Multifamily Domestic Hot Water Recirculation Survey

Final Report

ET24SWE0061

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July 27, 2026

Program paid for by ratepayers.

Acknowledgements

The project team would like to acknowledge the volunteering sites' staff and management for their participation in this study and for welcoming our team into their buildings. Energy efficiency and greenhouse gas emission impacts depend on forward-thinking facility owners and operators who believe in a more sustainable energy future. Thank you also to the designers, contractors, and subject matter experts for their support.

Executive Summary

Recirculation heat losses in multifamily buildings with central hot water systems typically represent a significant portion of the total load in both new construction and existing buildings. These losses can increase plant energy consumption, cause delivery problems, and drive inadvisable corrective actions without addressing root cause. They can also impact the performance of central heat pump water heaters. Central heat pump water heater (CHPWH) systems offer an electrified, high-efficiency water heating solution for multifamily buildings and are an important strategy for improving system performance and energy affordability in existing buildings.

The objectives of this study were to better understand domestic hot water recirculation loop energy losses, identify system characteristics that influence these losses, and inform design tools and program pathways to better address recirculation loads, especially in relation to CHPWH systems. Field monitoring, recirculation loss calculations, and qualitative system surveys were conducted at multifamily sites across California. Data collection included hot water supply and return temperatures, recirculation flow rates, documentation of system configuration, building characteristics, and maintenance practices. Stakeholder engagement included coordination with building ownership, maintenance staff, and third-party service providers to support system and market understanding.

Across the sites recirculation losses ranged from 24.1 to 99.9 watts per apartment with an average of 62.5 watts per apartment. Generally, these agree well with the standard assumption in CHPWH sizing tools that available on the market, including the oft-cited Ecosizer. There was not any obvious apparent correlation between building size or vintage and the recirculation load, although the sample size was small. Similarly, and perhaps again due to small sample size, there was not enough data to reliably correlate the recirculation losses to other building variables in a way that could serve as a prediction methodology for other buildings in the future. Overall, the study demonstrates that evaluating recirculation performance in any given building requires both quantitative and qualitative system assessment.

This study also investigated why measured temperature maintenance heat loss in multifamily hot water distribution systems consistently exceed theoretical predictions and evaluated measures to reduce that loss. It also examines best practices for recirculation system design in CHPWH installations.

Physics-based modeling of nine monitored buildings found that field-measured losses were 1.1 to 2.3 times higher than idealized calculations. Two mechanisms explain most of the gap. First, insulation imperfections — bare pipe, uninsulated fittings, or maintenance damage — can increase heat loss, though fully accounting for the gap would require implausibly large uninsulated fractions (20%+ in most buildings). Second, cold-water crossover, where pressure imbalances drive cold water into the hot distribution loop, registers as inflated heat loss in metering even though no additional heat is escaping the pipes. Field data from three sites show crossover effects ranging from subtle in new construction to severe and tenant impacting in retrofits.

Simulations of new construction built to the 2025 California Energy Code show that Appendix M pipe sizing and increased insulation thickness each offer modest savings (2–10 percent and 6–14 percent respectively against code baseline). The two measures together return up to 15 percent savings. However, adding insulation on small pipe sizes alone is likely not cost-effective given the small absolute savings.

For return-to-primary systems, an optimized configuration — routing hot water return and cold supply through a shared mixing valve cold inlet without a separate return branch — can lower heat pump inlet temperature, extend load-shift periods, and reduce storage drawdown. A digital mixing valve capable of fully closing its hot inlet is required. This configuration has not yet been field-tested. For dedicated temperature maintenance systems (swing tank or parallel loop tank), two commissioning issues commonly undermine performance: swing tank setpoints set too high and recirculation return flow not balanced toward the mixing valve cold inlet. Field corrections at two sites substantially reduced electric resistance runtime.

Crossover penalizes dedicated central heat pump water heater configurations with temperature maintenance systems more than in return-to-primary because cold water entering the distribution loop shifts load onto less efficient electric resistance elements rather than the primary heat pumps. As buildings age and fixture valves wear, crossover risk increases regardless of system type. Pre-retrofit crossover testing is recommended, and return-to-primary configurations offer a meaningful resilience advantage in existing buildings where full crossover remediation is not feasible or where crossover growth cannot be continuously managed over time.

Key recommendations include requiring pre-retrofit crossover testing, adopting Appendix M pipe sizing with added insulation on certain pipe sizes, and following Advanced Water Heating Specification guidance for temperature maintenance systems in central heat pump water heaters — specifically capping swing tank setpoints at 130°F and minimizing recirculation return flow to the temperature maintenance heater. Priority future research includes a controlled crossover quantification study, fixture-level crossover durability testing, and field validation of the optimized return-to-primary configuration proposed in this report.

Abbreviations and Acronyms

Acronym	Meaning
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
Btu/hr	British thermal unit per hour
Btu/hr-apt	British thermal unit per hour per apartment
MBtu/hr	Thousand British thermal units per hour
DHW	Domestic hot water
CDHW	Central domestic hot water
CHPWH	Central heat pump water heater
CO_2	Carbon dioxide
COP	Coefficient of Performance
CPC	California Plumbing Code
CPUC	California Public Utilities Commission
CPVC	Chlorinated polyvinyl chloride
CZ	Climate zone
EIA	U.S. Energy Information Administration
eTRM	Electronic Technical Reference Manual
gpm	Gallons per minute
hp	Horsepower
HPWH	Heat pump water heater
HWS	Hot water supply
HWR	Hot water return
IOU	Investor-owned utility

Acronym	Meaning
kW	Kilowatt
M&V	Measurement and verification
NEEA	Northwest Energy Efficiency Alliance
PEX	Cross-linked polyethylene
PG&E	Pacific Gas & Electric
PLT	Parallel loop tank
PNNL	Pacific Northwest National Laboratory
RASS	Residential Appliance Saturation Survey
RECS	Residential Energy Consumption Survey
RTP	Return to primary
TM	Temperature maintenance
UA/Apt	Heat loss rate per apartment
UPC	Uniform Plumbing Code
W	Watts
W/apt	Watts per apartment
W/unit	Watts per unit

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Introduction

This study explored central domestic hot water (CDHW) recirculation systems in California multifamily buildings, the temperature maintenance heat losses they incur, and the resulting impacts on central heat pump water heater (CHPWH) designs. Recirculating distribution is a standard plumbing design choice that ensures on-demand hot water is reliably and safely supplied to end-use fixtures throughout a building. Hot water is pumped throughout the building continuously, often through a set of parallel loops past various end-uses or non-recirculating apartment branches before returning to the water heating system for reheating. These systems are used in large multifamily and non-residential buildings with distributed end-uses, regardless of whether the primary heat source is natural gas, electric resistance, steam, or a heat pump. The conditions and efficiency of the recirculating distribution system have energy and performance implications for any of these heat sources, albeit with unique impacts when a CHPWH is used.

Recirculating hot water continuously loses heat to its surroundings through pipe surfaces, thermal siphoning, and other mechanisms. These heat losses are unproductive loads. Recirculation losses typically account for a substantial amount of the total thermal load thereby influencing the design, energy use, and sizing of hot water systems. This load exists even when building occupants draw no hot water, since the recirculating water itself must be reheated. Satisfying these unproductive loads by ensuring an acceptable building supply temperature is referred to as "temperature maintenance." The design, sizing, and control of any given recirculating CDHW system needs to consider these temperature maintenance loads. For instance, a CHPWH system can integrate or separate the temperature maintenance loads from the primary heat pump heat source. In any type of CDHW system, distribution and recirculation inefficiencies can cause issues such as large energy waste, reduced hot water availability, and low supply temperatures at the furthest end-uses, if not properly designed and managed.

Fortunately, there are many opportunities to minimize temperature maintenance losses through design choices, controls, and remediating measures in existing buildings. However, there are knowledge gaps regarding recirculating system performance and program opportunities, especially in existing buildings. A stronger understanding of recirculation loads, their driving factors, corrective actions, and their relationship to building characteristics could help improve existing CHPWH design tools, improve system performance regardless of heat source, and establish program support pathways.

To this end, the project team gathered field data from existing multifamily buildings to quantify recirculation loads and correlate them to as-built characteristics such as pipe sizing, layout, balancing, insulation, and thermally isolating pipe supports. The project team assessed these driving factors so existing design and modeling tools can adapt to accurately account for recirculation losses and recommend CHPWH configurations based on building conditions. Opportunities for recirculation system improvement through balancing, pipe insulation, pumping control, mixing valves, and crossover mitigation were explored and informed recommendations for existing measure updates, new measure development, and system design, especially as it relates to buildings that use CHPWHs.

Background

In most residential buildings throughout the United States, domestic hot water (DHW) use ranks as one of the largest energy end-uses next to space conditioning. According to the 2020 Residential Energy Consumption Survey (RECS), water heating accounts for approximately 30 percent of total energy consumption in multifamily buildings with five or more units throughout the country (U.S. EIA 2024). The 2020 RECS also indicates that based on survey responses, water heating accounts for about 45 percent of total site energy usage for California's multifamily buildings (U.S. EIA 2023). An estimated 50 percent of these multifamily buildings use central gas water heaters (California Energy Commission 2024).

Multifamily buildings typically use CDHW systems to meet their hot water demands due to several benefits over smaller, individual water heaters throughout a building, including reduced space requirements, reduced capital costs, and ease of maintenance (Kintner and Larson 2019). These systems also necessarily employ a temperature maintenance strategy. The main objective of temperature maintenance in DHW systems is to ensure that hot water can be reliably supplied at all fixtures throughout a building with minimal wait times to conserve water use and energy (PNNL 2021). The most common type of temperature maintenance mechanism uses a recirculation system, circulating hot water throughout the DHW distribution piping to ensure that hot water demand can be quickly met even at faraway fixtures. A dedicated pump circulates the hot water before it returns to the hot water source to be reheated (PNNL 2021).

An emerging, proven electrification strategy for CDHW systems in existing multifamily buildings is upgrading to a CHPWH. Heat pump water heaters (HPWH) can produce two to four times more heat per unit input as compared to electric resistance and fossil fuel-fired water heaters, making the process highly efficient (ASHRAE 2023). Inefficiencies in the existing hot water distribution system, however, often require upsized CHPWHs to accommodate both hot water demand and temperature maintenance losses and can impact system performance.

For recirculation systems, these inefficiencies are caused by heat transfer from the piping to the surroundings due to hot water being continuously circulated throughout recirculation loops. Recirculation losses typically contribute approximately 30 percent of total thermal loads in multifamily CDHW systems but can be greater. These losses can be attributed to, but are not limited to the following factors:

- Piping lengths and diameters
- Piping insulation and lack thereof
- Hot water flow balancing
- Crossover from hot to cold piping
- Thermal bridging through physical paths such as pipe hangers

Crossover is the flow of hot water into cold pipes or cold water into hot pipes through failed valves and open mixing points, driven by intrinsic pressure imbalances that occur as pumping and end-use demand ebbs and flows. Crossover from cold piping to hot can but does not necessarily impact hot water system efficiency; this is a nuanced topic that is further discussed in the Discussion section.

Previous Studies

Despite DHW being one of the largest energy end-uses in residential buildings, relatively few studies have examined how to optimize recirculation loops or reduce their associated thermal losses. All DHW piping experiences unavoidable heat loss to the surrounding environment (PNNL 2021). Pipe insulation helps reduce these losses, but more comprehensive strategies are needed to effectively manage losses and ensure energy and water are efficiently used throughout a CDHW system. Prior studies report that recirculation-related thermal losses can account for an average of 30 to 40 percent of total system load, accounting for 7 percent to 42 percent of total DHW energy use (PNNL 2021), (California Energy Commission 2013). These losses can also contribute 10 to 25 percent of the total building load and are influenced by factors such as fixture flow rates and dead-leg branches which are pipe branches not served by the temperature maintenance system (PNNL 2021). Although dead-leg branches are inherent to CDHW systems, keeping them under 50 feet can help reduce losses (PNNL 2021). Losses are further exacerbated by elevated supply temperatures and high recirculation flow rates (PG&E 2024).

Optimal design, operation, and maintenance for recirculation loops require careful consideration of the following components:

- **Return loop layouts** consisting of mains, subloops, and dead-leg branches to connect the hot water generation system to balancing valves and end-use fixtures.
- **Balancing valves** to regulate hot water flow in various parts of the return loop to balance heat losses and branch supply flows. Primary types are manual pressure-dependent, automatic fixed-flow, and thermostatic.
- **Recirculation pumps** to maintain hot water availability.

Figure 1 illustrates a typical recirculating DHW system, showing a two-loop configuration with a single riser, major components, water flow paths, and locations of heat loss. Heat losses occur throughout but may be exacerbated in piping leaving the hot water generation system and storage tanks where temperatures are highest and near valves. Dead-leg branches, where hot water is not circulating, may also increase energy consumption due to heat transfer to stagnant, unused water. An efficient system will have the return loop as close as possible to the hot water end-use fixtures and reduce the length of dead-leg branches to minimize hot water wait times and consequently reduce energy use (PNNL 2021). Insulated piping compliant with energy codes throughout the entire system will further support efficiency by helping maintain required hot water temperatures and reduce heat loss to the surroundings.

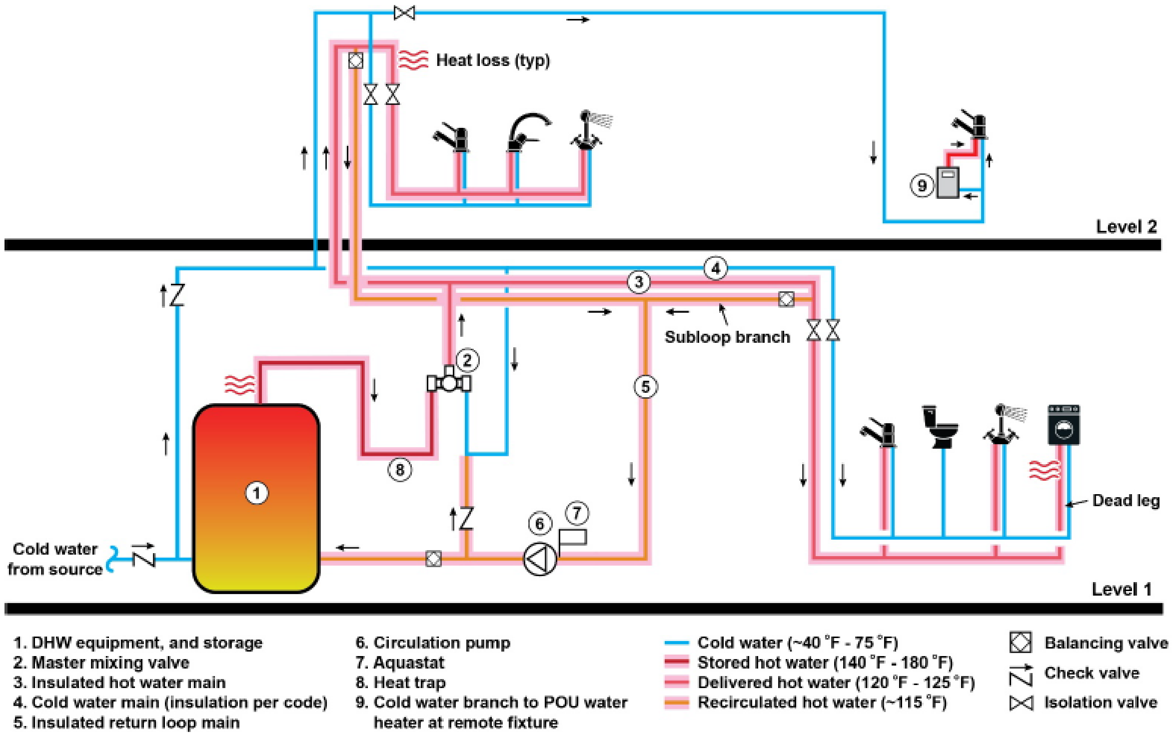

Figure 1: Example of efficient recirculating hot water system design.

Source: (PNNL 2021).

CDHW systems commonly use parallel paths to reach all parts of the building before water returns to the recirculation loop (PG&E 2024). In mid-rise and high-rise multifamily buildings, these paths are typically formed by vertical risers supplying hot water to groups of units on different floors. Balancing valves maintain appropriate recirculation flows across risers to ensure consistent hot water delivery to all units. Balancing valves are often placed after the loop passes the end-uses, before joining the return line. When recirculation flows become unbalanced, some risers may receive insufficient hot water, while others may receive excessive flow. These conditions may result in increased energy losses, piping erosion, pump stress or failure, and long wait times at distant fixtures (PG&E 2024). Building operators may opt to increase supply temperatures or flowrates to ensure adequate service at the most constrained end-use locations in response. Increasing temperatures to mitigate supply issues could cause increased losses or risk scalding if the temperatures are increased.

A recent Pacific Gas & Electric (PG&E) lab study evaluated manual, automatic, and thermostatic balancing valves in multifamily buildings. All balancing valve types helped risers reach target recirculation temperatures (PG&E 2024). Higher recirculation flow rates improved consistent temperatures across risers, with performance considered satisfactory for flow rates above 2.5 gallons per minute (gpm). At lower flow rates, automatic and thermostatic balancing valves showed greater variability in temperature distribution due to their design characteristics (PG&E 2024).

Each balancing valve type demonstrated distinct advantages and limitations:

- **Manual balancing valves** required time-intensive setups and readjustment during operational changes but produced the most uniform riser temperatures when configured on colder recirculation return flows. Their primary benefits are low initial costs and simplicity in design and operation.
- **Automatic balancing valves** offer moderate initial costs and ease of installation but require more complicated design considerations. There is limited flexibility if system conditions change after commissioning. The tested products maintained balanced recirculation over a range of operating conditions, including when recirculation flow rates were lower or slightly higher than the balancing valve's rated flow.
- **Thermostatic balancing valves** are simple to install and provide more operational flexibility but tend to have higher upfront costs and lower precision.

Recirculation system losses depend on various building and system characteristics. The PG&E findings illustrate an example of recent efforts to better quantify the performance and limitations of specific recirculation system components.

Ecotope conducted a literature review examining CDHW distribution losses in multifamily buildings. The literature review compiled findings from 46 existing buildings in California, New York, and Washington and found highly variable loop losses ranging from 10 to 553 watts per dwelling unit (W/unit), with an average of 143 W/unit. (Kintner and Larson 2019).

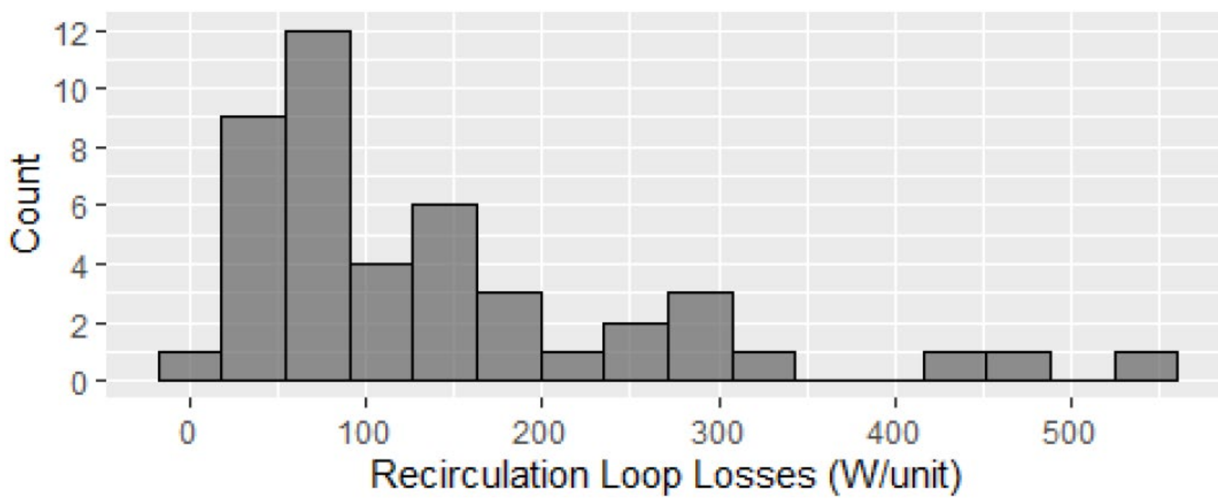

Figure 2: Histogram of recirculation loop losses from Ecotope's literature review.

Source: (Kintner and Larson 2019).

The literature review drew several key conclusions:

- Seasonal temperature differences significantly impact recirculation loop losses for CDHW systems located in unconditioned spaces.
- Pump controls and temperature modulation are the most common strategies to address recirculation losses. However, an earlier study from the California Energy Commission found these controls to be underused or improperly configured when implemented in California's surveyed multifamily buildings (California Energy Commission 2013).
- Reducing losses requires better documentation of system design details, including pipe length, size, insulation, and placement.
- Standard design practices for recirculation loop placement within conditioned spaces or piping layout requirements are limited; earlier research found that there were no widely accepted guidelines at the time.
- Code development and enforcement were still needed to address issues such as insulated piping, which was common in the reviewed buildings from previous studies referenced in the literature review, as well as failed recirculation pumps.

Together, these previous studies demonstrate the complexity of standardizing CDHW recirculation system design and accurately quantifying associated losses. Recirculation losses represent a large portion of the total water heating energy use, further highlighting the need for efforts to better characterize and remediate recirculation losses. These efforts require a more comprehensive understanding of recirculation system configurations, component performance, and maintenance practices. Additionally, this recirculation system survey clearly demonstrated the variation of conditions found in existing buildings and that recirculation losses can and do grow over time as distribution systems degrade and drift from their initial commissioned, code-compliant state.

Multifamily Central Domestic Hot Water System Market Share

Most new multifamily buildings use CDHW systems with a temperature maintenance system to ensure hot water availability (Kintner and Larson 2019). In California, central water heating systems in existing multifamily buildings are estimated to serve about 1.9 million residences (Valmiki, et al. 2023). Table 1 summarizes the distribution of multifamily building types with central water heating systems and the corresponding number of residences respectively across all 16 California Title 24 climate zones.

Table 1: Estimated market size of existing CA multifamily buildings with CDHW systems.

	Number of Buildings				Number of Residences			
CZ	Low-Rise 1-2 Story	Low-Rise 3 Story	Mid-Rise 4-6 Story	High-Rise 7+ Story	Low-rise 1-2 Story	Low-rise 3 Story	Mid-rise 4-6 Story	High-rise 7+ Story
1	99	83	30	17	969	1,618	2,315	2,673
2	590	493	179	102	5,755	9,610	13,749	15,876
3	3,075	2,567	934	529	29,990	50,080	71,651	82,731
4	1,616	1,349	491	278	15,758	26,315	37,649	43,471
5	260	217	79	45	2,535	4,234	6,058	6,994
6	1,832	1,529	556	315	17,865	29,834	42,684	49,285
7	1,693	1,413	514	291	16,509	27,568	39,443	45,542
8	2,839	2,370	862	489	27,684	46,230	66,143	76,371
9	6,304	5,262	1,915	1,085	61,480	102,666	146,888	169,602
10	1,835	1,532	557	316	17,899	29,890	42,765	49,378
11	475	396	144	82	4,629	7,730	11,059	12,770
12	2,641	2,205	802	455	25,757	43,011	61,538	71,053
13	894	746	271	154	8,715	14,554	20,822	24,042
14	459	383	139	79	4,477	7,477	10,698	12,352
15	232	194	71	40	2,265	3,782	5,411	6,248
16	160	133	48	27	1,556	2,599	3,718	4,293
Total	25,004	20,872	7,592	4,304	243,843	407,198	582,591	672,681

Source: (Valmiki, et al. 2023).

According to the 2019 California Residential Appliance Saturation Survey (RASS), only about eight percent of multifamily homes use an electric water heating system, which suggests relatively slow adoption of electrified systems (DNV GL Energy Insights USA 2021). Many of the buildings and residences in Table 1 likely use natural gas-fired or electric resistance water heaters and may be suitable candidates for HPWH system retrofits.

Although designers and engineering firms with expertise in heat pump and plumbing systems could implement heat pump-based retrofits for water heating, they frequently depend on updated technical guidance and sizing tools from subject-matter experts for CHPWHs. Current tools require improvements to account for recirculation loads more accurately, which will support optimal system configuration and sizing for CHPWH applications.

Code Compliance

Title 24

California's energy and plumbing codes provide requirements for water heating systems and recirculation loops. Section 160.4 and 110.3(c)4 of the 2025 Energy Code outline specifications for systems serving multiple units, and similar requirements are described in Chapter 5 of the California Plumbing Code (CPC). The CPC, however, defers to Title 24 for mandatory requirements. Recent additions to 160.4, including multifamily pipe insulation requirements, may create confusion towards which requirements are applicable under each section and where compliance overlaps across codes. Improved clarification and cross-referencing among the relevant water heating specifications in these codes may help streamline code interpretation and compliance. These requirements also primarily apply to new construction but reflect a broader shift towards higher DHW system efficiency when existing water heater systems undergo alterations or additions.

Pipe insulation remains a key strategy to reduce recirculation loop losses and is mandated for all DHW piping. Historically, pipe supports, hangers, and clamps were not required to be insulated, creating thermal bridges that increased heat loss. The 2025 code requires that pipe supports, hangers, and clamps need to be mounted outside rigid pipe insulation to avoid thermal bridging. (California Energy Commission 2025). The code also specifies that the first eight feet of inlet cold water piping from hot water storage tanks must be insulated and that all insulation seams on DHW piping must be sealed. Table 2 summarizes the minimum pipe insulation thickness requirements for multifamily DHW piping, based on pipe diameter and typical DHW operating temperatures between 105 and 140°F.

Table 2: California energy code DHW piping insulation requirements per Section 160.4

Insulation Rating	< 1" Pipe Diameter	1 to < 1.5"	1.5 to < 4"	4 to < 8"	≥ 8"
Thickness (in)	1.0	1.5	2.0	2.0	2.0
R-value	R 7.7	R 12.5	R 16	R 12.5	R 11

Source: (California Energy Commission 2025).

Section 170.2 of the 2025 Energy Code specifies prescriptive requirements for multifamily central hot water systems. Gas systems require a minimum thermal efficiency of 90 percent and central DHW systems must have a recirculation system with a thermostatic mixing valve on each distribution supply and return loop. Although these requirements may soon change under current proposals, CHPWH systems must return recirculating hot water to an electric recirculation loop tank (i.e., a swing tank or temperature maintenance tank) rather than the primary HPWH or thermal storage tank. The primary storage tank temperature setpoint must be at least 135°F and the recirculation loop tank temperature setpoint needs to be 10°F lower than the primary storage tank setpoint. To comply with prescriptive standards, all central, distributed DHW pipes shall be sized according to

Appendix M of the CPC based on the Uniform Plumbing Code (UPC). Any installed system is expected to have performance equal to or better than one with these requirements listed above.

California Plumbing Code

Designers have historically relied on UPC Appendix A to size plumbing pipes. It offers a general procedure to size hot water systems based on supply demand. Supply demand can be determined from the hot water fixtures throughout the building main, the principal branches, and risers on the hot water system. Appendix A sizing is based off the Hunter's Curve for estimating water supply demand, which was established in 1940 and well in advance of codes standardizing low-flow plumbing fixtures.

California adopted UPC Appendix M into its plumbing code in 2023, which offers an alternative demand load estimation method for new single-family and multifamily buildings. Appendix M is not mandatory unless otherwise adopted by a state agency or ordinance. However, Title 24, Part 6 does include Appendix M pipe sizing as a prescriptive requirement. Demand load estimates in Appendix M consider water-conserving plumbing fixtures which have lower expected peak flow rates compared to the Hunter's Curve. The methodology provides a Peak Water Demand Calculator to determine design flow rates for a building's risers, supply mains, and other major hot water distribution branches. Water piping sizes are still determined with the procedures defined in Appendix A, however the new methodology from Appendix M offers the potential to satisfy DHW system requirements with smaller pipe sizes since it assumes lower peak flow rates for the same quantity of fixtures.

Domestic Hot Water Recirculation System Challenges

Hot water distribution systems have long been identified as a target area for improving energy efficiency. It is often challenging to optimize temperature maintenance systems in existing CDHW systems. These difficulties create market barriers not only for enhancing system efficiency, but also for developing accurate sizing and design tools for system upgrades, including for CHPWH retrofits. Key optimization challenges include:

- Lack of standardization for DHW system design and recirculation piping layouts
- Constraints imposed by existing piping layout and system architecture
- Uninsulated or poorly insulated piping and degradation over time
- System location in an unconditioned space
- Limited monitoring, control strategies, and automation on pumps and loops
- Degraded or poorly implemented recirculation balancing procedures
- Crossover issues at failed valves or open mixing points
- Insufficient documentation of DHW system characteristics, especially in older buildings
- Aging water heating equipment and components such as heaters, fixtures, and valves
- Limited feasibility of system improvements as retro-commissioning measures
- Minimal field data and documentation on recirculation loop losses and mitigation actions

A variety of strategies exist to remediate these issues, including replacing aging components, adding pump controls, upgrading pipe insulation, installing balancing valves, and relocating the hot water system to a conditioned space. These strategies, however, may not be practical or financially feasible. Without clear incentives, building owners may be reluctant to replace equipment that still functions, even if performance is suboptimal. In older buildings, documentation may be limited to as-built drawings, which are often unavailable, making it difficult to assess current component conditions or select appropriate corrective actions.

Insulating the recirculation loop piping can help reduce thermal losses, yet many multifamily residences lack workable access to these pipes, or they may be embedded within walls. Additionally, adequate insulation is a relatively recent code requirement, meaning older buildings may not comply. (Ayala and Zobrist 2012). In many cases, insulation can only be added during construction or a major renovation, which are both efforts that will require additional costs and disruption for the building owners (Ayala and Zobrist 2012). Piping layout, system architecture, and equipment location also influence recirculation loads but may not be feasible to modify beyond the construction phase.

These challenges directly affect the design and deployment of CHPWH systems. Some specific impacts include:

- Oversizing equipment to account for both peak DHW loads and recirculation losses
- Increased first costs
- Larger space requirements for heat pumps and storage tanks
- Temperature maintenance configurations that lower the overall system efficiency
- Temperature maintenance impacts differing across different CHPWH configurations
- Existing sizing and design tools that lack sufficient empirical data on recirculation loads and distribution system conditions

As CHPWH adoption grows across more system configuration and balancing approaches, accurately characterizing and accounting for temperature maintenance loads during design and installation becomes increasingly important. Improved design tools that account for these loads under real-world conditions will encourage appropriate system sizing and broader deployment of CHPWHs in multifamily buildings. This study surveyed existing multifamily buildings with CDHW systems across California to potentially address these challenges. The project team captured data on recirculation system performance to build a stronger understanding of recirculation systems and their relationship to various building characteristics. These insights informed targeted improvement strategies and clarified the data needed to enhance CHPWH design tools, optimize retrofit outcomes, and justify program support pathways for recirculation remediation measures.

Technology Transfer Opportunities

This project aimed to characterize temperature maintenance loads in multifamily CDHW systems and understand how these loads are shaped by building characteristics and as-built plumbing conditions. This data is essential to advance appropriately sized, cost-effective CHPWH systems across various configurations while minimizing cost, space requirements, and grid impacts. As a result, the project supports multiple technology transfer opportunities not only for broader CHPWH adoption, but also for improving existing measures, programs, design practices, and tools related to multifamily hot water distribution.

Current CHPWH sizing tools, such as the publicly available Ecosizer, often rely on conservative assumptions for recirculation temperature maintenance loads due to limited empirical data and the absence of accurate load-prediction methods. This data gap also impacts manufacturers, who similarly depend on conservative sizing approaches. By capturing real-world recirculation load data, this project will help bridge information gaps and benefit the entire CHPWH market, from system designers to manufacturers and program implementers.

Several existing California programs address measures for multifamily hot water distribution systems, regardless of whether a site uses a CHPWH. These programs include the Multifamily Energy Efficiency Program and the Energy Savings Assistance Program, both administered by California investor-owned utilities (IOUs) under the California Public Utilities Commission (CPUC); TECH Clean California, administered by the CPUC, and the Low-Income Weatherization Program, administered by the California Department of Community Services and Development. The findings from this project may support updates to these programs by providing additional evidence, market potential, and technical justification to improve measures targeted at CHPWH adoption and addressing distribution system inefficiencies.

The California Electronic Technical Reference Manual (eTRM) has some measures relevant to multifamily domestic hot water systems that cover alterations or upgrades to the recirculation system as well as other components of the hot water system. These measures include SWWH028 for CHPWH fuel-switching retrofits, SWWH017 for pipe insulation, SWWH018 for hot water tank insulation, and SWWH016 for boiler temperature control. For recirculation pumps, SWWH015 is for the replacement of existing recirculation pumps with pumps using flow control methods to meet hot water demand and SWWH022 is for the use of properly sized, high-efficiency pumps with variable speed controls.

California's Codes and Standards Enhancement (CASE) Initiative also published proposed code changes to the 2025 energy code, including multiple sub measures for central DHW systems in multifamily buildings that were adopted. These new additions included (Feng, et al. 2025):

- Using pipe sizing methodology based on CPC Appendix M instead of Appendix A
- Field verification of installing code-required pipe insulation and insulation installation quality for new construction buildings
- Requiring thermostatic balancing valves on multi-riser central DHW systems for new constructions and for additions and alterations.
- Installing a thermostatic master mixing valve on the central heating plant hot water supply (HWS) outlet leading to the recirculation loop
- All new central DHW systems must be electric-ready. New construction multifamily buildings with gas or propane central water heating equipment must provide planning and infrastructure for future HPWH equipment

This study applies a physics-based calculation framework to evaluate recirculation heat losses and potential efficiency gains. The approach assumes ideal conditions for the sites presented and captures the combined effects of pipe sizing and insulation improvements, including the application of CPC Appendix M. Through the combination of measured field data with modeled performance, the study findings provide a robust basis for evaluating optimization strategies to reduce temperature maintenance loads and optimize CHPWH design and commissioning choices. Additional details on this approach and the results are presented in the Findings and Discussion sections.

The data collected in this study can also inform the development of new and updated measures that address remaining distribution system inefficiencies and CHPWH design procedures. In addition, the project supports evaluating optimization strategies across multiple DHW system elements, including recirculation pump controls, system rebalancing, thermal bridging remediation, crossover correction, and the performance of thermal mixing valves. Since these strategies also apply to existing gas and electric-resistance distribution systems, the results can help prepare buildings for future CHPWH upgrades and support California's broader electrification and decarbonization goals.

Objectives

The objective of this field study was to survey recirculation systems in typical CDHW systems across California's existing multifamily buildings. The study analyzed measured and modeled recirculation loads in relation to existing building and hot water system characteristics. Findings from the study can inform CHPWH design and temperature maintenance system performance. The project team provides several recommended measures and future research opportunities to minimize temperature maintenance losses for new construction buildings and support improved recirculation system design in CHPWH installations.

This study:

- Presents how temperature maintenance loads are influenced by building characteristics and as-built plumbing conditions.
- Provides recommendations on how to improve and adapt sizing tools and design guidelines for CHPWHs to incorporate an increased understanding of recirculation systems.
- Supports the advancement and development of appropriately sized CHPWHs in various configurations at minimal cost, size, and grid impact, which can lead to more efficient, lower-cost market transformation of the multifamily water heating sector.

Methodology & Approach

Host Sites

The project team recruited, screened, and conducted walkthroughs of multifamily buildings in California. To recruit as many sites as possible, the team did not have many screening criteria and were open to sites across any IOU territory. The minimal criteria included:

- A CDHW system
- Location in California IOU territory
- Over 30 residences using the hot water system
- Access to past energy bills and as-built plumbing drawings
- Recirculation flow and temperature monitoring feasibility

For each potential site, the project team:

- Conducted a site walkthrough.

- Documented building characteristics, hot water system specifications, and requested as-built plumbing plans.

The team had to exclude many screened sites where the minimum necessary data for the intended analysis could not be gathered. Mainly, these excluded sites either did not have original or as-built plans available, or the plumbing prohibited measurement of the recirculation flows and temperatures. Ultimately, the team was able to select five sites from the pool of recruits, all of which were low-income, affordable housing with two of the five located in disadvantaged communities as designated by Senate Bill 535. Since this was under the target sample size, the team opted to include eight sites which already had ongoing recirculation data monitoring from past connections with the project team. Those supplemental eight sites were well-known to the project team due to their having CHPWH systems installed through other engagements.

For each of these sites, the team collected data through various means and completed analysis of the recirculation loads and building conditions as much as data allowed. With a subset of the sites, the team also conducted a physics-based model of the recirculation loads for comparison to measured values. This model and comparison also allowed for some parametric runs of different insulation and pipe sizing to draw conclusions about possible measures and program recommendations. Finally, the team drew some conclusions about crossover impacts by diving deeper into a subset of the sites where crossover effects could be observed. The following table lists the sites, which data were available, and how the data was used in the study.

Table 3: Site data and analysis matrix.

Site	CDHW Type	Field-Measured Recirculation Load	As-built Plans	Site Walk-through	Physics-based Model	Crossover Analysis
Site 1	Gas	Yes	Yes	Yes	Yes	No
Site 2	Gas	Yes	Yes	Yes	No	No
Site 3	HPWH w/ Swing Tank	Yes	No	Yes	No	No
Site 4	Gas	Yes	No	Yes	No	No
Site 5	Gas	Yes	No	Yes	No	No
Site 6	HPWH w/ Swing Tank	Yes	Yes	No	Yes	Yes
Site 7	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No

Site	CDHW Type	Field-Measured Recirculation Load	As-built Plans	Site Walk-through	Physics-based Model	Crossover Analysis
Site 8	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No
Site 9	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No
Site 10	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No
Site 11	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No
Site 12	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No
Site 13	HPWH w/ Swing Tank	Yes	Yes	No	Yes	No
Site 14	HPWH w/ Swing Tank	No	No	No	No	Yes
Site 15	HPWH w/ Swing Tank	No	No	No	No	Yes

Site 1

Site 1 in the Bay Area in climate zone (CZ) 3 has 110 dwelling units consisting of studios and one-bedroom apartments. The building has approximately 72,192 square feet of residential housing and about 2,850 square feet of commercial floor space for community use.

Site 1 underwent a CHPWH retrofit during the study period. During initial site visits, the system comprised two natural gas water heaters with a storage tank and recirculation pumping in a rooftop room. After retrofit, the primary heat source was two CO_2 HPWHs configured with an electric resistance swing tank in the lower-level garage. The distribution system plumbing was otherwise unchanged, apart from reversing flow through the risers.

The initial hot water system for Site 1 is shown in Figure 3, comprising two 750 MBtu/hr natural gas water heaters, a 600-gallon storage tank, ½ hp constant speed recirculation pump, and a two-stage digital setpoint controller. The insulation in the mechanical room was aged, with some exposed fittings and valves, but was generally in good condition.

Figure 3: Site 1 DHW system mechanical room, recirculation pump, and controller.

After retrofit, hot water was delivered from a CHPWH system in the lower-level garage comprising of two HPWHs, an electric resistance swing tank, storage volume, digital mixing valve, and recirculation pump controlled to a constant return temperature of 110 °F as seen in Figure 4.

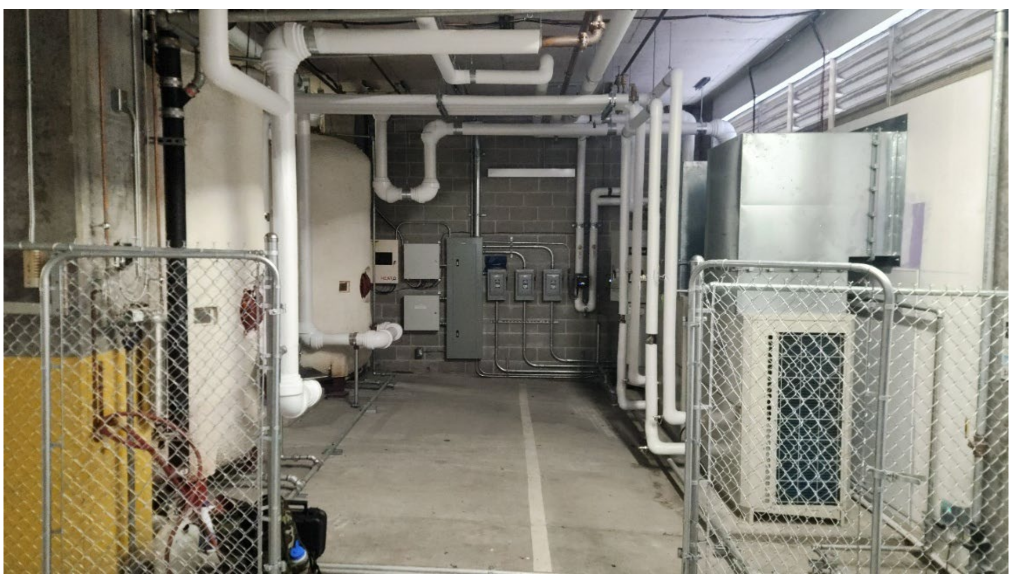

Figure 4: Site 1 CHPWH system.

Site 2

Site 2, also located in the Bay Area in CZ3, has 98 dwelling units consisting of studios, 1-bedroom, and 2-bedroom apartments. The building is committed to energy efficiency, has solar installed, and is one of the first multifamily buildings in Northern California to achieve a LEED silver certification. It has about 58,128 square feet of residential housing.

The hot water system at Site 2 is shown in

Figure 5, comprising two 500 MBtu/hr natural gas water heaters, smart recirculation pumps operating under constant return temperature control mode with a setpoint of 108°F, and a 600-gallon storage tank. Insulation quality was aging with exposed fittings and some drastic degradation and removed insulation in several high-temperature locations in the mechanical room.

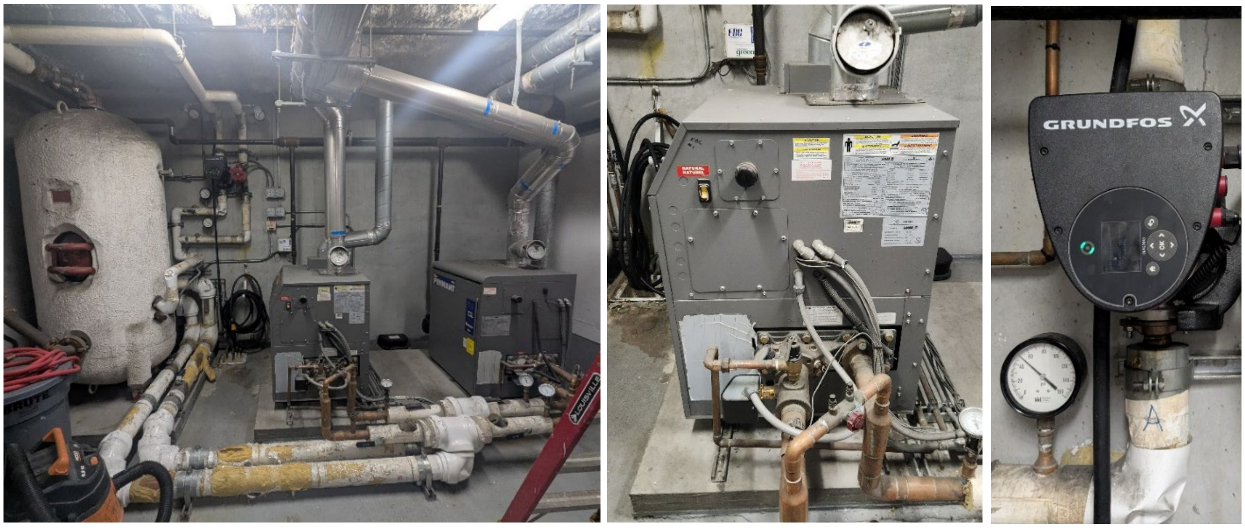

Figure 5: DHW system layout at Site 2.

Site 3

Site 3 in Southern California in CZ6 has 79 dwelling units. The building is 37 years old, has about 43,450 square feet of residential housing across four stories, and is almost fully occupied. There are communal spaces where regularly organized events are held.

The water heating system installed in late 2025 is a CHPWH system with eight 4.5 kW CO_2 HPWHs and an electric resistance swing tank for temperature maintenance. Figure 6 shows the water heating system comprising of a bank of HPWHs, 800 gallons of primary storage, a 13.5 kW electric resistance swing tank, and recirculation pump set at constant return temperature of 115°F.

Figure 6: Site 3 HPWHs, storage tanks, swing tank, and recirculation pump.

Exposed piping is well-insulated, with rigid foam insulation on all exterior piping and fiberglass insulation on all visible interior piping, except for a small portion of the recirculation line where the pump is located. The indoor piping has jacketed fiberglass insulation that is one inch thick on the hot water return (HWR) lines whereas the insulation is about two inches thick on the HWS lines. Any existing pipes between walls were left uninsulated according to the maintenance team.

Site 4

Site 4, also in Southern California in CZ6, is 40 years old and has 36 dwelling units across three stories. It has about 19,800 square feet of residential housing and is fully occupied. This building also has communal spaces for events.

The rooftop gas-fired hot water system shown in Figure 7 was installed in 2023 according to the maintenance team. The system comprises three 200 MBtu/hr natural gas hot water heaters, a 119-gallon storage tank set at 115°F, and constant speed recirculation pump.

Figure 7: Site 4 hot water system, water heaters, and recirculation pump.

The hot water system has black elastomer insulation with a UV coating on most of the pipes. It is one inch thick on the recirculation piping. A small portion of insulation that was missing along the piping was replaced for continuity.

Site 5

Site 5 in Southern California in CZ9 is about 30 years old with 105 dwelling units across four stories served by two identical CDHW systems, each serving half the units. Only one of these was measured.

Each hot water system consists of a 750 MBtu/hr natural gas boiler, storage tank set at 120°F, and variable speed recirculation pump set to operate at constant flow as seen in Figure 8.

Figure 8: Site 5 DHW system and recirculation pump.

The outside pipe insulation on both systems is one-inch-thick elastomeric foam with a UV coating that has been weathered from constant exposure to the elements. As a result, the coating is deteriorated in several locations and gaps are present in the insulation.

Table 4 provides additional high-level details for all the sites surveyed.

Table 4: Additional building details.

Site	Building Type	Stories	Housing Units	Year Built	Climate Zone	Total Circulation Length (ft)	Number of Risers	Pipe Material	Insulation Types
Site 1	High-rise, low-income seniors	9	110	2022	3	2.220	17	Copper	Fiberglass
Site 2	Mid-rise, low-income	4	98	2005	3	3,392	6	Copper	Fiberglass
Site 3	Mid-rise, low-income seniors	4	79	1988	6	No plans available	No plans available	Copper and CPVC	Fiberglass
Site 4	Low-rise, senior housing	3	35	1985	6	No plans available	No plans available	Copper	Elastomeric foam
Site 5	Mid-rise, low-income	4	53	1986	9	No plans available	No plans available	Copper	Elastomeric foam
Site 6	High-rise market rate	7	56	1915	3	1,146	5	CPVC	Polyethylene foam, fiberglass
Site 7	High-rise market rate	7	56	1926	3	1,249	5	CPVC	Polyethylene foam, fiberglass
Site 8	Market rate garden style	2	8	1914	13	175	0	PEX	Elastomeric foam

Site	Building Type	Stories	Housing Units	Year Built	Climate Zone	Total Circulation Length (ft)	Number of Risers	Pipe Material	Insulation Types
Site 9	Market rate garden style	2	8	2024	13	240	0	PEX	Elastomeric foam
Site 10	Market rate garden style	2	8	2024	13	175	0	PEX	Elastomeric foam
Site 11	Market rate garden style	2	8	2022	13	240	0	PEX	Elastomeric foam
Site 12	Market rate garden style	2	8	2022	13	149	0	PEX	Elastomeric foam
Site 13	Seniors	3	59	1957	10	686	6	CPVC	Could not be determined

Pipe insulation observations are also included since the estimated insulation R-value based on measured insulation thickness, as-builts, contemporary code requirements, and material conductivities referenced from the ASHRAE handbook were necessary features of the physics-based modeling assessment. For systems where the insulation has been weathered, damaged, or is discontinuous, actual R-values would significantly decrease and may facilitate greater heat loss compared to the estimated values. More details about insulation reporting and observed conditions are presented in the Findings section.

Measurement Plan

The project team deployed short-term monitoring equipment on the hot water recirculation systems at the first five sites to measure actual recirculation loads. The team also took spot measurements and gathered qualitative findings about the existing central hot water heating systems through surveys, plans reviews, and site walkthroughs. At the eight sites which had already been retrofitted with CHPWH systems, the team also gathered the same set of information but did not have to go on site since monitoring was already in place from prior engagements.

To determine recirculation loads, the project team measured three parameters:

1. Flow of recirculation return water (gpm)
2. Hot water supply temperature (ºF)
3. Hot water return temperature (ºF)

Figure 9 shows where these parameters are measured in the hot water system as denoted by the blue callout boxes. It comes from the Advanced Water Heating Specification (AWHS) Appendix H M&V guidelines for CHPWHs, but the location of monitoring equipment on the system is applicable for any CDHW system recirculation measurement, regardless of the water heater technology.

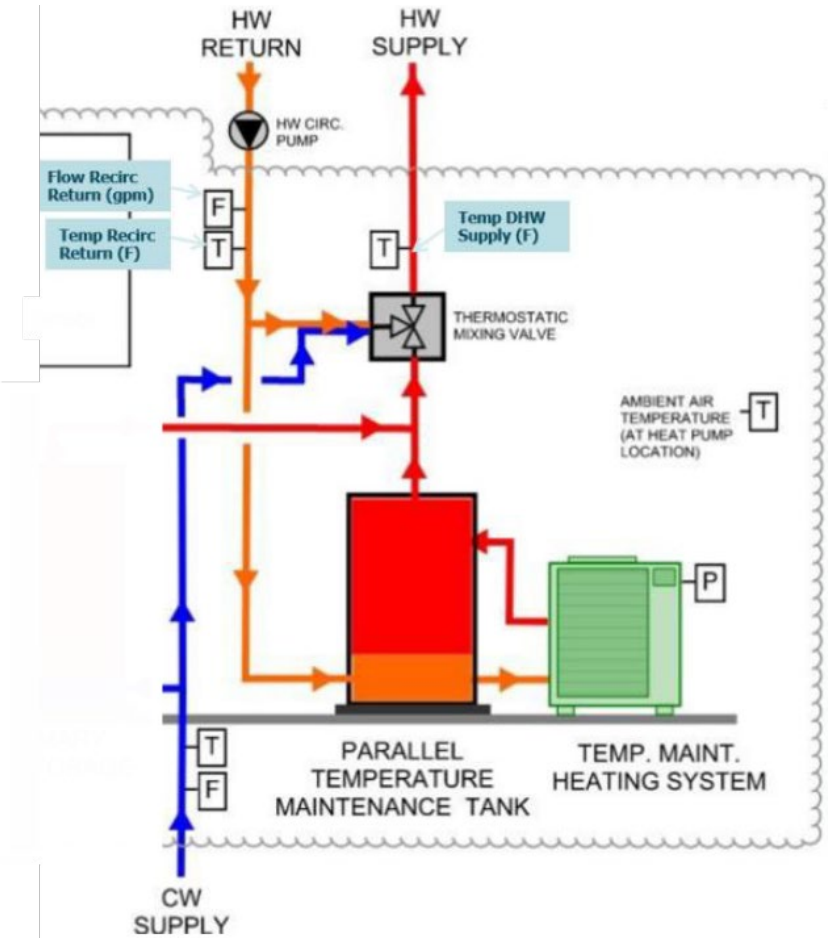

Figure 9: Schematic of M&V equipment setup on hot water recirculation system.

Source: (NEEA 2024).

All the equipment used for this study was non-invasive and had no impact on actual DHW system operation. Data monitoring took place over one week for each site, with the assumption that recirculation loads are relatively constant and unaffected by weather since it is purely a function of material properties, recirculation flowrate, and ambient temperatures which are usually conditioned or close to it. The monitoring equipment for the first five sites and their specifications are listed in Table 5. Although the recirculation return flow was measured at an instantaneous 10 second interval, the measured results were averaged out to align with the 1-minute interval of the temperature data. The results presented in this report were compiled into hourly averages from the minute data. Equipment issues at Sites 3 and 4 necessitated short time interval follow-up measurements to supplement the full datasets. Recirculation loads were calculated using data collected from the equipment in Table 5.

Table 5: M&V monitoring equipment details.

Parameter	Logging Equipment	Logging Frequency	Accuracy
Recirculation Return Flow	Keyence flow meter	10 seconds, instantaneous	+/- 3% of reading
Supply Water Temperature	HOBO temperature logger	1 min average	+/- 0.27°F
Return Water Temperature	HOBO temperature logger	1 min average	+/- 0.27°F

Figure 10 shows a sample of the M&V equipment deployed in the field, which includes the flow meter installed on the recirculation return pipe and the temperature sensor and its corresponding data logger. The insulation was re-sealed over the temperature sensor after installation to ensure accurate pipe temperature readings.

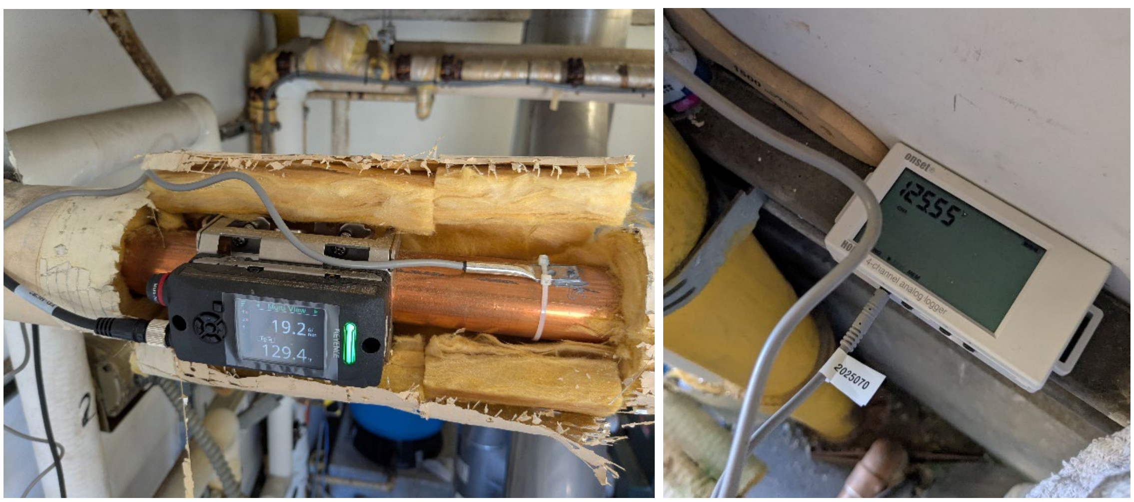

Figure 10: Flow meter and return water temperature sensor installation (left) with temperature logger (right).

Equivalent measurements with the same or better accuracy were gathered for the other sites, albeit with different temperature probes.

Recirculation Load Calculation

Total recirculation heat loss consists of two components: energy lost from continuous recirculation flow as water travels through the primary loop and risers and the additional pipe losses that occur in the branches during hot water draw events. (Kintner and Larson 2019). These losses are denoted as $\dot{Q}_{RecircFlowLoss}$ and $\dot{Q}_{DrawRecircLoss}$ respectively. Both are highlighted in Figure 11 which illustrates the key flows and energy losses within the DHW system.

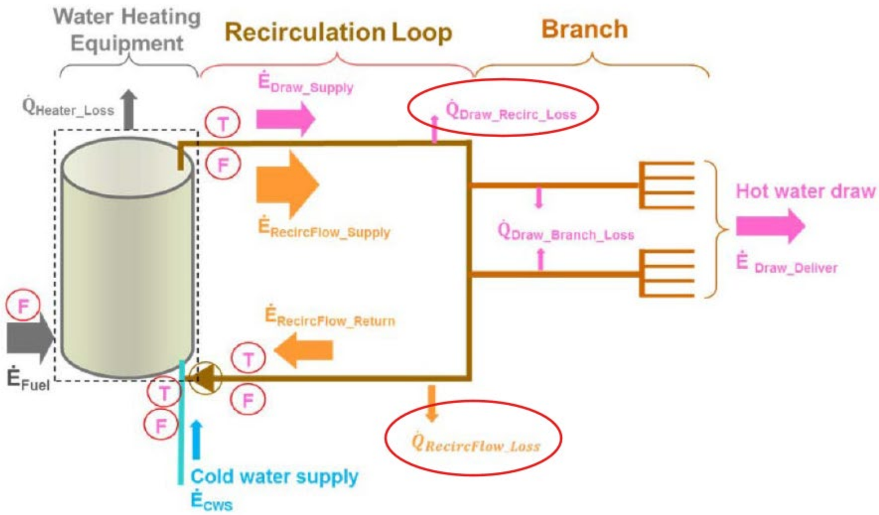

Figure 11: Energy sources and losses in a CDHW system.

Source: (Kintner and Larson 2019).

By measuring the recirculation return flow rate, draw flow rate, HWS temperature, and HWR temperature, the recirculation flow losses ($\dot{Q}_{RecircLoopLoss}$) in Btu/min can be calculated according to:

$$\dot{Q}_{RecircLoopLoss} = \dot{Q}_{RecircFlowLoss} + \dot{Q}_{DrawRecircLoss}$$

$$\dot{Q}_{RecircLoopLoss} = \rho C_p f_{recirc}(T_{HWS} - T_{HWR}) + \rho C_p f_{draw}(T_{HWS} - T_{HW\_Branch})$$

Source: (Kintner and Larson 2019)

ρ = density of water = 8.34 lb/gallon

C_p = heat capacity of water = 1 Btu/lb•°F

f_{recirc} = recirculation flow rate (gpm)

f_{draw} = hot water usage flow rate (gpm)

T_{HWS} = hot water supply temperature (°F)

T_{HWR} = hot water return temperature (°F)

T_{HW_Branch} = hot water temperature entering branch (°F)

Based on Ecotope's review of previous CDHW studies, hot water draw recirculation losses ($\dot{Q}_{DrawRecircLoss}$) were on average, two percent, compared to measured recirculation loop losses averaging at 33 percent (Kintner and Larson 2019). The hot water draw recirculation losses are assumed negligible in this analysis. So, the following equation was used to calculate recirculation load:

$$\dot{Q}_{RecircFlowLoss} \approx \rho C_p f_{recirc}(T_{HWS} - T_{HWR})$$

Distribution System Survey and Review

A distribution system survey was conducted for each field site and can be found in Appendix A. The survey was used to capture more detailed information about each site's building and DHW system characteristics. Site staff were interviewed to clarify equipment quantity, location, and specifications, as well as understand existing conditions and issues with their DHW system. Figure 12 shows example information that was gathered during site walkthroughs, insulation levels, pipe material, and pipe diameters at Site 5 in this case.

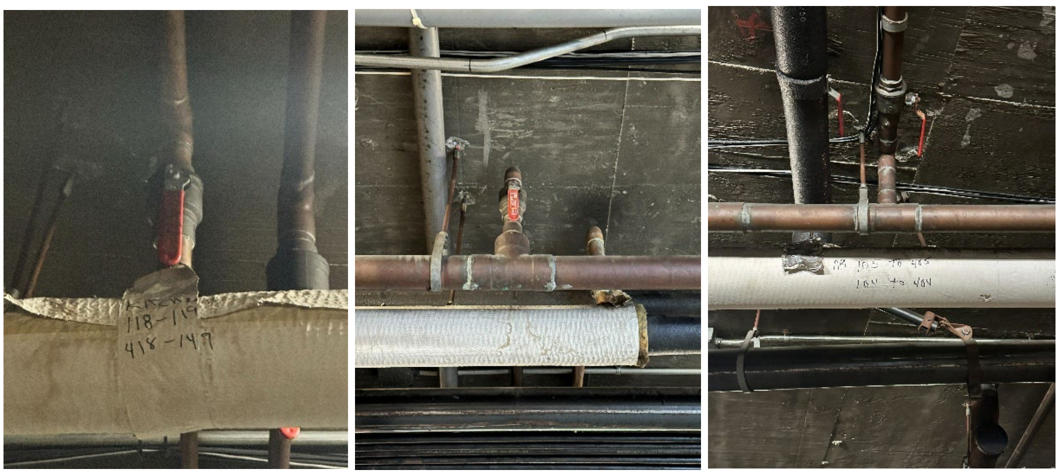

Figure 12: Risers and shut-off valves at Site 5.

This survey was, in part, to gather enough site details as inputs and context for a physics-based calculator to estimate theoretical heat loss for hot water circulation loops. This site review process was conducted for all the field sites and monitored CHPWH sites. The site review process, found in Appendix A, captures comprehensive quantitative details about the sites' DHW systems and as-built specifications. The site review process also compares identified observations and measurements in the field to specifications and settings labeled on site drawings for cross-referencing of multiple data sources added accuracy.

Physics-Based Modeling

The team developed a physics-based excel model to estimate theoretical heat loss for hot water circulation loops based on distribution system geometry, material properties, and operating conditions. Calculated values using this method were compared against measured heat losses at nine monitored buildings. Accurate total pipe lengths derived from as-builts were necessary to include a site in this comparative analysis, limiting the number of total sites that could be analyzed in this fashion.

The calculator determines the theoretical ideal distribution heat loss for each of the monitored buildings if their pipes were perfectly insulated and installed with clevis-style hangers directly mounted to pipes. The following inputs were used to compute this:

1. Total pipe lengths per pipe size from construction plans.
2. Insulation thickness per pipe size from building plans or from the energy code that aligns with the building's year of construction.
3. HWS and HWR temperatures and return flow rate measured using spot measurements or monitoring data.

The following outputs were calculated:

1. Heat loss per pipe segment using the series resistance equation for cylindrical geometry, summed to a total distribution loop heat loss.
2. Pipe hanger heat loss referencing a heat transfer analysis of a clevis-style pipe hanger, cross-referenced against CPC's pipe hanger spacing requirements and observed building pipe material.
3. Heat loss rate per apartment which can be used to compare hot water distribution system design efficiencies between buildings of different sizes.

Appendix C through Appendix E define this calculation methodology in more detail.

Findings

Given the wide range of recirculation loop losses reported in prior studies and the absence of a well-defined threshold for "acceptable" recirculation system performance, measured results for recirculation loads should be interpreted relative to documented building characteristics, system details, and operational context. Ecotope's literature review found that measured recirculation loop losses ranged from 10 to 553 W/unit based on an earlier field study, with a median loop loss of 93 W/unit (Kintner and Larson 2019). This study reported an average recirculation loop loss of 143 W/unit and estimated expected loop losses for a typical new construction building to be in the range of 30 to 60 W/unit. These findings were determined from a sample of 46 multifamily buildings that had anywhere from two to 15 stories and housed 11 to 384 dwelling units. There was no apparent relationship between per-unit recirculation losses and the size of the building. Rather, loop losses can be dependent on several factors specific to the control and condition of the CDHW system itself.

Recirculation, temperature maintenance heat losses were calculated using flow and differential temperature measurements for each site. Table 6 shows this heat loss rate normalized per dwelling unit for each site with reliable data. Average measured recirculation loads at these sites ranged from 24 to 99 W/apt without any apparent correlation to building size.

Table 6: Average recirculation losses for all sites with reliable data.

Site	Housing Units	Recirculation Flow rate (gpm)	Supply Temp (°F)	Return Temp (°F)	Recirculation Losses (Btu/hr-apt)	Recirculation Losses (W/apt)
Site 1	110	20.0	129.7	126.7	279	81.8
Site 2	98	7.5	120.7	115.9	161	47.1
Site 3	79	2.6	120.8	113.8	82	24.1
Site 4	35	2.8	119.3	116.6	111	32.5
Site 5	53	6.4	114.7	111.0	235	69.0
Site 6	56	3.7	123.5	116.4	234	68.6
Site 7	56	4.1	123.5	116.7	248	72.7
Site 8	8	3.0	124.0	122.5	288	84.4
Site 9	8	3.5	124.5	123.0	338	99.1
Site 10	8	3.0	125.0	124.1	163	47.8
Site 11	8	3.2	124.7	123.6	213	62.4
Site 12	8	3.4	125.0	123.6	288	84.4
Site 13	59	4.0	125	124.5	130	38.1

A deeper breakdown of individual site data can be found in Appendix B.

Ideal Distribution Heat Loss

Table 7 shows calculated and measured heat loss and the normalized heat loss rate per apartment (UA/Apt) value for each site with reliable and sufficient data for measured heat loss and the physics-based model. The calculated heat loss refers to the ideal distribution heat loss each building would theoretically exhibit with perfectly insulated pipes and clevis-style hangers directly mounted to pipes. To characterize the gap between idealized and actual performance, a measured-to-calculated heat loss ratio is computed for each site. This ratio ranges from 1.1 to 2.3, meaning that field measured heat losses consistently exceeded idealized heat losses.

Table 7: Calculated versus measured temperature maintenance heat loss.

Site	Pipe Material	Total Pipe Length (ft)	Calculated Heat Loss (Btu/hr)	Measured Heat Loss (Btu/hr)	Measured/ Calculated Ratio	Calculated UA/Apt (Btu/hr·°F Apt)
1	Copper	2,220	20,704	30,708	1.48	3.2
6	CPVC	1,146	6,582	11,942	1.81	2.6
7	CPVC	1,249	7,201	13,648	1.90	2.6
8	PEX	175	1,185	2,300	1.94	2.8
9	PEX	240	1,536	2,700	1.76	3.8
10	PEX	175	1,168	1,300	1.11	2.8
11	PEX	240	1,536	1,700	1.11	3.8
12	PEX	149	1,009	2,300	2.28	2.4
13	CPVC	686	5,237	7,694	1.47	1.7

Figure 13 shows these comparisons graphically.

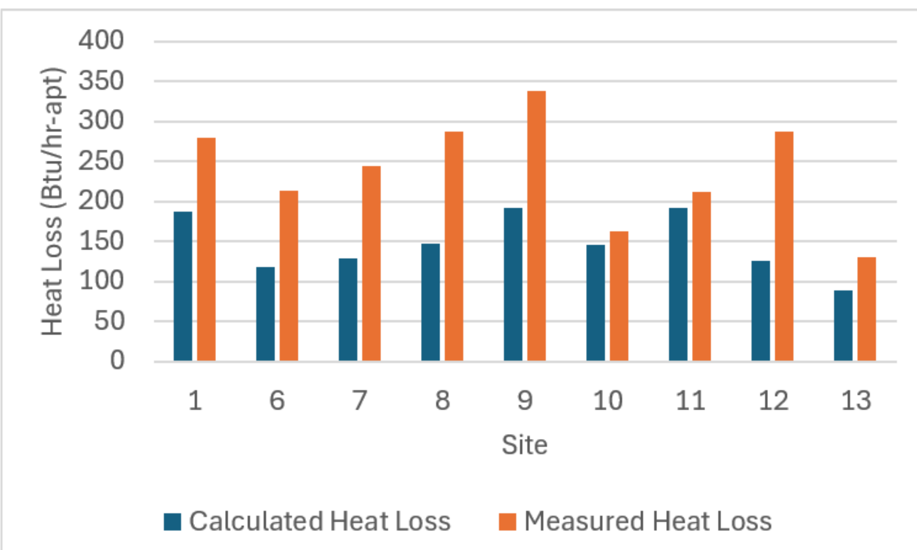

Figure 13: Calculated and measured recirculation heat loss rates.

Distribution Heat Loss Driving Factors

Two most-likely mechanisms through which real-world measured distribution heat loss may exceed the theoretical baseline were explored: imperfections in insulation installation and cold-water crossover into the hot water distribution loop.

Pipe Insulation Imperfections

A calculator was developed to assess how gaps in insulation could contribute to the discrepancy between calculated and measured heat loss. These gaps can result from bare pipe and fittings, valves, or sections where insulation was stripped or removed during maintenance and not replaced. This is particularly a concern for older buildings. Insulated sections are modeled at the code-minimum thickness for each building's construction year, using a fixed insulation conductivity of k = 0.26 Btu·in/hr·ft^2·°F.

Table 8 shows the fraction of total pipe length that would need to be completely bare to explain the measured heat loss. While it is plausible that some portion of the difference between calculated and measured heat loss is due to insulation gaps, the table shows that in most cases, over 20 percent of the distribution system would need to be completely uninsulated, which is implausibly high for most buildings in our sample, especially in newer-construction buildings. Buildings 6 and 7, for example, were constructed in 2022 and are unlikely to have degraded insulation or significant uninsulated sections, suggesting that other mechanisms such as crossover or heat exchange with uncirculated branch lines may be driving the higher-than-predicted measured losses.

Table 8: Insulation gap analysis.

Site	Calculated Heat Loss (Btu/hr)	Measured Heat Loss (Btu/hr)	5% Bare	10% Bare	15% Bare	Bare % to Match
1	20,704	30,708	26,784	29,963	33,141	12%
6	6,582	11,942	7,647	8,658	9,668	20%
7	7,201	13,648	8,396	9,532	10,668	22%
8	1,185	2,300	1,431	1,631	1,830	21%
9	1,536	2,700	1,820	2,041	2,262	19%
10	1,168	1,300	1,431	1,631	1,830	3%
11	1,536	1,700	1,820	2,041	2,262	3%
12	1,009	2,300	1,220	1,393	1,566	28%
13	5,237	7,694	6,426	7,321	8,217	11%

Crossover Presenting as Distribution Heat Loss

Crossover occurs when a faulty fixture valve or an uncontrolled open circuit at a hot/cold mixing point creates a connection between the hot and cold-water subsystems and a pressure imbalance drives flow across it (Ayala and Zobrist 2016). Crossover flow can occur in either direction, but the symptoms and metering signatures will differ accordingly.

When the cold line is at lower pressure than the hot line at the faulty crossover point - during a toilet flush, for example - hot water flows into the cold line. This hot water is effectively wasted and registers in metering as increased hot water usage, not as distribution loop loss. This hot to cold crossover is the less likely version.

Conversely, when the cold line is at higher pressure than the hot line - when hot water is being used - cold water can enter the hot pipes. If this cold water mixes with the hot water and exits through a hot water tap then it will not show up in data monitoring, and the only negative impact is if there is enough leakage to cause tenants to get insufficiently hot water. If cold water crossover leakage enters the HWR pipe to the mechanical room, crossover will show itself in the recirculation return flow and be confused in metering as increased distribution loop losses. Crossover does not increase the amount of heat lost from the hot water distribution loop but is measured as distribution heat loss because it raises recirculation return flow and lowers HWR temperature. Since standard distribution heat loss is calculated as $Q = 500 \times \text{flow} \times (T_{supply} - T_{return})$, this registers as increased heat loss even though no additional heat is leaving the pipes.

Table 9 shows how much cold-water crossover would need to enter the hot water distribution loop to account for the entire discrepancy between calculated and measured distribution heat losses, assuming the building is fully occupied. As with the bare-pipe analysis, this is an upper-bound single-cause estimate, the true gap is likely a mix of crossover, insulation imperfections, and other effects.

Table 9: Amount of crossover required to account for full heat loss discrepancy.

Site	Gap (Btu/hr)	Occupants	Crossover (gal/day)	Gal/day per occupant
1	10,004	93	482	5.2
6	5,360	100	292	2.9
7	6,447	107	352	3.3
8	1,115	30	60	2.0
9	1,164	12	64	5.3
10	132	30	7	0.2
11	164	12	9	0.8
12	1,291	24	68	2.8
13	2,457	75	129	1.7

CROSSOVER FIELD DATA

Three monitored sites illustrated how crossover appears in field data, ranging from an obvious, system-wide failure to subtle effects in new construction.

Site 14 is a monitored retrofit with a known crossover issue that was not included in the calculated versus measured analysis above due to unavailable building plans. The building often sees recirculation return water temperatures below 100°F, which is cause for tenant complaints. In January 2026, the site increased recirculation pump speed in an attempt to remedy low return temperatures but doing so dramatically increased crossover in the building. After the adjustment, more than half of total city water entered through the distribution loop rather than at the hot water plant where total hot water usage is being measured. Figure 14 shows the measured gallons/day/person at the primary plant at Site 14 dropping sharply in January 2026. The measured temperature maintenance load jumped by about 100 W/apt at the same time, shown in Figure 15. DHW supply temperatures are now set above 130°F so that residents at the end of the loop still receive water above 110°F.

This case demonstrates that crossover can substantially affect measured distribution losses. Here, monitoring data and tenant complaints made the issue obvious, but crossover can also occur on a much smaller scale while still inflating measured distribution losses.

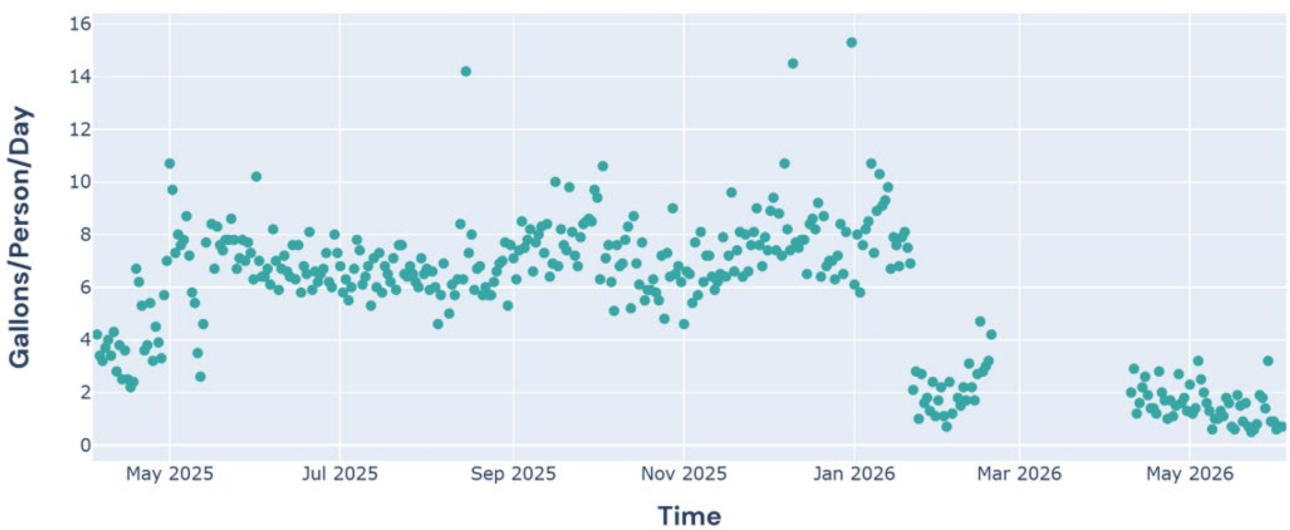

Figure 14: DHW usage drop at Site 14 after crossover event

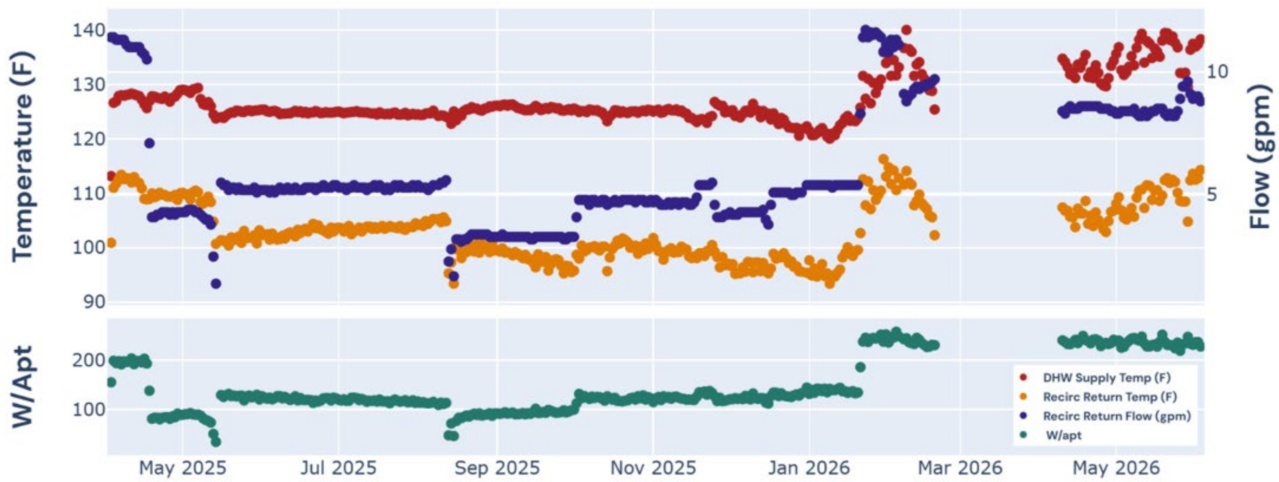

Figure 15: Increase in measured recirculation losses at Site 14 after crossover event.

Site 6 shows a subtler case. Overnight, when hot water usage is near zero, temperature maintenance losses are steady and low. During spikes in DHW consumption, return temperatures drop and recirculation losses rise. To examine this, hourly hot water usage was plotted against temperature maintenance losses. Figure 16 shows the relationship: as usage increases, so do losses, indicating that hot water draws allow cold water into the distribution loop.

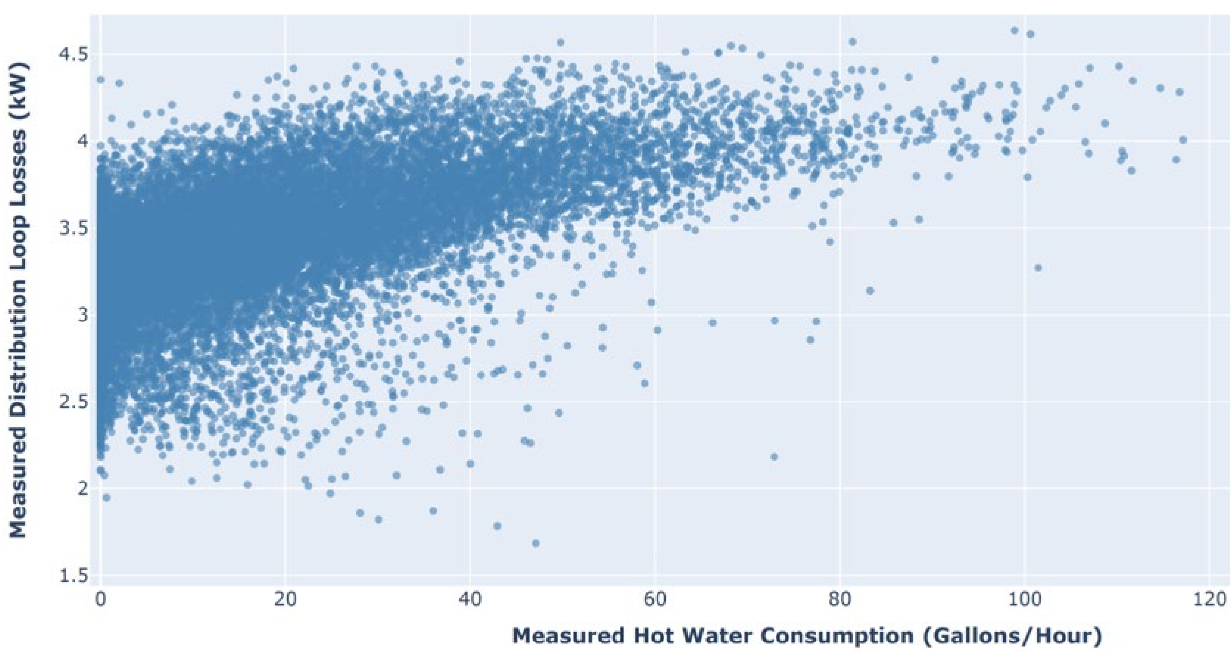

Figure 16: Increase in measured temperature maintenance losses with increased DHW usage at Site 6.

Even in this new building, the trend points to mild crossover that will account for part of the gap between measured and predicted losses. At Site 6, average heat loss at or below 5 gallons/hour of

DHW usage is 10.5 kBtu/hr. Treating this as a non-crossover baseline, the usage-driven increase above it explains over 25 percent of the discrepancy between measured and predicted distribution losses.

Site 15 shows that crossover can stay masked for months or years under one set of pump controls, then appears when controls or pump speed change and shift the pressure balance. Site 15, also excluded from the tables above for lack of building plans, shows two distinct operating patterns before and after a recirculation pump adjustment. Before the change, DHW usage had no effect on temperature maintenance losses. Afterwards, swing tank energy consumption increased and measured distribution losses increased, now attributed to crossover. Figure 17 shows the two operational states. This example demonstrates the need for physical crossover testing, even when no symptoms are present.

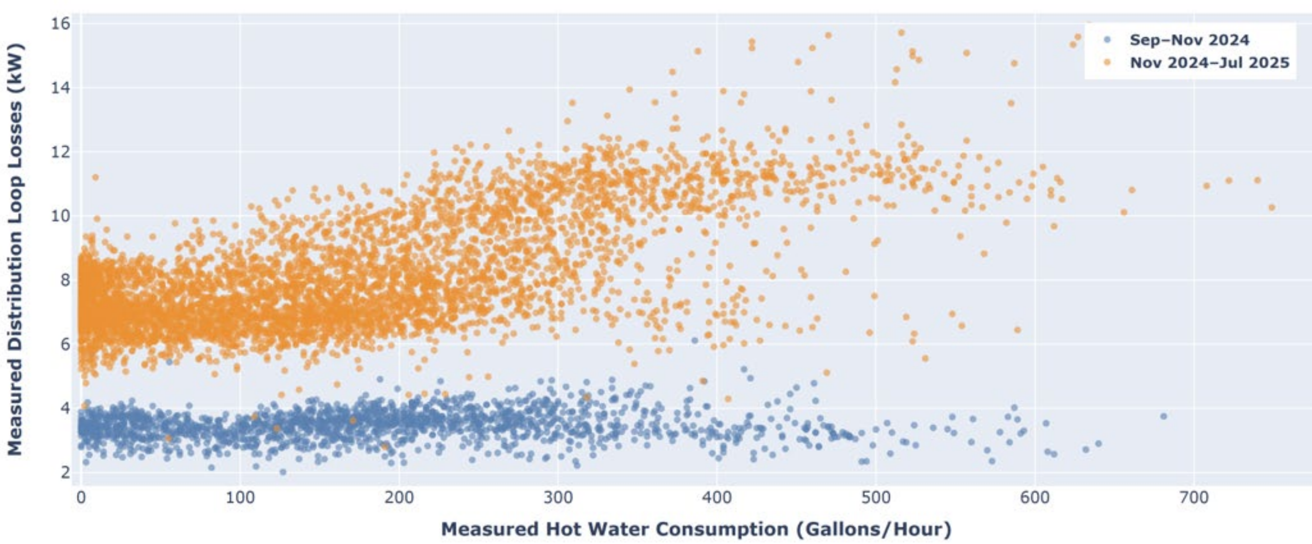

Figure 17: Impact of recirculation pump settings

This crossover data brings into question previous studies whose data suggested extremely high temperature maintenance losses. High temperature maintenance loss readings from monitoring have been misinterpreted in the past by this research team (and likely many others) as real heat loss when in fact a significant portion of measured losses can at times be coming from cold water infiltration into the return line. How the readings are interpreted will lead to different targets for energy efficiency measures.

Beyond inflating measured distribution losses, crossover has direct consequences for plant efficiency — and those consequences differ depending on how the recirculation load is handled at the plant. Later in this report we discuss why crossover resilience is a reason to favor return-to-primary configurations.

Insulation and Pipe Size Measures to Reduce Distribution Heat Loss

The total pipe lengths in these buildings were used to simulate the savings several measures would produce in new construction laid out similarly to the buildings studied. Because real-world installation practices drive discrepancies between ideal and actual heat loss, as seen above, this assessment considers only insulation and pipe size upgrades — measures that change the physical pipe geometry driving heat loss and can be cleanly quantified. The following steps were taken to accomplish this:

1. Calculator inputs were updated in each building to reflect an ideal case where a distribution loop was laid out in the same way as this study's buildings, but with continuous insulation and insulated pipe hangers (per 2025 California Energy Code), and insulation thicknesses driven by 2025 California Energy Code.
2. An analysis was conducted to determine updated pipe sizes if the engineer chose to size per CPC's Appendix M instead of legacy Appendix A.
3. A combination of pipe sizing and insulation thickness updates were entered, and ideal temperature maintenance heat loss was calculated against the 2025 code minimum baseline.

Table 10 shows the predicted Btu/hr losses and percent savings of current code baseline for specific measures if a new construction building were laid out the same way as each of the buildings in this study. The first two rows represent total heat loss based on the ideal calculations and then the current code baseline with the following rows representing additional sizing and insulation measures.

Table 10: Temperature maintenance measure impact on simulated new buildings

Efficiency Measure	Site 1	Site 6	Site 7	Site 8 & Site 10	Site 9 & Site 11	Site 12	Site 13
Total as-built heat loss (Btu/hr)	20,704	6,582	7,201	1,185	1,536	1,009	5,237
Total code baseline heat loss	14,160	5,632	6,206	993	1,260	830	4,470
Appendix M sizing	5.2%	2.3%	2.6%	9.7%	8.9%	9.9%	6.3%
Appendix M + 0.5" on 3/4" & 1-1/4"	12.4%	9.7%	10.1%	15.0%	13.9%	15.2%	11.8%
+0.5" on 3/4" & 1-1/4"	2.5%	5.5%	5.8%	8.2%	6.0%	8.5%	6.1%
+0.5" every pipe size	12.4%	13.7%	14.0%	14.1%	13.6%	14.3%	13.0%

In most cases, Appendix M sizing reduces pipe sizes by one increment throughout the distribution system, for example, from a pipe diameter of 2” to 1.5”. This lowers material cost and speeds hot water delivery, which can reduce hot water consumption. However, this analysis found that in some buildings, down-sizing piping with Appendix M results in small distribution system savings unless it is paired with an insulation upgrade on two specific pipe sizes. When Appendix M drives a high share of piping from a diameter of 1.5" to 1.25", or from 1" to ¾", the smaller size carries a lower code-required insulation thickness, which offsets some of the savings from the reduced geometry. The heat loss savings from adopting Appendix M can therefore be maximized by increasing insulation requirements on the smaller pipe sizes.

Stakeholder Feedback

The project team interviewed several subject matter experts including a hot water system researcher, CHPWH innovator and installing contractor, and plumbing service provider, all of whom have deep knowledge on the topic. Some key themes and consensus appeared in their responses.

Significant, impactful crossover was estimated to be in about 50% of existing buildings with cold to hot crossover being the far more likely scenario. One stakeholder stated, “most older multifamily buildings have it.” One stakeholder estimated only two percent of crossover is hot to cold. This makes intuitive sense since natural pressure imbalances will drive water in that direction. All the stakeholders suggested that most of the crossover in most of the buildings could be remediated as the majority of it occurs at failing end-use valves, most predominantly in shower and sink cartridges. Indeed, remediation is typically only a matter of cost. “They can always be solved if people are willing to pay for the time.”

One stakeholder estimated about 70% of crossover traces to shower cartridges which can usually be replaced for two or three hundred dollars by a professional plumber, including labor. Less commonly, costs can balloon to thousands if the entire valve needs to be replaced due to cartridge availability or stuck components. It can also be time consuming to identify the sources of crossover once it is confirmed with an overall system test. Crossover can be identified with a whole system pressure test, then narrowed down to individual risers, but after that it becomes more difficult and time consuming to identify specific end-uses. It may be easier to simply replace all the cartridges in a loop, if investigation is too time-consuming.

However, it is also clear that these issues do not get resolved as a matter of standard practice even though most plumbing service providers that work with large buildings have the knowledge and skills to do so. Maintenance staff and building owners typically are either unfamiliar with the issue or do not seek resolution even if they are. Proactive distribution system management is virtually non-existent. Crossover issues are not a priority and if they materialize as occupant complaints, pump speed or supply temperatures are simply increased to mitigate low temperatures at the taps. Unfortunately, this does not address the root cause and can mask the issue indefinitely. One stakeholder estimated that about five percent of maintenance staff will replace shower cartridges during unit turnover before a new occupant moves in.

Stakeholders were universally supportive of programs supporting distribution system remediation, especially when done in connection with a CHPWH retrofit. It was obvious that the most opportune and cost-effective time would be during the CHPWH retrofit process. Additionally, when it comes to crossover, remediation will only have real energy benefits for certain configurations of CHPWH such as swing tank or parallel HPWH temperature maintenance. Stakeholders suggested that they would be able to get more work done if programs supported remediation across the distribution system, including pump controls, insulation, crossover correction, and rebalancing. One stakeholder wanted to make clear that turning the recirculation pump off or down when loads are low is still one of the best opportunities for saving energy in existing central DHW systems.

Discussion and Recommendations

A key motivation for this research was to inform utility program design and project stakeholders in support of DHW distribution system remediation, especially in relation to CHPWH retrofits. Potential remediation measures identified through this study include recirculation pump upgrades, balancing valves, control tuning, insulation repair or replacement, correction of non-thermally isolated pipe supports, pipe sizing, and mitigating crossover if it is present. Through this study, the team sought to document the current condition of these systems and highlight observable issues that could potentially be addressed through targeted interventions.

The survey also revealed that maintenance practices were typically limited to annual routine or as-needed inspections, with broader system maintenance and troubleshooting delegated to third-party contractors. In several specific instances of existing plumbing, third-party contractors were the only knowledgeable party rather than in-house maintenance staff. This fragmentation presents a barrier to implementing remediation measures or ongoing maintenance, even when performance issues are identified and technical pathways for improvement exist.

An important outcome of this study is to define what information is most critical when surveying DHW systems and assessing recirculation loads, particularly in the context of CHPWH retrofits. This includes determining which system deficiencies warrant remediation, such as balancing, crossover, or insulation issues. It also includes determining which existing conditions can be reasonably accommodated by a CHPWH system without significant modification or oversizing. Consideration should also be given to whether remediation activities occur prior to, in parallel with, or independent of a CHPWH retrofit, and under what conditions these actions would be cost-effective and operationally feasible.

Recirculation Heating Best Design Practices

There are two general strategies for temperature maintenance heating in CHPWH systems: return-to-primary (RTP) and use of a dedicated temperature maintenance tank. In RTP systems, recirculation return water flows directly to the bottom of the primary storage tank. In dedicated temperature maintenance systems (either parallel loop tank or swing tank), a separate heater helps with temperature maintenance heating and prevents recirculation return water from entering the primary storage tank.

How the recirculation return piping is configured in the mechanical room affects performance differently for each system type. In dedicated temperature maintenance systems, it sets how much load falls on the temperature maintenance heater versus the primary heat pumps. In RTP systems, it affects storage stratification and the temperature of water entering the heat pump. The following section covers piping optimizations for both configurations and the implications of crossover for system selection.

Typical Return-to-Primary Configuration

Figure 18 shows a typical RTP piping configuration commonly encouraged by HPWH manufacturers. In this configuration, HWR flow branches so that a portion enters the cold inlet of the mixing valve while the remaining flow returns to the bottom of the primary storage tank. During periods of little or no hot water usage, HWR is the primary flow through the system, and the mixing valve sets the ratio of HWR entering the storage tank versus the mixing valve cold inlet. During higher usage, pressure drops through each branch determine the ratio of HWR flow through each path.

A balancing valve on the HWR branch to the primary storage tank serves two functions. The first is maintaining stable mixing valve operation during low DHW demand. With no hot water usage, the mixing valve must direct roughly 80 percent of total HWR flow through its cold inlet, with the remaining 20 percent returning to the bottom of the storage tank. Many thermostatic mixing valves lack the valve authority to achieve this 80/20 ratio, which allows excess hot water through the valve and causes mixed supply temperature to creep upward. The balancing valve corrects this issue by creating an artificial pressure drop on the HWR branch to the storage tank, increasing resistance on the hot side of the mixing valve and helping it achieve the required flow ratio. A check valve on the cold-water supply prevents the HWR branch from creating a low-resistance alternate flow path back to the storage tank.

The balancing valve's second, less recognized function is to direct more HWR toward the mixing valve cold inlet during high DHW usage, minimizing both HWR flow to the storage tank and storage tank inlet temperature. Since this function is less apparent to most designers and installers, the balancing valve is often left open and only throttled if supply temperature creep is observed — leaving HPWH inlet water temperature higher than necessary. Regardless, unless the balancing valve is fully closed, some fraction of warm HWR will always return to the storage tank in this configuration.

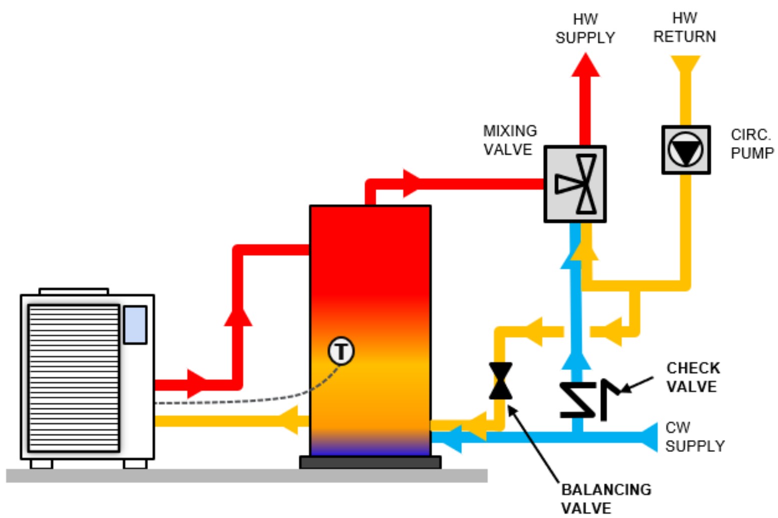

Figure 18: Typical Return-to-Primary piping

One approach to minimize HWR flow to the primary storage tank is the optimized return to primary piping configuration, shown in Figure 19, which has the added benefit of minimizing field piping. Here, HWR and cold water share a common pipe serving the mixing valve cold inlet and there is no HWR branch or balancing valve. Instead, hot water usage volume drives the amount of HWR water entering the storage tank.

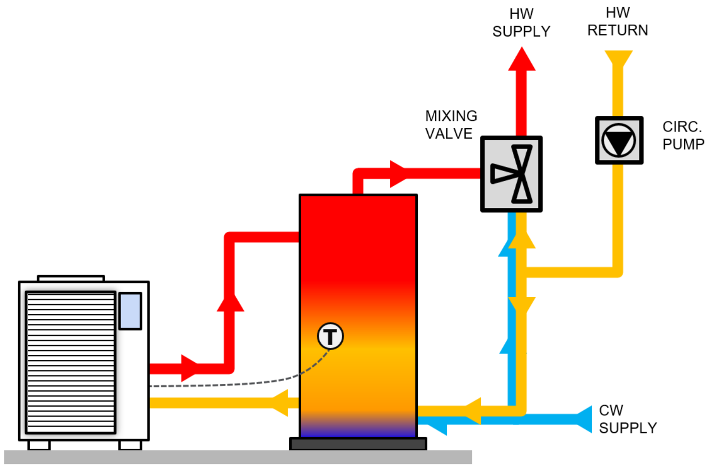

Figure 19: Optimized return-to-primary piping

HWR flow in this optimized configuration is best characterized by two DHW demand scenarios. During periods of little or no DHW usage, the mixing valve cold inlet receives only HWR, and any remaining HWR plus incoming cold water are directed to the storage tank. During high DHW usage, HWR alone is insufficient to satisfy the mixing valve cold inlet demand, so a portion of the cold-water supply combines with HWR to supplement it. The remaining cold-water supply enters the storage tank to replace hot water delivered to the building.

By directing cold water to the tank unless the mixing valve needs it, this configuration keeps tank temperature, and therefore HPWH inlet temperature, as low as possible. Less HWR entering the storage tank also means storage draws down more slowly when the HPWH is off. This allows longer HPWH cycle times and longer load-shift periods, during which the HPWH can stay disabled while primary storage serves the building. Figure 20 shows hot water flow in low and moderate-to-high usage periods.

Mixing valve selection matters in this configuration. With no balancing valve to limit HWR entering the tank during no-usage periods, a typical thermostatic mixing valve can allow temperature creep. A digital mixing valve that can nearly or fully close its hot water inlet should be selected instead. A mixing valve that can close its hot inlet completely can eliminate the risk of temperature creep in this configuration.

This configuration has not been field tested, so future research should include monitored field demonstrations to validate whether this configuration delivers the anticipated reductions in CHPWH inlet temperature and improvements in system efficiency.

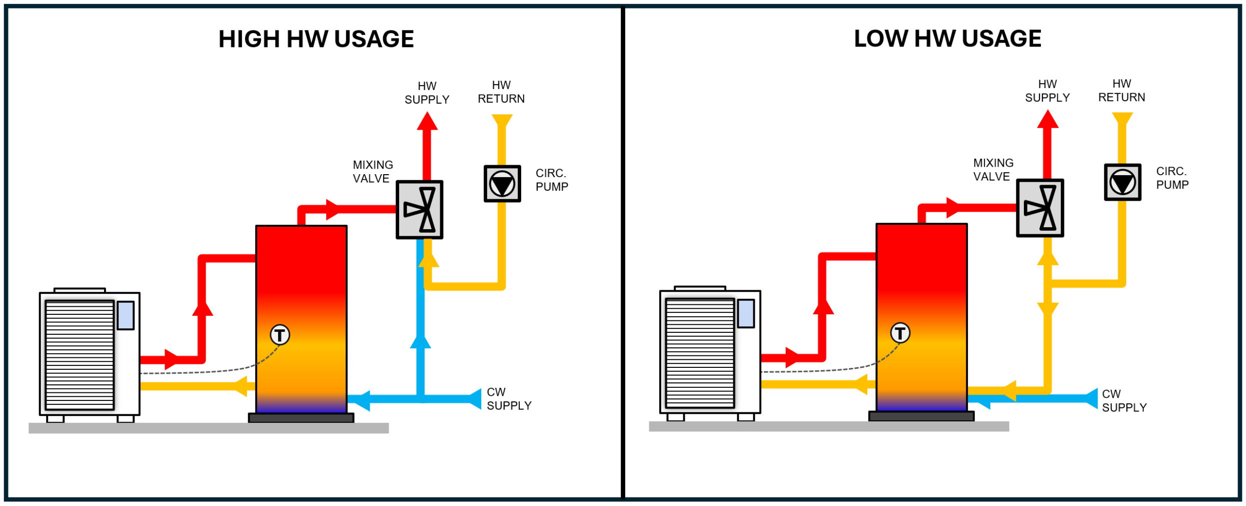

Figure 20: Low versus high hot water (HW) usage in optimized RTP configuration.

Dedicated Temperature Maintenance Heater Measures

Dedicated temperature maintenance heaters are commonly deployed in CHPWH systems using CO_2 primary HPWHs, where heat pump efficiency and heating capacity are more sensitive to inlet water temperature. Unlike RTP configurations, these systems route recirculation return water through a dedicated temperature maintenance tank rather than directly back to the primary storage tanks. This arrangement helps maintain lower HPWH inlet temperatures and improves CHPWH operating efficiency. Two common configurations, both of which are recognized as approved piping configurations in the AWHS are the swing tank and parallel loop tank (PLT) configurations, seen in Figure 21.

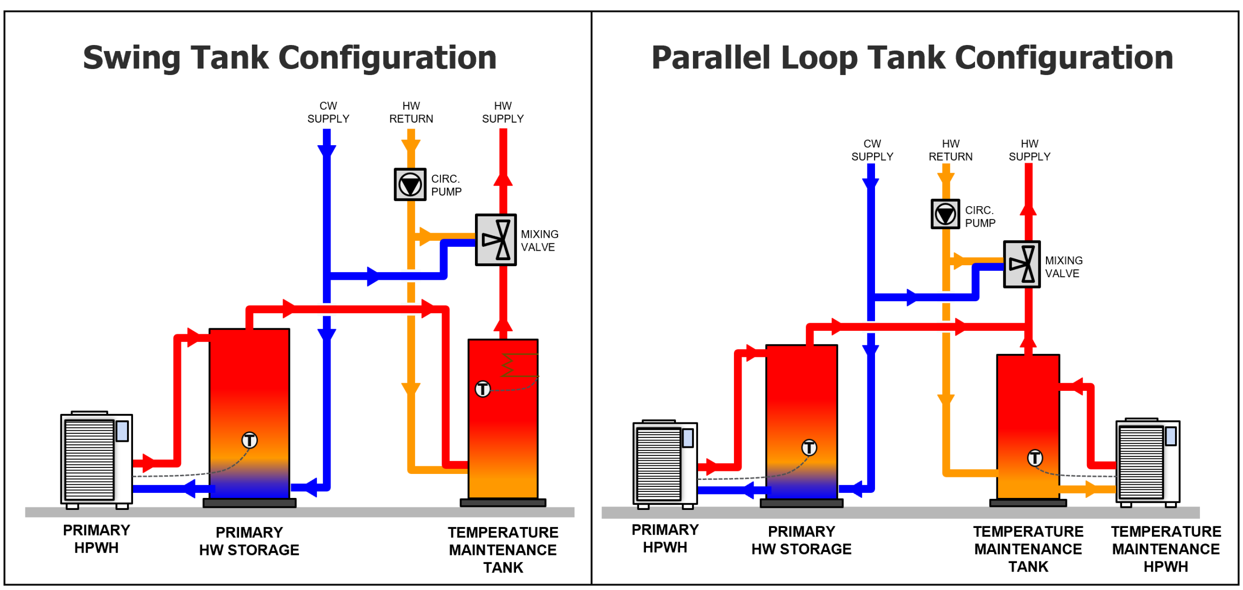

Figure 21: Dedicated temperature maintenance systems.

In a swing tank system, recirculation return water is piped back to an electric resistance heater in series with the primary storage tanks. When properly configured, the primary heat pumps still provide most of the energy required to offset temperature maintenance losses during normal operation. During DHW usage, incoming hot water from the primary storage tanks flows through the swing tank and maintains swing tank temperature with minimal electric resistance operation. The electric resistance elements should run primarily during periods of little or no DHW usage, when there is not enough hot water flow from primary storage to offset recirculation losses.

In a PLT system, a separate temperature maintenance HPWH — in some cases a unitary HPWH — is piped in parallel with the primary system. PLTs minimize or fully eliminate electric resistance use but carry a higher upfront cost.

Achieving high efficiency in either configuration requires two design and commissioning considerations: maintaining an appropriate temperature maintenance heater setpoint, and properly balancing recirculation return flow between the mixing valve cold inlet and the temperature maintenance tank inlet.

SETPOINT CONSIDERATIONS

Swing tank setpoints should stay far enough below primary storage temperatures that incoming water from primary storage can offset temperature maintenance losses during DHW usage. For example, primary storage near 140°F – 150°F paired with a swing tank setpoint near 120°F – 130°F lets incoming storage water hold swing tank temperature with little electric resistance operation. The Northwest Energy Efficiency Alliance (NEEA)'s AWHS recommends a swing tank setpoint of 130°F.

Appropriate setpoints also support efficient mixing valve operation. A lower swing tank temperature reduces the cold water needed at the mixing valve to hit the target supply temperature, which lets more cold water enter through the primary storage tanks, where the CHPWH can heat it. This maximizes the share of heating done by the heat pumps rather than electric resistance.

Field data across several projects indicated that elevated swing tank setpoints are a common operational issue. In some cases, swing tank temperatures are initially set too high during project startup. In other cases, maintenance staff may increase swing tank setpoints in response to occupant hot water complaints without addressing the underlying distribution or balancing issue. These adjustments can substantially increase electric resistance runtime and reduce overall system coefficient of performance (COP).

PLT systems require similar considerations. When a unitary HPWH serves as the temperature maintenance heater, a higher-than-necessary setpoint makes it more likely to engage onboard electric resistance elements to meet demand. For both unitary and split-system HPWHs, elevated temperatures also reduce compressor efficiency. In either case, inefficiently heating water above the target supply temperature only to mix it back down to 120°F - 125°F at the mixing valve wastes energy.

RECIRCULATION RETURN BALANCING

Proper balancing of recirculation return flow back to the primary plant is also critical for efficient system operation. Without flow restrictions on the recirculation return line, much of the return water flows directly to the dedicated temperature maintenance tank rather than the mixing valve.

Figure 22 shows a simplified swing tank schematic with a balancing valve on the recirculation return line to the swing tank. Without this balancing valve, recirculation return water preferentially flows to the swing tank, leaving the mixing valve cold inlet to draw primarily from the cold water supply. Because cold water enters the system at the mixing valve rather than at the primary plant, DHW usage drives less hot water from primary storage through the swing tank. Instead, the swing tank bears the full temperature maintenance load and, in worst cases, may also be required to supplement DHW delivery. This operation generally shifts excessive load onto the inefficient swing tanks from the primary HPWHs.

NEEA's AWHS recommends that the balancing valve on recirculation return branch to temperature maintenance heater be set to minimum possible flow that maintains stable mixing valve operation when the system has no hot water draw.

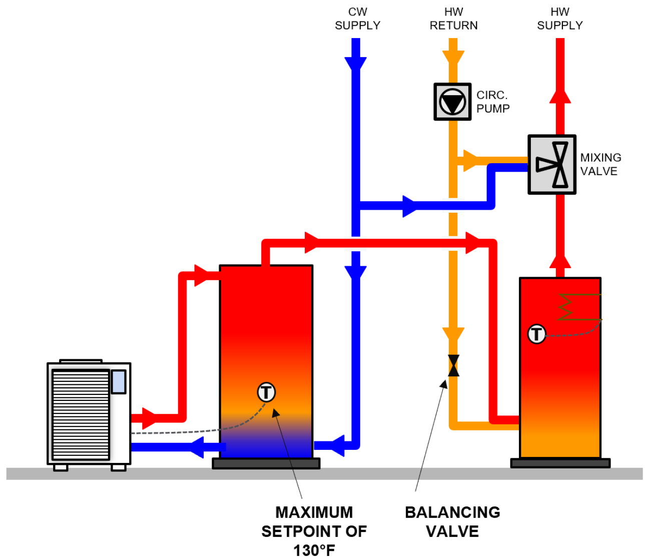

Figure 22: Recirculation return balancing.

The same problem affects PLT systems. When too little return water reaches the mixing valve cold inlet, the valve draws mostly from the cold-water supply, so achieving a 120°F – 125°F mixed supply temperature requires more cold water — increasing PLT load and, where applicable, the likelihood of electric resistance operation.

Elevated temperature maintenance tank setpoints and poor return balancing compound one another. A higher temperature maintenance tank setpoint raises the temperature on the hot side of the mixing valve, requiring more cold water at the cold inlet to hit the target supply temperature. If recirculation return flow is not directed to the cold inlet, that cold water demand falls entirely on the cold-water supply, further increasing temperature maintenance tank load and electric resistance runtime.

FIELD MONITORING RESULTS

Two multifamily CHPWH sites were monitored extensively before and after site visits at which the swing tank setpoint and recirculation balancing were corrected, allowing a direct comparison of energy use under the original and corrected settings. At Site 6, only the swing tank setpoint was lowered; at Site 7, the recirculation return was also balanced. During much of the monitoring period, DHW usage stayed relatively low due to partial occupancy in the newly constructed buildings. To separate the effect of these changes from occupancy-related load variation, a regression compared hourly electric resistance energy consumption against DHW usage. Figure 23 and Figure 24 summarize the results.

Before corrective action, Site 6 showed at least 3 kWh per hour of swing tank electric resistance consumption regardless of DHW demand, meaning nearly the entire 3.8 kW temperature maintenance load was being served by electric resistance. After the swing tank setpoint was reduced and the recirculation return line balanced, electric resistance consumption dropped substantially across all DHW usage levels.

At Site 7, where overall DHW usage was higher, the reduced swing tank setpoint lowered electric resistance operation during moderate-to-high usage periods. After tuning, higher DHW demand corresponded with minimal electric resistance operation, indicating that incoming primary storage water was offsetting the temperature maintenance load as intended.

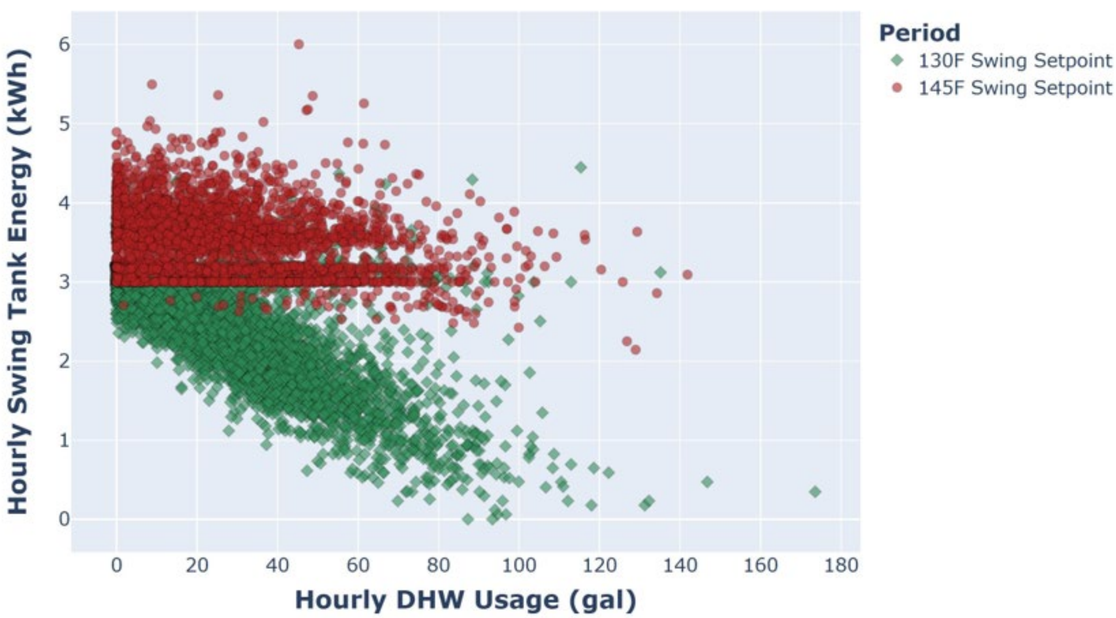

Figure 23: Site 6 electric resistance energy before and after corrective actions.

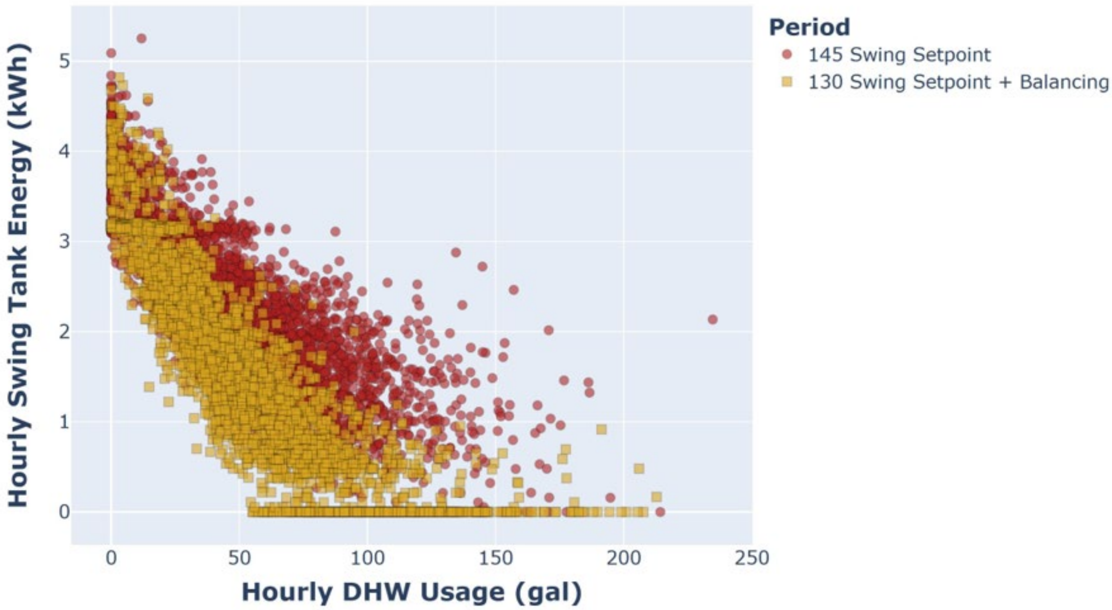

Figure 24: Site 7 electric resistance energy before and after corrective actions.

Crossover Implications for RTP and Temperature Maintenance Systems

Before a DHW retrofit, installers should verify that the system is free of crossover. Left unaddressed, crossover increases energy consumption and causes tenant discomfort. These problems are not caused by the DHW plant or its heat pumps — they originate in the distribution system — but they can be masked by elevated supply temperatures or recirculation pump settings. For example, supply temperature leaving the plant may be set higher than necessary to offset crossover-driven losses elsewhere in the loop, or pump flow may be raised to maintain adequate delivery temperatures, as seen in the crossover case study. This creates a risk during a CHPWH retrofit: when a new or reconfigured mixing valve is set to a standard 120°F –125°F supply temperature, previously masked crossover can surface and symptoms be wrongly attributed to the new system.

Testing For and Determining the Prevalence of Crossover in a Multifamily Central Domestic Hot Water Distribution System outlines several testing methods and identifies the pressure gauge method as the most practical approach for detecting crossover at the system level. For pinpointing crossover at individual fixtures, the Eatherton Method provides a non-invasive alternative (Ayala and Zobrist 2016).

Crossover should be addressed regardless of system type but leaving it unaddressed more heavily penalizes the energy performance of dedicated temperature maintenance systems. If a significant amount of cold water enters in the distribution system rather than in the primary plant, load is shifted onto the electric resistance swing tank, or onto the PLT heater, which is sized to heat recirculation losses – not to heat large volumes of water from city water to delivery water temperature. In contrast, RTP systems are comparatively agnostic to crossover, because all heating is done by the more efficient HPWH regardless of where cold water enters. Findings from this study suggest that crossover is relatively common and buildings are more susceptible to it as they age and fixture valves wear. For programs and designers prioritizing long-term system resilience, this is a meaningful argument in favor of RTP configurations, particularly in existing buildings where crossover cannot be fully assessed or remediated prior to retrofit.

Conclusions and Reframing the Distribution Loss Problem

This study sought to quantify temperature maintenance heat losses in multifamily hot water distribution systems and evaluated measures to reduce them. The results point toward a significant reframing of how the industry should think about this problem.

Conductive Pipe Losses are Modest

Physics-based modeling yields an average idealized heat loss of approximately 46 W/apt. In well-functioning buildings with typical real-world installation quality — accounting for thermal bridging at structural supports, horizontal apartment takeoffs, and difficult-to-insulate valves and fittings — measured losses in the better-performing buildings in this sample averaged around 72 W/apt. This gap appears largely inherent to practical installation, with only a fraction realistically reducible through better practices or code measures.

The savings available from improving distribution system thermal performance are correspondingly modest. Adding half an inch of insulation to all pipe sizes returns approximately 6 W/apt. Even combining that with a substantial improvement in installation quality yields an upper bound of roughly 19 W/apt in total savings — about the output of a single LED light bulb per apartment. Given the regulatory and inspection effort required, this return is likely not cost-effective as a code target.

This leads to a reassessment of code efforts focused on recirculation pipe lengths, loop geometry, and insulation requirements. Plumbing designers and installers already have strong economic incentives to minimize pipe lengths and sizes. Code measures attempting to further reduce distribution thermal losses are likely chasing savings already largely captured by normal design practice, and what remains is difficult to enforce.

High Measured Losses Are Likely Crossover, Not Heat Loss

Ecotope's 2019 literature review (Kintner and Larson 2019) reported temperature maintenance losses ranging from 10 to 553 W/apt across 46 buildings, with a mean of 143 W/unit and a median of 93W/apt, which is not a far-off sample from this study. The higher values drove significant attention toward reducing distribution system thermal losses. In retrospect, the high end of that distribution — buildings showing 200 W/apt or more — is very difficult to explain through pipe insulation deficiencies alone and is more likely dominated by cold-water crossover appearing as inflated temperature maintenance losses in the metering data.

Crossover occurs when pressure imbalances drive cold water into the hot distribution loop through faulty fixture valves. Because temperature maintenance heat loss is calculated as $Q = 500 \times \text{flow} \times (T_{supply} - T_{return})$, cold water infiltrating the return line raises measured flow and depresses return temperature, registering as increased heat loss even though no additional heat is leaving the pipes. The current study illustrates this clearly: at Site 14, a crossover event triggered by a pump speed adjustment caused measured losses to jump by roughly 100 W/apt overnight with no change in actual pipe heat loss. Field data from Site 6 shows measured losses rising with hot water draw events, with crossover accounting for over 25 percent of the measured-to-calculated gap even in this relatively new, well-functioning building.

This study's sample is small, and measurement uncertainty is meaningful in the smaller buildings. These results do not prove that crossover explains the high losses seen in prior studies, but they are consistent with that interpretation and suggest it is more likely than insulation deficiency for losses significantly above the 70–100 W/apt range.

Crossover is Not Uniformly an Energy Problem – But It Can Be

Cold-water crossover into the hot distribution loop does not, in most cases, represent a direct energy penalty. The infiltrating cold water is still heated by the primary plant — it is simply entering the system at a different point than intended. In gas-fired systems and return-to-primary heat pump configurations, this has little measurable impact on overall system energy use.

The exception is systems where crossover flow is routed through a temperature maintenance heater that relies on electric resistance. Swing tanks are the most common example: when significant crossover flow passes through an electric resistance swing tank rather than the primary heat pumps, system COP degrades substantially. This is not an inherent limitation of the swing tank configuration — a swing tank served by a heat pump rather than electric resistance would not carry the same penalty. It is a consequence of electric resistance being used for temperature maintenance in a system sized to handle recirculation losses, not large volumes of crossover flow. This makes crossover resilience a meaningful consideration in system selection and a practical argument in favor of configurations that keep all heating on the primary heat pumps, particularly in existing buildings where full crossover assessment prior to retrofit is not feasible.

The potentially more significant consequence of crossover is the reverse direction: hot water escaping into the cold pipes during large cold water draws such as toilet flushing. This represents wasted thermal energy — water that was heated and then lost from the hot water system without being used. Unlike cold-water infiltration, this loss would not appear in temperature maintenance measurements; it would show up as elevated hot water consumption at the plant, likely attributed to occupant usage rather than system leakage. This study has no data to quantify this effect, but it may represent a systematic source of underestimated energy waste in prior monitoring studies.

A Proposed Diagnostic Threshold and Shift in Research Priorities

Measured temperature maintenance losses below approximately 100 W/apt likely reflect normal installation reality and are not a problem requiring intervention. Losses above that threshold are more likely a signal of meaningful crossover than of insulation deficiency and should prompt investigation of the distribution system rather than upgrades to pipe insulation. Doubling pipe insulation in a building showing 200 W/apt of measured losses will not cut those losses in half.

The more productive research direction is to understand crossover: how prevalent it is across the building stock, which fixture designs are most susceptible, whether susceptibility increases with age and component wear, and whether check valves can reliably prevent it at the low flow rates typical of recirculation-driven pressure imbalances without creating delivery problems. Most importantly, the magnitude of hot-to-cold crossover and its contribution to wasted thermal energy needs to be quantified in a controlled study. Until that work is done, the full energy impact of crossover in the existing multifamily building stock remains unknown and may be substantially larger than temperature maintenance measurements alone would suggest.

Finally, this study highlights the need for further research and field demonstration of CHPWH system configurations that eliminate electric resistance from the temperature maintenance path entirely. This includes return-to-primary systems, where all heating is handled by the primary heat pumps regardless of where cold water enters the system, and in mild cases of roughly 100 W/apt or less, swing tank configurations where the temperature maintenance heater is a heat pump rather than electric resistance. Either approach would make system efficiency largely resilient to crossover, removing what this study identifies as one of the most consequential interactions between distribution system condition and plant energy performance.

Recommendations

The project team would like to make several recommendations for programs and those involved in the installation and maintenance of central DHW systems:

- Cold-to-hot crossover is an especially important factor for CHPWH retrofits. Systems should be pressure tested at any building planning a retrofit, with deeper investigation of the source if detected. Pressure testing at the whole system level is the quickest, easiest initial test that can inform decision making regarding CHPWH configurations, deeper crossover investigation, and possible remediation (Ayala and Zobrist 2016).
- Crossover can disrupt CHPWH stratification, penalize efficiency, and result in unacceptable hot water delivery in extreme cases. When present, crossover can usually be remediated and should accompany any CHPWH installation in existing buildings. This is particularly crucial in swing tank, parallel temperature maintenance, or other designs that are not RTP. In return-to-primary designs, crossover is less impactful on energy since the cold water crossover is simply displacing the city make-up water. However, even this could be somewhat disruptive, depending on where the return water is plumbed to the primary storage tank volume.
- RTP configurations are more robust and resilient against crossover impacts than other CHPWH configurations.
- The observed field data validate standard recirculation heat loss assumptions in the Ecosizer CHPWH sizing tool or 60 W/apt and 90 W/apt for new and existing buildings, respectively. Generally, swing tank CHPWH configurations can work well and efficiently up to these levels. It is likely that recirculation losses above 100 W/apt may be a sign of crossover that needs to be fixed and that RTP configurations may be warranted.
- For new construction or deep renovations, Appendix M offers meaningful energy savings over code minimum and standard practice Appendix A pipe sizing. However, insulation on the reduced ¾” and 1” pipes should likely be increased one increment over code minimums to receive the most intended benefit.
- Codes and standards teams should investigate the possibility of upsizing insulation requirements when pipes are reduced to ¾” and 1” using Appendix M sizing, since the accompanying minimum insulation requirements tempers the energy benefits.
- In CHPWH configurations with separate temperature maintenance systems such as swing tanks or parallel HPWHs, installation and commissioning should follow design guidance in the Advanced Water Heating Specification (NEEA 2024). More specifically, swing tank

setpoints should stay well below the primary storage temperature with a cap of 130°F and recirculation return flow to the temperature maintenance heater should be minimized.

- Preemptive and reactive maintenance protocols of CHPWH need continued guidance. Continuous monitoring and fault detection can help mitigate distribution system performance drift and maximize, sustained CHPWH efficiency benefits. Regular, periodic crossover prevention and mitigation may be necessary for long-term CHPWH performance and hot water safety in some non-RTP situations.
- Programs that incentivize water heating systems, including CHPWH retrofits, should establish explicit adders or prerequisite measures for distribution system remediation. Rebalancing, pump control improvements, insulation repair, and crossover remediation all have dependable benefits that can be incentivized and claimed by programs. In particular, these measures have compounding impacts with CHPWHs. The stakeholders engaged in this study have expressed support for this and interest in providing input to possible CDHW retrofit and retro-commissioning program and measure design.
- Future work should include a controlled crossover quantification study, fixture-level crossover durability testing, and field validation of the optimized RTP configuration in Figure 20.

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Appendix A: Distribution System Survey and Review

The project team characterized relevant information to each site's hot water distribution system. A template set of questions and observations was developed, as follows:

Site: ____

Staff Questions

Building age	
Building square feet	
Number of stories	
Number of apartments	
Percent of apartments occupied	
Number of residents	
Water heater age	
Underground hot water piping present (yes/no)	
Water heater setpoint (in hot water tank)	
Hot water supply temp (to building)	

Any problems or issues with water heating system to note?

Are there any hot water supply issues in the building? Perhaps in certain parts of the building or at the end of the hot water loop? Any complaints from occupants regarding hot water supply?

How long does it take for hot water to arrive at residences after hot water tap is opened?

What is the state of hot water piping insulation in the building? Are there any pipes that don't have any? Are there any pipes that have deteriorating insulation? Please describe rough percentage with these conditions and location, if possible.

Are shower valves dual or single handle?

Brand of shower cartridges?

Do you have a maintenance protocol for shower cartridges? How often do you check or replace shower cartridges?

Other spot measurements and observations

Document make, model, and settings of the following:

water heater

storage tank

recirculation pump

mixing valve

Describe status of hot water pipe insulation status on hot water piping, including on any hangers and penetrations into wall/floors. Take pictures and measure hot water pipe insulation thickness.

Spot measurements

Water heater setpoint	
Recirculation return temperature (at pump)	
Mixing valve temperatures (likely three)	
DHW supply temperature (could be at mixing valve)	
Recirc pump speed/flow if shown on pump screen	

Hot water risers

Identify location and quantity of risers.

Take pictures of balancing valves at each riser, if present. Document make and model.

Document state and take pictures of insulation on pipes, hangers, and penetrations into walls/floors.

Measure riser supply and return pipe diameter, insulation thickness, and temperatures.

Riser	1	2	3	4	5	6	7	8	9
Supply diameter									
Supply temp									
Supply insulation thickness									
Return diameter									

Return temp									
Return insulation thickness									

1. Record building details:
    a. Building Name:
    b. Address:
    c. Year built:
    d. Known renovations:
    e. Drawing type available:
    f. Code cycle (Typically specified in general notes):
    g. Occupancy (low income, market rate, etc.)
   h. Building shape / layout notes (include picture if possible):
2. Calculate unit density using the following:
    a. Inhabited square footage:
    b. # of stories:
    c. # of units (bedroom counts preferred as well):
    d. Occupancy (actual occupancy rate or align with occupancy type in Ecosizer):
3. DHW plant characteristics:
    a. Water heater type:
    b. Mixing valve (presence, make/model:
    c. HWC pump (horsepower rating and/or make-model):
    d. DHW plant location relative to dwelling units:
    e. Are operating setpoints specified on plans? Specifically, hot water circulation flow, water heater setpoint, mixing valve setpoint:
4. Distribution system characteristics:
    a. How is water pumped/distributed: e.g: main circulation loop with uncirculated risers or circulated risers?
    b. Balancing valve spec:
        i. Are they included in drawings?:
        ii. Are make/model scheduled?:
        iii. Is setting specified?:
    c. Are there any mounting details for piping? If so, screenshot them:

5. Piping:
    a. Piping type:
    b. Record required insulation thickness (often in a table on the cover sheet). If none stated, record insulation requirements from that year in California Energy Code.

        Insulation thickness table:
    c. Record total lengths of pipe of each size in conditioned and unconditioned space. Include in excel sheet:
    d. Make note of any drawing notes that would inform piping installation and insulation:

Site Data:

Site visit has/has not been conducted in the context of this study.

1. Check HWS, HWR, and riser sizes against plans.
   HWS size:
   HWR size:
   Do risers conform with plans:
2. Check mixing valve make/model against plans, note condition.
   Make/model:
   Condition:
   Conformance with plans:
3. Check HWC pump make/model against plans, note condition, speed, additional controls (where applicable).
   Make/model:
   Add'l pump control:
   Conformance with plans:
4. Note balancing valve type and setting (do they vary between risers?) and compare to plans.
   Make/model:
   Setting (and does it vary between risers?):
   Conformance with plans:
5. Note any deviations between distribution pipe routing and plans. Does the piping follow the same general pathway as the plans? Check for balancing valve locations via access panels in corridor ceilings to see where distribution piping runs.
   Deviations:

6. Note quality of insulation and thickness compared to plans.
   Insulation quality (1-5):
   1 Very Poor: Insulation is missing or severely damaged. Pipe fittings and valves are uninsulated. Significant heat loss likely.
   2 – Poor: Insulation is incomplete or loosely installed. Several joints, fittings, or valves are exposed.

   3 – Fair: Most piping is insulated, but some exposed areas or unsealed seams are present.
   4 – Good: Insulation is continuous and correctly installed on most runs. Minor gaps or compression observed, but overall quality is adequate.
   5 – Excellent: Insulation is continuous and sealed. Fittings and valves are fully insulated with good workmanship.

   Insulation thickness conforms to plans:

7. Note pipe mounting methods, presence of heat traps.
   Pipe mounting method:
   Any heat traps?:

Trend Data:

Using hourly data, record the average and standard deviation of circulation loop temperatures and flows:

	Average	StDev	
HWS Temp			°F
HWR Temp			°F
Recirc Flow			gpm
TM Heat Loss			kW

Notes:

Note any interesting characteristics from a qualitative view of minutely data.

HWS Temp:

HWR Temp:

Recirc Flow:

TM Heat Loss:

Pipe Insulation Matrix

The project team developed a pipe insulation matrix to be completed for each site at their field survey or from inspection of their plumbing plans. DHW systems may consist of both uncirculated and circulated piping. Total uncirculated piping accounts for the total piping length of end-use branches and total circulated piping accounts for the total piping length of the risers and HWS and HWR piping. Pipe sizes may vary throughout the building; hence the total pipe length is organized by common pipe diameters seen in DHW systems. The pipe insulation matrix template can be seen in Figure 25.

Site:

		Total Pipe Length Per Pipe Size (in.)						
COMPONENT	QTY	3	2.5	2	1.5	1	0.75	NOTES
RISER-HC1A								
RISER-HC2A								
RISER-HC5A								
RISER-HC7A								
RISER-HC1B								
RISER-HC2B								
HWS - Conditioned Space								
HWR - Conditioned Space								
Total circulated pipe lengths (feet)		0.0	0.0	0.0	0.0	0.0	0.0	
Total uncirculated pipe lengths (feet)		0	0	0	0	0	0	

PIPE INSULATION TABLE

MINIMUM PIPE INSULATION

FLUID/OUTSIDE TEMPERATURE	PIPE DIAMETER (INCH)				
	≤1"	1.25"-2"	2.5"-4"	5"-6"	≥8"
306-460	2.5	2.5	3.0	3.5	3.5
251-305	2.0	2.5	2.5	3.0	3.0
201-250	1.5	1.5	2.0	2.0	2.0
105-200	1.0	1.0	1.5	1.5	1.5
61-104	1.0	1.0	1.5	1.5	1.5
40-60	0.5	.75	1.0	1.0	1.0
BELOW 40	1.0	1.5	1.5	1.5	1.5
STEAM CONDENSATE	1.0	1.5	2.0	2.0	2.0

THE THICKNESS OF INSULATION LISTED IN THIS TABLE IS BASED ON MATERIALS HAVING A THERMAL RESISTANCE IN THE RANGE OF R-4.0 TO R-4.6 PER INCH. ADJUSTMENTS ARE REQUIRED FOR INSULATION MATERIALS OUTSIDE THIS RANGE.

Figure 25: Pipe insulation matrix.

Appendix B: Additional Site Results – Field Measurements

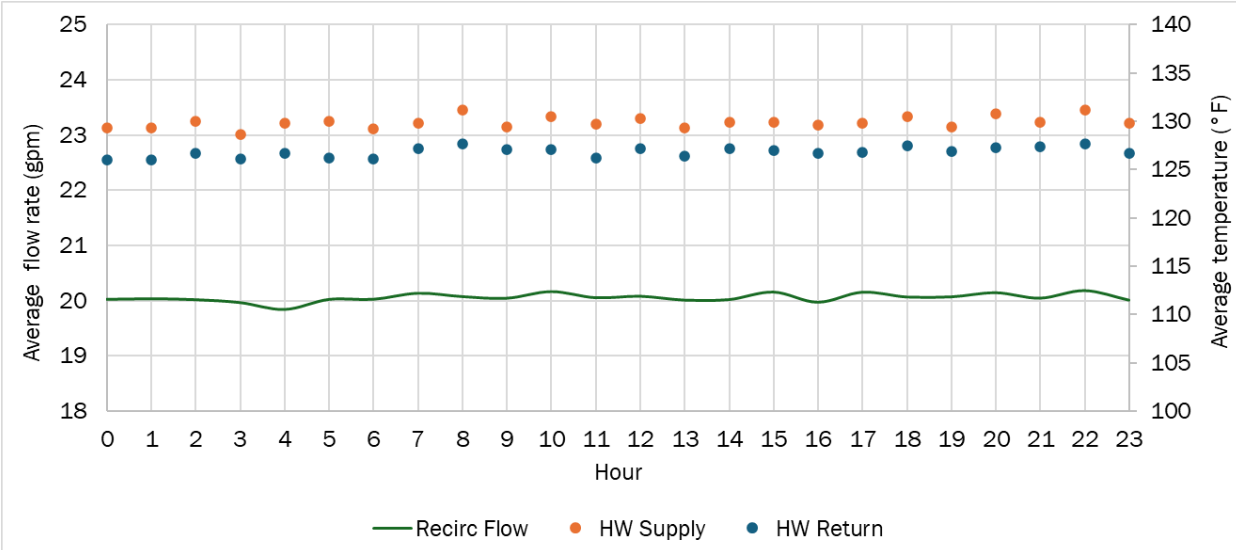

Figure 26: Site 1 hourly profile for measured recirculation flows and hot water temperatures.

Site 1	Hour Range							
8/20/25-8/26/25	Full dataset		Night		Night/morning		Daytime	
	0-23		**0-4**		**0-7**		**8-23**	
Variable	Average	St Dev	Average	St Dev	Average	St Dev	Average	St Dev
HWS Temp (°F)	129.71	0.83	129.21	0.87	129.32	0.87	129.90	0.74
HWR Temp (°F)	126.73	0.68	126.19	0.75	126.26	0.75	126.97	0.50
Recirc flow (gpm)	20.03	0.11	19.94	0.12	19.97	0.10	20.06	0.10
Heat loss (W)	9,000.46	1,348.60	8,883.01	1,404.10	9,032.94	1,342.55	8,983.87	1,358.56
Unit heat loss (W/apt)	**81.82**		**80.75**		**82.12**		**81.67**	

Figure 27: Recirculation load analysis at Site 1 for various time frames.

The project team took a small sample of new flow and temperature measurements at a follow-up visit conducted in April 2026. Site 1 underwent a CHPWH retrofit, yielding spot measurements reflective of the new system rather than the old gas system that was the basis of the original data logging. Average spot measurements were pulled from onsite meters for the new system instead of independent data logging due to preference from the site's maintenance team.

Table 11: Spot measurements at Site 1 for their new CHPWH system

Component	Average
Recirculation Flow (gpm)	3.9
Supply Temperature (°F)	120.0
Return Temperature (°F)	110.3
Total Recirculation Load (W)	5,625.7
Unit Recirculation Load (W/apt)	51.1

Key differences between the old and new hot water systems include a new energy-efficient recirculation pump located in the basement garage instead of the rooftop where the hot water system is. Balancing valves were installed at the top floor to reverse the hot water loop flow. Recirculation loads from the spot measurements are also observed to be about half of what was measured pre-retrofit, which is likely due to reduced HWS temperatures and pump control that shifted from operating at constant speed to constant return temperature.

Site 2 demonstrates constant flow during the daytime hours but experiences increased recirculation flow between midnight and 5 AM. HWS and HWR temperatures dip while the recirculation flow is elevated. For the remainder of the day, recirculation flow is steady and the supply and return temperatures demonstrate minimal variations. The reported average recirculation load for this site was determined for steady, stable flow conditions. Supply and return temperatures are elevated during the morning hours and may correspond to increased hot water use from residents during this time.

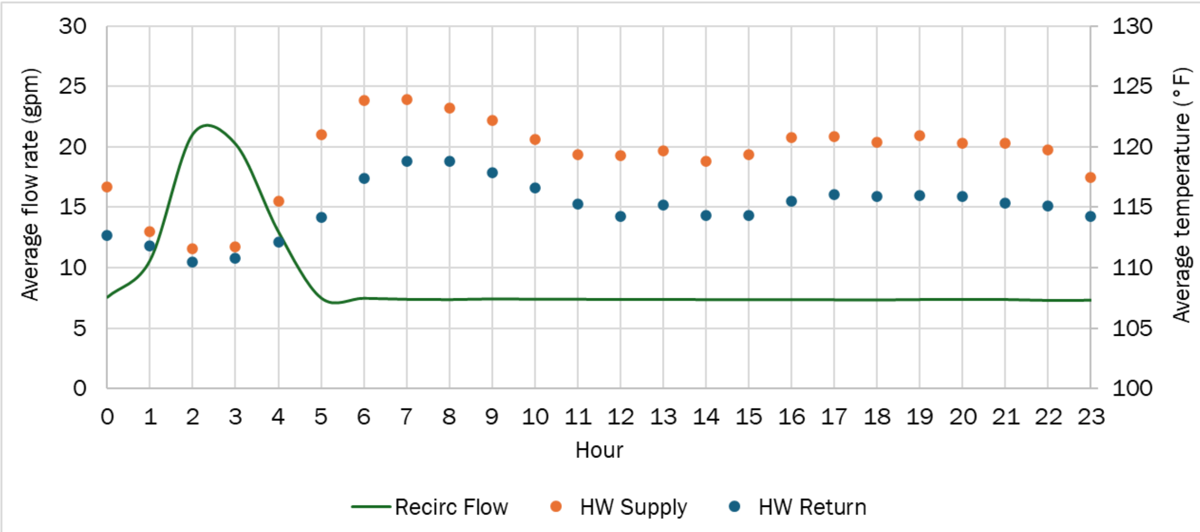

Figure 28: Site 2 hourly profile for measured recirculation flows and hot water temperatures.

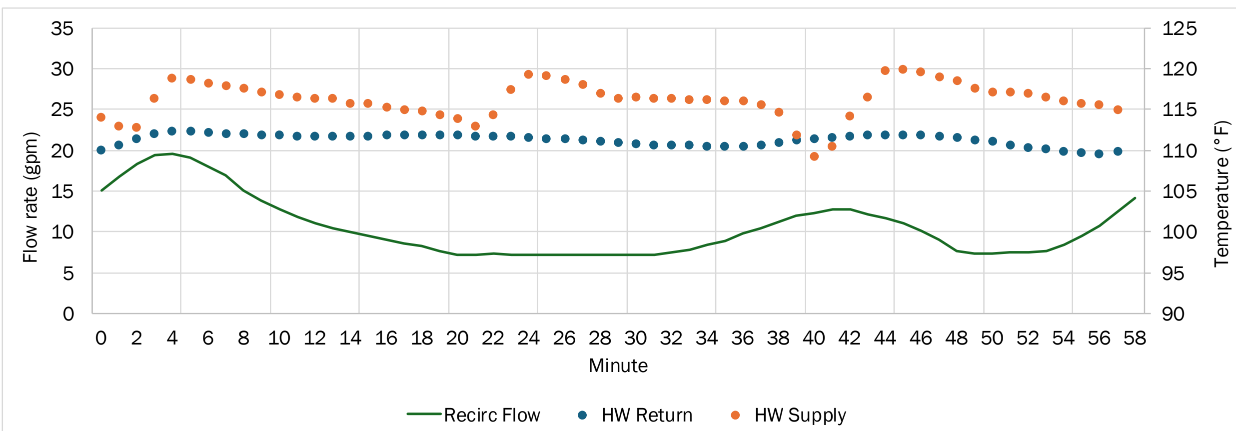

Figure 29: Site 2 minutely profile for spot measured recirculation flows and hot water temperatures.

Site 2	Hour Range									
8/26/25-9/1/25	Full dataset		Night		Night/morning		Daytime		Constant flow hours	
	0-23		**0-4**		**0-7**		**8-23**		**5AM – Midnight**	
Variable	Average	StDev	Average	StDev	Average	StDev	Average	StDev	Average	StDev
HWS Temp (°F)	119.40	3.45	113.99	2.70	116.98	4.76	120.65	1.35	120.69	1.88
HWR Temp (°F)	115.20	2.25	111.94	1.33	113.49	2.70	116.09	1.28	115.95	1.61
Recirc flow (gpm)	14.50	5.96	12.13	5.73	9.00	4.02	7.38	0.04	7.51	0.80
Heat loss (W)	5,138.44	1,097.49	4,616.50	1,476.77	5,488.60	1,731.03	4,956.88	444.06	4,616.50	1,476.77
Unit heat loss (W/apt)	**52.43**		**47.11**		**56.01**		**50.58**		**47.11**	

Figure 30: Recirculation load analysis at Site 2 for various time frames.

The measured data presented similar trends for recirculation flow at Site 4. The flow rate is steady with minimal variations after 8 AM, averaging at about 1.9 gpm. Recirculation flows are elevated between midnight and 7 AM, resulting in recirculation flows averaging between 4.7 and 4.8 gpm. While on-site, the recirculation pump cycled on and off. When the pump turned on, consistent flow was maintained between 4 and 5 gpm and then after a few minutes, ramped down until there was no flow through the pipe. Supply and return temperatures reduced during the elevated flow then ramped up to more consistent operation while there was consistent recirculation flow during the daytime hours.

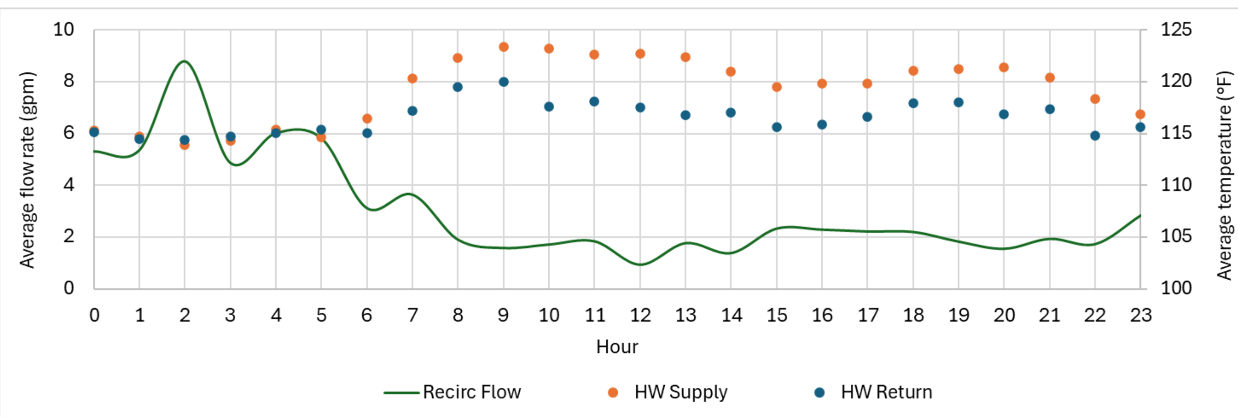

Figure 31: Site 4 hourly profile for measured recirculation loads and hot water temperatures.

Recirculation flows were steady for both surveyed hot water systems at Site 5 with an average measured recirculation flow of 6.4 gpm. The supply and return temperatures for HW1 showed minimal fluctuations, except between the hours of 7 AM and 12 PM when hot water use from residents likely increased.

Site 4	Hour Range							
9/17/25-9/24/25	Full dataset		Night		Night/morning		Daytime	
	0-23		**0-4**		**0-7**		**8-23**	
Variable	Average	St Dev	Average	St Dev	Average	St Dev	Average	St Dev
HWS Temp (°F)	119.32	3.10	115.42	1.57	115.88	2.08	120.69	2.07
HWR Temp (°F)	116.61	1.42	115.06	0.74	115.31	0.90	117.09	1.22
Recirc flow (gpm)	2.83	1.68	4.83	1.66	4.75	1.57	1.87	0.51
Heat loss (W)	1,137.73	302.70	1,115.61	391.79	1,290.96	386.62	997.18	840.42
Unit heat loss (W/apt)	**32.51**		**31.87**		**36.88**		**28.49**	

Figure 32: Recirculation load analysis at Site 4 for various time frames.

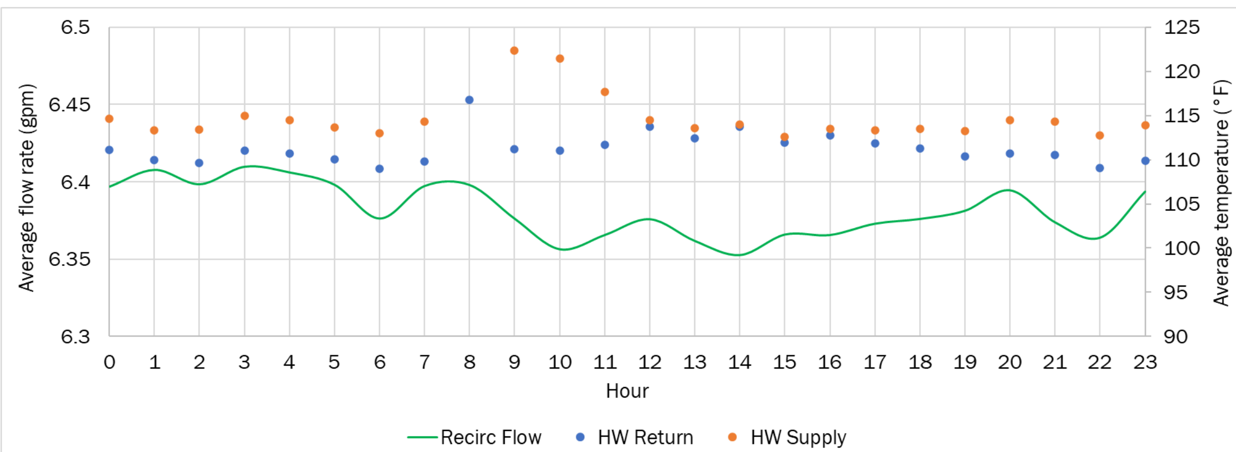

Figure 33: Site 5 HW1 hourly profile for measured recirculation loads and hot water temperatures.

Site 5 HW1	Hour Range							
3/12/26-3/20/26	Full dataset		Night		Night/morning		Daytime	
	0-23		**0-4**		**0-7**		**8-23**	
Variable	Average	St Dev	Average	St Dev	Average	St Dev	Average	St Dev
HWS Temp (°F)	114.75	3.33	113.86	0.75	113.85	0.79	115.20	3.98
HWR Temp (°F)	111.01	1.87	109.67	0.74	109.63	0.72	111.71	1.88
Recirc flow (gpm)	6.38	0.02	6.40	0.01	6.40	0.01	6.37	0.02
Heat loss (W)	3,657.55	2,515.29	3,930.73	459.87	3,949.81	436.52	3,509.10	3,066.59
Unit heat loss (W/apt)	**69.01**		**74.16**		**74.52**		**66.21**	

Figure 34: Recirculation load analysis at Site 5 for various time frames.

Appendix C: Physics-Based Pipe Heat Loss Calculation

This appendix gives the method for calculating standby heat loss per foot of recirculating hot water pipe. A single series-resistance equation covers insulated and bare pipe. The method returns a heat-transfer coefficient per unit length, UA_L, which is multiplied by the water-to-air temperature difference to result in heat loss per foot.

Governing Principle: Resistance in Series

Heat moving from hot water to room air passes through a series of thermal resistances. The total resistance per unit length is the sum of the copper wall, the insulation, and the outer surface convection:

1 / UA_L = R_copper + R_insulation + R_conv

Copper has high thermal conductivity, so R_copper is negligible and assumed equal to zero. The two remaining resistances are summed so the same equation holds whether the pipe is heavily insulated, lightly insulated, or bare.

Unified Heat Loss Equation

Keeping both the insulation conduction term and the external convection term, loss per foot is:

$$\dot{q}\_L = \Delta T \ / \ [\ ln(r\_out/r\_cu)/(2\pi \cdot k) \ + \ 1/(h\_o \cdot 2\pi \cdot r\_out)\ ]$$

Where:

Symbol	Definition	Imperial Units
ΔT	T_water – T_ambient	°F
k	Thermal conductivity of insulation	BTU/h·ft·°F
h_o	External convection coefficient	BTU/h·ft²·°F
r_out	Outer radius of insulation (= r_cu if bare)	ft
r_cu	Outer radius of copper pipe	ft

The first bracket term is conduction through the insulation layer; the second is external convection at the outer surface. As insulation thickens, the conduction term increases. As insulation thins, conduction approaches zero and convection makes up the majority of heat loss. At zero thickness, the outer radius equals the pipe radius ($r\_out \ = \ r\_cu$), the conduction term vanishes, and the expression reduces on its own to the bare-pipe limit $\dot{q}L \ = \ h\_o \cdot 2\pi \cdot r\_cu \cdot \Delta T$.

DERIVATION

1. **Cylindrical conduction.** For steady radial conduction through a hollow cylinder, Fourier's law gives heat per unit length $\dot{q}L = 2\pi k(T_1 - T_2) / ln(r\_out/r\_in)$, so the conduction resistance of a cylindrical shell is $R = ln(r\_out/r\_in) / (2\pi k)$.

2. **Insulation resistance.** Substituting $r\_in = r\_cu$ and $r\_out = r\_outside$ gives $R\_insulation = ln(r\_out/r\_cu) / (2\pi \cdot k)$.

3. **Convection resistance.** At the outer surface, $R\_conv = 1 / (h\_o \cdot 2\pi \cdot r\_out)$.

4. **Combine and invert.** Adding the two resistances and inverting ($1/UAL = R\_insulation + R\_conv$) gives the unified equation above, then $\dot{q}L = UAL \cdot \Delta T$.

Unit Notes

The ln ratio is dimensionless, so radii may be input in inches because the units cancel. But k must be in BTU/h·ft·°F, and in the convection term r_out must be input in feet. Conductivity of common insulation materials is as follows:

- fiberglass 0.022–0.027,
- foam 0.012–0.018,
- mineral wool 0.020–0.030 BTU/h·ft·°F.

Typical h_o for indoor air is:

Condition	h_o (BTU/h·ft²·°F)
Still air (low / mid / high)	1.5 / 2.0 / 2.5
Light air movement	2.5–4.5
Forced airflow / outdoors	4.5–18
Still air (low / mid / high)	1.5 / 2.0 / 2.5

EXAMPLE

Bare 1/2" pipe, r_{cu} = 0.02083 ft, h_o = 2.0, ΔT = 50°F. With no insulation r_out = r_cu, so the conduction term is zero and the equation reduces to $\dot{q}L = h\_o \cdot 2\pi \cdot r\_cu \cdot \Delta T$ = 2.0 × 2π × 0.02083 × 50 = 13.1 BTU/h per foot.

Appendix D: Clevis-Style Pipe Hanger Heat Loss

Standard cylindrical insulation calculations overlook point-source losses at uninsulated pipe supports. This appendix quantifies that loss for an uninsulated MSS SP-58 Type 1 adjustable clevis hanger in direct contact with a copper distribution line, using a steady-state extended-surface (fin) network.

Model and Boundaries

The assembly is a coupled two-stage fin system:

- **Primary fin (saddle/yoke):** the steel U-strap wraps the pipe circumference, forming a direct conductive interface. It acts as a circumferential fin, shedding heat by natural convection before routing the rest to the rod base. This gives a temperature attenuation (η_saddle) that scales with pipe outer diameter.
- **Secondary fin (suspension rod):** the threaded carbon-steel rod conducts heat vertically away from the yoke over length L = 4 in, cooling convectively along its perimeter before terminating in an anchor in the overhead structural deck.

Mathematical Framework

CIRCUMFERENTIAL SADDLE FIN

The strap has thickness t = 0.00278 m (12 ga) and width W = 0.0222 m (7/8 in). The conductive path from the pipe bottom to the rod root is about half the circumference:

$$L\_saddle = \pi \cdot OD / 2$$

The fin parameter for the flat saddle strap is:

$$m\_saddle = \sqrt{(\, 2h / (k\_steel \cdot t)\,)}$$

Assuming an adiabatic tip where the strap halves meet at the rod root, the saddle efficiency and the temperature delta at the rod base are:

$$\theta\_base,rod = (T\_pipe - T\_ambient) \cdot \eta\_saddle$$

VERTICAL SUSPENSION ROD FIN

Steady 1-D conduction along the rod with surface convection follows $d^2\theta/dx^2 - m^2\theta = 0$, where $\theta(x) = T(x) - T\_ambient$ and:

$$m = \sqrt{(\, hP / (k\_steel \cdot A\_c)\,)} = \sqrt{(\, 4h / (k\_steel \cdot d)\,)}$$

The tip condition at x = L matches conductive flux leaving the rod to conduction into the structure through an anchor of spreading resistance R_structure = 120 K/W:

$$-k\_steel \cdot A\_c \cdot (dT/dx)|\_\{x = L\} = (T(L) - T\_ambient) / R\_structure$$

Solving the system gives net heat loss per hanger:

$$Q\_hanger = \sqrt{(hP \cdot k\_steel \cdot A\_c)} \cdot \theta\_base,rod \cdot [\, (\sinh mL + \beta \cdot \cosh mL) / (\cosh mL + \beta \cdot \sinh mL)\,]$$

$$\beta = 1 / (m \cdot k\_steel \cdot A\_c \cdot R\_structure)$$

GLOBAL INPUTS (SI BASELINE)

- T_pipe = 51.67 °C (125 °F); T_ambient = 21.11 °C (70 °F); ΔT_core = 30.56 °C.
- L = 0.1016 m (4 in); h = 8.5 W/m²·K (natural indoor convection); k_steel = 43 W/m·K; R_structure = 120 K/W.

EXAMPLE 1 – 1/2" NOMINAL PIPE (3/8" ROD)

- Saddle: OD = 0.015875 m; L_saddle = 0.02494 m; m_saddle·L_saddle = 0.2975; η = 0.9714; θ_base = 29.69 °C.
- Rod: d = 0.009525 m; P = 0.02992 m; A_c = 7.1256×10^{-5} m²; m = 9.112 m^{-1}; β = 0.2984.
- Result: mL = 0.9258; bracket = 0.8421; √(hP·k·A_c) = 0.02791 W/K; Q = 0.698 W → 2.4 Btu/hr

.EXAMPLE 2 – 4" NOMINAL PIPE (5/8" ROD)

- Saddle: OD = 0.104775 m; L_saddle = 0.16458 m; m_saddle·L_saddle = 1.9634; η = 0.4896; θ_base = 14.96 °C.
- Rod: d = 0.015875 m; P = 0.04987 m; A_c = 1.9793×10^{-4} m²; m = 7.056 m^{-1}; β = 0.1387.
- Result: mL = 0.7169; bracket = 0.6940; √(hP·k·A_c) = 0.06014 W/K; Q = 0.624 W → 2.1 Btu/hr.

Hanger Heat Loss Table

Every value is reproducible from the framework and inputs above.

Nominal Size	Pipe OD (in)	Rod Dia. (in)	Fin Param. m (1/m)	Saddle η	Loss (W)	Loss (Btu/hr)
1/2"	0.625	3/8	9.11	0.971	0.70	2.4
3/4"	0.875	3/8	9.11	0.945	0.68	2.3
1"	1.125	3/8	9.11	0.912	0.66	2.2
1-1/4"	1.375	3/8	9.11	0.875	0.63	2.1
1-1/2"	1.625	3/8	9.11	0.835	0.60	2.1
2"	2.125	3/8	9.11	0.755	0.54	1.9
2-1/2"	2.625	1/2	7.89	0.679	0.68	2.3
3"	3.125	1/2	7.89	0.612	0.61	2.1
4"	4.125	5/8	7.06	0.490	0.62	2.1

Appendix E: Pipe Size Conversion From Appendix A to Appendix M

This appendix describes the process to convert existing CPC Appendix A (Hunter's Curve) pipe sizes to the pipe size that would have been selected using CPC Appendix M.

Core Assumption: 0.60 Flow Reduction Coefficient

Pipe sizing is driven primarily by maximum flow velocity, and assumed flow through any section of pipe is driven by Appendix A or Appendix M pipe sizing, based on number of fixtures downstream of the pipe. This study assumes the estimated flow is reduced by 40 percent when using Appendix M pipe sizing, based on the following studies:

- Stantec / IAPMO (2020), 45-unit building: Water Demand Calculator (WDC) peak 47.1 GPM vs. Appendix A 79.0 GPM — a ratio of ~0.596.
- Buchberger & Omaghomi (2017) binomial probability model replaces 1940s fixture-flow assumptions with empirical functions for modern low-flow fixtures, resulting in ~40 percent reduction in assumed flow.

Sizing Equations

Each segment is re-evaluated as:

$Q_M = Q_A \times 0.60$ $A = Q_M / v$

where A is the minimum internal cross-sectional area (in^2) and v is the maximum design velocity, capped at 5 ft/s to prevent erosion-corrosion. The result is rounded up to the nearest standard nominal size that meets the area.

Discrete Size Mapping (V ≤ 5 FPS)

Because nominal sizes are discrete, a 40 percent flow cut does not give a uniform size reduction.

Baseline (Appendix A)	Max Q_A @ 5 fps (GPM)	Appendix M Demand (×0.60, GPM)	Optimized (Appendix M)	Vol. Reduction/ft
4"	165	99.0	3"	~44%
3"	93	55.8	2.5"	~31%
2.5"	65	39.0	2"	~36%
2"	42	25.2	1.5"	~43%
1.5"	24	14.4	1.25"	~31%
1.25"	17	10.2	1"	~35%
1"	11	6.6	3/4"	~42%
3/4"	6.5	3.9	3/4" or 1/2" *	0% to 53%

Baseline (Appendix A)	Max Q_A @ 5 fps (GPM)	Appendix M Demand (×0.60, GPM)	Optimized (Appendix M)	Vol. Reduction/ft
1/2"	3.1	1.8	1/2"	0%

The 3/4" Swing-Size Split (50/50)

At 3/4", applying a 0.60 flow multiplier reduces demand from 6.5 to 3.9 GPM. Since 3.9 GPM exceeds the 3.1 GPM capacity of 1/2" pipe at 5 fps, a raw rounding rule would keep all 3/4" branches at 3/4" (0 percent reduction). But 3.9 GPM is a building-wide average, not the true per-unit stochastic load. This study assumes half of 3/4" branches drop to 1/2" and half stay. Justification is the following:

- Smaller units require ½" pipe: studio, 1BR/1BA, and 2BR/1BA units have WDC peaks of 2.4–2.9 GPM — below 3.1 GPM — so they drop to 1/2" (~53 percent local volume reduction).
- Larger units stay at 3/4": 2BR/2BA and 3BR units have higher simultaneous-use probability, pushing WDC peaks to 3.3–4.2 GPM, which exceeds the 5 fps max velocity allowance.
- Conservative estimate: under CALGreen fixtures the WDC often drives 60–70 percent of branches to 1/2". Modeling only 50 percent at ½" provides a conservative estimate.