Developing Actionable Operational Insights for Centralized Heat Pump Water Heating in Multifamily Affordable Housing

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ABSTRACT

Centralized heat pump water heating (CHPWH) systems are increasingly deployed in multifamily buildings as part of building electrification strategies, yet relatively limited field data exist on their operational performance under real-world conditions. This study evaluates seven centralized CO_2 heat pump water heating systems serving multifamily residential buildings using monitoring data collected between July 2024 and May 2025.

The analysis integrates system efficiency, operational drivers, cost performance, emissions impacts, and demand flexibility potential. Across the monitored buildings, average system coefficient of performance (COP) ranged from approximately 1.4 to 3.5, with substantial variation observed across buildings. Resistance heating contribution showed only a weak statistical relationship with COP, while hot-water load exhibited a stronger positive association with system efficiency.

Economic and environmental outcomes were closely aligned with system efficiency. Buildings with higher COP values generally exhibited lower normalized operating costs and lower emissions intensity. Aggregated load profiles indicate that CHPWH electricity demand overlaps with the utility peak demand window (4–9 PM), while operational headroom analysis suggests that meaningful load shifting potential exists through thermal storage operation.

These results highlight the importance of operational conditions, load characteristics, and control strategies in determining real-world CHPWH performance. Within the scope of the monitored operating-energy analysis, CHPWH cost intensity ranged from approximately $0.21 to $0.56 per therm of delivered heat, below a representative central gas-boiler operating-cost benchmark of roughly $2.2 per therm of useful heat based on recent San Diego–Carlsbad retail gas prices and 85% boiler efficiency. The results suggest that CHPWH systems can provide efficient electrified water heating while offering opportunities for operating-cost reduction, emissions mitigation, and demand flexibility.

1. Introduction

Building electrification has emerged as a key strategy for reducing greenhouse gas emissions in the building sector as electric technologies replace fossil-fuel end uses in buildings (Mai et al. 2021). Domestic Hot Water (DHW) production represents a significant share of energy consumption in multifamily buildings, making water heating an important target for electrification and efficiency improvements. Domestic hot water is a major end use in multifamily housing, accounting for approximately 32% of total energy use in buildings with five or more units. In California, domestic hot water production accounts for about 33% of total multifamily fossil-gas use, and approximately 50% of multifamily apartment buildings are estimated to use central gas water-heating systems, indicating that centralized DHW systems are an important electrification opportunity, particularly in multifamily affordable housing where one plant-level retrofit can affect many dwelling units (ETCC 2024; California Energy Commission 2024). Centralized heat pump water heating systems have increasingly been deployed in multifamily buildings due to their ability to efficiently serve large hot water loads using centralized equipment and shared storage infrastructure (Larson et al. 2018; New Buildings Institute 2023).

Heat pump water heaters (HPWHs) provide an efficient alternative to conventional electric resistance water heating by transferring thermal energy from ambient air rather than generating heat directly through resistance heating, allowing significantly higher efficiency under typical operating conditions (Sparn et al. 2014). Prior field studies provide important but still limited evidence: Hoeschele and Weitzel monitored one 10.5-ton central HPWH serving a student apartment building, Banks et al. evaluated a central CO_2 HPWH retrofit in a 60-unit multifamily building in the Pacific Northwest, and the CalNEXT field demonstration examined two low-income elder-living buildings in San Francisco. This study adds to that evidence base by analyzing seven monitored CHPWH systems within one regional portfolio using consistent device-level monitoring, cost, emissions, and demand-flexibility metrics. The multi-building dataset allows comparison of performance variability across similar system architectures rather than evaluating a single installation in isolation (Hoeschele and Weitzel 2013; Banks et al. 2022; Valmiki et al. 2023). Laboratory testing and manufacturer specifications typically report high efficiency values under controlled conditions, but field performance can vary due to system configuration, load variability, control strategies, and auxiliary heating operation. In addition to energy efficiency benefits, CHPWH systems may also provide opportunities for grid-interactive operation because thermal storage allows electricity consumption to shift across time without affecting hot water availability (Delforge and Larson 2018; Spielman et al. 2024).

To better understand real-world CHPWH operation, this study analyzes monitoring data from seven centralized heat pump water heating systems serving multifamily residential buildings in the San Diego region. Using monitoring data collected between July 2024 and May 2025, the study evaluates system efficiency, operational drivers of performance, economic and emissions outcomes, and demand flexibility potential.

The objectives of this study are to evaluate seasonal and diurnal system COP behavior across multiple CHPWH systems; identify operational drivers of system performance, including auxiliary heating contribution and load dependence; quantify economic and environmental performance using cost and emissions intensity metrics and assess demand flexibility potential through analysis of system load profiles and operational headroom. By integrating these analytical perspectives, the study provides a comprehensive evaluation of CHPWH performance in multifamily buildings and identifies operational factors that influence both system efficiency and grid interaction potential.

2. Project Overview and Monitoring Approach

2.1 Building Portfolio and CHPWH System Configuration

This study evaluates the post-retrofit field performance of CHPWH systems serving seven multifamily residential buildings in the San Diego region. The monitored systems replaced existing central gas-boiler water-heating systems with centralized heat pump water-heating plants. Because monitoring began after retrofit completion, pre-retrofit operational data were not collected, and this analysis does not present measured pre/post comparisons with the original gas systems. Although the buildings share a similar system architecture, they differ in size, hot-water demand, and operational settings, enabling cross-building comparison under varying operating conditions. Auxiliary electric heating is provided through swing tanks with resistance elements to maintain temperature setpoints during high-demand periods or when heat pump output is insufficient.

Each monitored building uses a similar centralized system configuration: three heat pump water-heater units piped in parallel, shared hot-water storage, a recirculating domestic hot-water loop, and a swing tank with electric-resistance elements for temperature maintenance and supplemental heating. Across the portfolio, the intended control sequence is consistent: the heat pumps serve as the primary heat source and operate in parallel to maintain storage temperature and meet hot-water demand, while the swing-tank resistance elements operate only as needed to maintain delivery temperature or supplement heat pump capacity. Two buildings have outdoor heat pump installations, but the overall system configuration and control intent are otherwise broadly consistent.

2.2 Monitoring Infrastructure

System performance was evaluated using a monitoring framework that collected device-level and system-level operational data from each building. The monitoring system records electricity consumption for individual system components and estimates thermal output using hot water flow and temperature measurements. Device-level electricity monitoring enables separation of heat pump energy use from auxiliary resistance heating, allowing evaluation of how auxiliary heating affects overall system performance.

2.3 Measured Variables

The following metrics were measured using monitoring infrastructure:

- Heat pump electricity consumption
- Auxiliary heating electricity consumption
- Total system electricity consumption
- Cold-water inlet temperature and flow
- Hot-water outlet temperature and flow from the heat pump array to the storage tank
- Storage tank inlet temperature
- Stratification tank outlet temperature

2.4 Performance Metrics and Tariff/Emissions Inputs

Performance was evaluated using technical, economic, environmental, and demand-flexibility metrics.

- System COP was calculated as the ratio of useful thermal energy delivered as hot water to total water-heating electricity consumption, including both heat pump and auxiliary resistance heating.

- Cost intensity and emissions intensity were calculated as operating cost and greenhouse gas emissions per unit of delivered thermal energy, respectively, allowing comparison across buildings with different hot-water demand levels.
- GHG emissions were calculated using the SGIP_CAISO_SDGE marginal GHG signal. The raw SGIP emissions signal is reported at five-minute resolution in kg CO_2/kWh and was averaged to hourly values to match the analysis time step. Monitored electrical data, originally available at 15-minute resolution, were also aggregated to hourly energy consumption before being multiplied by the corresponding hourly emissions factor.
- Cost calculations used SDG&E commercial time-of-use electricity periods, with the on-peak period defined as 4:00 PM to 9:00 PM, summer defined as June through October, and winter defined as November through May. Hourly CHPWH electricity consumption was assigned to the corresponding TOU period before costs were aggregated. For comparison with fossil-fuel water heating, a representative central gas-boiler benchmark was estimated using recent San Diego–Carlsbad retail natural gas prices from the BLS/FRED series and an assumed 85% boiler efficiency, yielding an approximate delivered-heat cost of $2.2 per therm of useful heat (SDG&E n.d.; BLS 2024). Demand charges and fixed customer charges were excluded from the normalized energy-cost comparison.
- Demand-flexibility potential was evaluated using operational headroom, defined as the difference between the maximum observed hourly load and the average hourly load. This metric provides an empirical estimate of available load-shifting capacity based on observed system operation and indicates the potential to improve load factor through control strategies.

2.5 Monitoring Period and Dataset

The dataset spans approximately eleven months, from July 2024 through May 2025. Monitoring data were aggregated to monthly time steps for system-level metrics, including COP, cost intensity, and emissions intensity, and to hourly time steps for load-profile and demand-flexibility analysis. Although twelve buildings were retrofitted at the site, only seven had monitoring data of sufficient completeness and quality for this analysis. The original building identifiers were retained for traceability, so the analyzed buildings are labeled 3, 4, 6, 9, 10, 11, and 12 rather than renumbered 1 through 7. Buildings 4 and 12 had shorter monitoring coverage, with approximately six months of usable data. Missing months were not estimated or backfilled; therefore, performance metrics for these two buildings were calculated only from valid measured periods, resulting in fewer monthly observations without extrapolation to unmonitored months.

2.6 Analytical Framework

Using the monitoring dataset and performance metrics described above, the analysis evaluates system performance across four performance categories:

1. Energy performance, measured through seasonal and diurnal COP behavior.

2. Operational drivers of performance, including auxiliary heating contribution and hot water demand levels.
3. Economic and environmental performance evaluated using cost and emissions intensity metrics.
4. Demand flexibility potential, assessed through load profile analysis and operational headroom.

Together, these analytical perspectives provide a comprehensive evaluation of CHPWH system performance and operational characteristics across the monitored building portfolio.

3. Analytical Results

This section presents operational results from July 2024 through May 2025 monitoring of seven CHPWH systems serving multifamily buildings. The analysis evaluates system COP, operational drivers of efficiency, cost and emissions intensity, and demand flexibility (DF) potential.

3.1 System Performance Analysis and Variability

Figure 3-1 summarizes the distribution of monthly system COP across the seven monitored buildings. The boxplots show substantial differences in both median COP and variability, with some buildings approaching or exceeding a median COP of 3 while others remain closer to 1–1.5. This comparison indicates that the systems do not perform uniformly despite operating in the same regional climate and using broadly similar system architecture. The observed spread suggests that building-specific factors, such as system configuration, commissioning, controls, or hot-water load characteristics, may have a larger influence on realized COP than seasonal climate alone.

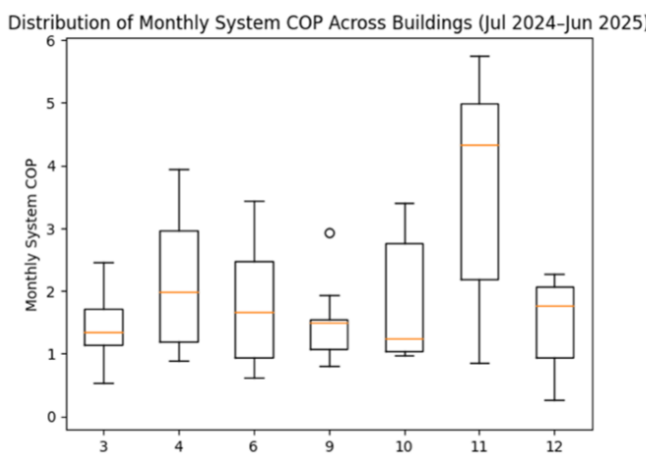

Figure 3-1. Distribution of monthly system COP across buildings

Figure 3-2 shows the calculated monthly COP values for each monitored building and further demonstrates that performance differences persist over time rather than occurring in a single month. Building 11 generally exhibits higher COP values across multiple months, while Buildings 3, 9, and 12 remain in lower efficiency ranges. Buildings 4, 6, and 10 fall within an intermediate range but show greater month-to-month variation. Although seasonal changes are visible, the relative separation among buildings remains apparent across much of the monitoring period.

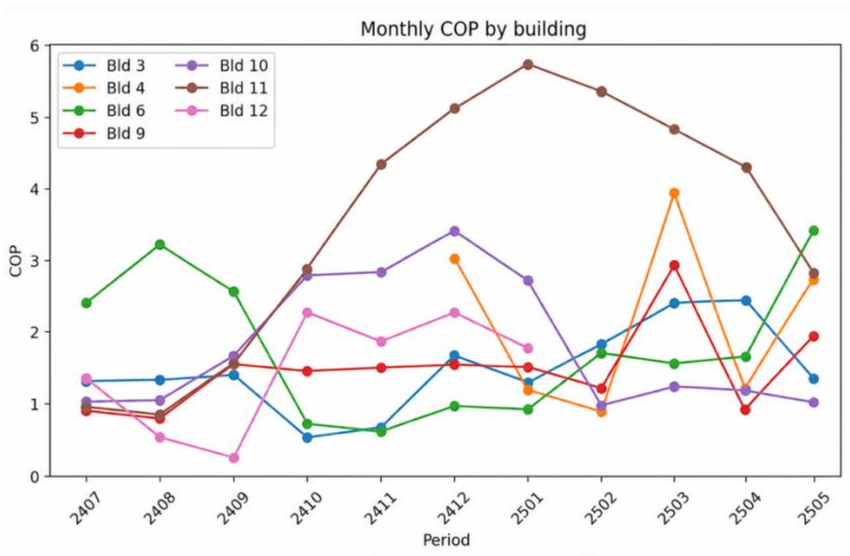

Figure 3-2. Monthly system COP by building

Figure 3-3 presents the seasonal COP of the monitored buildings, showing the average hourly COP in winter (December–February) and summer (July–September). Both seasons exhibit a broadly similar diurnal structure. COP values increase during the early morning hours (approximately 01:00–05:00), decline during the morning period (approximately 07:00–10:00), and recover during midday before stabilizing through the afternoon and evening hours. Although seasonal differences between the winter and summer mean curves are visible, the shaded percentile bands indicate that the spread in COP across buildings is larger than the difference between seasonal averages at most hours of the day. These results further indicate substantial performance variation across the building dataset.

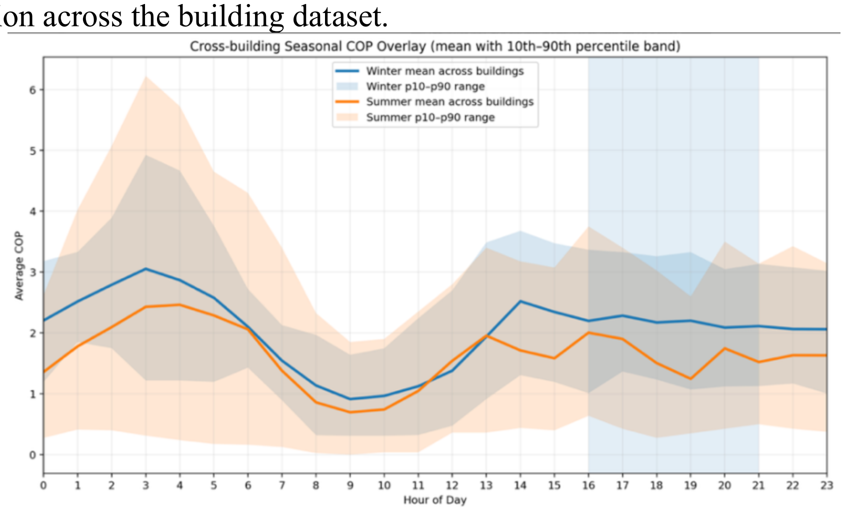

Figure 3-3. Cross-building seasonal COP overlay

Taken together, these figures demonstrate that realized CHPWH system performance varies substantially across buildings within the monitored portfolio. The persistence of these differences across seasons, months, and hourly operating periods suggests that building-specific characteristics play an important role in determining observed efficiency. The following sections examine several operational and system-level factors that may contribute to these performance differences.

3.2 Drivers of Performance Variation

3.2.1 Resistance Heating Contribution

Resistance heating contribution was evaluated using swing-tank resistance energy share, defined as swing-tank electric-resistance consumption divided by total CHPWH system electricity consumption. As shown in Figure 3-4, this metric was compared with calculated system COP to assess whether greater auxiliary resistance use corresponded to lower system efficiency.

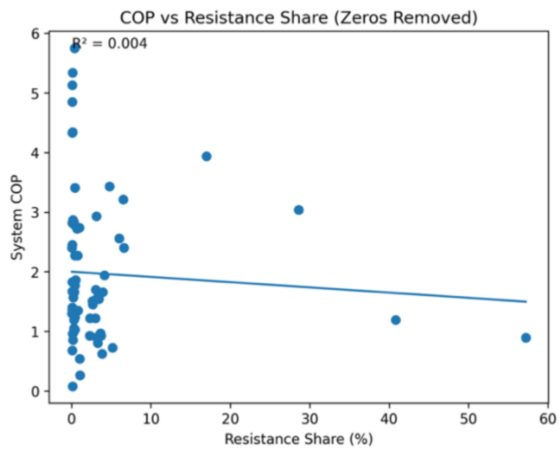

Figure 3-4. System COP vs. swing-tank resistance energy share. Resistance energy share is the percentage of total system electricity consumed by swing-tank resistance elements.

Figure 3-4 compares system COP with swing-tank resistance energy share, defined as swing-tank electric-resistance consumption divided by total CHPWH system electricity consumption, after observations with zero resistance use were removed. The nearly flat regression line and very low R^2 value (≈0.004) indicate that resistance share explains little of the variation in calculated COP. While some high-resistance observations correspond to low COP, many low-COP observations also occur when resistance share is small. This suggests that swing-tank resistance use alone does not explain performance differences; hot-water load, tank operation, heat pump staging, recirculation losses, and controls likely also contribute.

3.2.2 Component Energy Consumption Comparison

Device-level energy distribution provides additional context for interpreting the observed system performance. Figure 3-5 summarizes the relative energy contribution of system components across the monitored buildings. Most buildings are strongly heat-pump dominated, with more than 95% of device-level energy attributed to heat pump operation. Building 4 represents a notable exception, with approximately 36% of device-level energy associated with the swing tank. This higher auxiliary energy share coincides with lower observed COP values for that building relative to the rest of the portfolio. Across the remaining buildings, however, auxiliary energy contributions remain comparatively small, reinforcing the earlier observation that differences in realized system performance cannot be explained solely by resistance heating behavior.

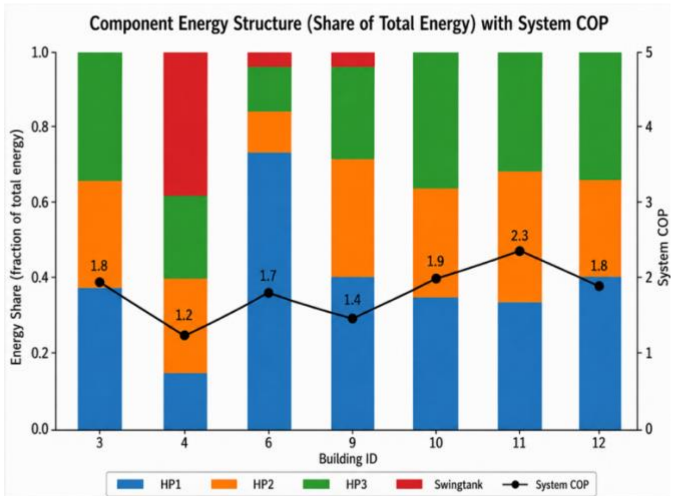

Figure 3-5 Component energy share by building

3.2.3 Load Dependence

System performance was also examined as a function of hot-water load. Previous studies have shown that heat pump water heater efficiency can decline under low-load or highly variable demand conditions due to cycling losses and auxiliary heating operation (Sparn et al. 2014; Banks et al. 2022). Figure 3-6 plots monthly system COP against monthly delivered hot-water thermal load across the monitored buildings.

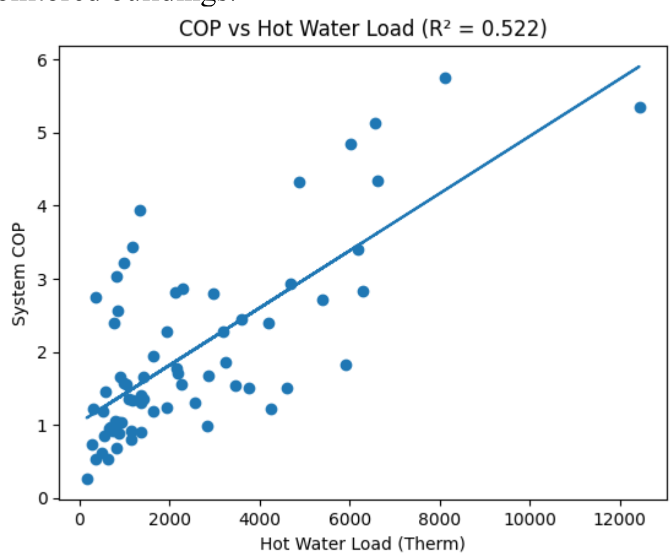

Figure 3-6. COP vs hot-water load

The regression indicates a positive relationship between hot-water load and system COP ($R^2 \approx 0.52$). Higher load conditions are generally associated with higher COP values, while lower load conditions tend to correspond with lower system efficiency. The scatter shows that months with relatively small hot-water loads frequently exhibit COP values between approximately 0.5 and 2.0, whereas higher-load months include several observations with COP ranging from approximately 1.4 to 3.5 on average, with some individual observations exceeding 4 under high-load conditions. Although the relationship is not perfectly linear and variability remains across observations, the correlation suggests that operating conditions associated with higher hot-water demand are generally associated with improved system efficiency.

3.3 Economic Performance of Monitored Systems

The previous sections demonstrated substantial variation in realized system COP across the monitored buildings. Because system efficiency directly affects electricity consumption required to produce a given amount of hot water, differences in COP are expected to influence the operating cost of hot water production. The following analysis examines the economic performance of the monitored systems by comparing normalized operating cost across buildings and evaluating how cost outcomes relate to observed system efficiency.

Figure 3-7 presents the normalized operating cost of hot water production across the monitored buildings, expressed as cost per therm of delivered thermal energy. The results show substantial variation in cost intensity across the portfolio. Cost per therm ranges from approximately $0.21/therm to $0.56/therm, representing more than a twofold difference across the monitored buildings. Because the metric is normalized by thermal output, these differences reflect variation in realized system operation rather than differences in system size or total hot-water demand. For context, regional retail natural gas prices in the San Diego–Carlsbad area averaged approximately $1.9 per therm in recent years (BLS 2024). Assuming a representative boiler efficiency of 85%, this corresponds to a delivered thermal cost of roughly $2.2 per therm of useful heat, substantially higher than the operating costs observed for the monitored CHPWH systems.

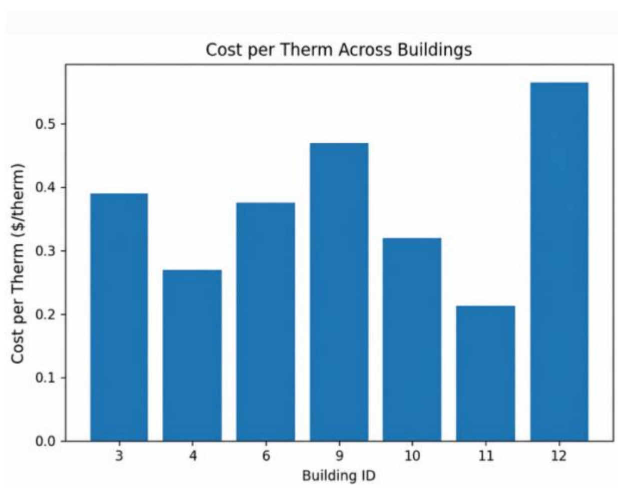

Figure 3-7. Cost per therm across buildings, representative gas boiler benchmark: approximately $2.2/therm useful heat (San Diego–Carlsbad retail gas price approximately $1.9/therm divided by 85% boiler efficiency).

Figure 3-8 further examines the relationship between system efficiency and economic performance by comparing average COP with normalized operating cost. The scatter plot indicates an inverse association between these variables: buildings with higher average COP generally exhibit lower cost per therm. The building with the highest average COP also corresponds to the lowest normalized operating cost, while buildings with lower COP values appear among the higher-cost observations. Although the number of buildings in the sample is limited and the analysis does not control for all operational variables, the observed pattern is consistent with the expected relationship between system efficiency and electricity consumption required for hot water production.

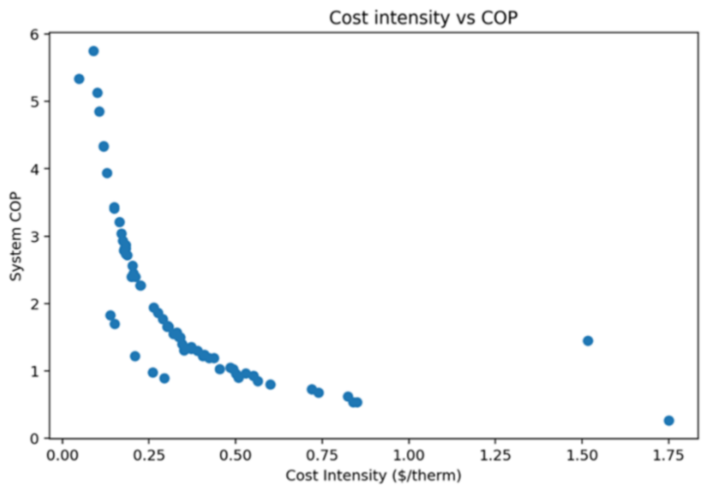

Figure 3-8. Cost intensity vs COP

Additional figures provide further insight into operational characteristics that may influence cost outcomes. Figure 3-9 summarizes the distribution of energy cost across system components for each building. While most buildings remain strongly heat-pump dominated, the relative contribution of auxiliary components varies across the portfolio, indicating differences in system operation and energy cost allocation among devices.

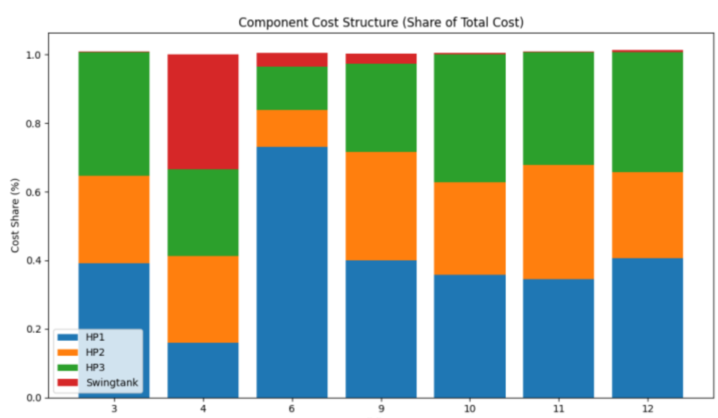

Figure 3-9. Component cost structure across buildings comparison

Peak-period cost exposure (Figure 3-10) also varies across buildings. The analysis shows that approximately 24–36% of total operating cost occurs during the utility peak pricing window. This indicates that tariff timing contributes meaningfully to overall operating cost. However, the peak-period cost share does not fully align with the normalized cost intensity across buildings, suggesting that tariff exposure and system efficiency represent distinct dimensions of economic performance.

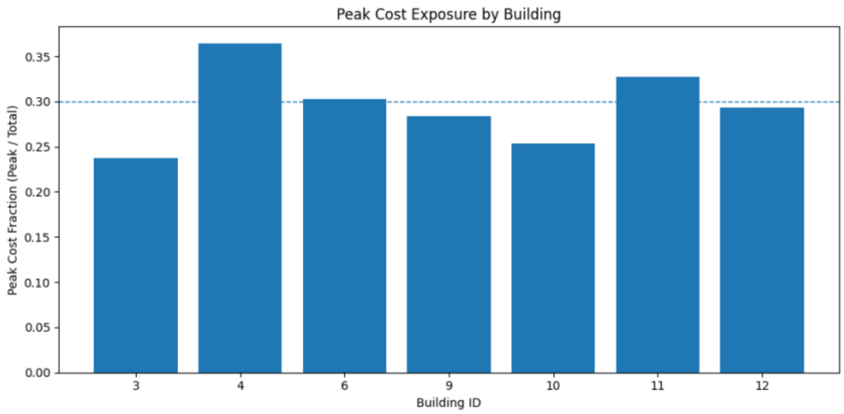

Figure 3-10. Peak cost exposure comparison by buildings

Taken together, these results indicate that the economic performance of CHPWH systems varies substantially across the monitored buildings. The analysis also shows that higher system efficiency is generally associated with lower normalized operating cost. The following section further examines how operational characteristics influence both technical and economic performance outcomes.

3.4 Greenhouse Gas Performance

The previous section showed that higher system efficiency generally lowers operating cost, and the same relationship is expected for Scope 2 GHG emissions because electric water-heating emissions are driven by electricity use. This section evaluates GHG performance using emissions intensity and hourly emissions profiles. Hourly emissions were calculated by matching CHPWH electricity consumption to the SGIP_CAISO_SDGE hourly marginal emissions factor, which varies throughout the day. Therefore, Figure 3-12 reflects both water-heating load timing and grid-emissions timing; elevated emissions may result from higher CHPWH electricity use, higher marginal emissions factors, or both.

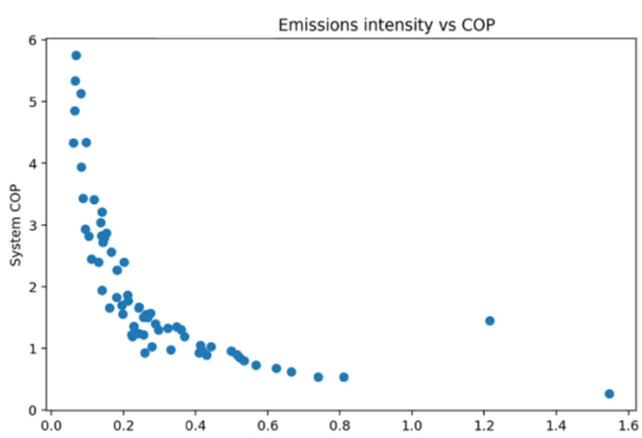

Figure 3-11. Emission intensity vs COP

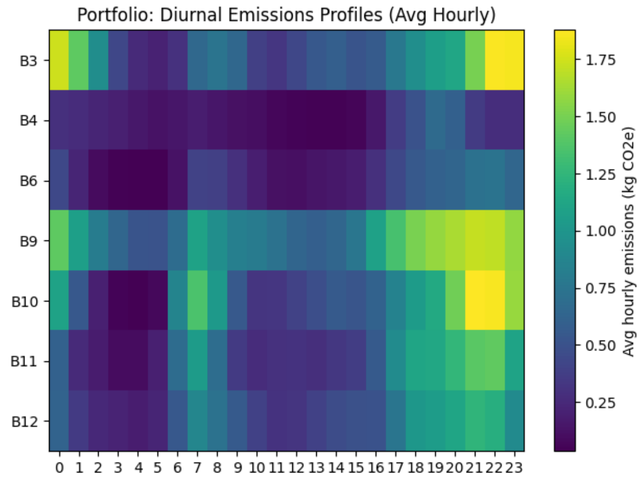

Figure 3-12 Diurnal emission profile heatmap across buildings

Emissions performance was evaluated using emissions intensity, expressed as kilograms of CO_2 per unit of delivered thermal energy. Figure 3-11 plots system COP against emissions intensity across the monitored observations. The scatter shows a clear inverse relationship between these variables. Observations with higher COP values generally correspond to lower emissions intensity, while lower COP values are associated with substantially higher emissions intensity. For example, observations with COP values above approximately 4 correspond to emissions intensities below roughly 0.1–0.2 kg CO_2 per therm, while observations with COP values below approximately 1.5 often exceed 0.4–0.6 kg CO_2 per therm. This pattern reflects the direct relationship between system efficiency and the electricity required to produce a unit of thermal energy.

Figure 3-12 provides additional context by showing the average hourly emissions profiles across buildings. The heat map illustrates substantial variation in emissions intensity both across buildings and throughout the daily operating cycle. Several buildings exhibit relatively low emissions levels during overnight hours (approximately 02:00–06:00), with average hourly emissions typically below about 0.3–0.5 kg CO_2e. Emissions generally increase during late afternoon and evening periods. For example, Building 10 exhibits average hourly emissions exceeding approximately 1.7–1.9 kg CO_2e during the late evening period (approximately 21:00–23:00), compared with values below about 0.3 kg CO_2e during early morning hours. Building 9 shows a similar pattern, with evening emissions frequently exceeding 1.5 kg CO_2e.

These hourly patterns suggest that the timing of hot-water production influences the resulting emissions intensity. Periods with lower hourly emissions—particularly during early morning hours—represent potential opportunities for emissions reduction if a portion of hot-water heating demand can be shifted toward these lower-emissions periods through storage utilization or load-management strategies. Taken together, these results indicate that greenhouse gas performance varies substantially across the monitored systems and is strongly associated with realized system COP. Buildings operating at higher efficiency levels generally achieve lower emissions intensity, while lower-efficiency observations correspond to higher emissions levels. These findings are consistent with the earlier economic analysis, in which higher system efficiency was also associated with lower normalized operating cost.

3.5 Portfolio-Scale Demand Flexibility Potential

This section extends the analysis from individual buildings to the aggregated monitored portfolio to estimate demand-flexibility potential when multiple centralized CHPWH systems operate as a coordinated resource. The intent is not to imply physical interconnection among buildings, but to assess potential grid value at a campus, portfolio, or program scale. Because centralized CHPWH systems include thermal storage and variable daily electricity demand, they may support load shifting to reduce peak demand or align operation with lower-emissions periods (Delforge and Larson 2018; Spielman et al. 2024). Portfolio-level flexibility is evaluated using aggregated load profiles and operational headroom.

3.5.1 Campus-Level Demand Flexibility Potential

To evaluate demand flexibility potential at the portfolio scale, the hourly electricity consumption of all monitored CHPWH systems was aggregated to represent the total campus water heating load.

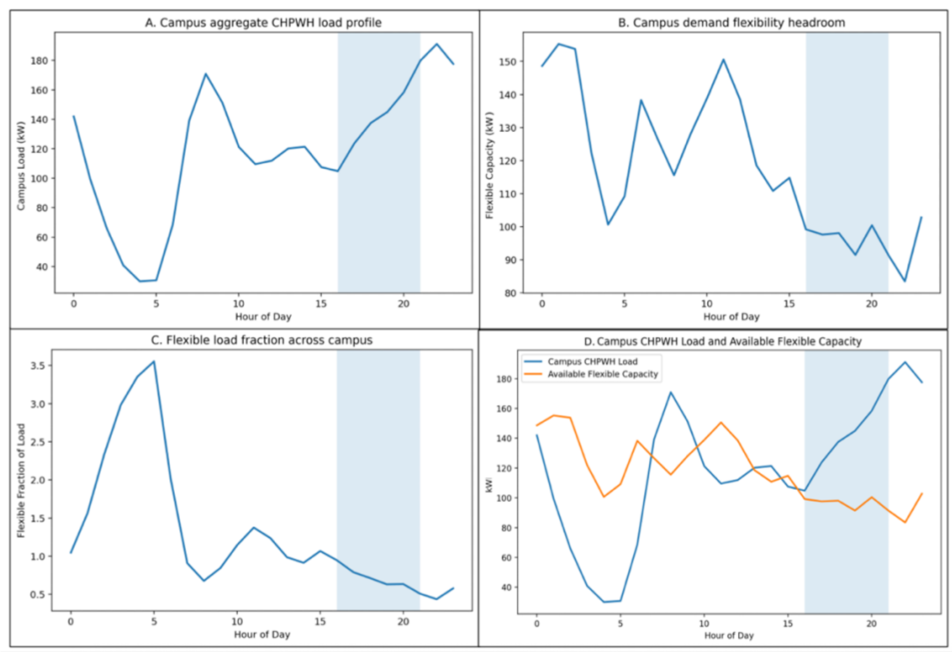

Figure 3-13. Campus-Level CHPWH demand flexibility panel plot (A) Aggregate campus CHPWH thermal load by hour of day (B) Campus demand flexibility headroom (C) Flexible load fraction, representing the ratio of available flexible capacity to the baseline load at each hour. (D) Comparison of baseline CHPWH load and available flexible capacity across the day. The shaded region indicates the typical afternoon–evening peak period (approximately 16:00–21:00).

Figure 3-13-A presents the resulting campus load profile. The aggregated system exhibits two prominent demand peaks. A morning peak occurs between approximately 7:00 and 9:00, with campus load reaching roughly 160–170 kW, while a second and larger peak occurs during the evening period between approximately 20:00 and 22:00, when campus load approaches 180–190 kW. The evening demand peak overlaps with the utility peak pricing window (16:00–21:00), indicating that CHPWH operation contributes to electricity demand during system peak conditions. Demand flexibility potential was evaluated using operational headroom, defined as the difference between the maximum observed hourly load and the average hourly load. Figure 3-13-B shows the resulting campus flexibility headroom profile. Across the daily operating cycle, available headroom ranges from approximately 85 kW to 155 kW. Headroom remains available throughout the peak pricing window. Between 16:00 and 21:00, available flexible capacity remains approximately 90–100 kW, indicating that a substantial portion of system load could potentially be shifted without exceeding previously observed operating limits. When expressed relative to average campus load, the flexible load fraction remains significant across the day. Figure 3-13-C shows that the flexible fraction reaches its highest values during early morning hours, exceeding 3.0–3.5 times the average load around 03:00–05:00, when campus demand is lowest. During the utility peak window, the flexible fraction declines but remains approximately 0.5–0.7, indicating that available headroom still represents roughly 50–70% of concurrent campus CHPWH load. Figure 3-13-D compares the campus load profile with the available flexible capacity. The comparison shows that flexible capacity remains comparable to or larger than the observed campus load across much of the day. Although flexible capacity decreases during evening hours, meaningful headroom remains available during the utility peak window.

Taken together, these results indicate that CHPWH systems possess measurable operational headroom that could support demand-flexibility strategies. Although individual systems may provide some load-shifting capability through thermal storage, the magnitude and reliability of flexibility increase when multiple buildings are aggregated. In this analysis, the flexibility estimate is based on the combined load of the seven monitored buildings and should therefore be interpreted as a portfolio-level opportunity rather than a guarantee that each individual building can provide the same controllable load. Shifting a portion of water-heating production toward lower-demand periods, such as early morning hours, may reduce peak-period electricity consumption while maintaining hot-water service; future work should evaluate the minimum system size, dwelling-unit count, storage volume, and control requirements needed to deliver dependable flexibility at both building and portfolio scales.

4. Discussion and Conclusion

This study evaluated the real-world performance of seven CHPWH systems serving multifamily residential buildings using monitoring data collected from July 2024 through May 2025. The analysis examined system efficiency, operational drivers, cost, emissions, and demand-flexibility potential.

Results show substantial variation in realized performance across the monitored buildings despite similar regional climate conditions and broadly similar system architecture. Some buildings consistently achieved higher COP values, while others remained lower across months, seasons, and operating periods. This persistent variability suggests that building-specific factors, including configuration, commissioning, controls, auxiliary heating behavior, and load characteristics, strongly influence field performance. It also represents a market-adoption concern because engineers, developers, and housing providers often require predictable operating costs and reliable performance when selecting central plant technologies. Large performance variation across similar installations can increase perceived risk and may slow broader CHPWH adoption unless addressed through better design guidance, commissioning, controls, and monitoring-based feedback.

No single operational factor fully explained the observed COP variation. Swing-tank resistance heating showed only a weak statistical relationship with COP, although higher auxiliary energy shares were generally associated with lower efficiency. Hot-water load showed a stronger positive association with COP, suggesting that realized performance depends on the combined effects of load, auxiliary heating, controls, tank operation, and system sequencing.

System efficiency was closely linked to both economic and environmental outcomes. Buildings with higher COP generally had lower normalized operating costs and lower emissions intensity because less electricity was required per unit of delivered thermal energy. Within the operating-energy cost boundary evaluated here, all monitored CHPWH systems produced hot water at a lower cost per delivered therm than the representative central gas-boiler benchmark, even though cost intensity varied across buildings.

The aggregated portfolio analysis also showed measurable demand-flexibility potential. CHPWH electricity demand overlapped with the utility peak period from 16:00 to 21:00, but operational headroom remained available throughout the day, including during peak hours. Available flexible capacity ranged from approximately 85 kW to 155 kW, indicating that some water-heating load could potentially be shifted through strategies such as off-peak tank preheating.

Overall, the results demonstrate that CHPWH systems can support multifamily electrification while offering opportunities for cost reduction, emissions mitigation, and demand flexibility. At scale, these retrofits could reduce fossil-fuel dependence in a building segment where central gas water heating is common, while also providing controllable thermal storage for load shifting. However, the observed performance variability remains a key limitation to broader market adoption, since engineers, developers, and housing providers often depend on predictable operating costs and reliable system performance when selecting central plant technologies. Therefore, design standardization, commissioning, monitoring-based diagnostics, and control optimization are needed to translate equipment potential into dependable cost, emissions, and grid-flexibility benefits. Future research should investigate operational strategies that improve system efficiency, reduce auxiliary heating use, and leverage thermal storage for demand flexibility while maintaining reliable hot-water service.

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Disclosure template

AI-assisted tools used: ChatGPT.
Used for: wording and grammar editing.
Human review: The authors reviewed and verified all content, calculations, and citations.