Performance of Integrated Thermal Storage and Heat Recovery Chillers in All-Electric Commercial Building

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ABSTRACT

The decarbonization of large commercial buildings presents significant challenges for heating, ventilating, and air conditioning (HVAC) system design, especially for all-electric configurations that are mostly dependent on air-to-water heat pumps (AWHPs). While AWHPs enable electrification, their performance limitations, high costs, and integration constraints often hinder efficiency and grid-responsive operation. Thermal energy storage (TES) has traditionally been used for peak cooling load management, but its broader potential remains underutilized. This paper evaluates the Time-Independent Energy Recovery (TIER) plant concept. The TIER system is an all-electric system that integrates heat recovery chillers, TES, and AWHPs to maximize heat recovery and reduce reliance on AWHP operation. Using measured operational data from a large commercial building in California, this study assesses system performance across multiple operating modes and weather conditions. Also, this paper compares the performance of the TIER plant with a conventional AWHP plant. Results show that the TIER system achieves higher heating and cooling coefficients of performance, particularly when operating in heat recovery mode. The better performance is mostly due to decoupling heating and cooling production and leveraging TES for energy recovery rather than load shifting alone. These findings demonstrate that TIER can deliver meaningful efficiency improvements and enhanced operational flexibility relative to conventional all-electric plants. The validated performance of the TIER concept provides evidence to support broader adoption and market transformation of all-electric HVAC systems in large commercial buildings.

Introduction

The accelerating push to electrify and decarbonize buildings has created significant challenges for the heating, ventilating, and air conditioning (HVAC) industry, particularly for large commercial buildings. Conventional all-electric plants remain costly, space-intensive, and often inefficient. The implementation of all-electric plants has shown some challenges, such as design limitations, improper use of new and evolving technologies, and unfamiliarity with new equipment constraints. As a result, some implementations of all-electric plants have not achieved their intended efficiency targets, underscoring the need for improved design approaches and clearer industry guidance.

Large commercial buildings have historically relied on separate gas-fired hydronic heating systems and chilled water cooling systems. Although these systems have benefited from incremental refinement over time and there are several resources and guidelines for their design and control (Taylor 2017; ASHRAE 2021; Cheng, Wendler and Raftery 2024), recent studies have shown that hot water plants often operate at significantly lower efficiencies than assumed. Common design and operational constraints such as improper staging and oversized equipment contribute to this underperformance (Raftery et al. 2018; Raftery et al. 2024; Cheng, Wendler and Raftery 2024). Achieving building decarbonization will require providing the HVAC industry with the support needed to resolve the current design and system integration challenges.

The large all-electric buildings have primarily relied on air-to-water heat pumps (AWHPs). While conceptually straightforward, AWHP plants have struggled to meet performance, cost, and compatibility requirements. AWHP efficiency declines considerably in cold weather, with heating coefficient of performance (COP) values above two achievable only in mild West Coast climates (Mendon et al. 2024). Most AWHPs can produce a limited range of hot water supply temperature (between 130 °F to 140 °F), which is often incompatible with buildings' hot water distribution systems and equipment (PickComfort 2025). Furthermore, as the hot water supply temperature increases, the AWHP's efficiency decreases. AWHPs are also relatively expensive, approximately $150–200 per kBtu/h of capacity compared to $15–30 per kBtu/h for condensing boilers based on expert judgment and practical experience. As mentioned above, they require more physical space or building footprint compared to other equipment.

Heat recovery chillers (HRCs) can provide high efficiency heating and cooling simultaneously, but only when concurrent loads exist. Early all-electric plants for large buildings have suffered from equipment misapplication and critical design oversights, leading to low operating efficiency and control challenges (Weitze 2024). Collectively, these issues illustrate the need for a new system design that reduces dependency on AWHPs, maximizes heat recovery, and simplifies system integration.

The Time-Independent Energy Recovery (TIER) plant concept addresses these challenges by integrating HRCs, thermal energy storage (TES) tanks, and AWHPs into a cascading system that maximizes heat recovery and maintains high system efficiency (Gill 2021; Stein and Gill 2024). Unlike traditional TES, which is used primarily for reducing peak cooling load, TIER leverages the TES as a heat recovery option, enabling HRCs to operate efficiently even when instantaneous heating and cooling loads are not aligned. Early analyses estimate that TIER can reduce energy use by approximately 40 % relative to current state-of-the-art all-electric plants. Initial implementations use condenser water TES, though hot water TES variants are also feasible. While TES can require significant space, TIER's design dramatically reduces required AWHP capacity, yielding substantial reductions in the required building space as well as initial cost (Gill 2021). In mild climates such as California, recovered heat from chilled water loop can meet heating loads for most of the year, allowing AWHPs to operate only intermittently and at higher efficiencies due to lower required lift. In contrast, a traditional AWHP plant operates with independent heating and cooling systems, without integrated heat recovery or TES. Cooling is provided by chillers, while heating is supplied separately by AWHPs.

Although all TIER components are commercially available, the integrated design and control strategy is complex, and real-world validation and assessment are essential to support broader adoption. This paper provides a comprehensive evaluation of a TIER plant, assessing its operational performance as well as comparing the performance of the TIER plant with a traditional AWHP plant under various operational and weather conditions. Occupant thermal comfort and cost-effectiveness were beyond the scope of this study and should be considered in future work to provide a more comprehensive assessment of system performance.

Methodology

Data from an operating TIER plant were analyzed to verify the underlying design concept and assess whether the plant's control strategies function effectively across a broad range of operating and seasonal conditions. Unlike most typical commissioning efforts that are limited to specific weather conditions, this study performed an extended evaluation, enabling a comprehensive assessment of plant behavior across multiple operating modes throughout the year.

In this paper, system performance was evaluated using COP, which is defined as the ratio of useful thermal output (i.e., delivered heating or cooling load) to electrical input, including all major equipment such as primary heating and cooling units, pumps, etc. Beyond assessing how the TIER plant performed across different seasonal and operational conditions, we also compared its heating and cooling COPs against those of a traditional AWHP plant to understand relative performance under varying loads and weather conditions. The next few paragraphs describe some characteristics of the building with the TIER plant and the building with the traditional AWHP plant, which is used and referred to as "baseline". Both plants are implemented in actual buildings located in California Bay Area (California climate zone 4).

The TIER study site is a large office building of approximately 1.2 million ft^2, equipped with a fully integrated condenser water TIER plant. The plant includes two variable speed centrifugal chillers, three HRCs with different capacities, two AWHPs with similar capacity, and three cooling towers. In addition, the plant has a TES tank that enables decoupling the heat recovery operation from instantaneous building loads, allowing recovered heat to be stored and deployed as needed. This configuration reflects the core features of the TIER concept, which are maximizing heat recovery, minimizing AWHP runtime, and using TES to maintain high system efficiency across a wide range of operating conditions. The building automation system (BAS) provides detailed monitoring of temperatures, flow rates, loads, and equipment power, enabling comprehensive performance evaluation.

The baseline study site is a 300,000 ft^2 office building with an all-electric central plant configuration. Heating is provided by two AWHPs with similar capacity, while cooling is served by a variable speed centrifugal chiller supported by two cooling towers. In this configuration, heating and cooling are produced independently, without the integrated heat recovery and TES strategy that characterizes the TIER plant. Similar to the TIER site, the baseline building is fully instrumented through its BAS, allowing for consistent and comparable data collection across both plants. Table 1 provides a summary of the TIER and baseline study sites.

Table 1. Summary of TIER study site and baseline study site.

	TIER Plant	Baseline
Building Occupancy Type	Office	Office
Building Size	1,200,000 ft^2	300,000 ft^2
Cooling-Only Chillers	Two variable speed centrifugal chillers	One variable speed centrifugal chiller
Heat Recovery Chillers	One variable speed centrifugal chiller Two screw chillers	N/A
AWHP Pumps	Two AWHPs	Two AWHPs
Cooling Towers	Three Cooling Towers	Two Cooling Towers
TES Tank	147,000 gallons	N/A

Because the TIER plant incorporates TES, heating and cooling production are not always synchronized with electrical input. For this reason, COP values were computed on a daily basis. Daily heating COP was estimated by dividing the average daily heating delivered to the building (average daily heating output) by the average daily electricity consumption of all heating equipment, including AWHPs, HRCs operating in heat recovery mode, chillers providing heat recovery (where applicable), condenser water pumps, and hot water distribution pumps. This approach captures plant-level efficiency by accounting for both primary equipment and auxiliary energy use. Daily cooling COP was calculated analogously, using average daily cooling output and the electrical input to chillers operating for cooling, HRCs in cooling mode, cooling towers, chilled water pumps, and cooling tower pumps. HRCs and chillers electricity use was categorized based on operating mode, such that HRCs and chillers were assigned to heating or cooling equipment depending on whether they were operating in heat recovery mode or cooling mode. As mentioned above, the required inputs such as temperatures, flow rates, loads, equipment power, etc. were obtained from the BAS of both the TIER and baseline plants.

To evaluate performance sensitivity to weather, outdoor air temperature data from the BAS were used to compute daily heating degree days (HDD) with 65 °F as the base temperature, cooling degree days (CDD) with 65 °F as the base temperature, and average daily outdoor temperature. These metrics enabled analysis of COP trends as a function of ambient conditions and weather severity. Furthermore, total daily heating and cooling loads were normalized by dividing them by the maximum values observed during the study period in order to estimate peak load ratios. Using peak load ratios load-binned analyses were conducted to assess part-load and peak-load performance of the TIER plant.

Data

Both the TIER plant and the baseline AWHP plant data can be defined as two main categories:

- Measured data: Values captured directly by sensors that were installed in the plants, including temperatures, flow rates, and electrical power measurements. Flow meters and entering and leaving water temperature sensors were available for major plant equipment, including chillers, HRCs, AWHPs, cooling towers, and the TES tank. These data form the foundation for calculating thermal energy transfer, equipment efficiencies, and overall system performance. While calibration records for all sensors were not available; the data were quality-checked for consistency and plausibility.
- Calculated or estimated data: Parameters not directly metered but estimated within the BAS using predefined algorithms and equations based on measured parameters and equipment specifications. Examples include estimated chiller and AWHP power consumption. Where direct measurements were not available, equipment electric power was estimated using manufacturer specification.

Data were logged either on a change of value basis or at time intervals between one and ten minutes. For the analysis presented in this paper, all data streams were resampled into five-minute intervals to maintain adequate temporal resolution while ensuring consistency across datasets.

Results and Discussions

TIER Plant Versus Baseline Plant Performance Comparison

This section presents a comparison of the TIER plant and the baseline plant to evaluate how each system performs under similar operating conditions. The analysis draws on data collected from April through August 2025 for both plants. A full twelve-month data was not available for this analysis due to ongoing BAS development during winter and testing activities that affected data quality in the following fall.

As summarized in Table 2, the TIER plant showed better performance over this period, with higher average heating and cooling COP values. The TIER plant achieved an average heating COP of 4.20 compared with 3.20 for the baseline plant, which is an improvement of roughly 31 percent. While a larger performance gap would be expected during colder months, when AWHP efficiency typically declines, winter data were unavailable due to some operational change in the baseline plant. The TIER plant also demonstrated higher cooling efficiency, with an average cooling COP of 5.96 compared to 4.39 for the baseline plant, representing an improvement of about 36 percent.

Table 2. Average COPs for the TIER and baseline plants

	Average Heating COP	Average Cooling COP
TIER Plant	4.20	5.96
Baseline Plant	3.20	4.39

Note: COPs evaluated from operating data from April to August 2025 (data does not capture winter operation)

Figure 1 through Figure 4 demonstrate the relationship between total daily heating energy and HDD and total daily cooling energy and CDD in both buildings or plants. A comparison of Figure 1 and Figure 2 indicate that daily heating energy in the baseline building exhibits a more clearly defined linear relationship with HDD than in the TIER building (baseline building R^2 is equal to 0.54 and the TIER building R^2 is approximately 0.21). The less linear relationship between total daily heating energy and HDD in the TIER building suggests that additional operational factors, such as occupancy, building characteristics, etc., may influence heating energy use beyond simple weather dependence.

For cooling, both buildings demonstrate a relatively strong positive linear relationship between total daily cooling energy and CDD (Figure 3 and Figure 4). As cooling degree days increase, daily cooling energy increases in a generally proportional manner for both systems.

Both buildings exhibit non-zero total daily heating energy use even on warm days when outdoor air temperatures never drop below 65°F. The same is true for the TIER building on the cooling side where at least some daily cooling energy is expended on cold days when outdoor air temperatures never rise above 65°F. These base loads are largely attributed to user behaviors such as 24/7 occupancy and 24/7 plug loads.

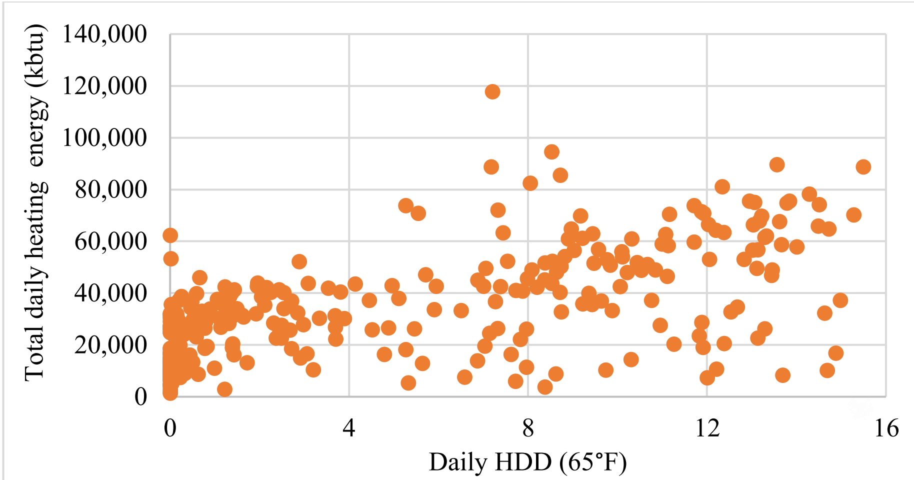

Figure 1. Correlation between total daily heating energy and HDD in the TIER building.

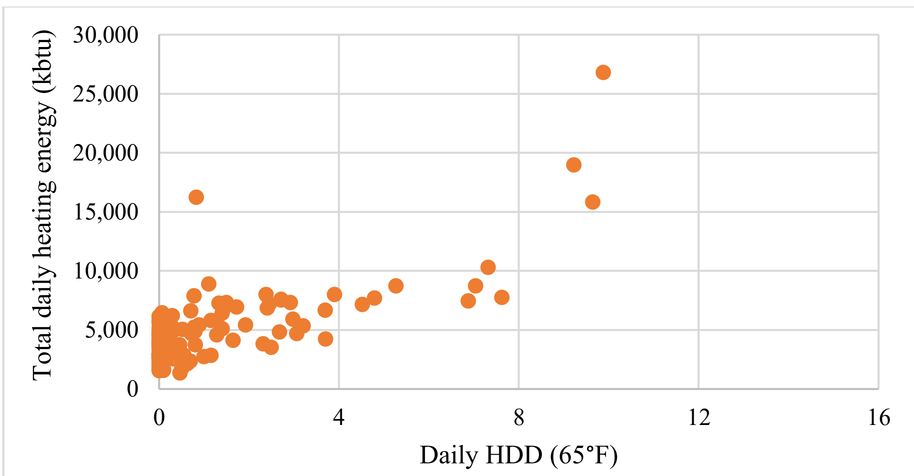

Figure 2. Correlation between total daily heating energy and HDD in the baseline building.

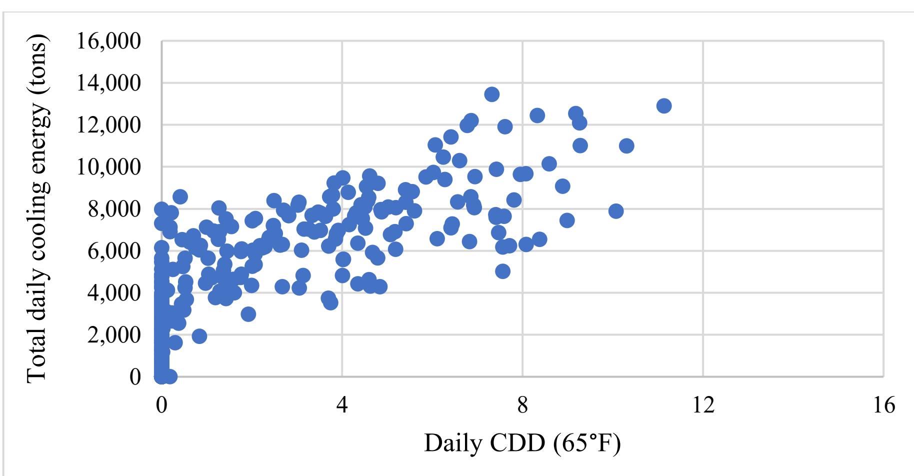

Figure 3. Correlation between total daily cooling energy and CDD in the TIER building.

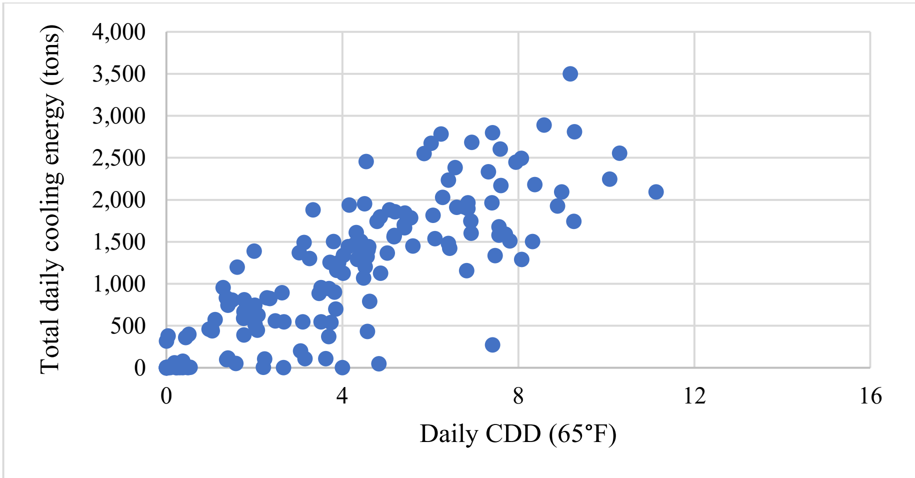

Figure 4. Correlation between total daily cooling energy and CDD in the baseline building.

Figure 5 shows that the TIER plant maintains a higher daily heating COP than the baseline system throughout the April to August period. The TIER plant heating COP mostly falls between 3.5 and 5.5, with occasional values near 6.0. The baseline plant more often operates between 2.5 and 4.0 and experiences intermittent heating COP drops below 2.0. Although isolated days show comparable performance, the TIER plant exhibits a consistently better daily heating COP profile.

Figure 6 illustrates a similar trend for cooling performance. The TIER plant sustains a daily cooling COP of roughly 5.0–7.5. The baseline system's daily cooling COP ranges from 3.5 to 6.0 and experiences multiple declines below 3.0 between May and July. During this period, the baseline AWHP plant shows noticeably lower cooling performance relative to the TIER plant.

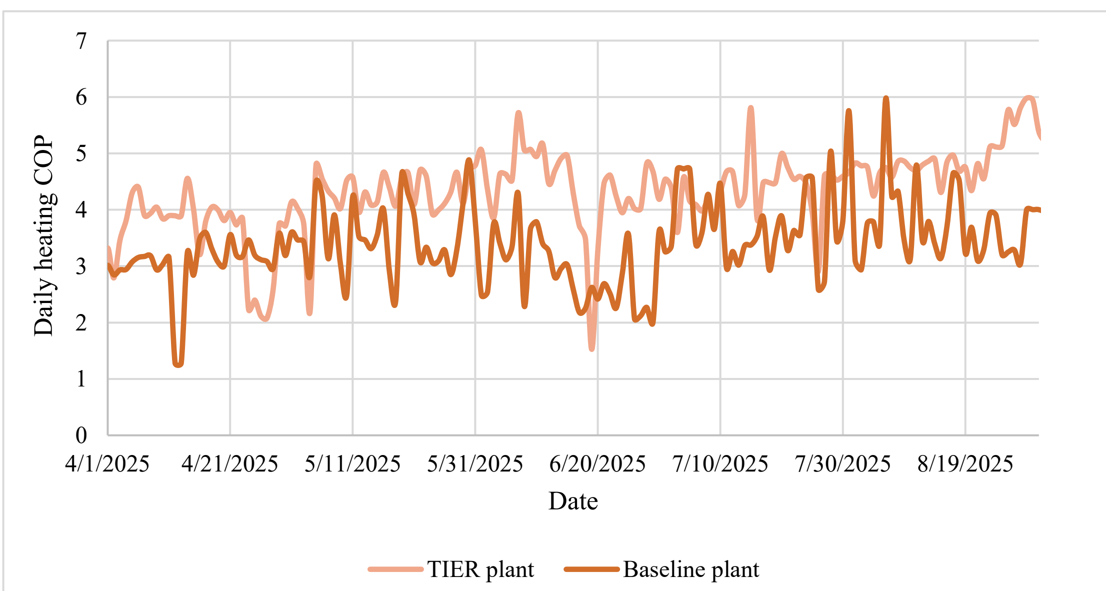

Figure 5. Daily average heating COP for the TIER plant and the baseline plant from April through August.

The main chillers of both plants are oversized relative to the buildings' base cooling loads, which results in frequent cycling at loads below their minimum unloading thresholds. Because of the operating conditions of both, there is always a need for chilled water; therefore, the cycling frequency was intentionally increased. The centrifugal compressors used in both plants are inefficient at minimum turndown and incur significant power penalties during startup. However, the TIER plant's cooling COP is less affected by these issues because chiller energy is attributed to heating whenever rejected heat is stored in the TES tank rather than rejected at the cooling towers.

Differences in chiller sizing further amplify performance disparities. The baseline plant's 400-ton chiller serving a 300,000 ft² building has a design capacity per square foot roughly 2.7 times larger than the TIER plant's 600-ton chiller serving a 1.2 million ft² building. This oversizing makes the baseline plant's chiller more prone to short cycling, increasing transient losses, and reducing cooling COP. In contrast, the TIER plant benefits from two smaller chillers and better staging capability. Although the baseline plant could have been designed with two chillers, this design approach was not pursued due to higher cost considerations.

As outdoor temperatures rise in late July and August, cooling loads become more consistent, which reduces cycling frequency. Under these conditions, the baseline plant's cooling COP improves (see Figure 6).

Figure 7 and Figure 8 illustrate the dependence of heating and cooling efficiency on outdoor air temperature to provide insight beyond aggregate performance benchmarking. Consistent with heat pump operating theory, both plants exhibit increasing average daily heating COP with higher outdoor air temperatures due to reduced compressor cycling.

The baseline plant shows relatively lower sensitivity to outdoor air temperature by having a narrow range of heating COP across different bins. On the other hand, the TIER plant COP shows a higher dependency on outdoor temperature with a considerable reduction in heating COP at lower outdoor air temperatures. This trend reflects both the operational characteristics of the TIER configuration and the COP accounting methodology employed in this analysis. As cooling demand decreases at lower temperatures, there is more cycling, which negatively impacts the heating COP of the TIER plant. Conversely, at higher outdoor air temperatures, more heat recovery availability and more stable chiller operation improve heating efficiency. This results in a higher heating COP relative to the baseline system (see Figure 7).

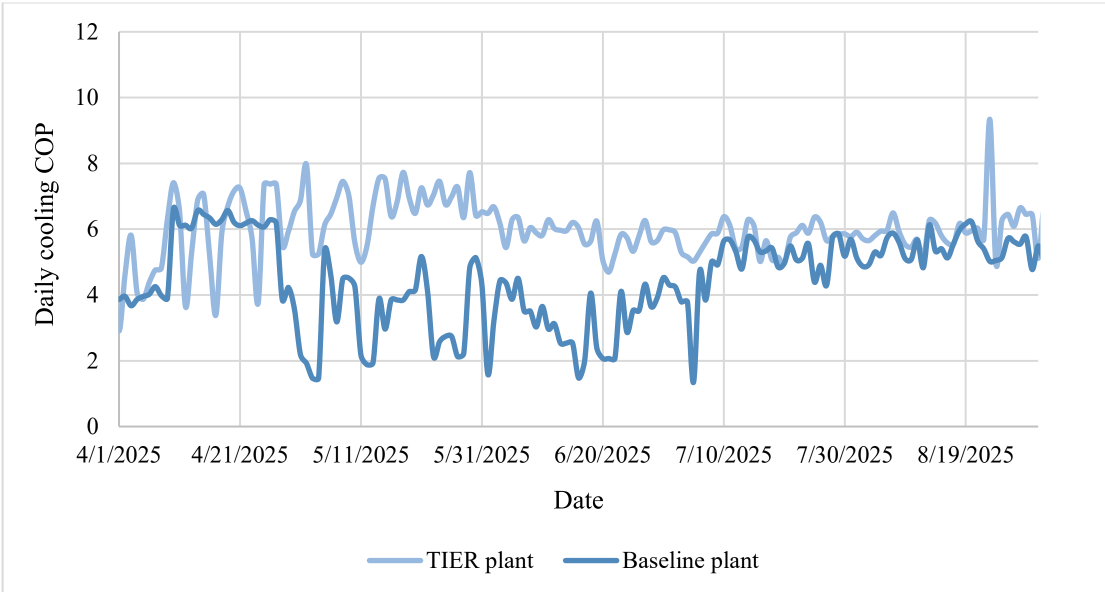

Figure 6. Daily average cooling COP for the TIER plant and the baseline plant from April through August.

Cooling performance as a function of outdoor air temperature is presented in Figure 8. Across all temperature bins, the TIER plant shows a higher average daily cooling COP than the baseline plant. This performance advantage is due to differences in chiller sizing and cycling behavior. In particular, chiller cycling penalties in the TIER plant are largely reflected in the heating COP. Also, the oversized chiller in the baseline plant increases cycling losses that degrade cooling efficiency.

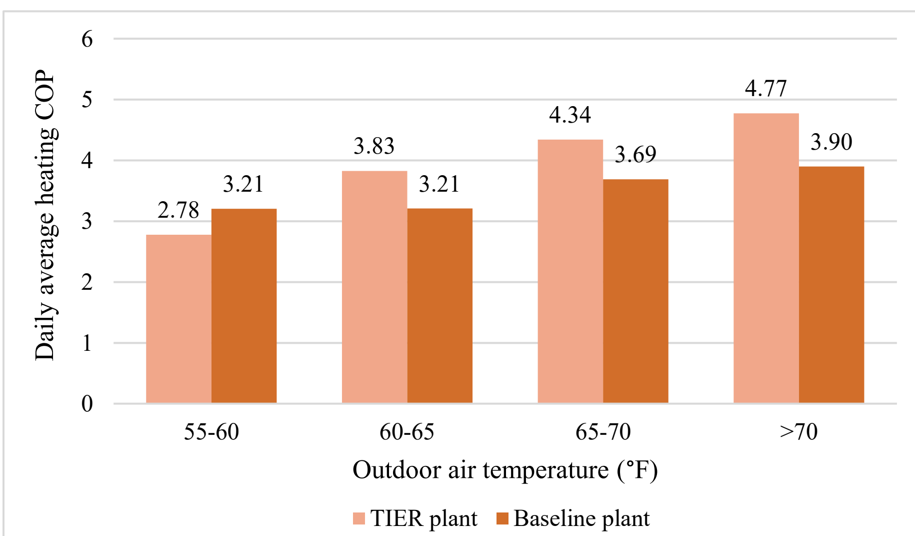

Figure 7. Daily average heating COP of the TIER plant and the baseline plant by average daily outdoor air temperature bins.

According to Figure 8, average daily cooling COP increases with rising outdoor air temperature in both plants as cooling loads become larger and more continuous, allowing chillers to operate above minimum unloading limits. At lower temperatures, intermittent and low cooling demand lead to increased cycling losses. At the highest temperature bin, daily average cooling

COP does not increase drastically compared to 65-70 °F because of the reduced efficiency of centrifugal chillers at full load compared to part-load operation. This effect is more evident in the baseline plant, whose oversized chiller operates more frequently at part load.

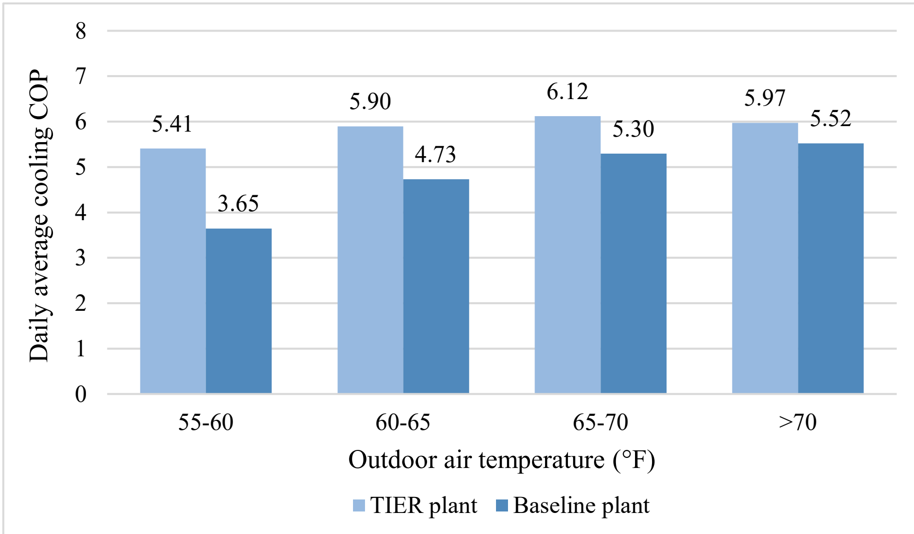

Figure 8. Daily average cooling COP of the TIER plant and the baseline plant by average daily outdoor air temperature bins.

The temperature-binned analysis has some limitations because of unequal sample sizes across bins during the April through August study period. The lowest temperature bin contains relatively few observation days, making its average COP more susceptible to operational variability and temporary control effects. On the other hand, higher temperature bins include substantially more observations and therefore benefit from more statistically robust averages. While the observed trends remain meaningful, results associated with the lowest temperature bin should be interpreted considering this limitation.

TIER Plant Performance Evaluation

In the previous section, performance of the TIER plant was compared with the baseline AWHP plant. This section focuses on the TIER plant to understand key drivers of efficiency and seasonal performance dynamics.

Figure 9 presents the daily average heating COP over a period slightly exceeding one year (January 2025 through January 2026). The seasonal trend shows lower heating COP values during the winter months and higher values during shoulder and cooling seasons. This trend is consistent with the design and operational characteristics of the TIER system. During colder periods, the plant is more dependent on AWHPs, which operate at lower efficiency under cold ambient conditions. In addition, chiller energy is accounted as heating energy because it is used to charge the TES tank, and higher compressor cycling during winter further decreases the daily average heating COP.

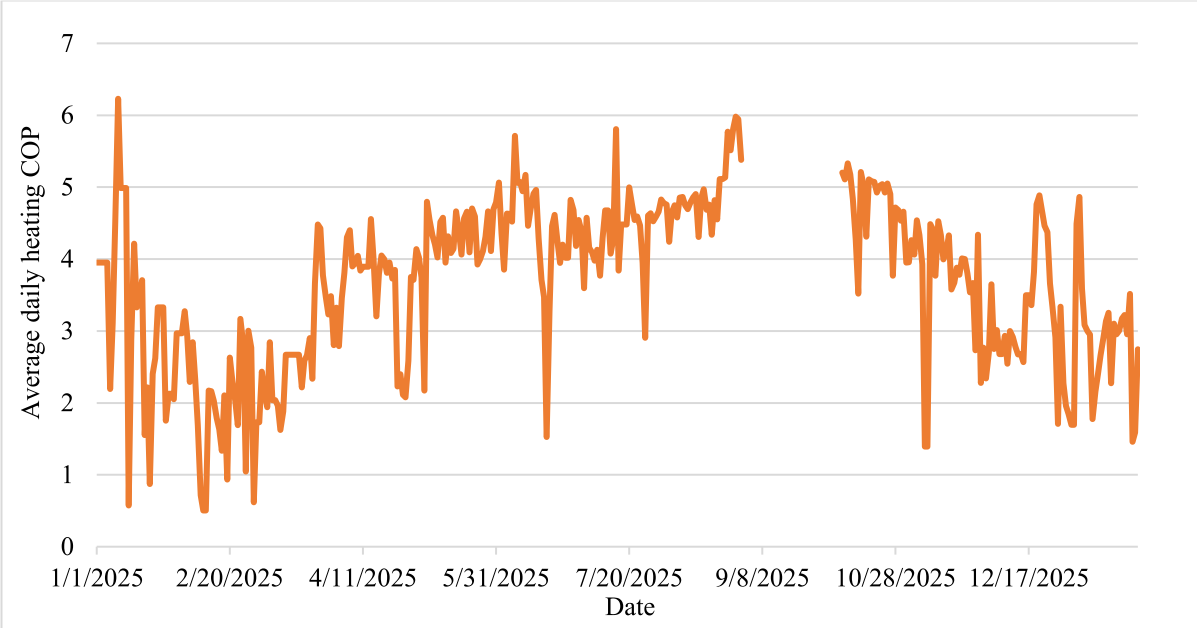

Figure 9. Daily average heating COP of the TIER plant from January 2025 to January 2026. Data from September 1 through October 7, 2025, are removed due to the impacts of active testing at the TIER plant, such as irregular operating conditions and control overrides.

Table 3. Daily average fraction of heating load met by AWHPs and average daily outdoor air temperature.

Average Daily Outdoor Air Temperature (°F)	Fraction of Heating Load Met by AWHPs (%)
50–55	6.7
55–60	3.7
60–65	0.7
65–70	0.0
>70	0.0

To further characterize the role of the AWHPs within the TIER plant, the fraction of total daily heating load supplied by the AWHPs was estimated. AWHPs' thermal output was calculated using entering and leaving water temperatures measured by installed temperature sensors and corresponding metered flow rates. Further, the thermal output was aggregated on a daily basis. This heating energy was then normalized by the total daily building heating energy to estimate the AWHP contribution. Figure 10 presents this fraction as a function of average daily outdoor air temperature. Results indicate that the AWHP contribution is negligible under moderate and warm conditions, remaining near zero for most days. The fraction increases as outdoor air temperature decreases, which shows more dependency on AWHPs during colder periods. It should be noted that both TIER and baseline plants are located in California (California climate zone 4); so, the ambient temperature is mild for most of the year.

According to Table 3, AWHPs contribution is greatest at lower outdoor air temperatures and declines to near zero under moderate and warm conditions. During colder weather, building's heating is high and simultaneously cooling demand is less, which limits the availability of recoverable heat from the chilled water loop for charging the TES tank. Therefore, AWHPs operate more frequently.

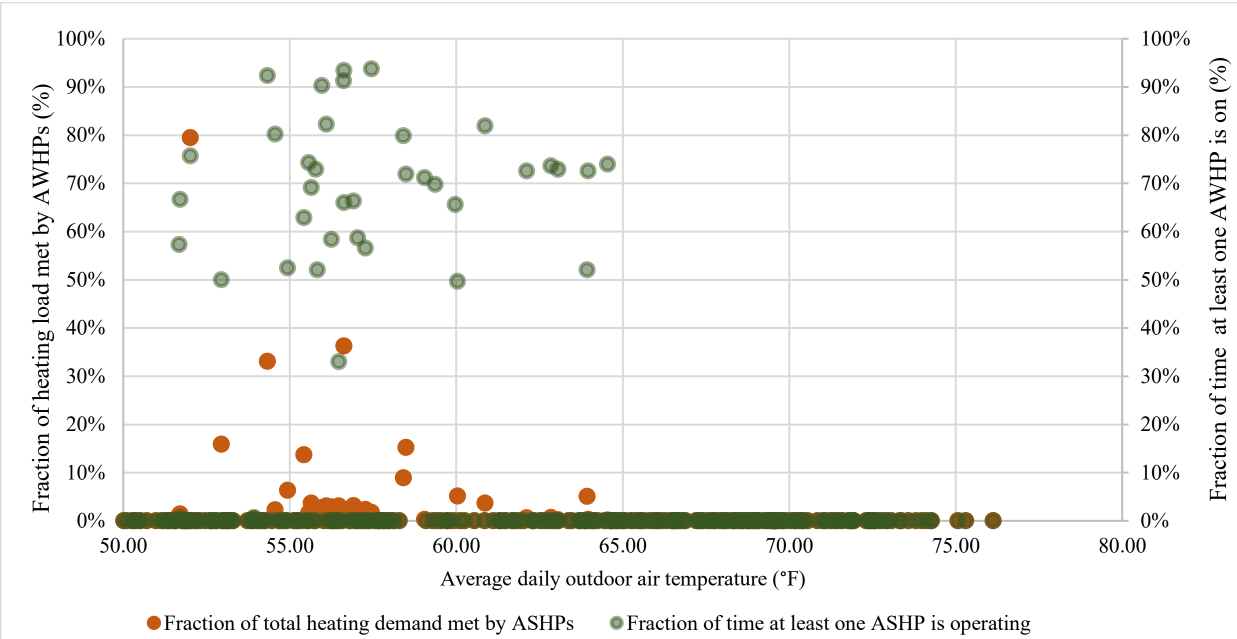

Figure 10. Fraction of daily heating load met by AWHPs and daily fraction of time that at least one AWHP was operating in the TIER plant as a function of average daily outdoor air temperature.

In addition to ambient conditions, the performance of the TIER plant is influenced by the magnitude of heating and cooling loads. Accordingly, the relationship between system efficiency and load was examined by evaluating heating and cooling COP as functions of normalized daily load.

A normalized peak daily heating load metric was defined (see Equation 1). For each day in the analysis period (January 2025 through January 2026), the total daily heating load was normalized by the maximum observed daily heating load over the study period. This peak load fraction was used to categorize days into bins, within which the average daily heating COP was calculated.

$$Peak\ Daily\ Heat\ Load\ Fraction_d = \frac{\sum_{t=1}^{Nd} Q_{d,t}}{max(\sum_{t=1}^{Nd} Q_{d,t})} \qquad \text{(equation 1)}$$

Where $Q_{d,t}$ is the heating load at time interval t on day d, and N_d is the number of time intervals in day d.

As shown in Figure 11, the heating COP varies systematically with peak daily heating load fraction. Higher COP values are observed at low load fractions due to less chiller compressor cycling. At higher load fractions (60-100%), heating COP also improves. This is because the HRCs' compressors are more efficient at full load. We followed a similar approach to evaluate cooling performance under different magnitudes of load. Total daily cooling loads were divided by the maximum observed daily cooling load to define peak daily cooling load fractions (see Equation 2). Further, the average daily cooling COP was calculated for each bin.

$$Peak\ Daily\ Cool\ Load\ Fraction_d = \frac{\sum_{t=1}^{Nd} Q_{d,t}}{max(\sum_{t=1}^{Nd} Q_{d,t})} \quad \text{(equation 2)}$$

Where $Q_{d,t}$ represents the cooling load at time interval t on day d, and N_d is the number of time intervals in day d.

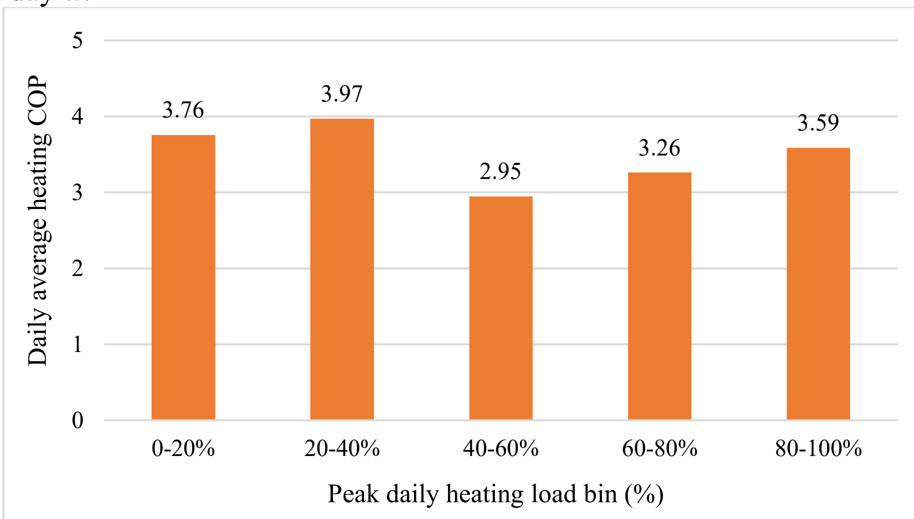

Figure 11. Average daily heating COP of the TIER plant by peak heating load range.

Based on Figure 12, the highest cooling COP occurs at moderate load levels (20-40%), indicating optimal system efficiency under part-load conditions. At very low load fractions (0-20%), cooling COP decreases probably due to increased short cycling of chillers even when the TES tank is fully charged. At higher load fractions (40-100%), cooling COP shows almost a similar value. This behavior is consistent with the part-load performance characteristics of the centrifugal lead chiller, which achieves maximum efficiency near 30-50 percent of rated capacity, as well as the favorable part-load efficiency of variable speed cooling tower fans, whose power consumption decreases nonlinearly with load.

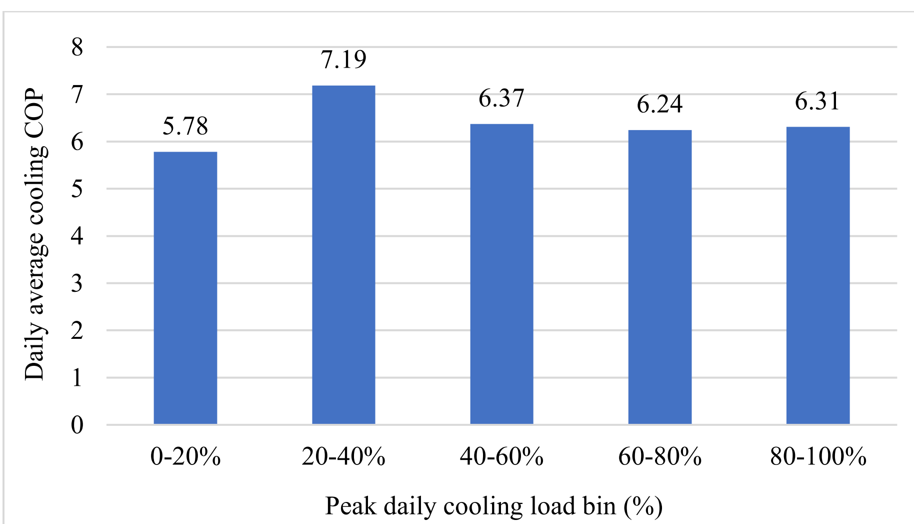

Figure 12. Average daily cooling COP of the TIER plant by peak cooling load range.

To evaluate how the TIER plant works on an hourly resolution, representative winter and summer days were selected and analyzed to characterize interactions among the TES tank state of charge, equipment power consumption, including HRCs, cooling chillers, AWHPs, and cooling towers, and overall system sequencing. Figure 13 shows results for a representative February day during the heating season. The TES tank is discharged throughout the day to provide hot water to HRCs and consequently, the hot water loop. Simultaneously, the TES tank is being recharged by the cooling chillers and supplemented by the AWHPs to reach full charge (80°F water) several hours before the subsequent morning warm-up period, when recoverable heat from the chilled water loop becomes minimal or unavailable. These profiles show asynchronous operation of plant equipment in coordination with the TES system to maximize overall efficiency.

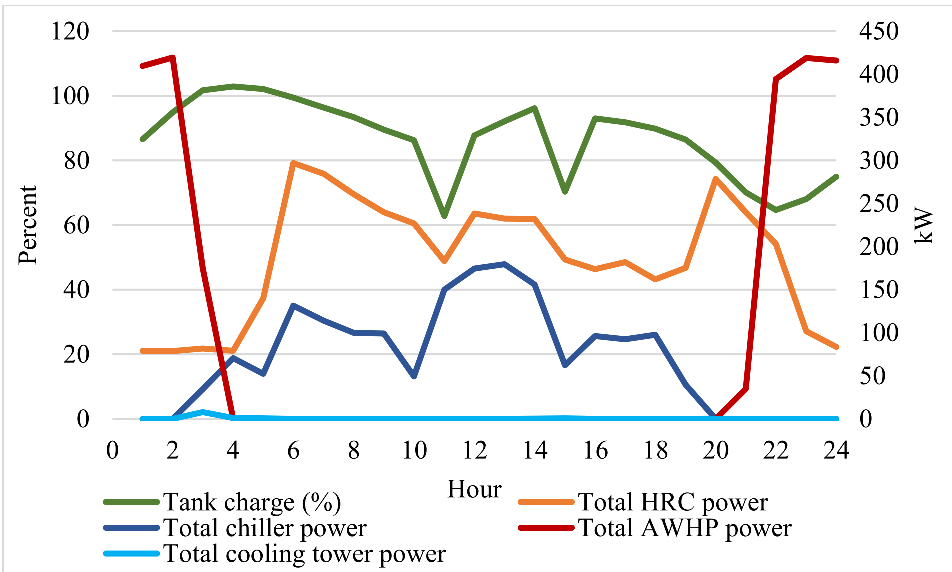

Figure 13. Hourly profile of the TIER plant for one representative day in February. X-axis represents hour of day, Y-axis represents tank state of charge (%), AWHPs, HRCs, chillers, and cooling towers' power (kW).

Figure 14 presents a similar hourly profile for an August day during the cooling season. As expected, total chiller power increases from late morning through the afternoon, peaking during the highest cooling demand period, that is usually between 3:00 pm to 5:00 pm. Cooling tower power shows a similar response to increased heat rejection from condenser water loop. Unlike chillers and cooling towers, AWHP power remains at zero kW throughout the day. This shows that the minimal heating demand on an August day is fully met by heat recovery from the chilled water loop. This operating pattern is consistent with expected summer sequencing, in which chillers serve as the primary source of thermal energy production.

During this cooling-dominated day, the TES tank state of charge remains relatively stable, fluctuating within a narrow range in the mid- to upper-70 percent band. The TES tank was manually limited to an 80% charge. This behavior indicates reduced charging and discharging activity compared to heating-dominated days. HRC power shows moderate operation during the morning and brief activity in the late evening, corresponding to periods of higher space heating demand.

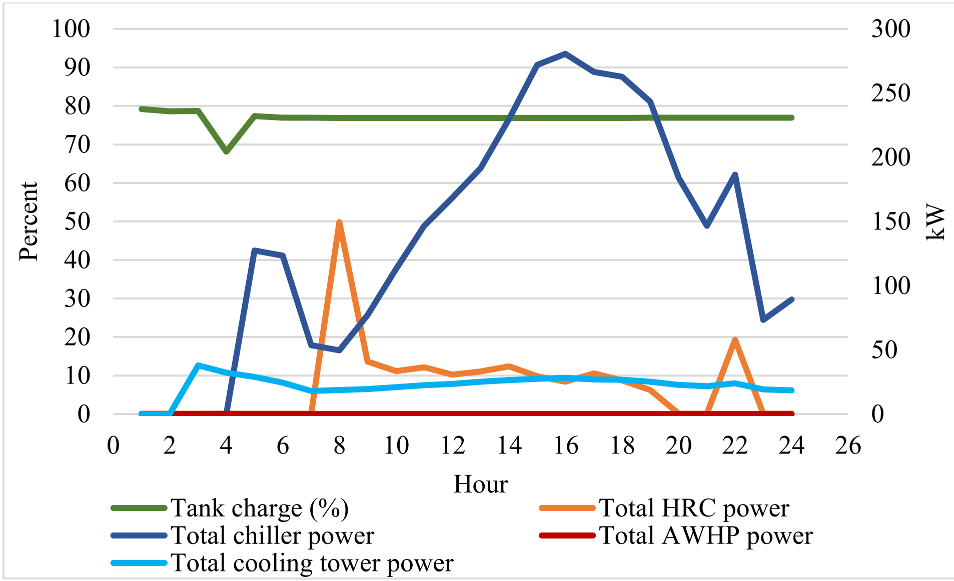

Figure 14. Hourly profile of the TIER plant for one representative day in August. X-axis represents hour of day, Y-axis represents tank state of charge (%), AWHPs, HRCs, chillers, and cooling towers' power (kW).

Conclusion

- The study conducted a performance evaluation of a TIER plant that integrates HRCs, TES, and AWHPs in a large office building.
- Data obtained from BAS were analyzed across multiple operating modes and weather conditions. The heating and cooling COPs were estimated as key performance metrics to evaluate the efficiency of the TIER plant.
- The TIER plant was compared to a conventional all-electric plant, enabling a direct comparison of efficiency and weather sensitivity under comparable conditions; however, analysis of thermal comfort and cost-effectiveness were not within the scope of this project. Evaluating these aspects in future work would provide a more comprehensive understanding of TIER system performance.
- Results demonstrate that the TIER system achieves higher heating and cooling COPs compared to the baseline AWHP plant.
- The analysis confirms that the TIER configuration significantly reduces dependencies on AWHP operation especially under moderate and warm ambient conditions. This highlighted the potential to improve efficiency, operational flexibility, and viability of TIER systems in large commercial buildings.

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