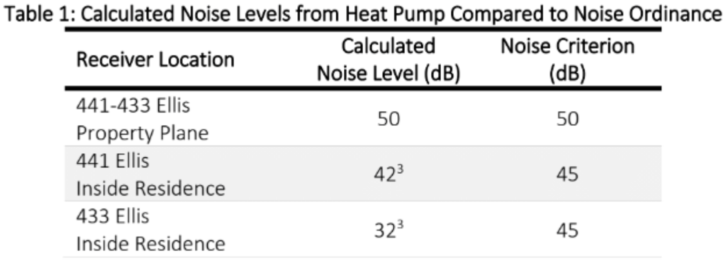

Table 1: Calculated Noise Levels from Heat Pump Compared to Noise Ordinance

Receiver Location	Calculated Noise Level (dB)	Noise Criterion (dB)
441-433 Ellis Property Plane	50	50
441 Ellis Inside Residence	42[3]	45
433 Ellis Inside Residence	32[3]	45

Figure 8: Initial calculated noise levels and criterion. *Source*: Salter Inc. Acoustic Report 3/5/2021

After construction completed in the winter of 2021-2022 some residents did comment about the new machine noise being produced in the courtyard, but these did not escalate to ongoing or formal complaints. However, during the summer, four residents in apartments closest to the HP equipment indicated noise was a nuisance at night when windows were open to provide cooling and ventilation. The acoustician returned to the site to measure sound levels inside of the apartments and at the equipment across multiple duty points (shown in Figure 9). Testing revealed two units exceeded interior noise level criterion of 45 dB. The design team elected to program the equipment to operate at 70% capacity at night to reduce sound further. Due to redundancy in heat pump sizing, this turndown was possible without compromising the system's ability to meet the hot water loads. After these adjustments were made, there have not been any additional noise complaints, nor has the system had any problem meeting hot water demand.[3]

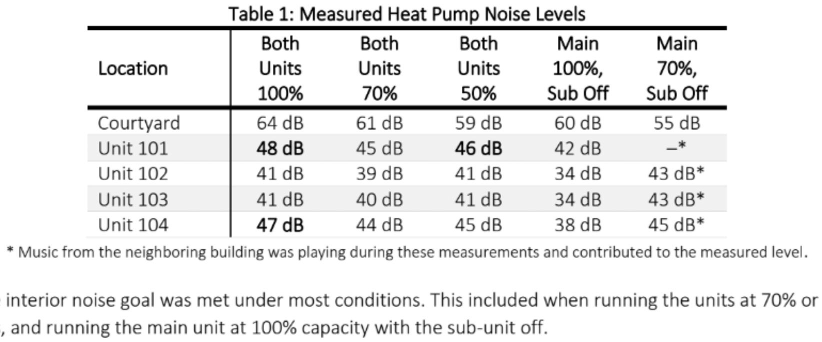

Table 1: Measured Heat Pump Noise Levels

Location	Both Units 100%	Both Units 70%	Both Units 50%	Main 100%, Sub Off	Main 70%, Sub Off
Courtyard	64 dB	61 dB	59 dB	60 dB	55 dB
Unit 101	**48 dB**	45 dB	**46 dB**	42 dB	–*
Unit 102	41 dB	39 dB	41 dB	34 dB	43 dB*
Unit 103	41 dB	40 dB	41 dB	34 dB	43 dB*
Unit 104	**47 dB**	44 dB	45 dB	38 dB	45 dB*

* Music from the neighboring building was playing during these measurements and contributed to the measured level.

The interior noise goal was met under most conditions. This included when running the units at 70% or less, and running the main unit at 100% capacity with the sub-unit off.

Figure 9: As-built noise levels and criteria.

When installing CHPWHs in buildings with close lot lines or apartments near the system location, certain strategies can reduce the risk of noise complaints:

- Identify alternative installation locations away from property line or resident windows (e.g., flat roof)
- If meeting nighttime requirements (which vary by jurisdiction) are more stringent than daytime, consider programming equipment in a reduced capacity/"quiet mode" during nighttime hours. For sites with typical load profile curves and swing tank designs, the HP may not need to operate at full capacity at night, and swing tanks may be able to cover any unmet load for worst case days of the year.
- While the impacts to noise levels have not been evaluated yet, the use of a snow hood on the discharge side of the fan may redirect some equipment noise horizontally away from a building.

Utility Cost Mitigation

Historical utility costs, as well as projected future costs, were analyzed for all demonstration sites to ensure CHPWH upgrades would not result in increased utility costs. The initial analysis showed that the CHPWH retrofits, along with modest efficiency measures, would result in utility cost savings or cost neutrality compared to keeping the existing gas DHW systems, for all but one of the demonstration sites: Lillian Place.

Lillian Place is located in San Diego, which at the time of this report's writing, had the highest electric rates in California, ranging from \$0.19 to \$1.10 per kWh, depending on season and peak versus. off-peak time of use (SDCP 2023). The project team worked with the owner to

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[3] With two exceptions: 1) when the HPs were accidentally switched into a mode that operated the compressor fans continuously at high speed, 2) when an internal water pump in one of the Heat2O units developed a failed bearing that squealed and needed to be replaced (perhaps due to damage during shipping).

conduct a utility cost projection to ensure the CHPWH retrofit, along with the package of additional efficiency measures, would not result in higher utility bills for the owner. In the end, the project team determined the only way to ensure utility cost neutrality for the site was to add additional solar PV and battery electric storage to the property. The team is securing funding for these additions to the project, which is under construction at the time of this writing.

System Performance

System performance is evaluated using two primary metrics: heat pump/machine COP and Plant COP. Machine COP is the operating efficiency of the heat pumps alone and does not take into account energy produced or consumed by the swing tank or any external pumps. It also does not account for any distribution system losses or the recirculation load. Plant COP is the operating efficiency of the system as a whole and accounts for all those additional elements.

Overall Performance

Table 4. CHPWH Plant Average Daily Operation Over a Typical Week (December 2023)

		Lassen	Light Tree	KVM
Heat Pumps	HP Run Hrs	8.6	3.8	17.0
	% of time	36%	16%	70%
	# of cycles	15.3	3.7	2.7
Swing Tanks	Swing tank run hrs	1.7	0.2	6.3
	% of week	7.2%	0.6%	26%
	# of cycles	40.2	2.7	50.3
COP	Machine COP	2.8	4.7	4.9
	Plant COP (M1)	1.2	4.2	1.7
	Plant COP (M2)	1.2	4.7	4.1

Table 4 presents a comparison of the runtime characteristics of the three plants over the course of a representative week in December. There is a striking difference in the runtime and on/off cycle count of both the HPs and the swing tanks at each of the three plants. Light Tree’s HPs and swing tank run for only 16% and 0.6% of hours in the week respectively, while Lassen’s run for 36% and 7.2%, and KVM’s run for 70% and 26%. KVM’s system consists of more heat pumps that are able to stage on/off, and this output capacity for the first stage allows the heat pumps to operate for longer blocks of time before satisfying the tank and shutting off, whereas the other sites have higher output capacity systems which satisfy the storage tanks more quickly. While the machine COP is highest for KVM, at a daily average of 4.9, the plant COP, which accounts for distribution system/recirculation losses and standby losses, is only 1.7. KVM has long distribution runs, and while most of those lines are insulated, there is a long section that runs the entire length of the attic that is uninsulated and another long run that is insulated but underground. These factors, as well as a low draw profile (which reduces the amount of preheated heat pump water from satisfying the swing tank), is likely contributing to the lower plant COPs.

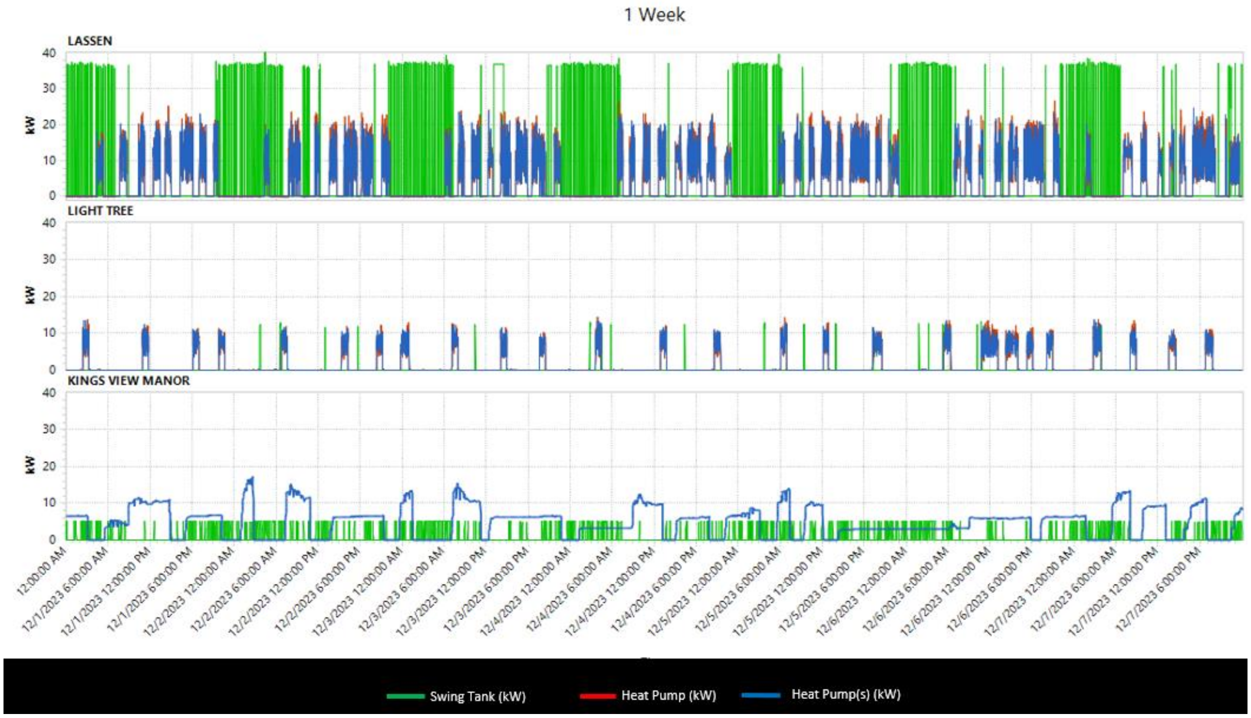

Figure 10. Heat pump and swing tank operation at Lassen, Light Tree, and Kings View Manor

An important finding of this study is that buildings with low hot water demand, high recirculation losses, relatively small swing tank sizes, or especially a combination of all three, are likely to have very high swing tank run times and therefore low plant COPs. The low hot water demand creates very little opportunity for primary storage tank water to flow through the swing tank, while the high recirculation flow rates and high distribution losses create the need for constant reheat of that recirculation water. This means that when considering CHPWH retrofits for buildings with low demand and high recirculation losses, which are frequently too complicated and costly to address, designers may want to consider alternative recirculation maintenance strategies. On option would be to increase the volume of the swing tank. During periods of demand, the HPs would charge the swing tank and the larger volumes would enable it to handle the recirculation maintenance for longer durations before the element would need to turn on. Alternatively, these scenarios may be good opportunities to use a small multi-pass HP to charge a non-powered swing tank.

Load Shifting

The QAHV equipment have the potential to use the CTA-2045 standard for load shifting commands and the ability to load shift following a repeating daily schedule. While new Waterdrop systems will also have the ability to receive CTA commands, the version used for the demonstration site is only configured to load shift using schedule-based controls via its onboard PLC controller. The team is currently finalizing the load shifting aspect of the study and will begin load shifting at the same time this paper is submitted. Results of this study will be shared in the forthcoming CEC research paper sharing full results of the study. Desired research from the load shifting study currently include 1) The duration potential and associated energy, demand, and carbon savings for load shifting 2) The potential to perform meaningful load shifting with CHPWH systems that weren’t designed with extra storage capacity for this purpose, 3) A review of potential CHPWH system design modifications that could improve load shifting performance.

Conclusion

There is a significant need for scalable solutions for all-electric CHPWH systems in multifamily buildings, and large capacity CO2-based systems offer unique advantages. To scale CHPWH installations successfully, manufacturers will need to continue to develop and refine product offerings, such as packaging sets of complex components, in response to experience in the field. Concurrently, plumbing engineers will need to standardize and simplify designs for these systems, such as establishing design criteria for elimination of a separate recirculation heater, that can work in a variety of situations. Such developments will enable contractors to successfully install CHPWH systems at a scale and pace needed to make a meaningful contribution to decarbonizing multifamily water heating.

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