Evaluation of Central Heat Pump Water Heater System Temperature Maintenance Methods for Multifamily Buildings

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ABSTRACT

Domestic hot water (DHW) systems in multifamily buildings represent a critical opportunity for energy efficiency improvements and electrification. This study evaluates central heat pump water heater (CHPWH) systems when using different temperature maintenance (TM) strategies to optimize performance and reliability. Testing was conducted at PG&E's Applied Technology Services laboratory using a full-scale hot water system designed to replicate realistic multifamily operating conditions. The experimental design builds on prior laboratory studies in which hot water distribution systems and central unitary HPWH configurations were characterized under controlled conditions.

Four system configurations were analyzed: (1) return to primary storage tanks, (2) temperature maintenance using a resistive heater in series with the primary storage tank (series TM–RE), (3) parallel temperature maintenance using a resistive heater (parallel TM–RE), and (4) parallel temperature maintenance using a heat pump water heater (parallel TM–HP). Each configuration was evaluated in terms of coefficient of performance (COP), effective hot water storage, and operational behavior, with particular attention to the impact of warm return water on heat pump efficiency and tank stratification.

Results demonstrate that thermal storage plant architecture strongly influences system efficiency. Measured Effective System COP values ranged from 1.05 in the parallel TM–RE configuration to 1.73 in the parallel TM–HP configuration, with intermediate performance observed for the series TM–RE (1.29) and return-to-primary (1.43) configurations.

Introduction

Domestic hot water (DHW) generation is one of the largest energy end-uses in the residential sector, accounting for approximately 30% of site energy consumption in multifamily buildings with five or more units (EIA, 2020). As building energy codes become more stringent and thermal envelopes improve, the relative share of total building energy attributed to water heating continues to rise, positioning DHW as a critical focus area for technology innovation efforts aiming to make buildings more affordable, efficient, healthy, and resilient (Langevin and Wilson 2025). In California and across the United States, policy initiatives and energy codes (such as California's Title 24) are accelerating the transition away from fossil fuels combustion toward beneficial electrification (Feng, et al. 2024). As a result, Central Heat Pump Water Heater (CHPWH) systems are rapidly becoming the standard for low-carbon multifamily construction and retrofits (Feng, et al. 2024).

While centralized systems offer notable advantages in maintenance, serviceability, and space efficiency compared to individual in-unit water heaters, they also face a major thermodynamic challenge: distribution heat loss. Large multifamily buildings require extensive piping networks to deliver hot water to all dwelling units. Without temperature maintenance, water in these pipes cools during periods of low draw, leading to long waiting times for occupants and substantial water waste (Parker and Butzbaugh 2020) and (Bozorgpanah, Amanlou and Safarzadeh 2022). To address this, plumbing designers employ continuous recirculation loops. In California, the energy code specifies that "systems serving buildings with more than 8 dwellings must have recirculation systems with thermostatic mixing valves on each supply and return loop" (CEC 2025). However, studies show that heat losses from these recirculation systems can represent 30% to more than 50% of total water heating energy use, depending on pipe insulation quality and system geometry (Kintner and Larson 2019).

Integrating high-loss distribution systems with modern HPWH technology introduces additional engineering complexity. CHPWHs rely heavily on thermal stratification within their primary storage tanks to achieve high COP and maintain efficient heat pump operation (Feng, et al. 2024). Conventional recirculation systems return warm water (typically 115°F to 120°F) to the plant, which, if blended directly into primary storage, disrupts stratification and raises the heat pump inlet temperature. This significantly degrades plant efficiency and reduces heating capacity (Zeyghami and Zhang 2024).

To reconcile the need for reliable hot water availability with the operational requirements of heat pump systems, several specialized temperature maintenance configurations have been developed. These include "swing tanks" (series temperature maintenance), parallel loop tanks, and point of use or heat trace solutions. Each strategy aims to hydraulically isolate the temperature maintenance load from the primary heating load, ensuring the heat pumps receive sufficiently cold return water to maintain performance while a secondary system manages distribution losses (Ecotope 2020) and (NEEA 2024).

Despite the theoretical advantages of these configurations, industry design practices remain in flux, and limited empirical data exist to compare their performance under controlled, repeatable conditions (NBI 2023). This study evaluates three distinct temperature maintenance strategies (parallel maintenance, series maintenance, and return to primary) to quantify their impact on overall CHPWH system performance for a typical small apartment building using commercial unitary HPWHs.

Methodology and Experimental Setup

Facility Description

The experimental campaign was conducted at the Pacific Gas and Electric (PG&E) / Applied Technology Services (ATS) / Advanced Technology Performance Laboratory (ATPL). During recent years ATS has been performing extensive laboratory evaluation of CHPWH systems as well as studying the interactions of hot multifamily DHW distribution components. To replicate realistic multifamily building operating conditions, the laboratory employs two separate tightly controlled test chambers constructed with insulated walls and ceilings which are equipped with environmental control equipment capable of maintaining precise ambient temperatures and humidity throughout long lasting operations.

Figure 1 depicts a simplified schematic of the CHPWH testing facility (i.e. test facility no. 1), showing the main equipment[1]. These controlled conditions enable repeatable evaluations of CHPWH performance under a range of load and environment scenarios. Additional details on

[1] Details including plumbing and instrumentation are omitted from the schematic, only showing main equipment placements

ATPL's CHPWH testing facility can be found in the prior published report (PG&E and SCE 2024).

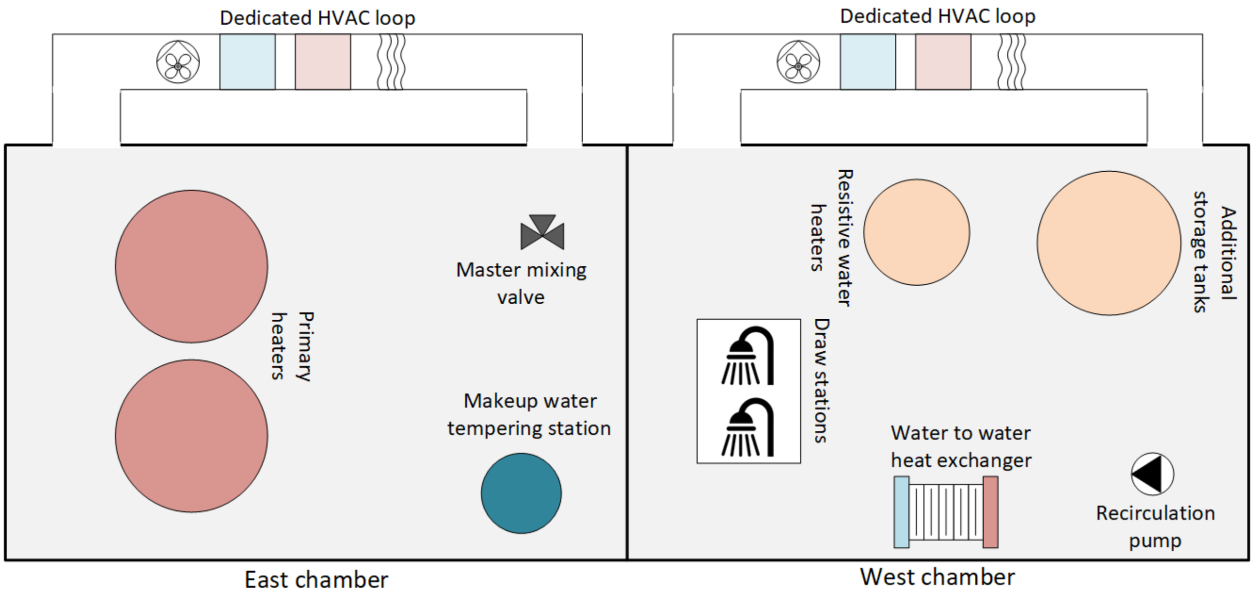

Figure 1 Schematic of the testing facility with placement of main equipment

During long duration tests ambient dry bulb temperature can be controlled between 40°F to 140°F, with a precision of ±1°F. Each space conditioning system consists of a chilled glycol cooling coil, a hot water heating coil, and a blower. Humidity levels can be controlled and maintained within a range of 30% RH to 80% RH with a precision of ±5%, using five sets of humidifiers. Also, for each test the inlet city water goes through a dedicated tempering process to make sure there is no fluctuation in the temperature of the makeup water during tests.

All instruments were calibrated following NIST[2] traceable calibration for tests. Flowmeters, temperature, and pressure sensors were calibrated at the beginning of testing and again after the testing was finished to ensure that readings had not shifted during the test. The other instruments, including the RH sensor and Yokogawa power meters, maintain current calibrations documented with NIST traceable calibration reports. More details about the instrumentation used during tests are included in Table 1.

The hot water distribution testing facility has been developed as a full-scale DHW recirculation system for a 3-story multifamily building (i.e. test facility no. two), with the intention to obtain in-depth understanding of recirculation system performance and evaluate improvement strategies. The findings and observations from extended testing in the Hot Water Distribution (HWD) testing were used to calibrate flow rates and heat loss rates of the distribution system in CHPWH test facility for this study. Additional details on ATPL's HWD testing facility can be found in the prior published report (PG&E 2025).

Table 1 CHPWH testing facility instrumentation details

Measurement	Instrument	Make	Accuracy

[2] National Institute of Standards and Technology (NIST)

Barometric Pressure	Multi-function weather station on roof of building	Vaisala WTX520	±0.007 PSIA (±50 Pa)
Chambers' dry bulb temperature as well as water temperatures in the setup	Fast-response resistance temperature detectors (RTDs)	Burns Engineering	±0.2°F
Temperature trees installed inside tanks	Type T thermocouple sensor	OMEGA	±0.2°F
Air humidity	HygroSmart S3 Probe	Michell's Instruments	±0.8% RH
Water pressure	General Purpose Pressure Transmitter ATM.ECO	PMC Engineering	≤0.2% FS
Water flow	Recordall Disc Meters	Badger	Model 25: ±1.5%
Supply power, voltage, and current	3-element true-RMS power meter with outputs for total power, voltage and current	Yokogawa WT330	±(0.1% of reading +0.1% of range)

HW Plant Architectures

The original multifamily central heat pump water heating evaluation project was designed to characterize the performance and operational limitations of central heat pump water heater systems under controlled boundary conditions. The original test campaign spanned several years and examined four different HPWH technologies (including unitary and split systems) configured as primary heating equipment. A series of application tests evaluated complete system performance across multiple temperature maintenance (TM) configurations, draw profiles, primary heaters and combinations of storage tank sizing and arrangements. Each test represented a simulated use cycle lasting 24 hours, allowing observation of equipment interactions in extended durational operation mode. Findings from the broader testing effort were previously published and presented in several conference and industry venues (PG&E 2025) and (Feng, et al. 2024).

One of the configurations tested in the original study was a Series TM-RE arrangement (i.e. swing tank), consisting of a commercial grade 120-gallon unitary HPWH and an electric water heater. The unitary HPWH serving as the primary heater, connected downstream to a 120-gallon resistive electric water heater (employing three independent resistive heating elements with total heating capacity of 18kW) acting as the swing tank. This setup was sized to address the DHW needs of a 16-unit multifamily building. Relatively low measured plant COP for the swing tank configuration was the motive to perform additional tests to evaluate other HW plant architectures.

For the current study, this swing-tank configuration was selected as the baseline against which two subsequent plant architectures were compared. The laboratory reproduced similar operating conditions used in the original testing, enabling a direct evaluation of additional plant configurations and their effects on system performance. Two more configurations were added:

- Return-to-primary operation, achieved by introducing a second unitary HPWH (similar to the primary heater). Two units were piped in parallel to manage both recirculation and demand loads; and

- Parallel temperature maintenance, where two HPWHs operate in parallel but one is dedicated exclusively to serving the recirculation load and the other only serving the draw demands.

For the new round of testing, two identical 120-gallon unitary HPWH were employed to study new configurations. Across all tests, hot water loads and total nominal plant storage volume were held constant to 240 gallons. This provides a fair performance comparison among plant design.

More Details on Configurations Analyzed

Figure 2 presents a schematic of plan designs with more details provided in the following section.

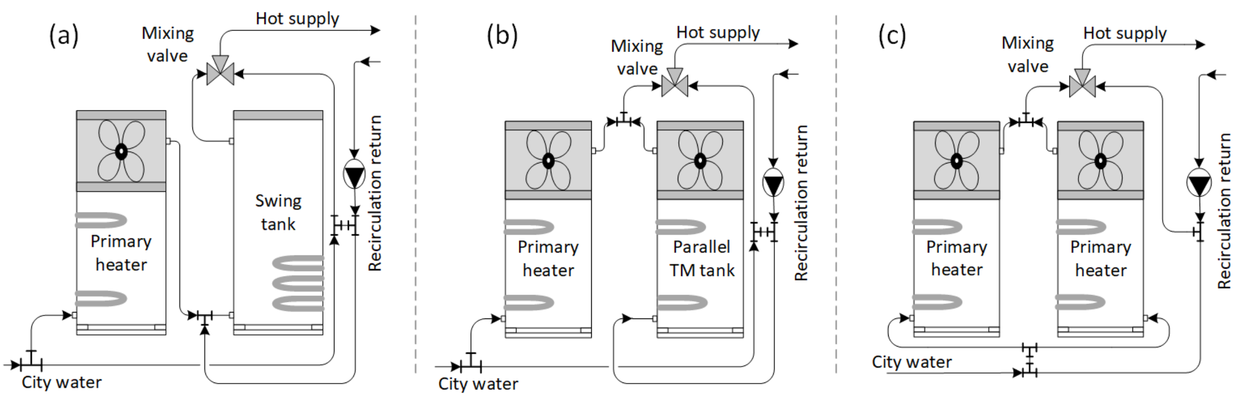

Figure 2 Plant designs: (a) temperature maintenance in series (Series TM-RE) (b) parallel temperature maintenance (Parallel TM-HP and Parallel TM-RE) (c) Return to primary

Series TM (Swing Tank): In this configuration, the unitary HPWH functions as the primary heater and storage tank. A resistive electric water heater (swing tank) is installed in series downstream to meet the TM load. This arrangement hydraulically isolates the recirculation load, ensuring the primary HPWH receives the coldest possible return water to maximize efficiency and maintain thermal stratification. Furthermore, during draw events the hot water supply from the primary heater (setpoint = 140 °F and COP ~ 3.0) is directed to the bottom of the TM tank. In theory the hot water flow from the primary tank would thermally charge the TM tank (set point = 125) and reduce the amount of heat needed from resistive elements (with a COP ~1.0).

Parallel TM: Here, one unitary HPWH serves as the primary heater and storage tank, while the second unitary HPWH (dedicated solely to the recirculation load) is installed in parallel. This configuration similarly ensures that the primary heater receives cold return water while the parallel unit manages all recirculation losses. For this configuration two rounds of tests were performed. One with the parallel TM tank set in efficiency mode and running as HPWH (Parallel TM-HP, setpoint = 125 °F). In efficiency mode the unit will operate in heat pump mode and electric resistive elements will only activate minimally following internal controls. The second run was performed with the parallel TM tank set in resistive electric mode (Parallel TM-RE, setpoint = 125 °F) to align closer with baseline test where used a resistive water heater as TM heater.

Return to Primary: In this configuration, both unitary HPWHs operate as parallel primary heaters and storage tanks (set point = 140 °F). The recirculation return water is directed to the bottom of both primary tanks, and both recirculation and demand loads are served directly by this combined primary storage. Unlike the previous two strategies, the recirculation load is not hydraulically separated from the primary plant.

Evaluation Metrics

To ensure valid comparisons amongst systems, the test conditions were kept uniform for all tests (i.e. environmental conditions, draw profiles, recirculation system flow rate and heat loss rates kept similar for all tests). The performance of each plant design was evaluated using the following metrics:

Coefficient Performance

Daily Unit_COP, Plant_COP, and Effective_System_COP values were calculated and compared across different configurations. Figure 3 depicts the energy balance boundaries for each analysis.

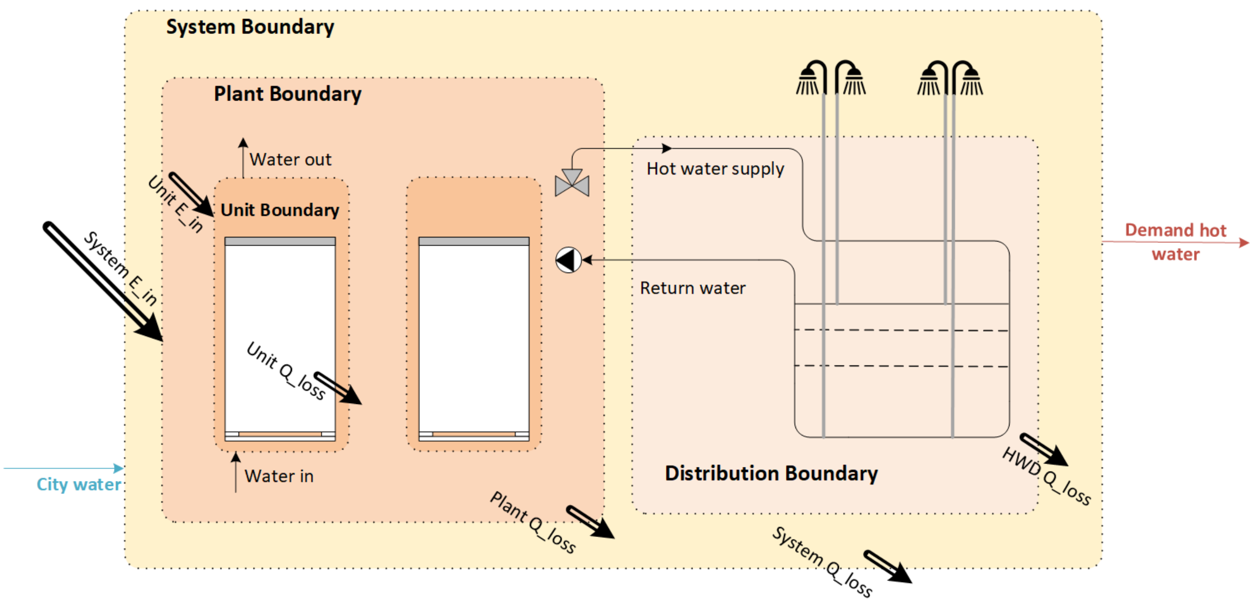

Figure 3 Energy balance boundaries for calculating Unit_COP, Plant_COP, and System_COP values

The daily Unit_COP for each water heater is defined as the ratio of the total useful thermal energy delivered over the 24-hour test period to the total electrical energy consumed by the water heater during the same period. It is computed using summed energy measurements from the flow meter installed on the inlet path of each water heater, inlet and outlet temperature sensors, and the electric power meter. The useful thermal energy delivered, Q_{unit}, is calculated by summation of the product of water mass flow rate and specific enthalpy difference across inlet and outlet of the unit in each time step. The electrical energy input, E_{in}, is obtained by integrating the instantaneous electrical power consumption of the heat pump system. The daily Unit_COP is then expressed as (see Figure 3 for unit energy boundary):

$$Unit\_COP = \frac{Q_{unit}}{E_{in}}$$

$$Q_{unit} = \sum_{i=1}^{n} \dot{m}_i (h_{out} - h_{in}) \Delta t_i$$

$$E_{in} = \int_0^{24h} P(t) dt$$

Here, $\dot{m}_i$ is the mass flow rate during each time step i passing through the unit, h_{out} and h_{in} are the specific enthalpy of water at outlet and inlet respectively, Δt_i is the duration of each time step, and $P(t)$ is the instantaneous electrical power draw of each water heater.

The daily Plant_COP represents the overall efficiency of the central water-heating plant by accounting for the combined thermal output of all heating equipment and the total electrical energy consumed by those heaters. Unlike Unit_COP, which isolates a single water heater's performance, Plant_COP integrates the behavior of multiple units, including staging, cycling interactions, recovery patterns, tank standby losses, and any auxiliary electric resistance heating occurring within the plant. Hence the effects of DHW plant architecture can be highlighted more clearly by comparing Plant_COP values for different plant designs. The delivered thermal energy Q_{plant} is calculated using boundaries of entire plant over a 24-hour period. Electrical input E_{in_total} includes all measured power to primary heaters as well as temperature maintenance heaters. It is worth mentioning that pump energy consumption is not included in the calculations. Plant_COP is defined as (see Figure 3 for plant energy boundary):

$$Plant\_COP = \frac{Q_{plant}}{E_{in\_total}}$$

$$Q_{plant} = \sum_{i=1}^{n} (\dot{m}_{mix} h_{mix} - \dot{m}_{recirc} h_{recirc} - \dot{m}_{city} h_{city}) \Delta t_i$$

$$E_{in\_totla} = \int_0^{24h} (P_{primary}(t) + P_{TM}(t)) dt$$

Here $\dot{m}_{mix}, \dot{m}_{recirc}, \dot{m}_{city}$ are water mass flow rates during each time step i passing through the mixing valve outlet, recirculation pump outlet, and city make up water to the plant respectively. $h_{mix}, h_{recirc}, h_{city}$ are the specific enthalpy of water at outlet of the mixing valve, recirculation pump and makeup city water during each time step respectively, and $P_{primary}(t)$ and $P_{TM}(t)$ are the instantaneous electrical power draw of the primary heater and temperature maintenance water heater.

Finally, the daily Effective_Sys_COP captures the overall energy performance of the domestic hot water system, accounting for all thermal and electrical processes between the city inlet water and the point of use. Effective_Sys_COP includes the thermal energy delivered at the fixture and compares it with the Electrical input E_{in_total}, total electrical energy consumed by all equipment in the system. This metric therefore reflects not only plant performance but also the effects of thermal losses in the distribution piping, and the operational strategies used to maintain temperature in recirculation systems (if any). Effective_Sys_COP is calculated as (see Figure 3 for system energy boundary):

$$Effective\_Sys\_COP = \frac{Q_{sys}}{E_{in\_total}}$$

$$Q_{sys} = \sum_{i=1}^{n} (\dot{m}_{draw} h_{draw} - \dot{m}_{city} h_{city}) \Delta t_i$$

Here $\dot{m}_{draw}$ is the mass flow rate during each time step i passing through the draw station outlet, and h_{draw} is the specific enthalpy of water at the draw station water during each time step respectively.

Thermal Storage Stratification and Capacity:

To monitor the state of the thermal charge in tanks a thermocouple tree made of 12 sensors spread evenly, was installed inside each tank. Recording the temperature distribution inside the tanks provides the necessary tools to evaluate effects of plant design on thermal stratification within the storage tanks. Emphasis was placed on how each configuration preserved or disrupted the temperature stratification inside tanks, influencing each water hear performance and instantaneous effective storage capacity.

Several evaluation indices are being used by researchers to compare the performance of different storage tanks in terms of stratification. Stratification Factor introduced by (Wu and Bannerot 1987) which is defined as the mass weighted mean square deviation of water temperature in the storage tank from the mean temperature of storage tank divided by total mass of tank will be used to compare the stratification levels during tests:

$$SF = \frac{1}{M_{store}} \sum_{1}^{j} M_j (T_j - T_{avg})^2$$

Here M_{store} is total mass of water in the tank, M_j is the mass of water in the control volume around the temperature sensor j. T_j and T_{avg} are the temperature of the water at sensor j and tank's mean water temperature respectively.

Furthermore, the instantaneous effective hot water storage capacity is considered as a performance metric that reflects the amount of usable hot water in the plant. Effective capacity is defined as the portion of a storage tank's total volume that can deliver water at the required delivery temperature without any water heating recovery. Unlike nominal tank volume, the effective capacity depends on temperature stratification, inlet water temperature, and mixing of hot and cold flows during draw events. Strong thermal stratification increases effective capacity by preserving a well-defined hot upper layer, whereas thermal mixing reduces it by eroding the thermocline and lowering the usable volume of hot water.

Results and Analysis

The experimental evaluation of the different TM strategies revealed significant variations in overall plant performance as well as unit performance and thermal behavior. It is worth mentioning that despite all efforts to reproduce test conditions between all tests, it is not an easy task to replicate the conditions very tightly in an automated 24-hour test. Furthermore, the baseline testing was performed in 2023, and the new round of tests were performed in early 2026. New round of testing has been performed with a different mixing valve as well as brand new water heaters. As shown in Table 2 test conditions were kept uniformly across all tests as close as possible. However, there has been some variations in the mixing valve outlet temperature (due to new mixing valve minimum operating temperature of 122 °F) as well as recirculation return temperature drops, which resulted in 20% more daily distribution heat losses during the new round of testing. Figure 4 shows the amount of heat demand for hot water draws as well as energy requirement for keeping the recirculation loop hot as well as the draw profile used during the test.

Table 2 Test conditions and observations (over the test duration (24-hr))

	Series TM – RE	Return to primary	Parallel TM – HP	Parallel TM – RE
Total draw (Gal)	578.5	578.8	579.0	578.8
Makeup water averaged daily temperature (°F)	58.1	58.2	58.3	58.3
Water heaters setpoints	Primary- 140 TM- 125	Primary- 140 Primary- 140	Primary- 140 TM- 125	Primary- 140 TM- 125
Recirculation averaged daily flow rate (GPM)	2.0	2.0	2.0	2.0
Mixing valve averaged daily outlet temperature (°F)	120	121.5	121.5	121.5
Recirculation return, averaged daily temperature drop (°F)	5.13	5.76	5.63	5.68
HWD averaged daily heat loss rate (Btu/hr)	5,160	6,284	6,240	6,283
Test chamber averaged daily dry bulb temperature (°F)	67.07	67.5	67.5	67.5
Test chamber averaged daily relative humidity (%)	56.54	50.50	49.94	51.76

The performance of each plant architecture at unit level, plant level, and system level is presented in Table 3. The analysis of the test data yielded to daily average Unit_COP values ranging from 2.17 to 3.15 for the primary heater across the different configurations. As expected, when the recirculation return is not directed to the primary heater, a more stratified tank results in a higher Unit_COP. The highest and lowest primary heater's Unit_COP observed during series TM-RE testing and return to primary testing accordingly.

Observed Plant_COP values vary between 1.57 and 2.57 and Effective_System_COP and values vary between 1.05 and 1.73. The highest Plant_COP and Effective_System_COP were calculated in parallel TM-HP configuration and the lowest Plant_COP, Effective_System_COP were calculated in parallel TM-RE configuration.

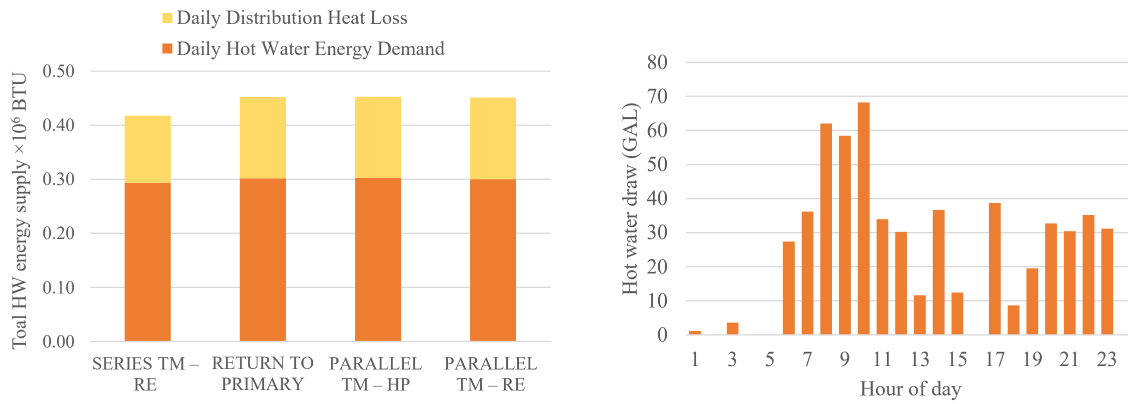

Figure 4 The heat supplied for the hot water demand and distribution losses (left) total hourly hot water draw profile during 24-h test

Effective hot water capacity is depicted in Figure 5, that reflects the true amount of usable stored energy available to meet the loads within a given configuration. Figure 5 shows the variation of effective hot water storage capacities during each test. Return to primary (with average 196 Gal of effective hot water storage) followed by series TM design (with average 185 Gal of effective hot water storage) result in considerable higher hot water storage availability compared to parallel TM configurations. As shown in Figure 5, in return to primary design, effective hot water storage has not dropped below 175 gal which resulted in the most stable water storage capacity amongst all tests. In parallel TM plant designs, temperature maintenance storage capacity cannot be used to fulfill the hot water demand.

Table 3 Performance comparison between different tests – average daily values

	Series TM – RE	**Return to primary**	**Parallel TM – HP**	**Parallel TM – RE**
Unit_COP primary heater	3.15	2.40 2.17	2.97	2.96
Unit_COP TM heater	0.96	-	2.36	0.94
Plant_COP	1.86	2.13	2.57	1.57
Effective_System_COP	1.29	1.43	1.73	1.05

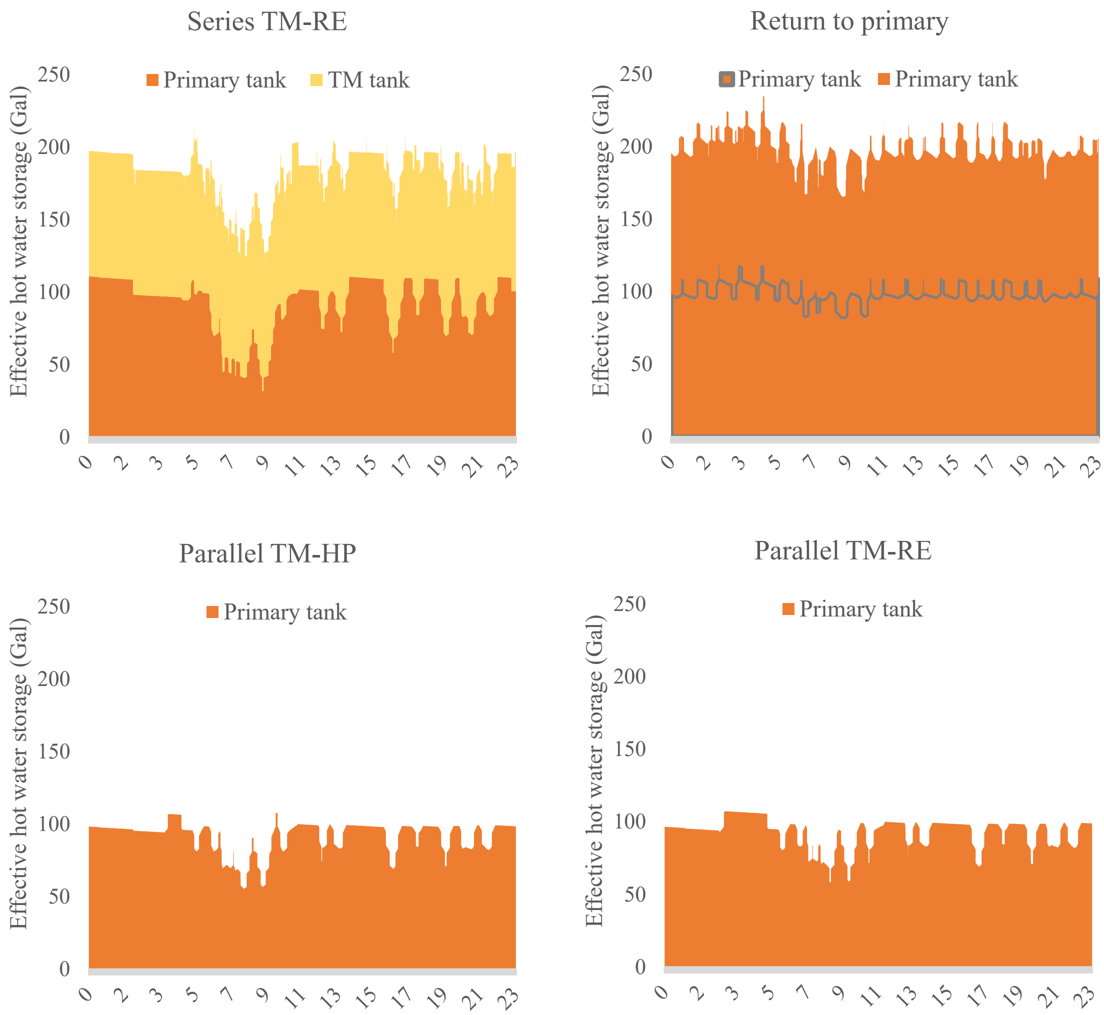

Figure 5 Effective hot water storage capacity during tests

Figure 6 shows the variations in the stratification factors for primary and TM tanks during tests. As expected, plant designs with recirculation return separated from the primary heaters resulted in higher stratification factor ranges for primary heaters (average ~650 for series TM test and ~740 for parallel TM tests). One interesting observation is the low stratification factors calculated when using a unitary HPWH dedicated as TM heater. Since the unit setpoint at 125 °F is close to the recirculation return temperature at ~115 °F calculated tank stratification factor (average ~17) is considerably lower than primary heater stratification factors. However, the daily Unit_COP of the TM HPWH at 2.36 is not dramatically lower than daily Unit_COP of the primary HPWH at 2.97.

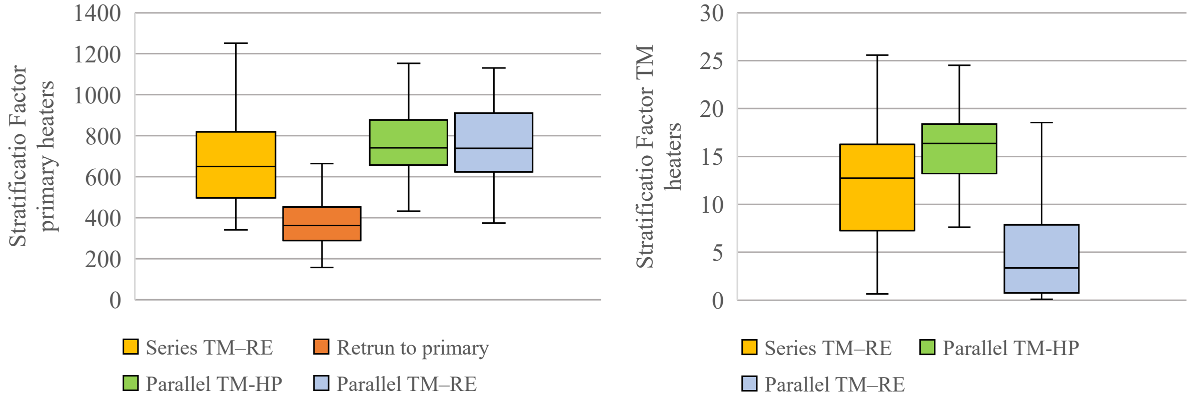

Figure 6 Stratification factor variations during tests for primary and TM heaters

Discussion

The experimental comparison of TM strategies revealed clear tradeoffs among plant efficiency, effective storage, and operational complexity, with results shaped by both hydraulic separation and the thermal conditions imposed on the primary heat pumps. Across tests, separating the TM load from the primary HPWHs (series TM and parallel TM) generally improved primary-unit stratification and Unit_COP relative to configurations that returned warm recirculation water directly to the primary tanks. The highest primary Unit_COP (3.15) occurred in the series TM – RE case, consistent with the expectation that colder return water to the primary tank preserves stratification and lowers evaporator lift; conversely, return to primary produced the lowest primary Unit_COP (2.17 and 2.40) as the warm recirculation return eroded stratification and elevated inlet temperature to the HPWHs.

At the plant level, however, how the TM load is met has a more obvious effect on the Plant_COP. When the TM duty was met with a HPWH (parallel TM-HP), the plant achieved the best daily Plant_COP (2.57) and the highest Effective_System_COP (1.73), indicating that shifting the recirculation losses to a dedicated heat pump avoids penalizing the primary plant while also avoiding the efficiency penalty of resistive elements. In contrast, supplying TM with resistive heat dragged overall efficiency down; the parallel TM-RE case exhibited the lowest Plant_COP (1.57) and Effective_System_COP (1.05), underscoring the high energy cost of meeting continuous loop losses with COP≈1 heating.

Thermal storage behavior can further clarify these outcomes. Return to primary and series TM offered substantially higher effective hot water storage, averaging ~196 gal and ~185 gal respectively, and the return-to-primary configuration maintained the most stable storage, never dropping below ~175 gal during the 24-h cycle. These configurations keep more usable energy available to ride through clustered draws, which can simplify sizing or reduce the need for aggressive recovery control. In parallel TM arrangements, the TM tank's capacity is technically unavailable to meet fixture draws, reducing the combined effective storage seen by the load despite acceptable primary Unit_COP values.

Stratification metrics corroborate the efficiency trends. With the TM loop hydraulically separated from the primary plant, the primary tanks sustained higher stratification factors (average ~650 in series TM and ~740 in parallel TM), while the dedicated TM HPWH (operating at a setpoint (125 °F) close to loop return (~115 °F)) exhibited very low stratification (average ~17). Notably, low TM-tank stratification did not imply poor TM heat-pump performance: the

TM HPWH still achieved a daily Unit_COP of 2.36 because its lift and cycling profile remained modest when serving a narrow temperature band around the loop setpoint.

Two methodological nuances are important for interpreting these comparisons. First, although test conditions were controlled and nominally uniform (identical draws, similar chamber conditions, matched loop flow, and fixed total plant volume of 240 gal), a newer mixing valve and new water-heater hardware were used in the 2026 tests versus the 2023 baseline, resulting in slightly higher mixing-valve outlet temperatures (~121.5 °F vs. 120 °F) and larger average loop temperature drops. These differences increased daily distribution heat losses by ~20% in the newer rounds, which tends to depress Effective_System_COP and accentuate the penalty of resistive TM strategies. Second, pump energy was excluded from COP accounting at the plant boundary, so real-world Effective_Sys_COP values would be somewhat lower when circulation power is included; this omission does not change the relative ranking of configurations but should be recognized in applications.

From a design standpoint, the results suggest three practical takeaways.

- Prioritize HPWH-based TM when feasible: dedicating a HPWH to the loop yielded the best Plant_COP and Effective_Sys_COP while preserving a cold return to the primary plant.
- Use resistive TM sparingly and strategically: while series TM with a resistive swing tank can protect primary stratification and deliver high primary Unit_COP, the resistive shoulder load materially lowers Plant_COP and Effective_Sys_COP; it may be acceptable only for small TM fractions or as backup. The resistive swing tank should be sized conservatively to avoid unnecessary oversizing.
- Account for effective storage, not just nameplate volume: configurations that pool storage across all loads (return-to-primary, series TM) provide higher usable capacity and stability under peaks, which can offset a lower primary Unit_COP in specific cases.

These system-level considerations are essential when right-sizing tanks, staging heat pumps, and setting TM setpoints and control bands.

Future research will expand this work through testing at ATPL's Hot Water Distribution (HWD) facility. The study will incorporate circulation pump energy into the system boundary to improve Effective_Sys_COP estimates, evaluate heat tracing as an alternative temperature-maintenance strategy, examine a wider range of load and distribution loss scenarios to support equipment sizing recommendations, and assess advanced control approaches (including adaptive temperature-maintenance setpoints, dynamic storage temperature control, and demand-responsive recirculation operation) to improve stratification, and enhance overall system performance.

Conclusion

This study demonstrates that TM strategy plays a decisive role in the overall performance of CHPWH systems in multifamily buildings. By experimentally comparing three distinct configurations (i.e. series TM, parallel TM, and return-to-primary) under controlled boundary conditions, we observed meaningful differences in COP performance, thermal stratification, and effective hot water storage capacity. Systems that hydraulically separated the TM load from the primary heat pumps (series TM and parallel TM) consistently preserved stronger stratification within the primary storage tanks and achieved higher primary Unit_COP values, confirming the importance of delivering cold return water to maintain efficient HPWH operation. However, when TM was met with resistive heat, the plant and system level efficiency penalties were significant, reinforcing the need to minimize or avoid resistive heating for continuous recirculation loads.

Among all configurations tested, parallel TM using a dedicated HPWH produced the highest Plant_COP and Effective_System_COP, highlighting the value of transferring loop losses to an efficient heat pump rather than burdening the primary plant with warm return water or relying on resistive elements. Meanwhile, the return-to-primary configuration provided the highest and most stable effective storage capacity, suggesting advantages for peak-load management even though primary efficiency was reduced due to stratification erosion. These results underscore that no single configuration is universally optimal; rather, designers must balance efficiency priorities, equipment sizing, redundancy, and storage needs based on project-specific constraints.

Overall, the findings offer practical insights for engineers and practitioners seeking to optimize CHPWH system design for multifamily buildings. Prioritizing HPWH-based TM solutions, preserving stratification through hydraulic separation, and evaluating effective (not just nominal) storage capacity can substantially improve real-world system performance. Future research should extend this work to field deployments, incorporate pump energy into full system boundaries, and explore adaptive control strategies that dynamically respond to varying load and environmental conditions.

Acknowledgement

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AI-assisted Tools: Disclosures and Responsibility

- AI-assisted tools used: MS Copilot.
- Used for: Drafting and grammar checks.
- Extent: light editing.
- Human review: The authors reviewed and verified all content, calculations, and citations.

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