Toward Net-Zero Data Centers: A Framework for Energy Optimization and Offsetting Emissions

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Abstract: ***The explosive growth of artificial intelligence (AI), machine learning (ML), and high-performance computing (HPC) is driving soaring energy demands and heat generation in modern data centers. While much of this energy is traditionally lost as waste heat, emerging strategies are exploring how to repurpose this thermal byproduct to support sustainable applications, such as heating schools, swimming pools, and other public infrastructure. This paper presents a comprehensive review of energy consumption modeling, thermal management techniques, and innovative heat reuse initiatives within data centers.***

Keywords: data centers, energy reuse, thermal management, artificial intelligence, sustainable computing

1. Introduction

Data centers are large scale, mission critical computing infrastructures that operate continuously, 24/7 serving as the backbone of the modern digital economy. Over the past two decades, their significance has grown exponentially, primarily driven by two key factors. First, the surge in global demand for data processing, computation, and storage—fueled by cloud-based services from tech giants such as Amazon Web Services (AWS), Microsoft Azure, Google Cloud, Meta, and Apple—has led to the rapid expansion of hyperscale data centers housing hundreds of thousands, even millions, of servers. Second, the increasing need to support a broad range of applications—from short-lived tasks to always-on services—has necessitated highly scalable, flexible, and powerful computing platforms [1].

The advent of artificial intelligence (AI) and machine learning (ML) has further accelerated this expansion. AI & ML workloads require substantial computational power and storage capabilities, driving data centers to adopt specialized hardware like GPUs and TPUs to efficiently handle these tasks. This shift has led to a significant increase in power density and cooling requirements within data centers. To meet these demands, operators are investing in advanced cooling technologies and exploring sustainable energy solutions to manage the heightened energy consumption and environmental impact associated with AI and ML operations [3].

As AI & ML applications continue to permeate various industries—including telecommunications, finance, healthcare, and entertainment—the reliance on robust, efficient, and scalable data center infrastructures becomes increasingly critical. This trend underscores the importance of ongoing innovations in data center design and management to support the evolving computational landscape.

The energy consumption of data centers has become a focal point of concern. In 2025, data centers are projected to consume approximately 536 terawatt-hours (TWh) of electricity, accounting for about 2% of global electricity consumption [2]. This represents a significant increase from previous years and highlights the escalating energy demands driven by the proliferation of AI and ML workloads. Addressing these challenges necessitates the development of energy-efficient technologies and sustainable practices to mitigate the environmental impact of data center operations

2. An overview of Both Traditional and Innovative Cooling Strategies

2.1 Underfloor (Raised Floor) Air Distribution:

In this approach, a raised floor creates a plenum space beneath the server room. Cool air is delivered into this plenum and directed upward through perforated floor tiles positioned near the equipment. This method ensures that cool air reaches the server inlets effectively. However, it requires careful design to prevent airflow obstructions and maintain consistent cooling performance.

2.2 Overhead Ducted Air Distribution:

Alternatively, cooling air can be supplied through ductwork installed above the server racks. This overhead system delivers conditioned air directly to the equipment, with return air ducts channeling warm air back to the cooling units. This method can be advantageous in facilities where underfloor air distribution is impractical.

2.3 In-Row Cooling:

In-row cooling units are positioned between server racks within the aisles as shown in Figure [1]. These units draw in warm air from the servers, cool it, and then discharge the cooled air back into the aisle, ensuring immediate temperature regulation. This close-coupled cooling approach enhances efficiency by reducing the distance air must travel, minimizing energy losses.

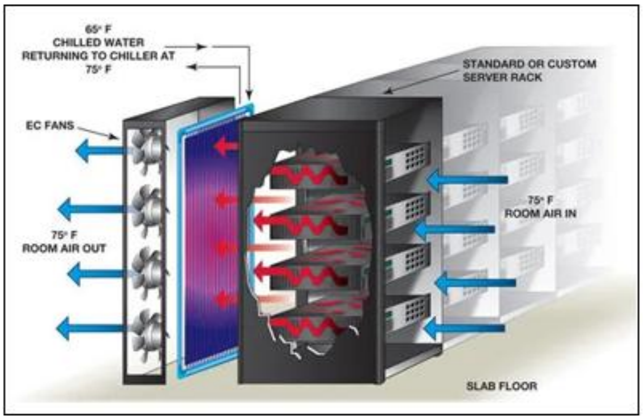

Figure 1: In Row Cooling Racks, Source: Energy Star

2.4 Evaporative (Adiabatic) Cooling:

This technique leverages the evaporation of water to absorb heat, cooling the air that is then used to lower the temperature of the data center, as shown in Figure [2]. It's particularly effective in climates where the ambient air is dry, offering energy savings over traditional mechanical cooling methods.

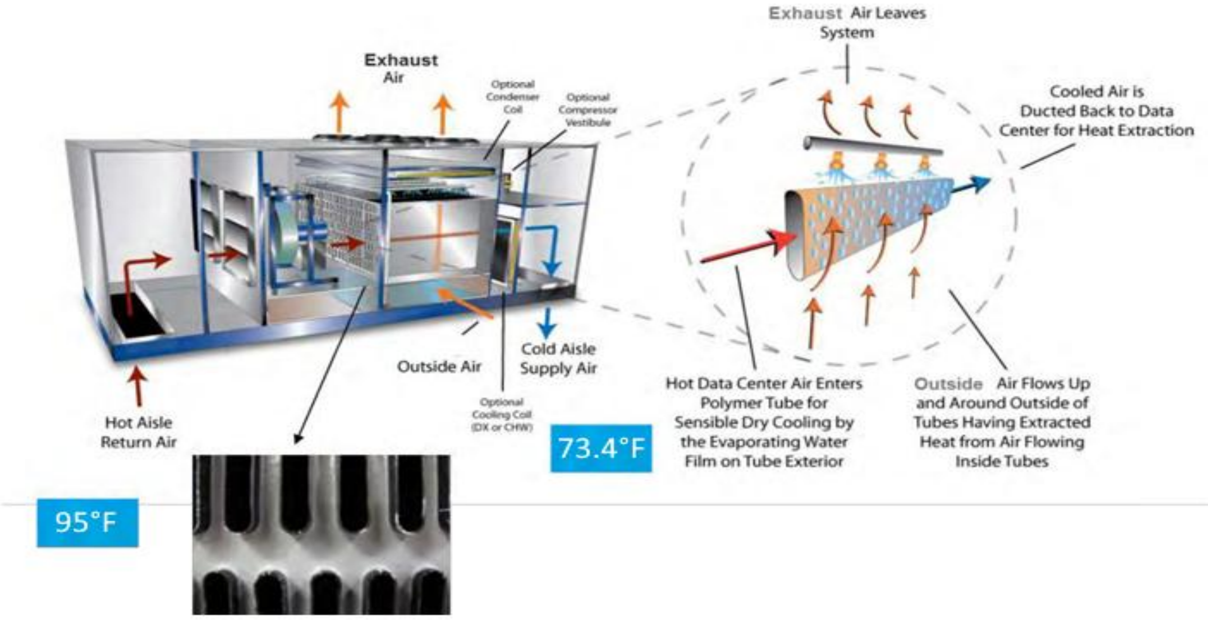

Figure 2: Indirect Evaporative Cooling, Source: Munters

2.5 Chilled Water Systems

Utilizing chilled water circulated through cooling coils, these systems can be integrated with both underfloor and overhead air distribution methods. Chilled water systems are known for their efficiency and are adaptable to various data center designs, including slab floor configurations.

3. Energy Consumption within the Data Center

3.1 Energy Consumption by Data Center vs Other Sectors

In 2025, U. S. data centers are projected to consume approximately 501.5 billion kilowatt-hours (kWh) of electricity. Given that nearly all of this energy—about 97%—is converted into heat during operation, this translates to an estimated 486.5 billion kWh of waste heat dissipated into the environment.

Breakdown of heat energy consumption by sector as shown in Figure [3]:

- **Residential:** The residential sector is expected to consume approximately 11.3 quads of energy, primarily for space and water heating, with natural gas and electricity as the most-used energy sources [5].
- **Commercial:** Commercial buildings, such as offices, warehouses, and food service buildings, are projected to consume approximately 9.34 quads of energy, with a significant portion of space heating [5].
- **Industrial:** The industrial sector, including manufacturing and agriculture, is estimated to consume around 26.06 quads of energy, with thermal processes representing a significant portion [5].
- **Electric Power:** The electric power sector is projected to consume around 32.11 quads of energy, including the use of fossil fuels, nuclear power, and renewables to generate electricity and produce useful thermal output [5].

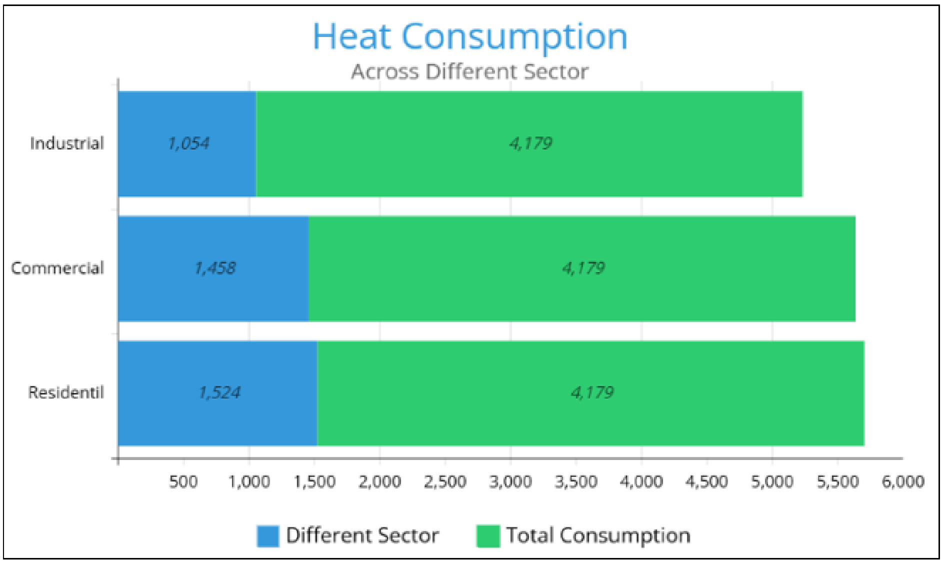

Figure 3: Heat Energy Consumption by Sector, Source: Reuters

3.2 Energy Consumption Within a Typical Data Center

Let's break down the energy consumption within a typical data center by different equipment categories in 2024. Keep in mind that these percentages can vary based on the specific design, efficiency measures, and workload of an individual data center, but these figures represent general trends.

In 2024, the largest portion of energy consumption within a data center is attributed to the IT equipment, encompassing servers, storage devices, and networking gear. This category typically accounts for around 40-50% of the total energy usage [Uptime Institute, 2024]. The power demands of increasingly dense server racks and high-performance computing contribute significantly to this consumption.

The next major energy consumer is the cooling infrastructure, which includes Precision Air Conditioning (PAC) units, Computer Room Air Conditioners (CRACs), chillers, cooling towers, and pumps. Efficiently managing the heat generated by IT equipment is crucial, and this often represents approximately 30-40% of the total energy consumption [18].

Power infrastructure, which involves uninterruptible power supplies (UPS), power distribution units (PDUs), and transformers, accounts for roughly 10-15% of the energy usage [Vertiv, 2024]. These components ensure a stable and reliable power supply to the critical IT equipment.

Finally, lighting and other miscellaneous loads, such as security systems and office equipment within the data center facility, typically constitute a smaller fraction, generally around 1-5% of the total energy consumption [19].

4. Waste Heat Sources and Recovery Potential in Data Centers

Air-side cooling is currently the most commonly used technology in data centers. It provides reliable cooling capacity and generates a large amount of low-temperature waste heat. Although there has been a lot of research into reusing this waste heat, the low thermal quality makes it difficult to use it efficiently on a wide scale.

In contrast, liquid cooling systems—while not as widely adopted—produce higher-temperature waste heat, which makes them more promising for recovery and reuse. Table [1] highlights the temperature ranges and potential for heat recovery from different cooling methods in data centers. A star rating system (☆) is used to indicate the potential—more stars mean better recovery potential [7].

Air-side cooling systems dominate the market, so they have the highest overall potential in terms of volume. However, in terms of temperature and quality of waste heat, liquid cooling systems come out ahead. These systems can return hot water at temperatures between **122°F and 140°F**, making the recovered heat more useful. On the other hand, condenser coolant temperatures—whether from air-side or air-to-liquid systems—typically range between **104°F and 122°F**, which still presents a good opportunity for reuse.

Table 1: Recycling Potential Rank for Different Cooling Forms

DC Cooling Form	Reference	Description	Potential Heat Source	Temperature (°F)	Recycling Potential Rank	
					Waste Heat Temp.	Application Scope
Air-side cooling	CRACs [11]	Room-level cooling	Return warm water	59–68°F	☆	☆☆☆☆
			Return hot air	77–116.6°F	☆☆☆	☆☆☆☆
	CRAHs		Condenser coolant	104–122°F	☆☆☆☆	☆☆☆
Air-to-liquid	Heat exchanger	In-row & rear door cooling	Return warm water	68–86°F	☆☆	☆☆
			Condenser coolant	104–122°F	☆☆☆☆	☆☆
Liquid cooling	[12]		Return hot water	122–140°F	☆☆☆☆☆	☆☆

In comparison, hybrid or standalone air-side cooling systems often return warm water at only **59°F to 86°F**, which limits their potential for effective heat recovery.

When it comes to air handling technologies, data centers may use CRACs (Computer Room Air Conditioners) or CRAHs (Computer Room Air Handlers), depending on factors like data center size, existing infrastructure, and specific cooling needs [7]. CRAC units are standalone systems that cool and dehumidify the air directly, while CRAHs are part of a centralized system that circulates chilled air from a larger cooling plant.

As shown in Figure [4], waste heat in data centers primarily comes from two sources: the return hot air and the liquid coolants. If not properly recovered or reused, this heat is typically released outdoors, contributing to environmental heat pollution.

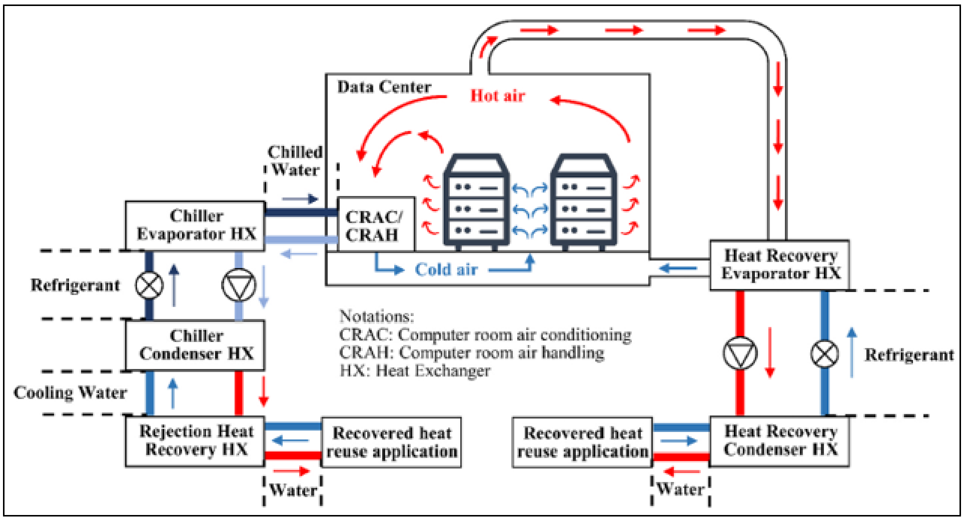

Figure 4: WHRs in DCs with CRACs/CRAHs [9]

4.1 Harnessing Data Center Waste Heat for Sustainable Urban Heating

Figure [5] presents a schematic of a system designed to efficiently recover, store, and repurpose waste heat generated by IT equipment in a localized data center. In this setup, thermal energy produced by servers is captured using Computer Room Air Conditioning (CRAC) units and heat exchangers. This heat is then transferred to a working fluid, which can either be expelled via a cooling tower or redirected for beneficial thermal applications, such as heating nearby buildings or powering absorption chillers. Implementing such waste heat recovery systems enhances energy efficiency and supports sustainability goals by reducing the environmental impact of data center operations.

Instead of wasting this thermal energy, it can be:

- **Stored in thermal tanks or underground boreholes** for later use (thermal energy storage).
- **Supplied directly to nearby buildings** for space heating or hot water needs.

Smart valves and pumps manage the flow of heat based on demand, allowing the system to switch between cooling, heat rejection, and heat recovery modes. This approach enhances energy efficiency, reduces carbon emissions, and supports sustainable urban heating through district energy systems [7].

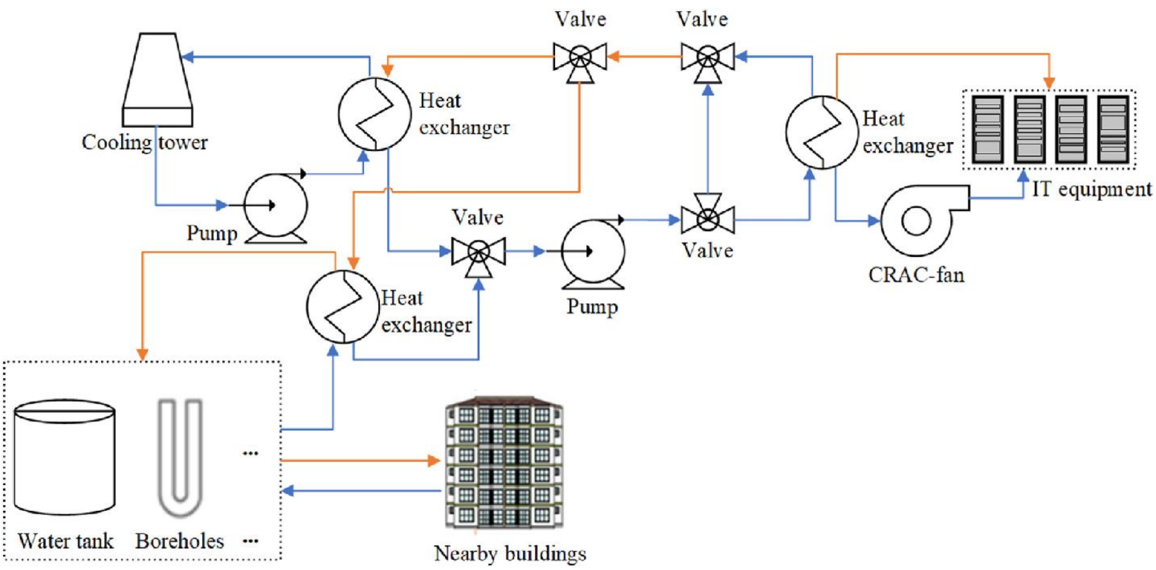

Figure 5: Using thermal energy storage to store waste heat from DCs [10].

4.3 Sustainable Heat: Reclaiming Energy for District Heating Networks

In addition to directly using waste heat from data centers (DCs) for heating nearby buildings or for pre-heating purposes, this excess thermal energy can also be recovered and used to supplement heat demands in district heating (DH) networks. Utilizing waste heat in DH systems not only enhances the overall efficiency of data center operations but also helps reduce carbon emissions associated with conventional district heating sources, as shown in Figure [6]. Unlike waste heat recovery (WHR) systems used for nearby building heating, which can operate effectively at a range of temperatures (68–131°F).

When waste heat is available at approximately **95°F (35°C),** it cannot fully meet DH temperature requirements on its own. Nonetheless, it can be effectively used for **preheating** the return water in DH systems, significantly reducing the energy demand for final temperature boosting. At this temperature level, **an estimated 40–60% of the total heating load** can be offset, depending on system design and heat pump efficiency [7]. This approach contributes to improved energy efficiency, lower carbon emissions, and better utilization of otherwise wasted thermal energy from data centers.

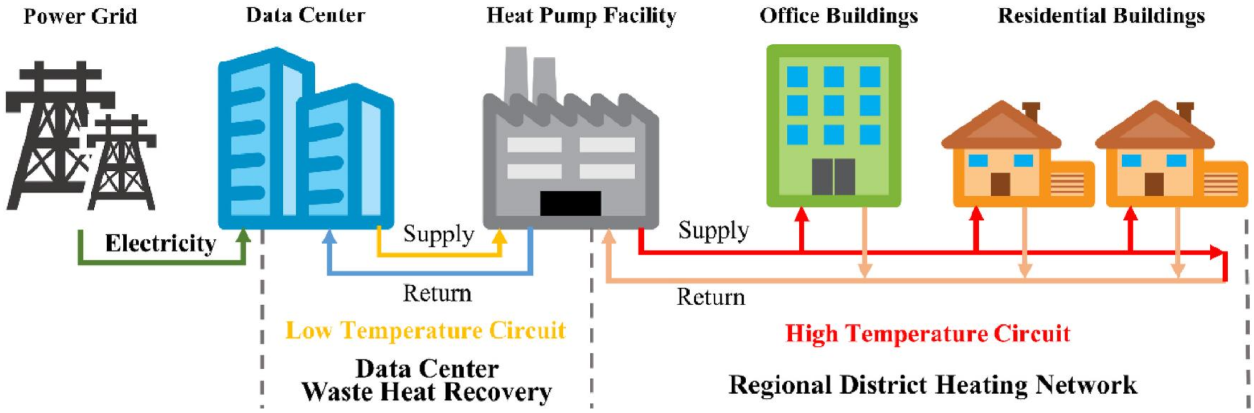

Figure 6: WHR (low-temperature) in DCs to DH systems (high-temperature) [14].

4.4 Reducing Carbon Footprint in Data Centers via Heat Recovery Chillers

Integrating Heat Recovery Chillers (HRCs) with Condenser Water-based Thermal Energy Storage (CW-TES) systems presents a transformative approach to reducing natural gas dependency in commercial buildings. By capturing and storing waste heat, these systems enable efficient space heating, even when heating and cooling demands are not simultaneous.

Two case studies highlight the efficacy of Condenser Water-based Time-Independent Energy Recovery (CW-TIER) systems and heat recovery chillers in significantly diminishing natural gas consumption for heating in existing buildings.

4.3.1 Case Study 1: San Diego Manufacturing Facility-CW-TIER Implementation

A manufacturing facility in San Diego retrofitted its infrastructure with a Condenser Water-based Time-Independent Energy Recovery (CW-TIER) system. This included a 50, 000-gallon condenser water storage tank (approximate installed cost: $200, 000), a heat exchanger, and a heat recovery screw chiller capable of producing 170°F hot water [13]. By intentionally isolating the new heat recovery chiller from the existing chilled water system for simplification and cost reduction, the facility anticipates a space heating natural gas consumption decrease exceeding 90%.

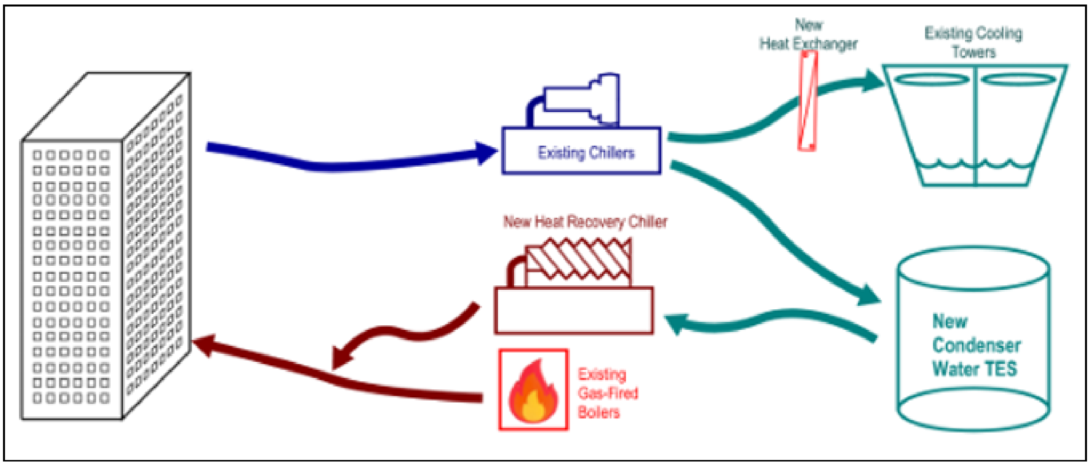

Figure 7: CW TIER retrofit

4.3.2 Case Study 2: San Francisco Hospital-Heat Recovery Chiller and Exhaust Air Recovery

A proposed retrofit for a San Francisco hospital involves integrating a heat recovery chiller and an exhaust air heat recovery coil. The heat recovery chiller will cool exhaust air during periods when air handlers do not utilize chilled water, recovering thermal energy for building heating. Despite the lack of space for thermal energy storage, the projected reduction in annual space heating natural gas usage is over 90%. Even without the exhaust air heat recovery coil, a significant 60% reduction is expected [13].

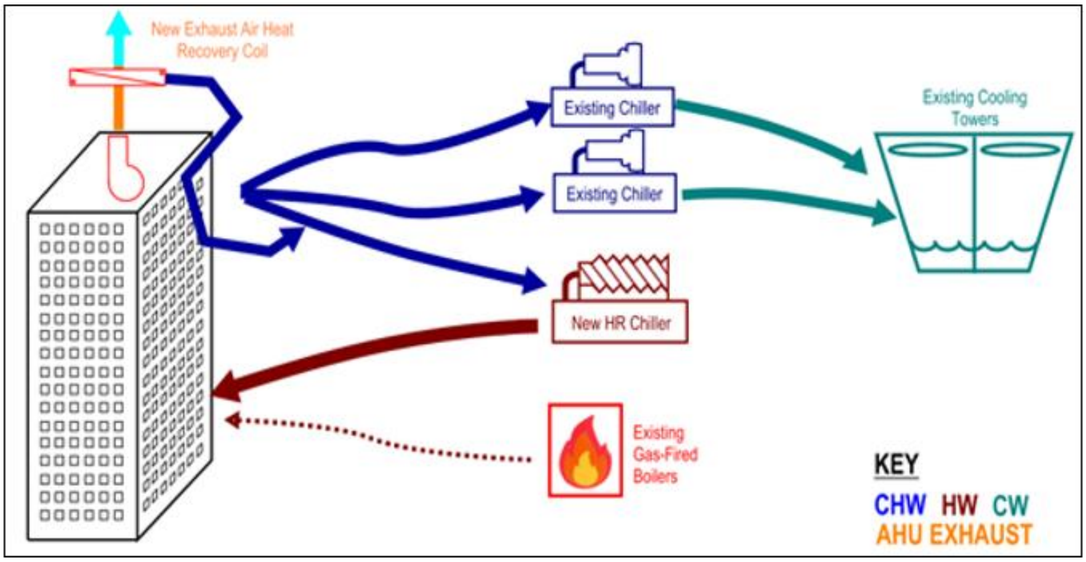

Figure 8: Proposed heat recovery chiller retrofit

These case studies illustrate the substantial potential of CW-TIER systems and heat recovery chillers, as depicted in Figure [8], to significantly diminish or eliminate natural gas consumption in existing buildings, often offering a more cost-effective pathway to electrification compared to alternatives like air-source heat pumps or electric boilers.

5. Conclusion

Waste heat recovery (WHR) from data centers (DCs) represents a transformative opportunity to enhance energy efficiency, reduce greenhouse gas emissions, and enable sustainable electrification. The continuous operation of high-performance computing infrastructure generates a significant amount of low-to-medium grade waste heat, which, if unutilized, contributes to environmental thermal pollution. Numerous studies have validated the technical, economic, and environmental feasibility of recovering this heat for use in nearby buildings, district heating (DH) networks, and even in industrial and agricultural processes.

Recent innovations, such as Time-Independent Energy Recovery (TIER) systems utilizing heat recovery chillers and thermal energy storage (TES), offer scalable, cost-effective solutions, especially for large commercial buildings. These systems provide flexible heating solutions, reduce reliance on fossil fuels, and support grid-interactive efficient building (GEB) goals. However, the applicability of TIER varies by building size and use case, with smaller commercial buildings benefiting more from simpler electrification solutions like single-zone heat pumps.

Key Findings:

- **80% of Local Heating Demand:** Google's data center in Hamina captures excess heat and channels it into the local district heating network. This recovered heat meets approximately 80% of the annual heating demand for the area, providing a sustainable and carbon-efficient solution for local households and public buildings [15].
- **Long-Term Benefits:** A study demonstrated that implementing WHR in an 18 MW data center could reduce CO_2 emissions by 603, 366 tons over 25 years, equating to approximately 24, 135 tons annually [16].
- **Localized Solutions:** In Paris, a data center's waste heat is used to warm the Olympic Aquatics Center, resulting in an annual reduction of 1, 800 metric tons of CO_2 emissions [17].

To meet the surging demand for AI-capable data centers sustainably, the tech industry, hyper-scale, and utilities must prioritize infrastructure that balances time-to-market with long-term energy resilience. This includes strategic investment in WHR technologies, integration with low-carbon thermal storage, and alignment with broader electrification and decarbonization efforts in the industrial sector. Going forward, the optimization of WHR systems, their integration with combined cooling, heating, and power (CCHP) systems, and alignment with local energy demands should be prioritized. Collaborative action from regulators, technology providers, and data center operators will be critical to overcoming existing policy and market barriers and to scaling these technologies for meaningful climate impact.

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