Title

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ABSTRACT

Heat recovery chillers (HRCs) are systems that utilize waste heat from the condenser side for heating purposes. As an electrification strategy, they offer the potential to reduce operational carbon emissions associated with heating, while providing higher coefficient of performance (COP) than air-to-water heat pumps and a much smaller equipment footprint. However, limited research has been published on the real-world performance of HRCs in this configuration. This study investigates the performance of HRCs in a newly constructed all-electric building located in ASHRAE climate zone 3C. The building is a five-story, 182,800 ft² (17,000 m²) outpatient surgery and medical office facility. In this facility, HRCs serve as the primary plant equipment to meet the building's heating and cooling loads, with exhaust air coils functioning as either a heat sink or source to balance loads on the HRCs. The building entirely relies on the HRCs and exhaust air coils for all cooling capacity and has no storage (aside from buffer tanks). We analyze high-resolution measured data from the building's central plant, including water-side loads and electrical power, across multiple seasons, focusing on how plant performance varies with outdoor air temperature, building heating and cooling load profiles, and the balance between heating and cooling loads. When thermal storage is limited, the balance between heating and cooling load becomes a more critical factor in determining system performance. When there is a mismatch between the two loads, the system either rejects or sources heat to or from the exhaust air to balance the loads on the HRCs. This balance is driven by both outdoor air conditions and building loads. Unlike true simultaneous heating and cooling loads, the exhaust air loads are not used for a purpose within the building and effectively reduce overall system efficiency. This study captures the complexity and variability of actual system performance and proposes a new metric for assessing performance in these systems. The building demonstrates the technical feasibility and high performance of using HRCs with exhaust air coils in all-electric medical buildings.

INTRODUCTION

As many conventional HVAC systems depend on natural gas for heating, growing environmental concerns have increased interest in electricity-based alternatives. In this context, the benefits of air source heat pumps (ASHPs) have received attention. However, considering the current performance limitations of ASHPs, such as reduced efficiency and capacity in cold climates

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and the large footprint required for installation (Gill 2021), water-to-water heat recovery chillers (HRCs) coupled to appropriate heat sources and heat sinks also offer a strong strategy for decarbonizing large buildings. In an HRC, the condenser-side heat, which is a by-product of cooling and would otherwise typically be rejected to a cooling tower, is instead used for building heating. Ideally, this allows the system to provide heating and cooling simultaneously with a high simultaneous heating and cooling coefficient of performance (COPshc) (ANSI/AHRI Standard 550/590-2023 (I-P) 2023). Additional benefits occur through reduced cooling tower power and water consumption. However, this is not free energy. To use the condenser heat for building heating, the condenser water temperature must be raised to a usable level. This lift temperature increase reduces chiller efficiency compared to a typical water-cooled chiller plant. According to previous studies, a 10 °F (5.6 °C) rise in condenser water temperature can result in a 7 to 14 % increase in power consumption (Cai, Du, and Wu 2011). Additionally, due to the (typically) lower supply temperature of the recovered hot water, pumping energy may also increase, though this is a relatively small effect, and terminal unit heat exchangers must be sized larger than for typically higher design temperatures.

Heat recovery chillers are not the optimal HVAC solution for every building. Prior research has indicated that HRCs are most suitable for multi-story buildings with a high proportion of interior zones, where internal heat gains are significant, exterior insulation is moderate, and the building has high space heating or domestic hot water demand (Dorgan and Dorgan 2000). Another study found that buildings operating 24 hours a day and having a cooling capacity with at least 6 million BTU/hr (1760 kW) of heat recovery potential are suitable candidates. Such building types include offices, labs, healthcare facilities, and hotels (Winiarski 2004). The applicability of HRCs depends primarily on the simultaneous occurrence of heating and cooling loads. Various HRC configurations have been proposed to address this challenge. One well-known approach involves the use of ground source heat exchangers, although this can be prohibitively expensive, particularly in retrofit scenarios. To avoid high costs while addressing the issue of time dependency, the use of thermal energy storage (TES) has been proposed. Traditional TES systems, such as chilled water or ice storage, have been widely deployed, particularly at the campus or district scale. More recently, one study showed that combining TES with HRCs allows efficient operation of thermal sources and saves space, making it an effective decarbonization strategy for large buildings (Gill 2021). Another study demonstrated that connecting a building to a campus distribution system can also mitigate the time dependency problem (Peterson 2019).

Another less common strategy involves using heat recovery chillers with exhaust air heat recovery coils, where chilled water passes through the coil and serves as a source of heat for HRC. A prior study presented a hospital retrofit proposal in San Francisco involving a heat recovery chiller with an exhaust air coil. Although there was no space to install TES, the study estimated that exhaust air coil could reduce gas consumption for space heating by up to 90 percent (Stein 2024). Other studies have noted that healthcare and laboratory buildings, which have high ventilation air requirements, are especially well-suited for HRCs integrated with exhaust air coils. Water-cooled equipment such as computed tomography and magnetic resonance imaging units can also serve as supplementary systems that help balance heating and cooling demand (McClanathan 2014). In one laboratory example, exhaust air coils were used to cool the exhaust air during the heating season, thereby increasing the operation of the heat recovery chiller (Hobbs 2020). In yet other applications, the exhaust air coils can switch between serving as a heat source (chilled water in the coils, when the building has a net heating load) and as a heat sink (hot water in the coils, when the building has a net cooling load). Thus, HRCs coupled with exhaust air coils hold significant potential. However, there is limited information on the real-world performance of these systems, as well as on the practical challenges and possible improvements observed in field applications. This paper analyzes the real-world performance of a healthcare building in the ASHRAE climate zone 3C that is equipped with heat recovery chillers and exhaust air coils for both heat recovery and heat rejection. Overall, this system serves all of the building's space heating and cooling needs. The paper also discusses the strengths and limitations of HRCs as a partial and full decarbonization measure for large buildings.

METHOD

The case study building is a newly constructed, five-story, 182,800 ft² (17,000 m²) medical office building located in ASHRAE climate zone 3C. The HVAC system includes four heat recovery chillers (HRCs) designed to provide N+1 redundancy, each with a nominal capacity of 275 refrigeration tons (968 kW), screw compressors, and dual refrigeration circuits. The system also features exhaust air coils and runaround coils on six air handling units (AHUs). In addition, two emergency backup boilers are installed to provide supplemental heating capacity during contingency events. Thermal energy storage is limited to buffer tanks, 850 gallon (3,200 L) for the chilled water system and 1,480 gallons (5,600 L) for the hot water system. Monitoring data spans from September 2024 through end of August 2025, and we aggregated the various recording intervals (e.g. 1 min, 5 min, 15 min) into hourly intervals for consistency and analysis. For the sections analyzing domestic hot water and fan power consumption, however, we utilized 5-min data due to the high variability within hourly periods. From October 29th to November 1st, 46 hours of hot water loop data were not available, so we excluded these timesteps from the analysis. During the analysis period, the case study building has energy use intensity of 74 kBtu/ft²·yr (232 kWh/m²·yr).

The chilled water system incorporates a limited supply temperature reset range of 42-45 °F (5.6-7.2 °C), while hot water maintains a constant 115 °F (46.1 °C) setpoint for better control stability. The design ΔT values of 14 °F (7.8 °C) and 16 °F (8.9 °C) for chilled water in cooling and heating modes respectively, and 20 °F (11.1 °C) and 24 °F (13.3 °C) for hot water. For load analysis, the building data includes hot water load, chilled water load, and the absolute value of load on the exhaust air coil, which served as either a heat sink or source depending on net building heating and cooling demands. The measured hot and chilled water loads include heat transferred to or from the exhaust air coil. To estimate actual building thermal loads, we determined whether the exhaust air coil was in sink or source mode based on supply and return temperatures of the changeover piping serving the exhaust air coils. In sink mode, the coil load was subtracted from the hot water load. In source mode, it was subtracted from the chilled water load. This yields the net building heating and cooling loads respectively (i.e, independent of the exhaust air coil load).

Additionally, the building's domestic hot water (DHW) load is served by flat plate solar hot water collectors, ASHPs, and multiple heat exchangers that tie this system into the HRCs. One heat exchanger allows the solar collectors to reject heat to the hot water loop when solar collector temperature is high and the building has a net heating demand (rare in practice, just 1 % of the time). Another pair of heat exchangers allow the hot water loop to preheat the incoming cold water for the DHW system (overall 5 % of the operating hours and 0.3 % of the annual hot water load). This system design is protected by US patent No.11767987 (Blaevoet 2023).

Performance metrics for heat recovery chillers

We estimated chiller power using measured current data and a power factor of 0.84. We selected this power factor by aligning the electrical power estimated using measured current and assumed power factor, to the electrical power estimated using the difference between condenser and evaporator side thermal loads, assuming 5% losses to account for chiller motor and VFD losses. This current and power factor was used for all COP calculations. We subsequently cross-validated the estimated power factor using submetered electrical power measurements that were only available for a recent two month period.

According to ANSI/AHRI Standard 550/590-2023, the coefficient of performance (COP) is defined as follows:

$$\text{Cooling COP } (\text{COP}_c) = \frac{Q_{\text{evaporator}}}{E_{\text{input}}} \qquad \text{Simultaneous Heating and Cooling COP } (\text{COP}_{shc}) = \frac{Q_{\text{evaporator}} + Q_{\text{condenser}}}{E_{\text{input}}}$$

RESULTS

Building load patterns and exhaust air coil operation

To understand the operational characteristics of a building equipped with heat recovery chillers (HRCs) and exhaust air coils, we analyzed the seasonal patterns of outdoor air temperature, heating load, cooling load, and exhaust air coil load throughout the analysis period (see Figure 1). During the analysis period, outdoor air temperatures ranged from a minimum of 44 °F (7 °C) to a maximum of 98 °F (36 °C), with a mean of 60 °F (16 °C) and median of 59 °F (15 °C). Building loads are driven primarily by ventilation requirements instead of envelope loads, with minimum outside air flow requirements of 0.82 cfm/ft² (4.1 L/s·m²) at design occupancy. Building heating loads exhibited clear daily patterns, with lower loads during nighttime hours and weekends compared to typical building operation hours due to reduced ventilation requirements during periods with low occupancy. The magnitude of heating loads remained stable when comparing across seasons. In contrast, cooling loads were significantly lower from November to March and increased substantially with rising outdoor air temperatures. While cooling loads showed less pronounced daily patterns than heating loads, they peaked during daytime hours, particularly in the early afternoon.

The exhaust air coil represents a thermal load that must be rejected or recovered to balance loads on the heat recovery chillers. When cooling load and compressor power input exceed building heating demand, the heat generated on the condenser side cannot be fully utilized by the hot water load, causing hot water temperatures to rise. The exhaust air coils reject this excess heat by heating the exhaust air, a condition referred to as sink mode (shown in red in Figure 1(d)). Conversely, when heating demand is greater, the exhaust air coils cool the exhaust air to recover additional heat for the building, a condition referred to as source mode (shown in blue in Figure 1(d)).

The last figure (Figure 1(e)) illustrates the proportion of the exhaust air coil load relative to the hot water load during sink mode and to the chilled water load during source mode. As shown in the figure, there are time steps where the exhaust air coil load accounts for a significant portion or even the majority of the hot water or chilled water load. This operation indicates that the thermal energy generated by the HRCs is not being fully utilized, as potentially useful heat is being rejected through the exhaust air rather than serving building loads. The utilization of HRCs-generated heat could be improved by optimizing the existing domestic hot water system connections. Currently, only 5% of timesteps utilize HRCs for DHW preheat, and potentially extending this duration could enable more effective use of excess heat from HRCs. This excess heat could be stored in thermal energy storage systems or supplied to adjacent campus buildings through hot water distribution networks where infrastructure permits.

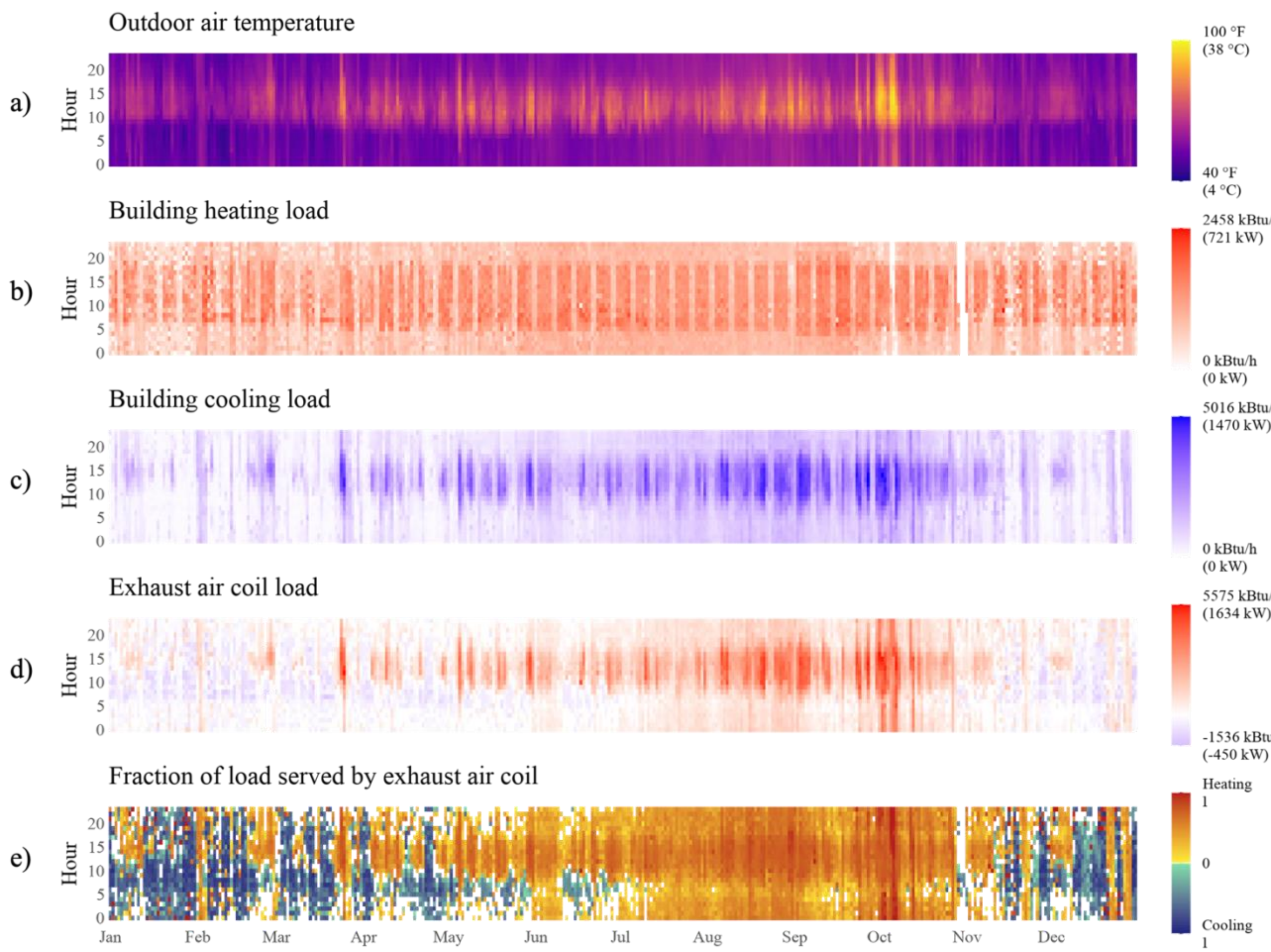

Figure 1 Building load patterns and exhaust air coil operation from September 2024 to August 2025. (a) Outdoor air temperature, (b) Building heating load, (c) building cooling load, (d) exhaust air coil load, (e) fraction of hot water load or chilled water load served by exhaust air coils

Figure 2 illustrates the relationship between outdoor air temperature and exhaust air coil load. In this building, approximately 54.4 °F (12.4 °C) serves as a critical transition point. Below this, the exhaust air coils typically operate in source mode, while above this they operate in sink mode, with loads increasing substantially with rising outdoor air temperatures.

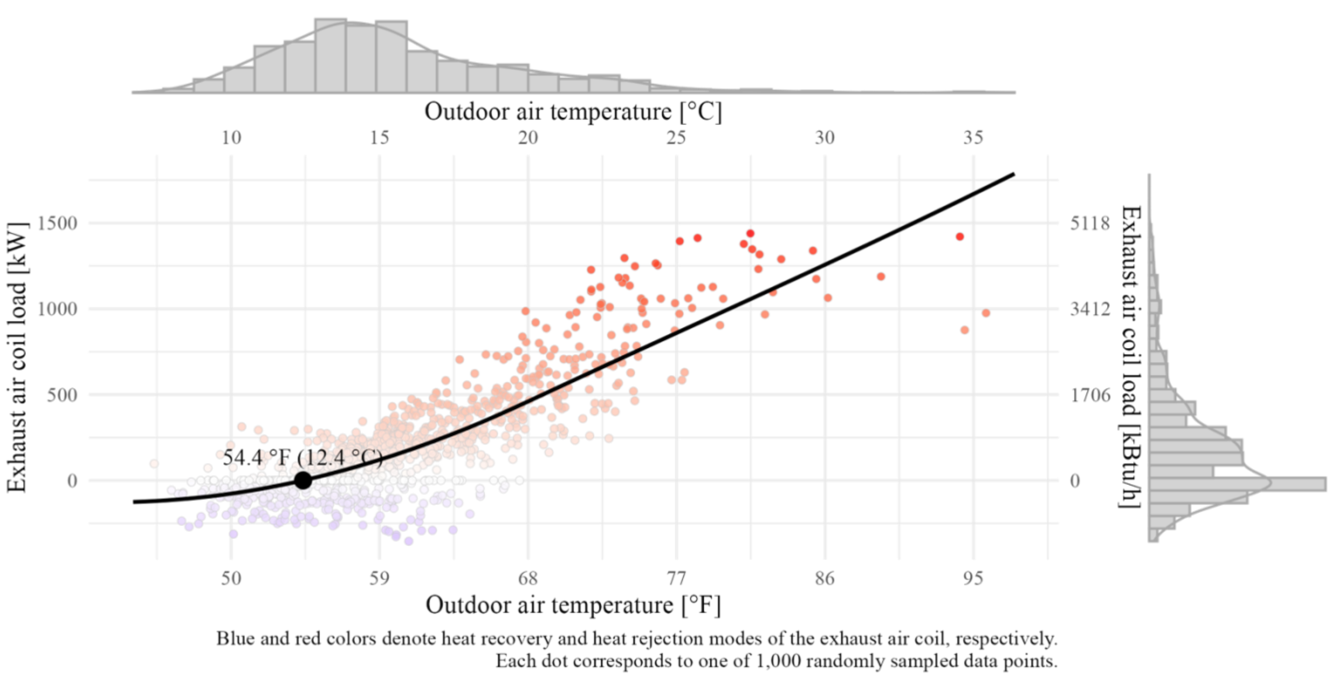

Figure 2 Outdoor air temperature dependence of exhaust air coil operation showing mode transition at approximately 54.4 °F (12.4 °C).

Furthermore, exhaust air coil operating mode switched throughout the analysis period, with a median of 2 mode changes per day (25^{th}, 75^{th} , 100^{th} percentiles are 0, 3 and 11 times respectively). Mode transitions through neutral states (e.g., sink mode to neutral, sink mode to neutral and back to sink mode) were not counted as mode switches. While the predominant pattern shows transition from source mode in the morning to sink mode in the evening as expected, more frequent mode alternation suggests potential for optimization through enhanced control strategies and/or relatively small thermal energy storage systems which could reduce power consumption.

To quantify the overall potential of dual thermal energy storage, we analyzed the effect of a combined hot water and chilled water storage with hot water ΔT of 20°F and chilled water ΔT of 5°F. With dual 10,000 gal (37,900 L) tanks, exhaust air coil loads could be reduced by 5.8% in sink mode and 20.3% in source mode, with offsets of 2.5% of overall hot water load and 1.1% of overall chilled water load. When scaled to 500,000 gallons (1,890,000 L), the point at which additional thermal storage yields diminishing returns, exhaust air coil load reductions could reach 20.4% in sink mode and 73.4% in source mode, with overall offsets of 8.3% for hot water and 5.5% for chilled water load. The limited effectiveness stems from long sink mode periods, an average 16-hour delay before heat recovery begins, and small usable temperature stratification relative to thermal loads. Without substantial and consistent demand, thermal storage benefits remain constrained.

COP and temperature conditions

The case study building is equipped with four HRCs. However, all four units never operated simultaneously during any timestep, which aligns with the typical redundant design strategy for critical buildings, where backup capacity is essential (i.e., n+1 design). The manufacturer's nominal COP is specified as 2.9 for cooling mode and 4.8 for heating mode at the design entering water temperature (EWT) and leaving water temperature (LWT) listed in Table 1.

Table 1. Manufacturer's design water temperature conditions

	Evaporator		Condenser	
	EWT	LWT	EWT	LWT
Cooling mode	56 °F (13.3 °C)	42 °F (5.6 °C)	110 °F (43.3 °C)	130 °F (54.4 °C)
Heating mode	56 °F (13.3 °C)	40 °F (4.4 °C)	96 °F (35.6 °C)	110 °F (43.3 °C)

During the monitoring period, the measured median water temperatures were 47.6 °F (8.7 °C) and 43.5 °F (6.4 °C) for the evaporator side EWT and LWT, respectively, and 108.6 °F (42.5 °C) and 114.5 °F (45.8 °C) for the condenser side EWT and LWT. Chilled water exhibited a mean ΔT of about 4.6 °F (2.5 °C), and the hot water showed a mean ΔT of approximately 5.2 °F (2.9 °C). These mean ΔT values during system operation are notably lower than the design conditions. The overall mean COPc during the monitoring period was 2.1, with individual HRC performance ranging from 2 to 2.2.

COP metric adjustment for heat recovery chillers

In the case study building, the exhaust air coil functions as a heat sink or source, and its thermal load is included in the chilled water or hot water loop. As a result, when using the evaporator or condenser heat as the basis for COP calculations, the load includes energy that is not always directly useful for conditioning the building. This can lead to an overestimation of system performance. To more accurately reflect the useful thermal load delivered to the building, the portion of heat exchanged through the exhaust air coil can be subtracted from the chilled water or hot water loop loads when the coil is acting as a heat sink or source. The revised COPshc ($COP_{shc,EAexcl}$) definition are provided below.

$$\text{Simultaneous Heating and Cooling COP } (\text{COP}_{shc,EAexcl}) = \frac{Q_{\text{evaporator}}+Q_{\text{condenser}}-Q_{\text{exhaust air coil}}}{E_{\text{input}}}$$

Figure 3 below compares the distributions of COP_{shc} and $COP_{shc,EAexcl}$. The analysis shows that more than half of the timesteps operate at COP values above 4 when using the COP_{shc} metric, with a mean COP_{shc} value of 5.0. However, the $COP_{shc,EAexcl}$ distribution reveals that 56% of timesteps operate within the COP range of 2-4, indicating that a significant portion of the thermal energy generated by the HRC is utilized for exhaust air conditioning. This comparison demonstrates that using the COP_{shc} index may lead to overestimation of system performance.

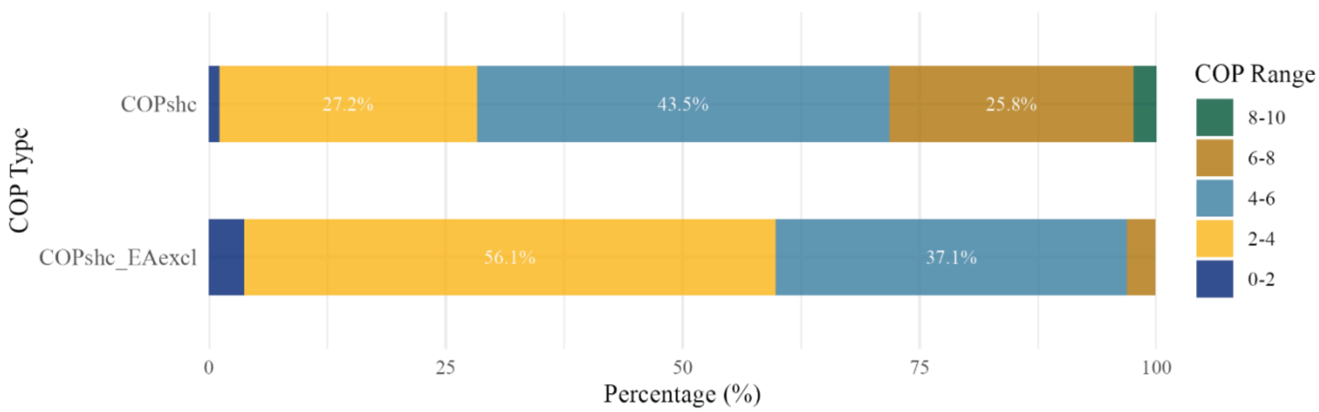

Figure 3 Comparison of COP_{shc} and $COP_{shc,EAexcl}$ distributions showing the impact of excluding exhaust air coil load on system performance evaluation.

Figure 4 shows the distribution of $COP_{shc,EAexcl}$ as a function of outdoor air temperature. To minimize variability in data-sparse regions, the trend line represents 95% of the data, excluding the top and bottom 2.5%. The analysis reveals that $COP_{shc,EAexcl}$ increases with rising outdoor air temperature in the lower temperature range. However, beyond approximately 60°F, $COP_{shc,EAexcl}$ no longer increases with further temperature rise and stabilizes at approximately COP of 4.1. The mean and median $COP_{shc,EAexcl}$ during the analysis period were 3.8 and 3.7, respectively. Note that when directly comparing systems between this building (HRC with exhaust air coil heat rejection and recovery) and ASHPs system used for both heating and cooling, the $COP_{shc,EAexcl}$ is a much more appropriate metric than COP_{shc} as it accounts for the exhaust air loads.

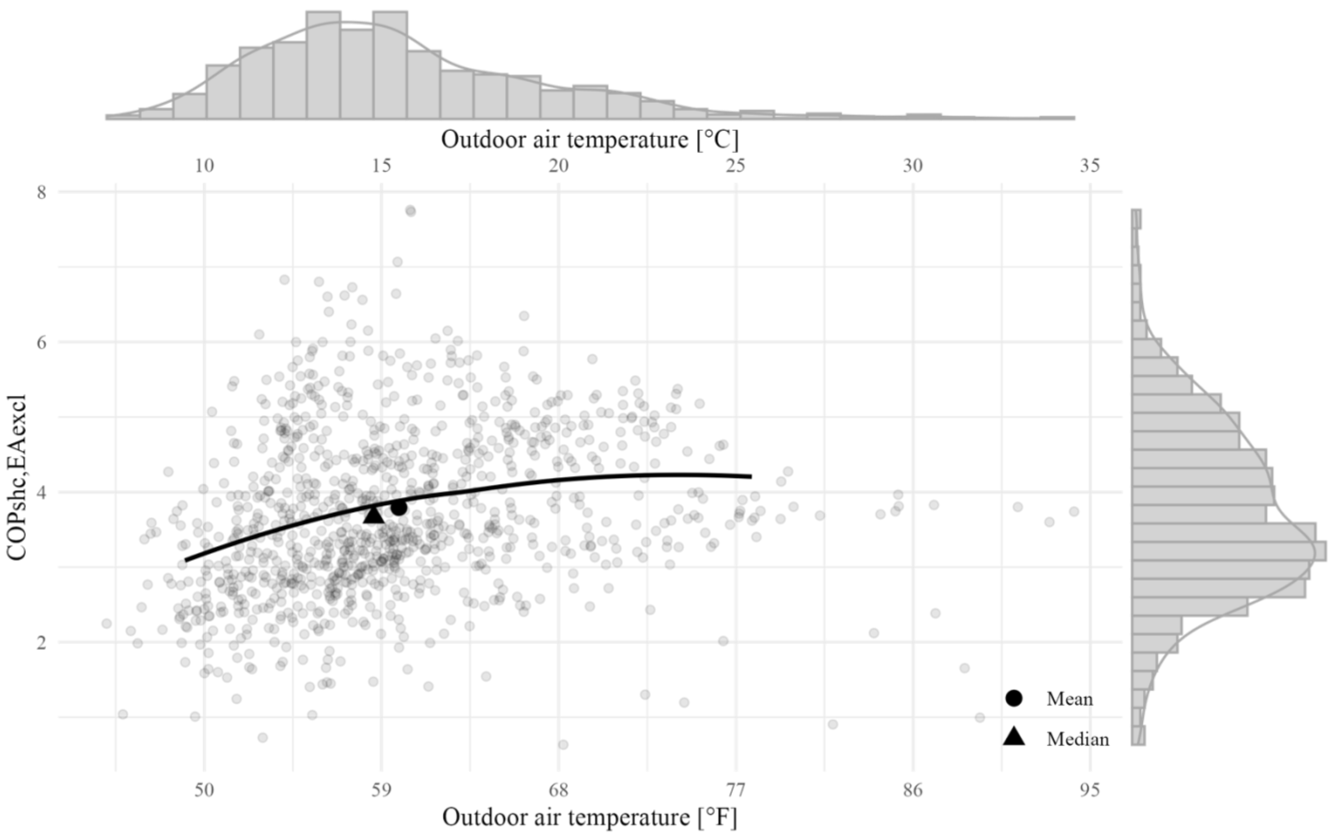

Figure 4 $COP_{shc,EAexcl}$ distribution as a function of outdoor air temperature with marginal density plots, trend line based on 95% of data excluding 5% most extreme data on x-axis.

The case study building uses exhaust air coils to balance loads on the heat recovery chiller. The six AHUs each contain exhaust air coils with 8 rows and 10 fins per inch, resulting in a significant air-side pressure drop when bypass dampers are closed. For context, assuming 70% fan efficiency and 70% design airflow, the annual fan energy increase due to exhaust air coil use would be approximately 235,000 kBtu/year (68,900 kWh/year). This corresponds to an energy intensity of 1.3 kBtu/ft²·year (4.1 kWh/m²·year). When comparing with alternative system designs such as those using ASHPs, this increased fan energy consumption must be considered in the overall system evaluation. For context, using the above assumed flow and efficiency, including this additional fan power consumption as part of the electrical power used to calculate $COP_{shc,EAexcl}$ would decrease the mean to 3.6 and median to 3.4. In addition, in this particular design, each AHU is also equipped with an 8-row runaround coil on the supply side, while the exhaust side contains both an 8-row runaround coil followed by the exhaust air coil in series. Although bypass dampers exist on the exhaust side, air must pass through all three coils in order for the exhaust air coil to operate, leading to further fan energy consumption.

Cooling tower water savings

In conventional water-cooled chiller systems, condenser heat generated during cooling operation is typically rejected through a cooling tower. However, the case study building eliminates the need for a cooling tower by recovering condenser heat to meet the building's heating demand, with any excess heat rejected through exhaust air coils. This design eliminates the energy and water consumption associated with cooling tower operation. To quantify the potential water savings enabled by this design, we employed a physics-based method following EnergyPlus engineering reference (EnergyPlus Version 24.2.0. Engineering Reference 2024). The method estimates cooling tower makeup water by calculating evaporation, drift, and blowdown losses. We assumed an average COP of 4 for a conventional chiller and calculated the condenser heat based on the building's cooling load for a fair comparison. We further assumed that all condenser heat contributes to evaporation, providing an upper-bound estimate of water consumption. The evaporation volume is calculated using the total condenser heat rejection and the latent heat of vaporization. Additional water losses are estimated assuming typical cooling tower operating conditions: drift losses of 0.005% of circulating water, airflow ratio of 1.0, and blowdown calculated with a cycle of concentration of 4.

Due to the availability of reliable building water meter data, the analysis covers the period from September 10, 2024 to August 30, 2025. During this period, the total cooling tower water consumption would have been 1,910,000 gallons, while the actual building water consumption without cooling tower operation was 1,800,000 gallons. The heat recovery chiller system therefore eliminates 51% of the total building water consumption that would be required with a conventional cooling tower system. At the current water rate of \$27.9 per CCF (\$0.04 per gallon), this water conservation translates to cost savings of \$71,100 over the analyzed period.

CONCLUSION

This study analyzes the real-world performance of heat recovery chillers (HRCs) with exhaust air coils for both heat rejection and heat recovery (under sink mode and source mode), serving an all-electric medical facility. A key finding is that the exhaust air coil load frequently accounts for a significant fraction of the total thermal load, indicating that substantial thermal energy does not directly serve building loads. This led to developing a revised COP metric ($COP_{shc,EAexcl}$), which considers only the thermal energy usefully utilized in the building by excluding the exhaust air coil load, revealing that conventional COP calculations may overestimate system performance by not accounting for non-useful thermal loads. The average value across the measured data period was 3.8. This demonstrates an overall high level of performance, for example, when compared to more common all-electric designs utilitzing air-to-water heat pumps for building heating and cooling demand, which rely on outdoor air instead of exhaust air as the heat sink or source (and many of which also have limited heat recovery capabilities). The exhaust air coil played a critical role in HRC operations and accounted for a significant portion of the total hot water and chilled water loads. However, when accounting for the increased fan power consumption associated with the airside pressure drop across the exhaust air coil, the average COP would decrease to approximately 3.6. Therefore, when comparing HRC systems that utilize exhaust air coils for condenser heat rejection with alternative HVAC systems such as ASHPs, it is essential to consider both the thermal energy rejected to or recovered from the exhaust air coil and the additional fan power consumption associated with it. The system eliminates cooling tower operation, achieving 51% water savings and \$71,100 in cost savings over the analyzed period. This study provides valuable insights for HRC system design and operation, demonstrating both the benefits and optimization opportunities for all-electric building decarbonization strategies.

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