Design Innovation to Advance the Commercial HPWH Market

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ABSTRACT

Central heat pump water heating (CHPWH) systems in multifamily buildings have been shown to deliver significant energy savings, reliable hot water service, and grid-flexible thermal storage. However, relatively high cost and system complexity remain barriers to widespread market transformation. This paper describes a series of design innovations developed and field-demonstrated by Carbon Zero Buildings, in collaboration with Ecotope and industry partners, to reduce cost and complexity while improving performance and reliability. Beginning with the industry-standard swing tank configuration, the team has iteratively developed and monitored multiple design evolutions: (1) return-to-primary (RTP) switching valves, (2) full RTP with non-CO_2 heat pumps, (3) parallel temperature maintenance using lower-priced integrated CHPWHs that benefit from mass-production, and (4) an unpressurized thermal storage system using inexpensive non-potable tanks and hydronic heat pumps. Each innovation addresses specific cost or performance limitations identified in prior installations, and overlaid controls and monitoring have provided the transparency and access to iteratively refine system operation within each design strategy. Field performance data, installation lessons, and applicability guidance are presented for each strategy. The paper also discusses ongoing work to standardize the most promising configurations as plug-and-play solutions, including integration with Advanced Water Heating Specification (AWHS), authored by Northwest Energy Efficiency Alliance (NEEA), and the Ecosizer sizing tool, to enable broad market adoption.

Introduction

Central heat pump water heating (CHPWH) systems are increasingly recognized as a key technology for decarbonizing domestic hot water in multifamily buildings. These systems use refrigerant-cycle heat pumps to deliver three to four times more useful heat energy per unit of electricity compared to electric resistance (ER), while thermal energy storage (TES) enables load shifting and peak demand management.

Despite a growing track record of successful installations, CHPWH systems face persistent barriers to widespread adoption. Installed costs remain high and system complexity demands specialized design and installation expertise that is not yet common in the trades.

Carbon Zero Buildings (CZB), working with design partner, Ecotope, and controls integrator, A Thing Story, has installed over 100 CHPWH systems across a portfolio of multifamily buildings in California that are reliably delivering domestic hot water. The team has adopted a design-build-monitor methodology: implement systems using both proven and novel configurations, monitor performance rigorously per Advanced Water Heating Specification (AWHS) Appendix H monitoring protocol that informs standardized performance metrics, and feed findings back into refined designs and standardized specifications.

This paper traces the design evolution across five system generations and introduces a sixth—the unpressurized storage system currently in field demonstration. For each configuration, we describe the problem being solved, the technical approach, performance results where available, and key applicability criteria.

Background: Key Barriers to CHPWH Scale-Up

Three cost and complexity drivers dominate CHPWH system economics in multifamily buildings:

1. Post-commissioning opacity. Without purpose-built controls and monitoring, system performance is invisible until a failure causes tenant complaints. Low efficiency and equipment degradation can go undetected for months.
2. System cost. HPWH system installations include higher water heater cost, higher required storage volume, specialized installation labor, and additional components in systems that use dedicated heaters for temperature maintenance (TM) heating.
3. Hot water return (HWR) loop management. Multifamily buildings maintain a continuous hot water recirculation loop to provide instant hot water at fixtures. The return temperature of this loop, often 110–120°F, can drive heat pumps using CO_2 refrigerant to operate inefficiently or unreliably. CO_2 is a popular refrigerant for heat pumps in CHPWH applications based on its low global warming potential (GWP), and high efficiency and heating capacity in cool ambient air temperatures, but heat pumps using CO_2 refrigerant operate at much lower efficiency as their inlet water temperature rises above approximately 80°F (Nawaz et al. 2017).

Each design generation described below directly addresses one or more of these drivers.

Swing Tank System

Swing tank systems are the current industry-standard approach recommended by CO_2 HPWH manufacturers for domestic water heating. In this design, primary CO_2 heat pumps charge a pressurized storage tank array with high-temperature water. A separate swing tank—equipped with ER elements—receives the hot water return loop. A mixing valve blends storage supply and swing tank water to deliver domestic hot water at the fixture setpoint. Figure 1 shows the swing tank system, as displayed in the Advanced Water Heating Specification (NEEA 2024).

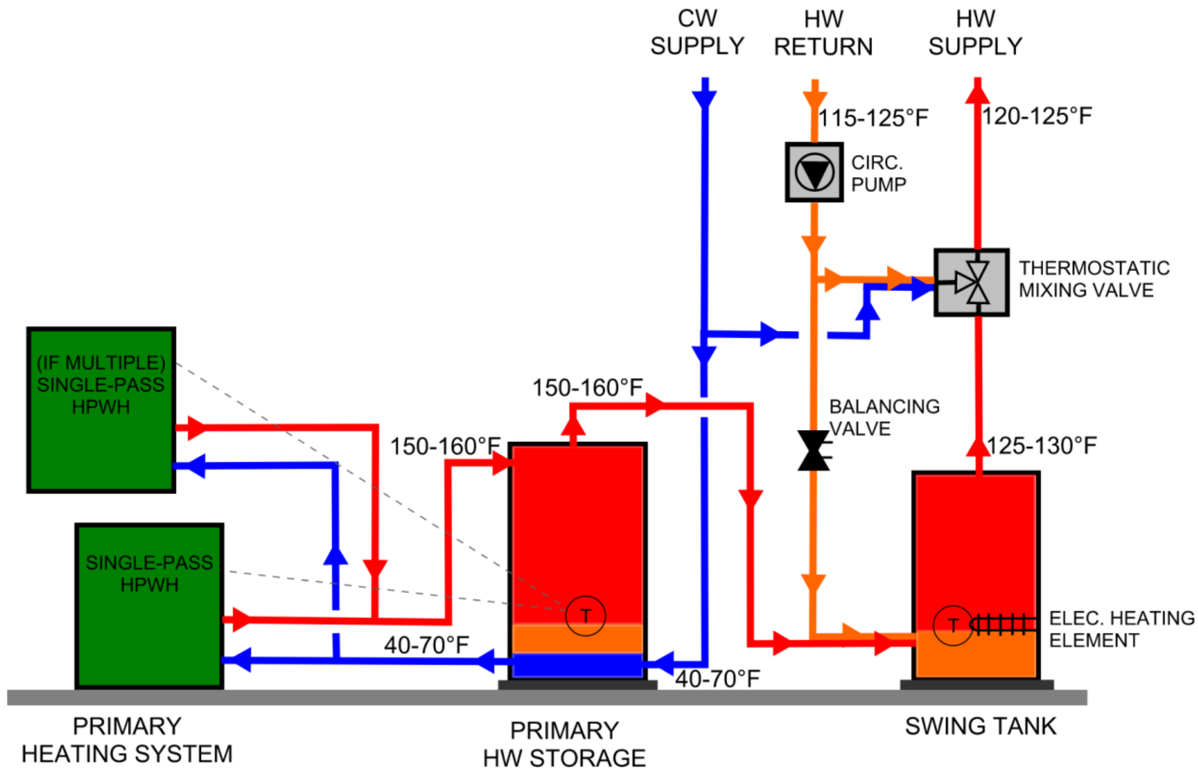

Figure 1. Swing tank piping configuration.

The swing tank effectively isolates the primary CO_2 HPWHs from the HWR loop, protecting them from elevated inlet temperatures. However, it introduces a significant efficiency penalty: the ER element in the swing tank must reheat some of the recirculation losses, which average 30% of total building hot water load in well-insulated multifamily buildings (Kintner and Larson 2019).

Swing tank energy usage cannot be avoided when there is no hot water usage and there is heat loss from consistent TM. However, Ecotope has identified two strategies to significantly reduce swing tank energy usage when there is hot water usage in the building. First, the swing tank setpoint must be set to its minimum acceptable temperature, roughly 5°F warmer than domestic hot water (DHW) supply temperature depending on the mixing valve. This allows hot water flowing from the primary storage tank to provide more heating to the cooler swing tank. Second, the balancing valve on the branch to the swing tank should be set throttled down as much as possible. This forces warm return water back to the mixing valve instead of to the swing tank in periods of moderate-to-high hot water usage, which reduces the amount of warm return water that is reheated by the swing tank. Figure 2 shows a comparison of swing tank energy usage with high swing tank setpoint (145˚F) and a fully open balancing valve (red points), compared to the same swing tank with a lower setpoint (130˚F) and partially closed balancing valve (yellow points). This adjustment drove a 30% reduction in swing tank energy usage, driving more efficient hot water loop management and lower system cost over time.

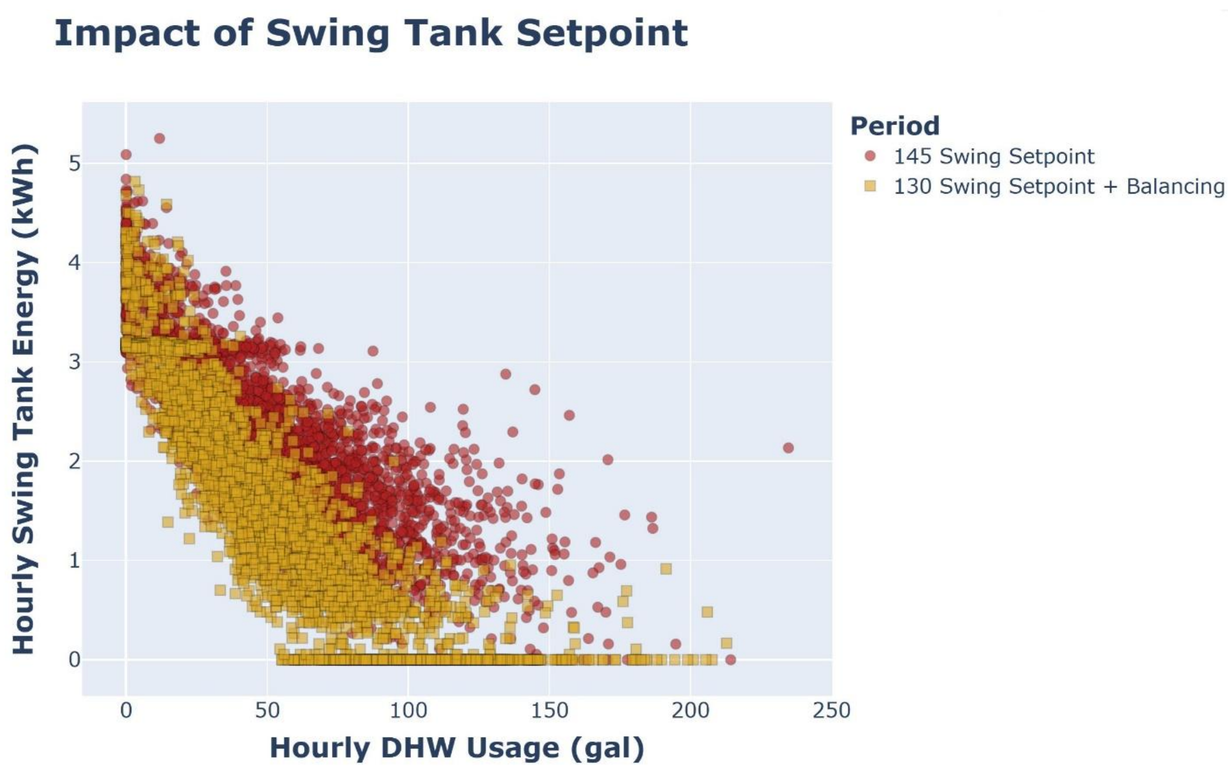

Figure 2. Impact of swing tank setpoints and balancing on ER usage.

Controls and Monitoring Overlay

The first system iteration beyond a swing tank baseline addressed the first cost and complexity driver described above: there was no way to proactively assess long-term system efficiency and reliability after commissioning was complete. Efficiency was partially visible in monthly utility bills but masked by other building appliances, equipment issues were unknown until hot water complaints emerged, and manufacturer controls did not support custom setpoints or remote diagnostics.

The team solved this problem by installing a central controller on all new HPWH system installations. The controller provides continuous trend data streamed to an online dashboard to inform key diagnostic temperatures and calculate metrics like heat pump Coefficient of Performance (COP) and whole-system COP (Ratio of total water heating energy provided per unit energy consumed by the system). Data is used to trigger critical alarms before cold water is sent to the building if issues occur, and is used to inform preventative maintenance by comparing heat pump operating parameters against learned benchmarks. If the team determines a system could operate more efficiently with an update to the controls sequence, a sequence is pushed to the controller remotely.

Custom control capabilities have allowed CZB to implement standardized load shift logic into every system they have installed since this central control strategy has been implemented. Load shift control logic is based on three surface-mounted tank sensors and is in alignment with the load shift control sequence described in system diagrams supporting the AWHS. Load shift controls have been successfully implemented by CZB on several sites to satisfy local load flexibility installation incentives. The impact of load shift controls on CZB's systems hasn't been studied directly, but their load shift strategy aligns with proven strategies whose benefits have been quantified by Ecotope (Spielman, Johnson, and Valmiki 2024).

Monitoring is implemented per AWHS Appendix H protocols, providing a standardized basis for performance comparison across sites. This controls layer has been incorporated into all of CZB's CHPWH system installations.

The following plot shows a case where high ER usage in integrated HPWHs was observed using remote monitoring. This informed adjustments to hot water circulation loop flow and balancing, and adjustments to TM heater setpoints, which nearly eliminated ER usage. Figure 3 shows power spikes to roughly 13kW when the integrated heaters' onboard ER elements engaged before setpoint updates on March 13th, compared to roughly 3kW power draw after March 13th when the integrated heaters' compressors managed the load without additional ER.

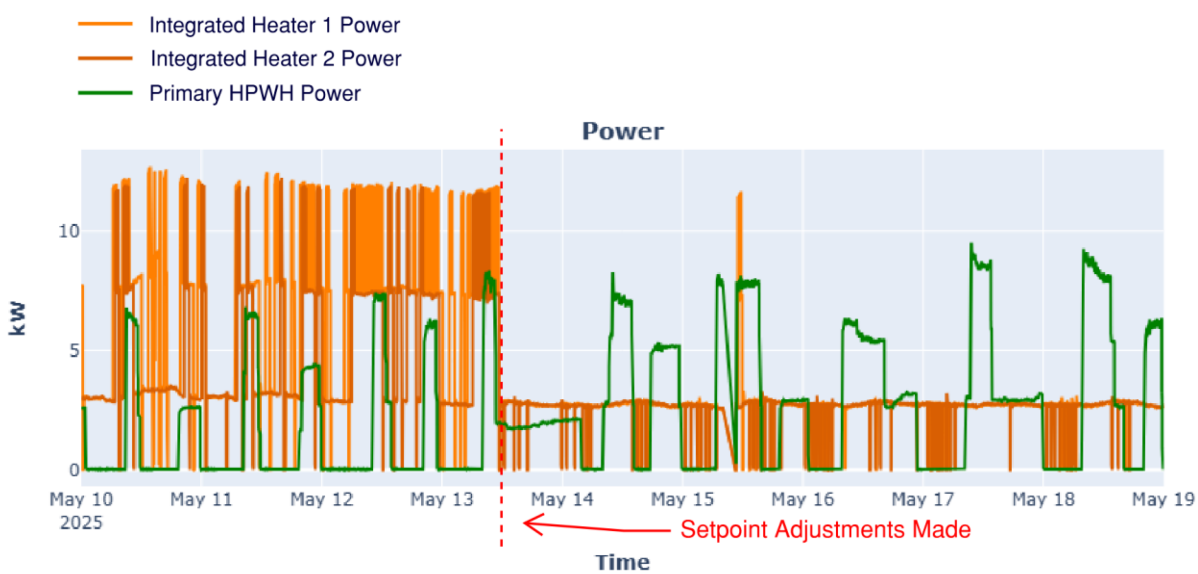

Figure 3. TM tank power reduction after setpoint adjustment on March 13th.

Switching Return to Primary

Even with an optimized swing tank and monitoring, the ER contribution from the HWR loop remains significant in most buildings. Analysis revealed that hot water recirculation losses are a large fraction of total load, and crossover events—in which cold makeup water reaches the electric swing tank during peak demand—drive substantial additional resistance heating.

To address the barrier of hot water return loop management, the team introduced an automated return-to-primary (RTP) switching valve to test CO_2 HPWHs in return to primary configuration while keeping a fallback option to revert to swing tank operation. This valve allows warm return water to enter the primary storage tanks to be reheated by the HPWHs, but can revert to swing tank operation (hot water circulation returning to the swing tank) if the

HPWHs cannot keep up with the load or have any issues related to warm entering water. Figure 4 shows a switching RTP system in both modes.

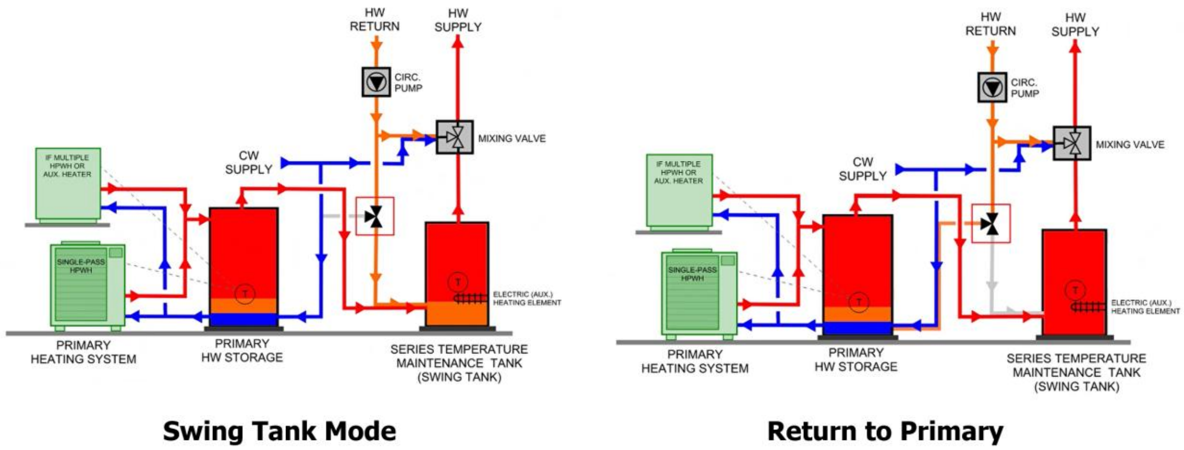

Figure 4. Switching return to primary system.

Employing CO_2 HPWHs in an RTP operation using this valve resulted in operating issues related to HPWH inlet water temperature. When RTP was active and hot water usage was low, lower storage tank temperature and HPWH inlet temperature were near HWR temperature. This resulted in short-cycling of the HPWHs in this test because inlet temperatures were higher than is allowed by the HPWH's internal safeties in low usage cases.

All CO_2 HPWHs operate less efficiently when inlet water temperature is close to HWR temperature, and many CO_2 HPWHs simply will not operate with such high inlet temperature. Table 1 shows performance of four anonymized CO_2 HPWHs. It shows COP and heating capacity are both reduced when inlet water temperature increases, and many manufacturers have maximum inlet temperature allowances that are much lower than standard HWR temperatures. The combination of these factors means CO_2 HPWHs will either operate with reduced performance, or they will not operate at all when in RTP configuration.

Table 1. Impact of increased inlet water temperature on CO_2 HPWH performance.

HPWH #	Inlet temp (°F) @ nominal capacity rating	Max inlet temp (°F)	Capacity de-rate @ higher inlet temperature	COP de-rate @ higher inlet temperature
1	50	118	13% @ 85°F 24% @ 100°F	17% @ 85°F 30% @ 100°F
2	75	140	0% @ 84°F	4% @ 84°F
3	70	90	Not published above 70°F	Not published above 70°F
4	68	86	11% @ 86°F	12% @ 86°F

The findings from this test do not suggest that *all* CO_2 HPWHs should be prohibited from operating in RTP, but designers and program implementers need to fully consider the equipment-specific impact of warm inlet water in coordination with equipment manufacturers before applying them in this fashion. If CO_2 HPWH manufacturers wish to approve their equipment for return to primary operation, they need to clearly state the capacity derates associated with warm (80-100°F) inlet water temperature for equipment sizing in peak-usage scenarios, the efficiency de-rates across the full inlet temperature range (60-125°F), and confirm their equipment will operate with the high inlet water temperatures required to control return to primary systems (up to 130°F).

Full Return to Primary with Non-CO_2 Heat Pumps

To address the barrier of cost and hot water loop management, the team eliminated the swing tank and switching valve entirely by installing non-CO_2 HPWHs capable of handling elevated HWR inlet temperatures. In mild California climates, modern non-CO_2 heat pumps (using R-32 or similar refrigerants) perform well across the range of inlet temperatures encountered in multifamily HWR loops without the thermal management constraints of CO_2 HPWHs. However, current non-CO_2 HPWHs have a greater reduction in capacity and efficiency in cold temperatures than CO_2 HPWHs, so annual air temperatures should be considered carefully.

In the full RTP configuration, HWR piping returns directly to the primary storage tanks, which are heated directly by the HPWHs. Eliminating the swing tank and switching return to primary valve drives simpler piping and eliminates the need for ER in cool-to-mild climates. Figure 5 shows a return to primary system as presented in Advanced Water Heating Specification (NEEA 2024).

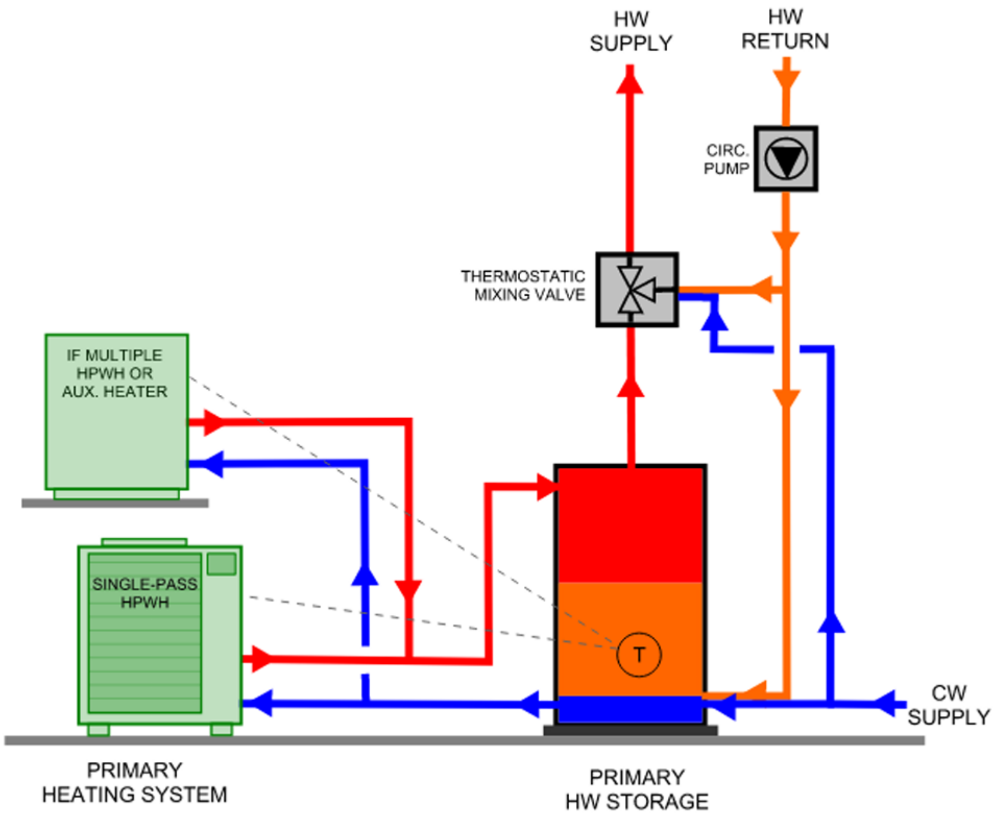

Figure 5. Return to primary piping configuration.

Full RTP is most applicable in climates where non-CO_2 heat pumps maintain acceptable COP year-round and where HWR loop temperatures are well-controlled. In colder climates or buildings with high-temperature HWR loops, a full understanding of the selected HPWH's capabilities is needed before adopting this configuration. The equipment must operate in the coldest design air temperature, operate efficiently near the average outdoor air temperature, and satisfy both these requirements with inlet water temperatures climbing up to 125°F.

Figure 6 shows the system COP of a Return to Primary system with R513a HPWHs vs outdoor air temperature in Oakland, CA, with COPs averaging above 2.5 with outdoor air temperatures ranging from 40°F to 60°F. This data shows the R513a HPWHs applied to this site can heat in a Return to Primary configuration efficiently in mild temperatures. For the purposes of this evaluation, efficient system performance is defined as maintaining a combined system COP of 2.5 or greater, which aligns with the upper tier of optimized central heat pump water heating systems monitored in recent field demonstrations (Banks et al. 2022; CalNEXT 2026). More field studies need to be conducted in cold climates, and with a larger range of non-CO_2 HPWHs in this configuration, including use of variable speed compressors that maximize cycle times and minimize required discharge pressure to satisfy variable loads, which increases system COP.

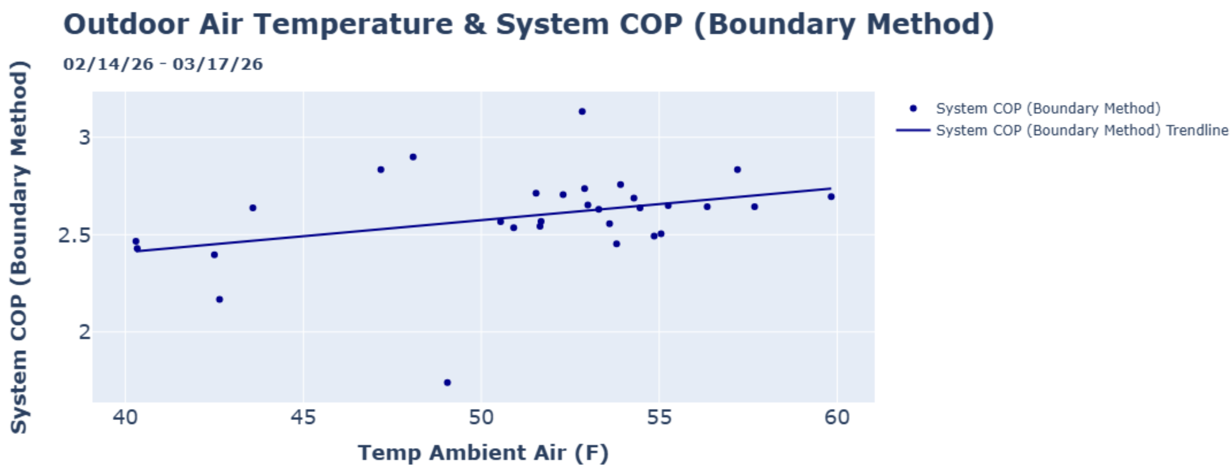

Figure 6. Return to primary system - Outdoor air temperature vs system COP.

Parallel Temperature Maintenance

Another option to address the barrier of TM loop management is to use appropriate HPWHs to heat the TM loop in parallel with CO_2 HPWHs that heat the primary storage tanks for hot water usage.

To address the cost barrier, this approach leverages widely available, competitively priced equipment for both functions. The team used mass-produced, high-efficiency CO_2 HPWHs to heat the incoming city water in the primary storage tank for hot water usage, and integrated HPWHs using R-134a refrigerant for TM heating in parallel. Figure 7 shows the parallel TM system similar to that presented in the Advanced Water Heating Specification (NEEA 2024), but with an integrated HPWH replacing the split TM heater.

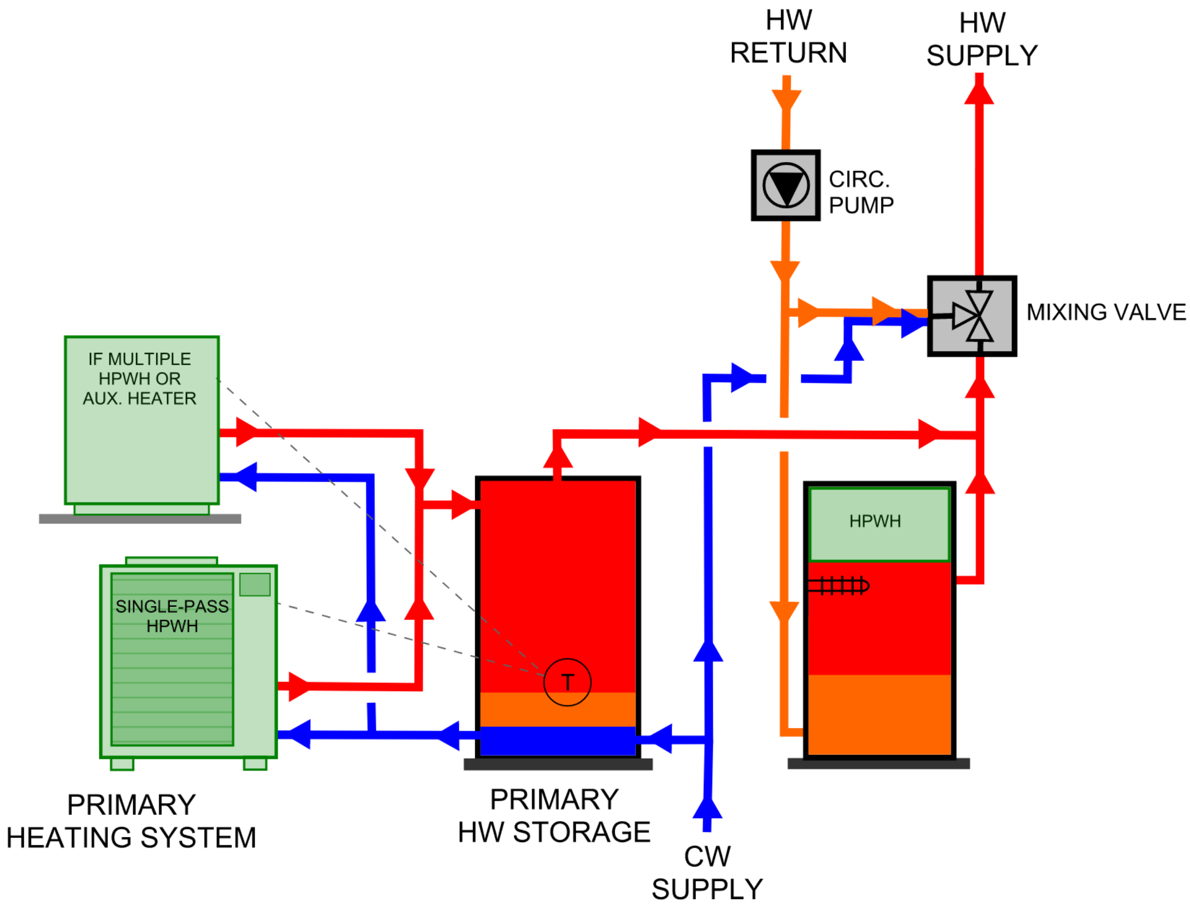

Figure 7. Parallel temperature maintenance system piping configuration.

The primary risk when using integrated HPWHs for TM heating is setpoint misconfiguration, which could drive excessive ER heating from the ER element built in to the integrated HPWH. The manufacturer's logic is proprietary, meaning designers will not know exactly what equipment setpoint will minimize ER usage or how the equipment will react to varying HWR temperatures. Manufacturer transparency around equipment operation and remote monitoring and setpoint refinement are crucial to avoid this issue.

Figure 8 shows System COP was maintained above 3.0 in a parallel TM system in Los Angeles, CA, despite TM heating (Energy In TM 1 and Energy In TM 2) making up over 50% of the water heating system's total energy usage. The high TM heat loss in this building was a result of high cross-over of cold water into hot water distribution pipes, an issue with hot water distribution piping not related to the HPWH plant configuration, which would have driven a significant reduction in System COP if TM had been heated by ER.

Figure 8. System COP of parallel temperature maintenance system.

Unpressurized Storage

The most significant cost innovation currently under field demonstration is the use of unpressurized thermal storage tanks with heat exchange to the pressurized domestic hot water circuit. This approach was proposed in a 2022 study by Ecotope, funded by Bonneville Power Administration, which identified unpressurized thermal energy storage (TES) as capable of reducing storage costs by a factor of four compared to pressurized potable water tanks—from a range of $20–$35 per gallon to approximately $5–$10 per gallon (Spielman et al. 2022). Potable water has historically been stored and heated in pressurized tanks and delivered directly to the building. CZB, in collaboration with Ecotope, manufacturer Solera Systems, and controls integrator A Thing Story, has developed a repeatable, premanufactured DHW system using Thermal Energy Storage hydronic heat pumps, and a plate-and-frame heat exchanger. Integrated controls and monitoring address the market barrier of post-installation opacity, hydronic heat pumps capable of heating high inlet water temperatures manage the barrier of hot water return loop management, and less expensive thermal energy storage, common hydronic components, and factory assemblies address the barrier of system cost. The installation cost of this system including materials and labor is roughly 30% lower than the next least expensive system CZB has installed: a swing tank system with mass-produced CO_2 HPWHs. At the date of this publication, CZB has installed 45 unpressurized DHW systems.

System Architecture

The system uses unpressurized thermal energy storage sized to supply the building during peak hot water usage periods. An R32 hydronic heat pump heats the storage tank to 130°F in a single-pass fashion. A bypass valve mixes heat pump outlet water back to the inlet to maintain a target inlet water temperature, while the heat pump compressor operates at variable speed to maintain a target leaving water temperature that is returned to the top of the stratified storage tank. Controlling heat pump flow and inlet temperature maximizes efficiency by minimizing required compressor speed when outdoor air temperature is warm or hot water usage is low.

A heat exchanger separates the potable hot water supply to the building from the non-potable thermal energy storage. Variable speed pumps vary the non-potable, high-temperature flow to the heat exchanger to match the domestic hot water heating load and maintain target supply water temperature. This configuration means no potable water is stored; it is heated on demand.

In-tank sensors are paired with load shift control logic to execute load shifting without significant additional cost. If time of use periods are substantial where this system is installed, thermal storage volume can be increased with little incremental cost increase to allow the heat pumps to shut off during high energy cost periods.

Figure 9 shows a simplified piping configuration of the unpressurized HPWH system.

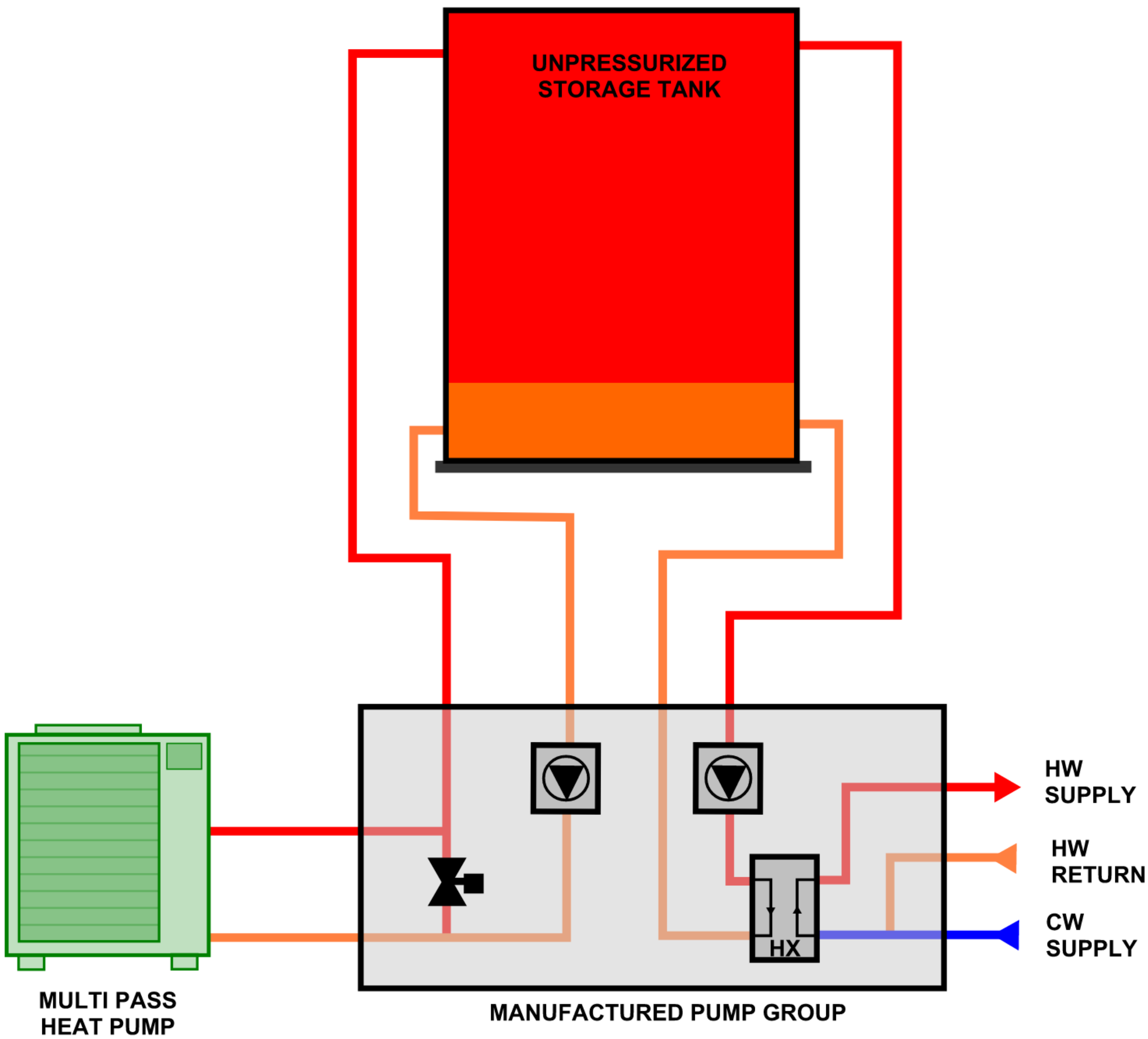

Figure 9. Unpressurized HPWH system piping configuration.

Component Design and Sourcing

This system is cost effective for several reasons. Unpressurized storage tanks do not hold high pressure, so they can be constructed of inexpensive materials and do not require an ASME rating. They can also be site-assembled, clearing path of egress issues that would otherwise require door frame removal or crane operation to locate large storage tanks on a roof or in an interior room. Unpressurized storage tanks have been manufactured for decades to support solar thermal installations.

Because all moving parts manage non-potable water, they do not require expensive lead-free certifications and materials, and all components are readily available from hydronic suppliers. Further reducing installation complexity, the team worked with a systems integrator to assemble all major components in a pre-manufactured pump module. This maximizes construction efficiency because field installation scope is limited to mounting the heat pump, storage tank, and pump module, then installing pipe between these components.

Installation Process

The first commercial installation of this system was a 230-gallon tank installed in a 40" × 40" mechanical closet. The installation sequence was engineered to minimize field labor. The tank was positioned with pre-installed diffusers, suction strainers, supply/return piping, and temperature sensors. The pump module was then bolted and piped to the tank using manufacturer-supplied flex hose connections, and pre-configured wiring harnesses were provided to connect the controller, tank, and heat pump. A Modbus communication wire was run to the heat pump, and current transformers (CTs) were installed at the power panel for energy monitoring. Default settings were downloaded remotely to the heat pump prior to startup, with control settings updated remotely as needed.

The simplified installation process allowed a small work crew to remove gas water heaters and install and commission two HPWH systems on one site in a single day.

Applicability and Limitations

Unpressurized storage is applicable across a wide range of building types but carries specific design requirements and constraints. The heat exchanger must be properly sized for peak domestic hot water demand, as under-sizing will limit supply temperature during peak loads. The unpressurized systems installed to date have been in mild climates, so considerations for glycol and/or other means of freeze protection should be made in cooler climates. In high-rise buildings where system pressures exceed 125 psi, special pressurized tanks and components may be required. In an unpressurized system, however, the heat exchanger is the only component that needs to be capable of withstanding the high pressure.

Standardization and Scale-Up Pathway

Field demonstrations of individual design innovations are necessary but not sufficient for market transformation. The team is pursuing parallel standardization activities to develop these configurations into repeatable, low-labor solutions.

Prequalified system configurations developed through the NEEA Advanced Water Heating Specification (NEEA 2024) reduce design time and provide a vetted basis for utility incentive programs. Swing tank, return to primary, and parallel temperature maintenance systems are already listed as qualified piping configurations, but unpressurized storage systems need to be added. Standardized system monitoring is also necessary to ensure systems are operating as intended to maximize efficiency and reliability. The Advanced Water Heating Specification outlines standard measurement and verification guidelines, and Ecotope has developed EcoDash, an online dashboard that displays data in a format tailored for HPWH system review. EcoDash has been implemented on dozens of HPWH plants and has used standard monitoring points to inform multiple research studies and utility collaborations.

Ecosizer can be used to size systems repeatedly and reliably. Ecosizer is an open-source HPWH system sizing tool used by several HPWH manufacturers and design engineers across the country. Ecosizer has been refined to accommodate return-to-primary sizing and more advanced tank stratification characteristics for single-pass systems, meaning that single-pass return-to-primary systems like those demonstrated in this paper can now be sized using Ecosizer.

Contractor training is another priority: the plug-and-play installation sequence developed for unpressurized storage reduces skill requirements at the field level, and formalizing this sequence into training materials and a contractor certification pathway will accelerate adoption.

Finally, ensuring that utility and state incentive programs — particularly in California, where significant support currently exists for central HPWH installations — recognize novel but proven configurations including unpressurized storage is essential to maintaining cost-competitiveness.

Conclusions and Future Work

The design evolution described in this paper demonstrates that heat pump water heating system cost and complexity can be substantially reduced through iterative, field-validated innovation. The progression from swing tank to full return to primary to unpressurized storage reflects a systematic approach to eliminating the most expensive and least efficient components at each stage.

Controls and monitoring are foundational for a system to continuously operate efficiently and reliably. Without visibility into system performance, efficiency gains are difficult to sustain and equipment issues go undetected. Flexible controls may also allow for load shifting, providing potential benefits to building owners with time-of-use rates.

Eliminating the swing tank and electric resistance backup through return-to-primary configurations significantly improves system efficiency in mild climates. Various manufacturers of CO_2 and non-CO_2 HPWHs should be investigated to validate return to primary as a reliable and efficient configuration and to better compare the system COP impact of using each refrigerant. Where large-capacity return-to-primary-optimized heat pump water heaters are not yet cost-competitive, the parallel temperature maintenance configuration provides an interim solution by pairing mass-produced CO_2 HPWHs with R-134a integrated HPWHs for temperature maintenance heating.

Unpressurized storage offers a step-change reduction in storage cost, with field demonstration now underway. Early installation experience confirms the feasibility of the approach, and performance monitoring will quantify efficiency outcomes. Inexpensive storage per gallon and integrated controls also make increasing thermal energy storage for load shifting more feasible and less risky, as large volumes of stagnant water are no longer interfacing with building occupants.

Future work priorities include full-year performance monitoring and analysis of unpressurized storage installations, and development of larger unpressurized tank configurations for high-demand buildings. Regarding Qualified Products List listing, unpressurized system operation can be modeled using the Advanced Water Heating Specification's current return-to-primary modeling protocol, and CZB's unpressurized system has been added to the Qualified Products List based on this modeling and data from successful field demonstrations. Plans for future revisions of the Advanced Water Heating Specification include discussion of unpressurized thermal storage as a qualified piping configuration. Additional future work includes refinement of variable compressor control strategies to maximize heat pump efficiency across varying load and ambient conditions.

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AI-assisted tools used: Claude (Anthropic). Used for: drafting text sections and document formatting. Extent: drafting sections with substantial author review and revision. Human review: The authors reviewed and verified all content, calculations, and citations.

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