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Data center waste heat for district heating networks: A review

Xiaolei Yuan [a,*], Jiayi Liu [a], Sijia Sun [a,b], Xiaojie Lin [c], Xiaojun Fan [d], Weixin Zhao [a], Risto Kosonen [a]

[a] School of Engineering, Aalto University, Espoo, Finland
[b] State Key Lab of Subtropical Building and Urban Science, South China University of Technology, Guangzhou, China
[c] College of Energy Engineering, Zhejiang University, Hangzhou, China
[d] Berkeley Education Alliance for Research in Singapore, Singapore

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ABSTRACT

This paper investigates the integration of data center waste heat into district heating networks, evaluating its potential from technical, energy, economic, and environmental perspectives. It offers a comprehensive review of global efforts to recover waste heat from data centers, focusing on existing research, practical applications, and the effectiveness of current technologies. Key challenges are identified, including complex technical issues, economic constraints, policy limitations, and gaps in infrastructure. The study proposes solutions to address these challenges, aiming to improve the efficiency and feasibility of waste heat recovery systems. Additionally, the paper examines future trends in advancing data center waste heat recovery, with an emphasis on sustainable development and technological innovations such as smart energy systems and thermal energy storage solutions. The goal is to provide a detailed overview of the current landscape and offer actionable recommendations for enhancing the integration of waste heat into district heating networks. By doing so, the paper aims to promote greener energy solutions, reduce carbon emissions, and contribute to a more sustainable energy future worldwide.

1. Introduction

In Europe, district heating (DH) is regarded as an efficient alternative to individual heating systems that burn fossil fuels and mitigate the carbon-related climate change (e.g., urban heat island effect and global warming). Its large centralized production units and an extensive distribution network allow for the use of diverse heat sources (e.g., solar energy, biomass and waste heat) and a wide variety of energy management and optimization approaches (e.g., heat pumps, thermal energy storage, demand response) [1].

Table 1 shows the share of DH in building heating sector across different European countries, and obvious difference exists between them [2], which is primarily influenced by different factors (e.g., energy policies, infrastructure development, market demand, and the availability of energy resources). It is noted that Nordic countries (e.g., Denmark, Sweden, and Finland) have the highest DH coverage, because they benefit from their extensive use of renewable energy (e.g., wind, solar, and hydrogen), advanced heating technologies (e.g., ultra-low temperature DH network), supportive government policies, and substantial infrastructure investment. In contrast, DH systems are relatively limitedly used in Southern European and some Eastern European, as they have lower heating demand and strong reliance of electricity and natural gas for the energy infrastructures.

The majority of European countries are increasing the proportion of renewable energy in DH systems to promote environmental protection and sustainable development, and are committed to improving the energy efficiency of DH systems and reducing energy waste through technological innovation [1,3]. Governments support the upgrading and expansion of DH systems through regulations and incentives.

According to Heat Roadmap Europe, the thermal energy share by DH networks suggests it would be beneficial to increase from 13 % to 50 % by 2050 [4], and some corresponding strategies have also been approved (e.g., balancing the heat supply and demand, recovering waste heat sources, adopting heat storage techniques, and proposing new business models for efficient energy renovation) [5]. The heating energy for buildings in Finland, being the second-highest category of final energy consumption, accounted for 26 % of the country's total energy usage in 2020 [6], while DH occupies around 45 % of the Finnish market share in public, commercial and residential buildings [7]. With the

* Corresponding author.
E-mail address: Xiaolei.yuan@aalto.fi (X. Yuan).

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Nomenclature

Abbreviations

AI	Artificial Intelligence
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
COP	Coefficient of Performance
CRACs	Computer room air-conditioning units
CRAHs	Computer room air-handling units
DC	Data center
DH	District heating
HE	Heat exchanger
HP	Heat pump
LCOE	Levelized cost of energy
IEA	International Energy Agency
PUE	Power Usage Effectiveness
TES	Thermal energy storage
TWh	Terawatt-hours
1GDH	1st generation district heating
2GDH	2nd generation district heating
3E	Energy, economic, and environmental
3GDH	3rd generation district heating
4GDH	4th generation district heating
5GDH	5th generation district heating

Table 1
The share of DH in building heating across different European countries [2].

Region	Share, %	Main heating resources	Example
Nordic and Baltic	35–65	Biomass, waste heat	Denmark, Sweden, Finland, Estonia, Latvia
Central and Eastern	20–35	Coil, natural gas, biomass	Hungary, Austria
Western	5–20	Electricity and natural gas	Netherlands, France
Southern	1–10	Electricity and natural gas	Spain, Portugal

further integration of renewable energy and the continuous application of new technologies (e.g., waste heat recoveries, renewable energy solutions, demand response, smart control), DH systems will play an increasingly important role in European future energy landscape.

DH systems have a long history, which can be dated back to the 1880s, and have evolved through several generations. Fig. 1 compares the different DH generations in the past around 140 years [8]. Unlike the 1st and 2nd generations of DH (1GDH and 2GDH), utilizing different carriers (e.g., steam and super-heated water respectively), the 3rd generation of DH (3GDH) focused on optimizing heating systems. This included utilizing a wider range of heat sources, lowering supply water temperatures, and increasing distribution efficiency [9].

While the 4th Generation (4GDH) further improved upon 3GDH in several ways. It lowered both supply temperatures (to 50–60 °C) and return temperatures (to 25 °C) [10], increasing system efficiency. In

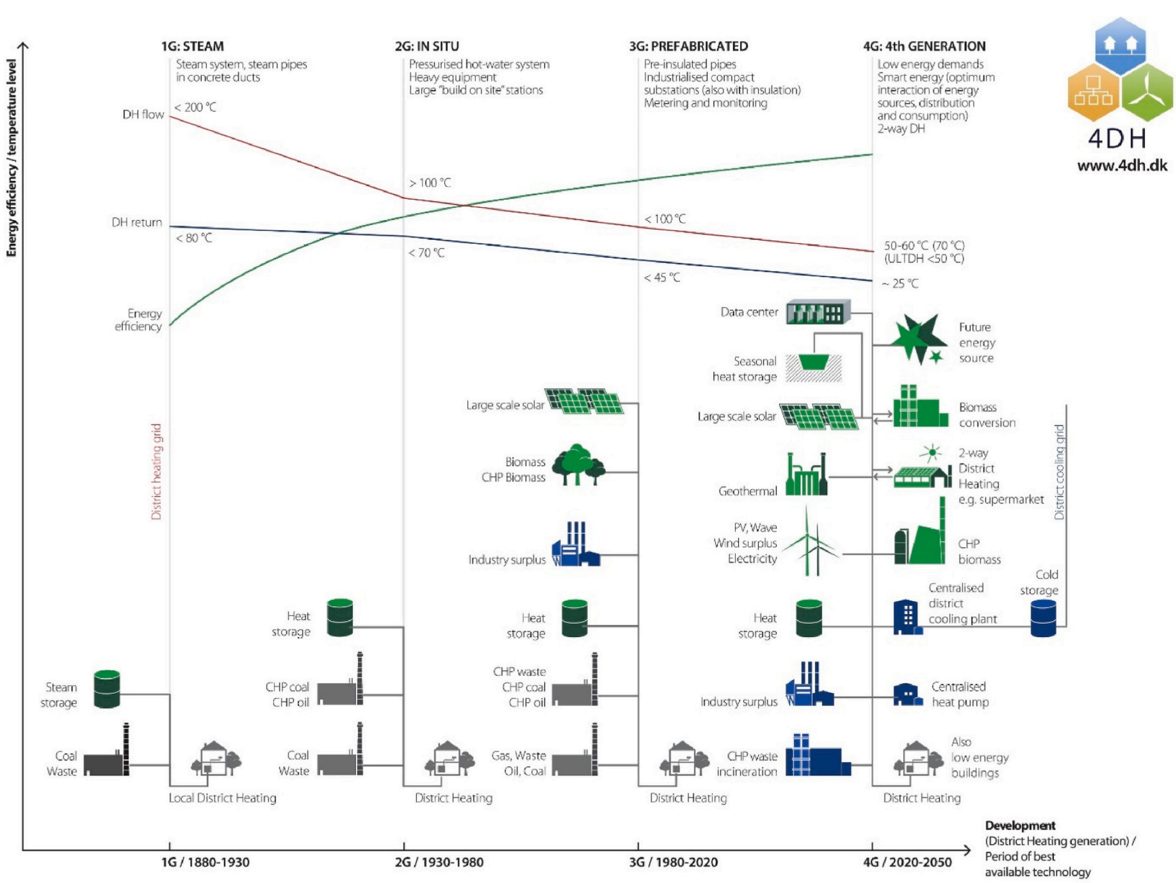

Fig. 1. Comparison among different generations of DH networks [10].

addition, more renewable energy sources are integrated into the 4GDH as well as employed smart technologies (e.g., heat pumps and thermal energy storage solutions) to manage the variability of renewable energy supply [11]. Additionally, 4GDH incorporated district cooling, two-way DH for specific consumers, and utilized waste heat from industrial processes and data centers (DCs) [11].

Furthermore, the 5th Generation DH (5GDH) system represents a significant evolution beyond 4GDH, not merely in its sustainability goals, which are shared with previous generations, but in its technical configuration and operational paradigm [8]. Unlike 4GDH, which typically operates with supply/return temperatures of 50–70 °C/25–30 °C, 5GDH systems function at ultra-low and near-ambient temperature levels (often below 40–50 °C), thereby minimizing distribution heat losses and enabling more efficient use of low-exergy heat sources such as DCs and ambient geothermal energy [12]. A defining feature of 5GDH is its bidirectional and decentralized network design, which allows buildings to operate as both heat consumers and suppliers (prosumers) depending on their thermal profile and on-site energy systems. These networks typically operate at low pressure and incorporate modular components, offering greater adaptability to local heat demands and infrastructure constraints. While sustainability and renewable integration are also key aims of 4GDH, 5GDH distinguishes itself by its system-level emphasis on flexibility, decentralization, and the direct use of very low-temperature renewable and waste heat sources without the need for significant temperature boosting. These characteristics support higher energy efficiency and broader alignment with smart energy systems and carbon neutrality targets [13].

[8,12,13]Aste et al. [14] investigated the energy, economic, environmental performances for the DH networks in Northen Italy, and they highlighted the importance and potential of WHR from industrial systems as a supplementary heat source in DH networks. In cities, abundant existing waste heats originate from different aspects (e.g., industrious production, buildings, and DCs) [15]. As shown in Fig. 2, the application of waste heat in DHs can contribute to energy, economic, environmental (3E) and societal benefits [9,16,17]. Therefore, the application of WHR technology in DH network has immense potential for the future, as it can significantly enhance energy efficiency, reduce carbon emissions, and drive the transition towards more sustainable and intelligent heating solutions [18,19].

The lower supply temperatures (60–70 °C) in 4GDH and ultra-low

Fig. 2. Significant benefits of WHR in DH networks [9,16,17].

supply temperatures in 5GDH (less than 50 °C) can increase the heating efficiency due to lower heat losses from the DH distribution system [8], and are closer to end users' actual heating demands, which facilitates the use of waste heat sources considering economic and energy feasibilities in DH networks [9]. As mentioned in Fig. 1, waste heat sources mainly come from two sectors globally, namely the waste heats from industrial processes and DCs [11].

Recent research by Sorknæs et al. [20] provides empirical evidence for the techno-economic synergies between 4GDH systems and energy-efficient DCs. Through comprehensive case studies in Denmark, their analysis demonstrates that transitioning from 3GDH to 4GDH infrastructure yields annual system cost reductions of €220 million, translating to savings of €0.7 million per TWh of delivered heat. Notably, their sensitivity analyses revealed that optimizing DC waste heat output temperatures could generate additional system value ranging from €52–59 million annually. These findings substantiate the operational advantages of 4GDH systems in waste heat integration and establish critical benchmarks for subsequent research in low-temperature DH applications.

WHR technology for industrial process is already well-established and extensively researched [21]. However, WHR from DCs also holds significant potentials. With the rapid rise of Artificial Intelligence (AI), Internet of things and big data in recent years, the demand for data processing and the number of high-density DCs have boosted, leading to a dramatic increase in their energy consumption [22]. The servers generate considerable heat during operation, and the 24/24hrs and 365 days/year operation of the air conditioning system [23] also creates a huge waste heat potential. This makes DCs the second-largest producers of waste heat, only behind industrial process. As a result, harnessing waste heat from DCs can provide a substantial opportunity for improving energy efficiency and sustainability in the growing digital economy [24].

Currently, DCs account for approximately 1–2 % of global electricity consumption. Although this percentage may seem small, considering its enormous scale of global electricity consumption, the actual energy consumption of DCs is quite substantial [25]. According to data from the International Energy Agency (IEA), global DCs have an annual electricity demand of approximately 240–340 TW-hours (TWh). This figure is comparable to the total electricity consumption of some medium-sized countries (e.g., Argentina, South Africa) [25].

IT equipment directly converts 30–50 % of the total DC electricity consumption into heat, while the remaining energy is indirectly transformed into heat through cooling, power distribution, and auxiliary systems [26]. From a thermodynamic perspective, 100 % of the input energy ultimately manifests as heat, but the spatial and temporal distribution of these thermal loads critically impacts cooling design. Depending on the scale and efficiency of the DCs, the global annual waste heat generated by DCs can reach approximately 70–170 TWh. Considering that about 50–70 % of them can be effectively recovered and used, the recoverable waste heat in DCs is about 35–85 TWh globally, which is almost equivalent to the Singapore's annual electricity consumption [27]. In France, the estimated recoverable waste heat was around 1 TWh from DCs in 2020, which is equivalent to the heat demand in 1 million housing units, while the figure is foreseen to 3.5 TWh by 2030 [28]. Similar trends are observed in other European countries. The electricity consumption and waste heat volume of DCs are increasing each year. Therefore, technologies and research related to WHR in DCs will remain highly promising and important for a long time to come, in addressing the global energy crisis and environmental climate problems.

Some countries are already leading the way in DC WHR. Germany's newly introduced Energy Efficiency Act mandates the reuse of "waste" heat, with an ambitious target of achieving a 10 % heat reuse rate by 2026 and a 20–30 % rate by 2028 in DCs [29]. Similar goals are set by other European countries: France aims for 15–25 % by 2030–2035 [30], Sweden and Denmark target 25–35 % by 2025–2030 [31,32], and the Netherlands aims for 20–30 % by 2030 [33].

Considering the importance, market potential, and feasibility of integrating DC WHR into DH networks, this paper will offer a comprehensive analysis and summary of its development and prospects from the perspectives of energy, economics, and the environment impacts. Several review studies have addressed aspects of DC WHR, but often with a narrow focus. Yuan et al. [15] reviewed WHR technologies in DCs, emphasizing heat sources and system design, but without addressing their integration into DH. Huang et al. [34] explored DCs as energy prosumers in district energy systems, primarily discussing cooling and electricity use. Ebrahimi et al. [35] focused on the technical potential of low-grade heat recovery but lacked economic or environmental analysis. Oró et al. [36] evaluated energy efficiency strategies in DCs, with limited attention to DH network applications.

Most existing review studies predominantly concentrated on the technical dimensions of DC operation (e.g., cooling technologies, waste heat characterization, and energy efficiency enhancement within the facility boundary). While these efforts contribute to understanding component-level performance, they generally lack an integrated perspective on the system-level utilization of DC waste heat within DH networks. Moreover, few reviews adopt a multi-dimensional analytical framework that concurrently addresses energy performance, economic feasibility, and environmental implications (3E analysis), which are essential for evaluating real-world applicability and long-term sustainability.

In contrast, this study offers a novel, interdisciplinary synthesis that explicitly focuses on the integration of DC waste heat into next-generation DH systems. It contributes by providing a structured 3E assessment, consolidating empirical case studies from diverse geographical contexts, categorizing integration approaches according to DH system generations (4GDH and 5GDH), and reviewing emerging optimization strategies such as AI-driven control schemes and thermal energy storage-enhanced configurations.

The objectives of this paper are as follows.

- Evaluating the existing research and implementation of DC WHR in DH networks globally.
- Examining the main challenges and barriers to effective DC WHR in DH networks.
- Analyzing future trends and opportunities for advancing DC WHR in DH networks.

While several reviews have examined waste heat recovery (WHR) from DCs or DH systems separately, this study provides a comprehensive synthesis that uniquely.

- Systematically evaluates the integration potential between these two systems across technical, economic and environmental dimensions;
- Identifies critical gaps in current research through comparative analysis of global case studies;
- Proposes a novel framework for assessing implementation feasibility based on generation-specific DH requirements;
- Provides original recommendations for overcoming integration barriers through emerging technologies like AI-optimized thermal storage systems.

The cases presented in this review were selected based on several key criteria to ensure their relevance and significance in the context of DC WHR in DH systems. These criteria include the representativeness of the case studies in terms of geographical diversity, technological advancements, and the impact of the research on energy efficiency, economic viability, and environmental sustainability. In addition, we focused on case studies from high-impact publications that have demonstrated practical applications and measurable results. This approach helps in providing a comprehensive overview of the current state and future potential of DC WHR integration into DH networks.

2. Methodologies

2.1. Review methodology

To ensure a comprehensive and systematic review of DC WHR for DH networks, a semi-structured literature review methodology is adopted as commonly used in engineering and energy system research [37].

Firstly, a keyword-based search is performed across four major academic databases (Scopus, Web of Science, ScienceDirect, and Google Scholar), covering literature published between 2010 and 2024 [38]. The keywords included combinations of: "data center waste heat", "district heating", "waste heat recovery", "heat pump", "thermal energy storage", "energy efficiency", "economic analysis", and "carbon emissions". The goal was to identify peer-reviewed articles, review papers, high-quality conference proceedings, and highly cited technical studies.

A total of over 250 documents were initially collected. After screening for relevance, clarity, and originality, 60 sources were retained for in-depth analysis. These were selected based on inclusion criteria such as.

- direct relevance to DC WHR integration in DH networks,
- provision of empirical results, simulations, or practical implementations,
- regional diversity (e.g., Northern and Western Europe, China),
- and contributions to one or more aspects of the 3E analysis (energy, economic, and environmental) [15].

In addition to academic literature, we consulted industry standards, technical guidelines, and regulatory documents from national and international agencies. These include publications by the International Energy Agency (IEA) [39], the European Commission [16], Annual report on China building energy efficiency [40], as well as national policies such as Germany's Energy Efficiency Act (2023) [29], the French Green Growth Law (2016) [30], and Finland's DH transformation strategy [41].

To complement these, we referred to official statistics (e.g., Statistics Finland [7], IEA energy reports [42]) and real-world project documentation published by district energy utilities (e.g., Fortum, Helen, Green Mountain, Facebook Odense) [43–46]. We also reviewed corporate sustainability reports, case descriptions on DC operators' websites, and open-access engineering resources for operational parameters, project economics, and emission baselines.

We then categorized the selected materials into thematic clusters focusing on technical integration (e.g., heat pump types, waste heat temperature ranges), energy performance (e.g., COP values, heat recovery rates), economic evaluation (e.g., payback period, LCOE), and environmental impact (e.g., CO_2 reduction, system-level benefits) [47,48]. For each study or case, we documented cooling strategies, integration topology, system boundary conditions, and policy context.

This hybrid review methodology, combining academic rigor, industry relevance, and policy context, provides a holistic basis for evaluating the current landscape and future potential of integrating DC waste heat into DH systems.

2.2. Importance of waste heat and its temperature levels

Recovering waste heat in DCs is becoming increasingly important due to the following drawbacks if not addressed in Fig. 3. The reusable waste heat will cause significant energy loss if not recovered and decrease the overall energy efficiency in DCs [49], while low energy efficiency increases the carbon footprint and cause CO_2-related environmental impact (e.g., Global warming, heat island effect) [50]. Furthermore, failure to recover the extra waste heat may result in increased cooling needs and thermal pollution in outdoor situations, raising operating and energy costs [15]. Moreover, DCs, the world's second-largest source of waste heat after industrial output, would

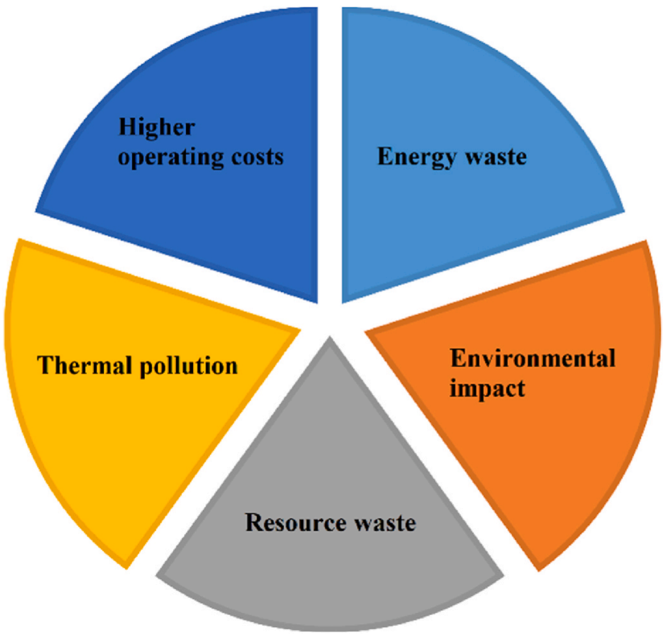

Fig. 3. The impacts of waste heat in DCs.

worsen resource scarcity and waste if waste heat is not utilized, driving up the demand for primary energy as the world's energy demand rises.

In global DCs, air-side cooling dominates with an estimated market share exceeding 80 % [51], which remains the most common in DC market due to its widespread adoption and easy-implementation despite growing interest in alternative cooling technologies like liquid cooling and immersion cooling, which are recognized for their high energy efficiency and suitability for high-density servers [52]. Air-side cooling can continuously produce a large amount of reliable waste heat, but with relatively low temperatures [35]. Compared to air-side cooling, liquid-side cooling holds a much smaller market share but produces higher temperature waste heat, which also offers great potential for WHR. In short, both air-side and water-side cooling systems offer significant potential for WHR, but they differ in their strengths with large quantities of heat and high waste heat temperatures, respectively [34].

There are four kinds of cooling systems widely adopted in DCs, namely air-cooling systems based on computer room air-conditioning units (CRACs) or computer room air-handling units (CRAHs), air to liquid cooling systems based on heat exchangers (HEs), and two-phase refrigerant-cooling systems [15]. While CRAHs are a component of a larger system that circulates chilled air from a central cooling plant, CRACs are freestanding machines that cool and dehumidify air directly [36]. A thorough assessment of waste heat sources and the associated temperatures in various DC cooling systems is given in Table 2 [53,54]. The possible waste heat sources include the return warm water, return hot air and condenser coolant, whose waste heat temperature levels are 15–60 °C, 25–47 °C, and 40–50 °C, respectively. CRACs hold the largest market share, indicating they generate the most waste heat. In contrast, liquid cooling systems operate at the highest temperature levels of 50–60 °C, representing the highest waste heat grade. In Table 2, the temperature levels are ranked based on the maximum temperature of the waste heat in each case. The rankings are as follows: 1st for 51–60 °C, 2nd for 41–50 °C, 3rd for 31–40 °C, 4th for 21–30 °C, and 5th for temperatures below 20 °C. The 20–30 °C range appears as 3rd or 4th depending on whether higher temperatures are present in the dataset. This table provides an initial evaluation of waste heat temperature levels, which is critical for the subsequent analysis of recovery potential in later sections.

Fig. 4 shows the WHR system and its heat and cold flow process in DCs with CRACs and CRAHs, while for the liquid cooling and two-phase refrigerant-cooing systems, the WHR process is similar [56]. Again, the waste heat sources are return warm water, return hot air, condenser coolant.

2.3. Heat pump

Since waste heat from DCs is categorized to be a low-grade heat source, it cannot be directly used in DH networks. As illustrated in Table 2, the temperature of this waste heat varies between 15 and 60 °C depending on the specific waste heat sources. Only a small portion of the waste heat from liquid-side and two-phase refrigerant cooling systems is capable of meeting the temperature requirements for ultra-low temperature DH networks. Although the concept of 5th Generation District Heating and Cooling (5GDHC) has been proposed as a complementary development to 4GDH, the majority of existing DH systems in Europe still operate at 3GDH or even 2GDH levels. Only a limited number of systems, mainly in Nordic and Central European countries, have begun adopting 4GDH features, such as lower supply temperatures (50–60 °C), renewable integration, and smart grid compatibility [10,12]. These two systems represent parallel rather than sequential developments, as discussed in Ref. [8]. Consequently, the waste heat from DCs generally does not meet the supply temperature requirements (60–70 °C) of 4GDH [57], while this issue is even more pronounced with other DC cooling methods (e.g., air-cooling and air-to-liquid cooling) that produce lower waste heat temperatures (15–50 °C) [15]. Thus, DC waste heat needs to be upgraded before it can be used for high-temperature or high-grade heating applications.

While heat pump (HP) technology is regarded as one of the most promising methods for WHR. It can be linked to various heat sources, such as waste water and air, and is capable of upgrading low-quality or low-temperature heat energy to a higher quality or temperature level [58]. A HP operates by using four main components, namely evaporator, compressor, condenser, and expansion valve, to transfer heat from a

Table 2
Detailed comparison of waste heat sources and their corresponding temperature levels.

Cold source	Cooling units	Cooling level	Reference	Waste heat sources	Temp. (°C)	Recovery potential ranking	
						Market share	Temp. levels
Air-side	CRACs	- Room level	[53]	Return warm water	15–20	1st	5th
		- Row-level		Return hot air	25–47		3rd
	CRAHs			Condenser coolant	40–50	2nd	2nd
				Return hot air	25–47		3rd
Air to Liquid	HEs	- Room level		Return warm water	20–30	3rd	4th
		- Row-level		Condenser coolant	40–50		2nd
Liquid-side		- Rack-level	[15,54]	Return warm water	50–60	4th	1st
		- Server-level					
Two-phase refrigerant-cooling		- Row-level	[55]	Return hot air	20–40	5th	3rd
		- Rack-level		Return warm medium	20–40		3rd
		- Server-level		Condenser coolant	40–60		1st

Notations: CRACs= Computer room air-conditioning units; CRAHs=Computer room air-handling units; HEs= Heat exchangers; Temp. = Temperature.

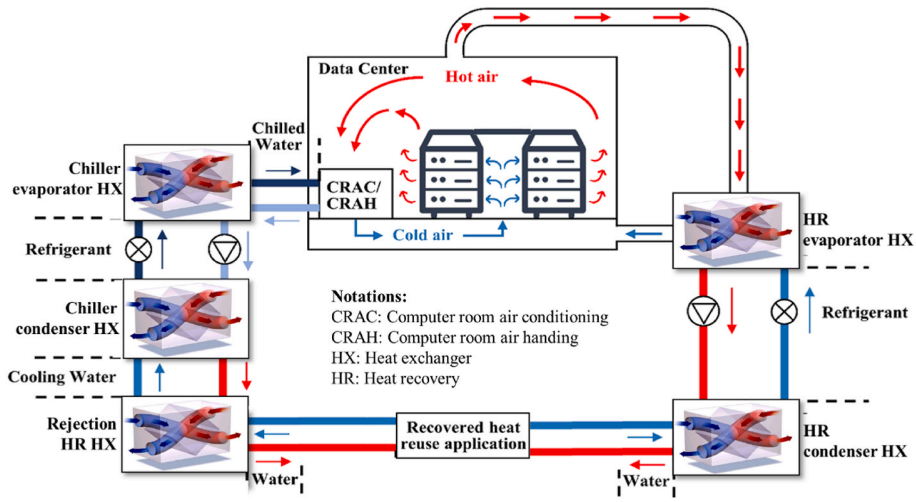

Fig. 4. WHR system in DCs with CRACs and CRAHs [56].

low-temperature environment to a high-temperature area, providing efficient heating or cooling [59], and its equipment and schematic diagram are shown in Fig. 5 [60]. During the HP operation, the low-temperature, low-pressure liquid refrigerant first enters the evaporator, where it absorbs heat from the environment and turns into a gas. This gas then enters the compressor, where it is compressed into a high-temperature, high-pressure gas. Next, it flows into the condenser, where it condenses into a high-temperature, high-pressure liquid. This liquid passes through the expansion valve, cooling and depressurizing to become a low-temperature, low-pressure liquid again, ready to repeat the cycle. This process allows the HP to efficiently transfer heat from a cold area to a warm one, enabling both heating and cooling [60].

The use of HP technology has been a key factor, which can contribute to the significant reduction in DH required supply temperatures [61], and has positive impacts on the efficiency of heat generation equipment, grid losses, and the potential for recovering heat from various waste sources [58,62]. The lower the supply temperatures, the less the heat losses in DH distribution networks, which can lead to higher energy efficiency and economic benefits [63]. HP technology plays a pivotal role in the heating systems, with around 180 million HPs currently in use globally in 2020 [11], and has garnered increasing attention in both research and the market with various kinds of HP products (e.g., air source, water source and ground source HPs) [39].

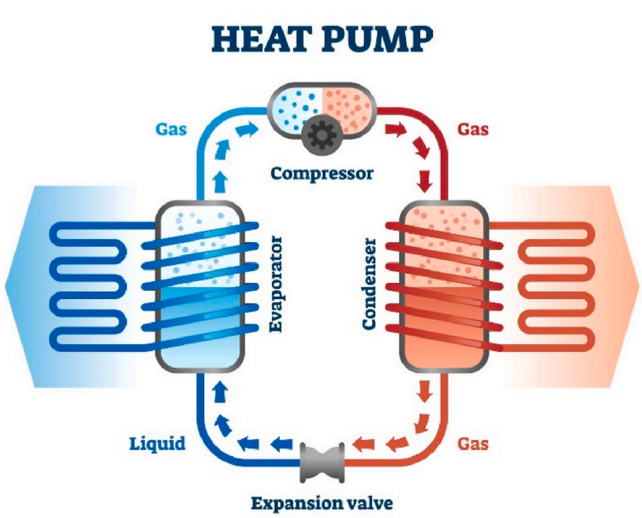

Fig. 5. Equipment and schematic diagram of HPs [60].

Fig. 6 shows the connection schematic between waste heat recovered from DCs to the DH networks [15]. The waste heat is recovered in DC WHR system and the HP uses minimal electricity to preheat the waste heat to meet the DH temperature and grade requirements before being transferred to the DH system. "Minimal electricity" refers to the small amount of electrical energy required to elevate the recovered waste heat to the necessary temperature for district heating, with the energy consumed being significantly less than that recovered from the waste heat itself. Ultimately, it is distributed through the DH network to provide heating demands for various buildings (e.g., apartment buildings, detached houses, office buildings, hospitals).

2.4. Thermal energy storage

In addition to HPs, Thermal Energy Storage (TES) offers the benefit of shifting the use of waste heat from DCs. While minor losses may occur during storage and retrieval, TES stores excess heat when production exceeds demand and releases it when demand is higher, optimizing the use of recovered waste heat and reducing reliance on additional energy sources [64]. TES includes conventional water-based storage and, in some cases, battery storage systems. Battery and “electricity” storage are included only when explicitly coupled with heating functions—for example, when batteries power heat pumps or when power-to-heat conversion (e.g., electric boilers) is part of the system [65]. TES functions as a buffer to reduce the temporal mismatch between the DCs’ intermittent and variable waste heat production and any connected building’s fluctuating heat requirements. By storing surplus heat when demand is low and releasing it during peak consumption periods, TES provides a more steady and secure heat supply. It not only increases the energy efficiency of the WHR unit, but also reduces the need for auxiliary heating and the associated fossil fuel consumption. TES also helps to level out operational variations, thus enhancing the resilience of the system and its stability for load fluctuations, thereby enhancing the quality of service and ensuring more consistent heating delivery to the end-users [65].

Fig. 7 shows the connection between waste heat recovered from DCs to the DH networks with TES [64]. The DC transfers the waste heat generated through heat exchangers to the HP system, where the temperature of the low-grade waste heat is increased, making it suitable for DH network. Prior to being connected to the DH network, the waste heat first enters a number of HP units where it is improved using heat exchangers (HEs). As a buffer, the TES system, which is seen on the bottom left, stores extra heat produced by the DC and releases it to the DH system during times of high demand. In the end, this heat is piped to the building complex seen at the bottom right, where it provides heating

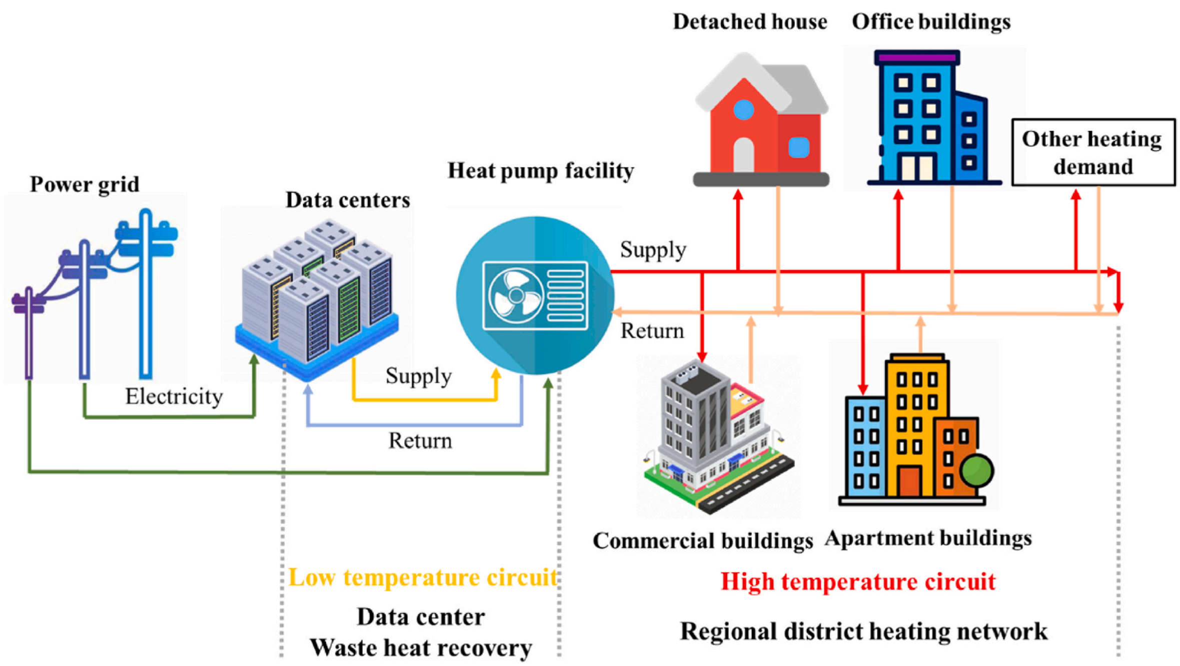

Fig. 6. Connection between waste heat recovered from DCs to the DH networks [15].

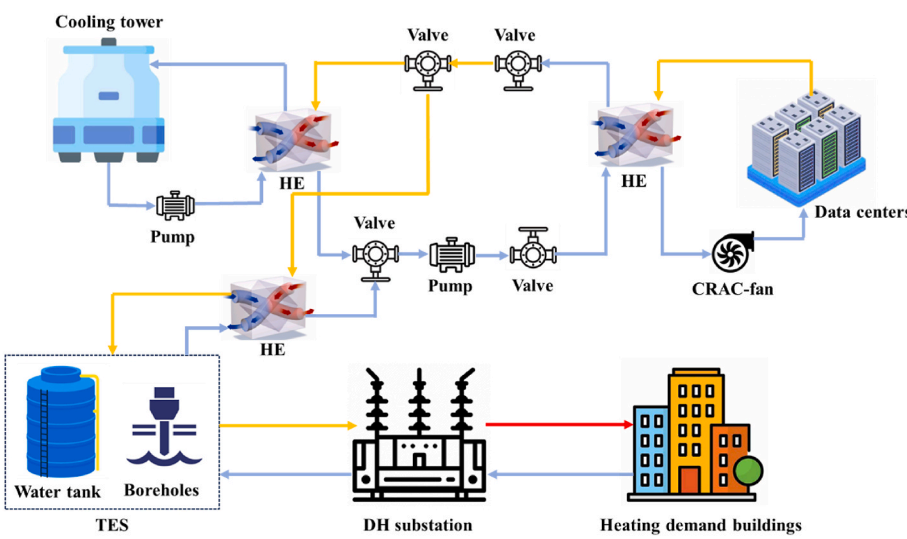

Fig. 7. Connection between waste heat recovered from DCs to the DH networks with TES [64].

services. The system efficiently tackles the mismatch between waste heat availability from the DC and the heat demand of buildings by integrating HPs with thermal energy storage to optimize heat delivery. This lessens dependency on conventional heating sources and increases overall energy efficiency.

2.5. E analytical framework

The classification of studies in this paper is based on a 3E (energy–economic–environmental) framework. Energy analysis refers to assessments of system efficiency, energy savings, and thermal performance. Economic analysis evaluates capital and operational expenditures, payback period, or levelized cost of energy (LCOE). Environmental analysis focuses on emissions reduction, fossil fuel displacement, and carbon mitigation potential. Studies were assigned based on their stated analytical goals and quantitative outputs.

3. Application and outcomes of DC WHR in DH

Researchers have highlighted the potential of using waste heat from DC for DH systems, as DCs generate significant heat due to their continuous operation [56]. This aligns well with the low-grade heat needs of DH systems, sparking increased research on the technological, financial, and environmental benefits of DC WHR in DH.

[56].

Oró et al. [53] explored the potential of WHR solutions in air-cooled DCs to improve the energy efficiency and flexibility of DH networks. They focused on two cooling methods: CRAHs with chiller and with rear door cooling technology. Two types of waste heat sources were considered, namely waste heat from the hot aisle using a water-to-air heat exchanger, and waste heat from the chiller condenser using a water-to-refrigerant heat exchanger. A commercial heat pump (HP) was used to raise the waste heat temperatures to the required 90 °C for DH networks. Their analysis, based on DCs with a 1 MW capacity in

Barcelona, Spain, showed that WHR is generally not feasible for most traditional air-cooled DCs. Nonetheless, WHR may become financially feasible with specific air-side cooling configurations, particularly rear door cooling. They also highlighted that HPs were essential for increasing the operational temperature of waste heat to meet the high-temperature demands of medium and high-temperature DH networks. Although they are negative about the use of WHR from air-side cooled DC for DH systems, their research may only be applicable to southern European countries like Spain, given that the heating needs in Spain are low and the DH network is in the early stages of development. By "negative," it is meant that the Oró et al. [36] study found waste heat recovery from air-cooled data centers to be financially unfeasible for most traditional configurations due to high investment and operational costs, though certain configurations like rear door cooling were identified as potentially more viable. In addition, they also acknowledge that other forms of cooling (e.g., rear door cooling) can bring benefits to the use of WHR from DCs for DH systems.

Most of the existing research indicates that while the potential benefits of integrating DC WHR into DH systems are promising, there are also challenges. Lund et al. [10] highlighted that liquid-based cooling systems can capture waste heat at temperatures between 50 and 60 °C, which aligns with current DH applications. However, incorporating DC waste heat into DH systems carries risks due to the operational disparities between the fast-paced DC industry and the long-term stability needed by DH networks. DCs, driven by rapid technological advancements and market demands, typically have shorter planning cycles, whereas DH systems have life spans of 40–50 years. This discrepancy calls for strategic risk management and contractual agreements, akin to portfolio diversification, to reduce dependencies and ensure a consistent heat supply [66].

3.1. Europe application

The application of WHR from DCs in DH systems has been implemented in many countries, and its feasibility in terms of energy, economy and environment has been proven in actual projects. Abdurafikov et al. [41] explored and compared the effects of various heating energy scenarios on energy consumption and emissions in a typical district-heated area in Finland. Their analysis coverd a 20-year period (2015–2035), considering the expected evolution of building stocks. They included waste heat from DCs as one of the scenarios, specifically focusing on exhaust air. This system was integrated into the DH network in the 10th year. Their findings show that the WHR scenario could reduce centralized heat production by 32 % and cut carbon emissions by up to 50 % annually, even with only a 20 % share of waste heat in the total supply.

Also, Fortum, which runs the DH network in Espoo, Finland, plans to eliminate coal by 2025 by adopting low-carbon technologies like WHR from DCs, new HPs, and biomass power plants [43]. According to their analysis, Espoo's decarbonization efforts might be greatly aided by a sizable HP that uses the surplus heat from its DCs to meet its heating needs [1]. The Telecity Group also runs a number of DCs, some of which provide waste heat to the DH system for the benefit of several residences and apartments. For example, the Tieto DC in Espoo provides a substantial amount of waste heat to Fortum's network and has received recognition for its environmental efforts [67]. Helsinki, Finland's Helen Energy [44] works with several DCs to recover their waste heat at low temperatures so that it can be utilized in the city's DH system. Using HPs, the waste heat from the DCs is heated up and then sent to the metropolitan heating network. According to Helen Energy, this strategy can heat thousands of city homes annually, lowering the need for conventional energy sources like coal and gas.

One of the first DCs in the world to be carbon-neutral is EcoDataCenter, which is situated in Falun, Sweden [68]. By immediately recovering waste heat from servers and incorporating it into the DH system, it accomplishes this. An air-liquid cooling solution is used by the DC's cooling system to absorb the waste heat produced by the servers. After then, the heat is transported to the DH network, warming the nearby homes and businesses. What makes this system innovative is the combination of utilizing both biomass combustion and waste heat from the DC, reducing carbon emissions and improving overall energy efficiency. In Norway, Green Mountain DC project [45] is launched, which is located near Bergen, Norway, and uses unique cooling technology to cool its DC. The DC is situated in a region with cold seawater circulation. also uses a deep saltwater cooling system to keep the servers cool, and also recovers waste heat that would otherwise be wasted to heat the neighborhood. The DC uses primarily hydropower and other renewable energy sources, which drastically lowers its carbon footprint.

Facebook's DC in Odense, Denmark [46] collaborates with the local DH company to recover waste heat generated by its server operations, providing heating for surrounding communities. The DC employs an advanced heat recovery system that upgrades the temperature of the waste heat to a suitable level and distributes it to residents through the DH network. This marks Facebook's first large-scale attempt at a WHR system, with plans to expand this model to other DCs in the future.

In London, Davies et al. [56] proposed using waste heat from DCs to supply both heating and cooling for a DH network in London. Specifically, the cooling is achieved through absorption chillers or similar technologies that utilize waste heat to generate cooling. They assessed the system's technical, energy, carbon, and cost benefits. Their findings showed that a 3.5 MW DC could lead to reductions of over 4000 tonnes of CO_2 emissions and save nearly £1 million annually. Additionally, without including renewable heat incentive payments, which could provide an extra £0.7 million per year in cost incentives, the system still offers substantial financial and environmental benefits.

3.2. China application

Utilizing advanced technology, Tencent's Tianjin DC [69] in China recovers waste heat from servers and directs it into the neighboring DH system. The project efficiently converts the waste heat from the DC into domestic heating by using a low-temperature WHR technology based on magnetic levitation HPs. Magnetic suspension technology eliminates mechanical friction by using magnetic fields to levitate the compressor shaft, resulting in higher energy efficiency, reduced maintenance, and improved operational stability compared to conventional compressor systems. According to the analysis, all of the office buildings in the park can have their heating needs met by recovering a portion of the DC's heat, which would result in a significant reduction in energy use, carbon dioxide emissions, and heating expenses. This method significantly increases energy efficiency while also reducing reliance on conventional heating energy sources. Furthermore, the Guiyang, Guizhou, China DC [70] recovers waste heat from servers by means of advanced technology and feeds it into the DH system that is located nearby. The project adopts a low-temperature WHR technology based on HPs, effectively converting the DC's waste heat into heating and hot water for residential use. This project showcases the successful application of DC waste heat in Chinese cities, reducing reliance on traditional heating energy sources while improving energy efficiency.

Table 3 shows the energy, economic and environmental potentials of the practical operating projects using DC WHR into the DH networks, and each project can provide heating for thousands of households, with annual energy savings ranging from 15 GWh to 100 GWh, while heat recovery from DCs can effectively reduce the energy costs for DH systems, with cost savings typically between 20 % and 40 %. The CO_2 emission reductions reported in Table 3 were sourced from various DCs that have implemented WHR systems. However, the methodologies used to calculate these reductions are not consistently provided in the references. As such, the CO_2 numbers cannot be directly compared across the cases, and we advise caution when interpreting these values, as the differences in calculation methods are not known. The majority of cases have achieved a COP value between 3.2 and 5.0, which is higher than

Table 3
Summary of energy, economic and environmental benefits of the practical operating projects using DC WHR into the DH networks.

Project name	Location	Year	Source	Energy saving	Energy cost saving	CO_2 emission reduction
EcoDataCenter	Falun, Sweden	2019	[68]	85 % reduction of heating demand from DH network	40 % of DH	5000 tons (Annual emissions of 1000 passenger cars)
HelenDataCenter	Helsinki, Finland	2020	[44]	100 GWh annual heat is recovered to warm 25 000 homes.	€ 2.5 million of DH	10 000 tons (Annual emissions of 2000 passenger cars)
FortumDataCenter	Espoo, Finland	2023	[43]	30 GWh of waste heat is recovered to warm 500 single houses and 4500 block apartments	N/A	N/A
Green Mountain	Oslo, Norway	2021	[45]	30 GWh annual heat is recovered	N/A	8000 tons (Annual emissions of 1600 passenger cars)
FacebookDataCenter	Odense, Denmark	2020	[46]	100 GWh annual waste heat is recovered to warm 6900 homes	-€ 20 million of energy −15-25 % of total energy	−15 000 tons (Annual emissions of 3000 passenger cars) −10-20 % total carbon emission
GuiyangDataCenter	Guiyang, China	2021	[70]	15 GWh annual heat is recovered to warm 5000 homes.	30 % of DH	5500 tons (Annual emissions of 1100 passenger cars)
LondonDataCenter	London, UK	2016	[56]	N/A	£ 1 million of energy	Over 4000 tons annual reduction in a 3.5 MW DC (Annual emissions of 800 passenger cars)
TencentDataCenter	Tianjin, China	2020	[69]	– 28.5 % reduction of heating demand from DH network - Warm 5100 homes	€ 2.5 million of DH (fully recovered)	160 000 tons (Annual emissions of 32 000 passenger cars)

Notations: DH = District heating; DC = Data center.

the typical COP range of 3–4 for conventional heat pumps. This indicates a significant improvement in energy utilization efficiency, owing to the combined use of WHR technology and optimized cooling technologies. Additionally, each case helps to reduce carbon dioxide emissions by thousands of tons annually, resulting in a collective reduction of tens of thousands of tons of CO2 per year, which improves the city's environmental profile and supports sustainable development. These quantitative findings not only validate the viability and financial advantages of this technology in real-world applications, but also show the significant potential of DC heat recovery in raising energy efficiency and lowering carbon emissions.

4. Integration and optimization of the WHR system

Based on the above-mentioned, the practical application of DC WHR into DH systems has already been implemented in various actual projects, which contributes to positive results. These projects demonstrate significant benefits in terms of energy efficiency, cost savings, and environmental impact. As a result, more researchers have turned their attention to this field, exploring ways to optimize and enhance its potential.

At the research level, several scholars have proposed technical solutions to improve the performance and scalability of DC WHR for DH integration. For example, Wahlroos et al. [48] explored the use of heat pumps and TES to address supply-demand mismatch in low-temperature DH networks. Hou et al. [71] developed a model predictive control framework to reduce energy costs and stabilize heat delivery from DCs. Similarly, Li et al. [72] evaluated short-term and seasonal TES solutions to improve system flexibility and reduce peak loads, while Du et al. [73] applied data-driven optimization to enhance real-time system performance. Collectively, these advancements contribute to making DC WHR more efficient, scalable, and better suited for integration into next-generation urban energy systems.

4.1. Technological advances and system optimization

To enhance the efficiency of DC WHR in DH networks, many scholars have concentrated on applying high-efficiency HPs, TES systems, and AI-based smart control strategies, which are considered advanced technologies due to their ability to significantly optimize energy recovery, reduce operational costs, and improve system adaptability under varying thermal loads [71,72,74]. By leveraging these cutting-edge advancements, researchers aim to significantly improve the overall performance and sustainability of WHR systems.

He et al. [75] integrated a distributed cooling system and a HP into a real DC in China to improve the temperature level and temporal stability of the waste heatt. Their study showed that about 10 % of the annual power consumption could be reduced through WHR from the DC to the DH networks. They found a Power Usage Effectiveness (PUE) as low as 1.13, indicating high energy efficiency in the DC. PUE, defined as the ratio of total facility energy use to IT equipment energy use, reflects how efficiently a data center operates. A lower PUE means more energy is used for computing rather than for cooling or other support systems [76]. Additionally, this integration could result in an annual savings of over 18 000 tons of coal for the DH network and 10 % power demand. By efficiently utilizing the waste heat from the DC, the study highlighted significant potential for energy savings, underscoring the importance of WHR systems in improving the sustainability of energy networks. Huang et al. [74] suggested a novel WHR system for DCs that made use of heat pipes and a three-fluid heat exchanger in addition to other technological advances. Additionally, they included a TES tank for heat storage. There were three modes of operation for the system: mechanical cooling, heat pipe, and heat recovery. In heat recovery mode at a heating water temperature of 50 °C, the system achieved an energy efficiency ratio of 4.5, defined as the ratio of useful thermal output to total electrical input. This system can capture around 9.5 MWh of heat from a 5 kW DC, which is sufficient to meet the heating requirements of a 60 m^2 residential room in Tianjin, China.

Furthermore, AI-based techniques (such as performance analysis and smart control strategies) can offer useful instruments for optimizing waste heat integration into distributed heating networks, as well as lower energy usage and better system performance overall. Hou et al. [71] explored optimal control strategies for DH systems that recover waste heat from DCs, specifically focusing on DC waste heat-based heat prosumers and TES. Their proposed model predictive control framework can ensure stable chilled water for DC cooling and reduce monthly energy costs by 3.2 %. To identify performance patterns in a shared energy recovery system, Du et al. [73] suggested using data mining. Their findings demonstrated that, with an instantaneous WHR rate of 572.9 kW, a waste heat temperature of 57.2 °C, and an HP coefficient of performance of 2.0, optimal performance happened during 34 % of the operating period. The analysis also showed how the temperature of the DH substation supply water and the outside air have an impact on system performance, showing that even while the shared energy recovery system creates variations in the amount of heat supplied, it may still cut energy usage.

4.2. Energy and economic impacts

In addition to improving the energy efficiency of DH systems, DC WHR can have a significant positive financial impact. As noted by Hou et al. [71], WHR offers operators significant long-term cost benefits by lowering DC cooling expenses and reducing dependency on conventional energy sources.

As Petrovic et al. [77] noted, this economic benefit is further enhanced when connected with Denmark's energy system. They examined the possible place of DCs in Denmark's future energy system and evaluated the potential effects on the energy industry of using the waste heat from these DCs. According to their conclusions, DCs might have a big influence on Denmark's DH and electricity industries. More specifically, an estimated 3 GW of additional offshore wind capacity may be needed to support the increased electricity demand from expanding data center operations in Denmark. However, the waste heat recovered from these DCs could supply between 4 % and 27 % of the national DH demand after 2040, significantly reducing the reliance on fossil fuels or other expensive heating sources [77]. This dual role, increased electricity consumption paired with valuable heat recovery, represents a system-level efficiency gain, where part of the investment in renewable electricity is offset by lower heating costs and reduced carbon emissions. Thus, despite the need for additional generation capacity, the integration of DC waste heat into DH networks contributes positively to both the economic and environmental performance of the national energy system.

Building on this foundation, Keskin and Soykan [78] introduced a comprehensive approach to managing energy costs in DCs by integrating combined cooling, heating, and power (CCHP) systems with a WHR setup for both cooling and power supply, as well as DH networks. They applied mixed integer linear programming to determine optimal operational strategies for the system. They found this integrated system could cut annual energy costs of the CCHP system by 40.3 %, with a payback period of approximate 6.6 years.

By optimizing WHR for high-performance computing facilities utilizing cutting-edge cooling techniques (such as liquid-side and phase-change cooling), Ljungdahl et al. [79] increased our grasp of this topic. By taking into consideration a number of factors, including coolant and DH supply temperatures as well as DH load coverage, the model aimed to optimize WHR systems. Greater DH load coverage was made possible by the system's ability to run at higher temperatures (50–60 °C) and store excess waste heat for seasonal usage with the integration of liquid coolant and latent TES. The model produced annual electricity savings of 8.14–10.8 % by reducing the electricity consumption of cooling systems, a WHR potential of 85–576 MWh annually, and operational cost savings of 8–18 % in a Danish DC case study.

Wahlroos et al. [66] also focused on optimization, using HPs to recover waste heat from DCs into DH networks and TES units to store excess heat To balance the time mismatch between heat supply and demand. They examined the system's potential and energy efficiency for low-temperature distributed heating networks. According to their research, WHR can save energy costs at the operational level by 0.6–7.3 % and shorten the time that heat-only boilers and CHP plants must run. Furthermore, the waste heat could be used during 95–99 % of operational hours, regardless of electricity prices, and in high electricity price conditions, it could achieve a 12.2 % reduction in total production costs.

And Khosravi et al. [18] further illustrated the potential of WHR by integrating DCs with 5G smart poles, which are multifunctional streetlight poles equipped with 5G antennas and other technologies, and proposed a WHR system utilizing heat from a DC and 5G smart poles for a low-temperature DH network in Espoo, Finland. They compared this system with HPs and heat-only boilers. Their findings revealed that the proposed system generated an average of 2.16 MWh of heat annually, which covered about 38.8 % of the area's heating demand when HPs were used, and 30.25 % from the DC and 8.55 % from the 5G smart poles. Without the use of HPs, the heat recovery share from these sources would be only 9 %. The study also found that the LCOE for the HP and WHR system was significantly lower compared to the heat-only boiler scenarios.

4.3. Energy and environmental impacts

Apart from the advantages of enhancing energy efficiency via DC WHR, more and more scientists are examining its effect on carbon emissions and researching methods to improve the total environmental impact that the DC WHR to DH networks causes. Studies reveal that when more DCs incorporate waste heat into DH systems, the strategy not only increases the effectiveness of energy consumption but also dramatically lowers greenhouse gas emissions. The benefits of using low-carbon energy efficiency technologies in DCs in Ireland were assessed by Coyne et al. [80] from the perspectives of energy and carbon emissions. According to their calculations, implementing these technologies might result in a 26 % decrease in the industry's energy use and produce 12.40 TWh of hot water for a 4GDH network. Furthermore, technology implementation could lower the demand for renewable electricity generation by 6.92 % and reduce total system emissions by 3 %. These findings highlight the substantial benefits that technology adoption can bring to both private and public stakeholders.

While Oltmanns et al. [81] proposed a direct hot-water (45 °C) cooling system that used the waste heat for DH networks or directly for nearby buildings. Waste heat was recovered by both HPs and TES, achieving a waste heat utilization rate of 20–50 % depending on the specific heat use. Additionally, the proposed system could reduce annual CO_2 emissions by up to 720 tons, accounting for approximately 4 % of the total carbon emissions at the university campus.

4.4. Energy, economic and environmental impacts

As more researchers explore the application of WHR from DCs in DH systems, their analysis is becoming increasingly comprehensive. This includes not only technological and performance improvements but also considerations of energy efficiency, energy costs, and environmental issues related to carbon emissions. By examining these various aspects in depth, researchers aim to thoroughly assess the potential of this technology and explore its benefits in enhancing overall energy management and reducing energy costs and environmental impact.

Adamski et al. [82] examined the reuse of waste heat from DCs at a university campus connected to DH networks. Their case study revealed that heat reuse efficiency was capped at 89.5 %. Simulations of an expanded DC infrastructure predicted a 58 % reduction in carbon emissions compared to those of nearby buildings, with a current capacity reduction of 23 %. These reductions also resulted in significant cost savings, with annual savings of approximately €450,000. With an initial capital investment of €3 million, the Return on Investment was estimated at 6.7 years. Furthermore, the study suggested that efficiency and energy use could be enhanced by utilizing high-temperature coolant directly.

Continuously, Li et al. [83] developed a new WHR system using CO_2 transcritical HPs for integrating DC waste heat into DH networks. They assessed the system's performance in terms of technical aspects, energy efficiency, costs, and carbon emissions. Their study found that using waste heat from cooling water in IT rooms improves performance compared to using heat from chillers, with an 18.2 %–28.9 % increase in the COP and a 4.2 %–10.2 % reduction in system investment costs. The choice between using an internal heat exchanger or a simple cycle depends on electricity and heat prices. The system can lower energy costs by 23.0 %–75.0 % compared to traditional methods and reduce CO_2 emissions by 12 880 tons annually compared to gas heating. Additionally, the energy efficiency of the DC improves, with the annual energy reuse effectiveness dropping from 1.296 to 0.902 over 121 heating days, i.e., the ratio of reused waste heat to total energy consumption during the heating season, where a lower value indicates better waste heat utilization.

Furthermore, Li et al. [72] argued that although utilizing waste heat from DCs in DH systems is feasible, its potential was limited by the mismatch between heat supply from DCs and heat demand in DH systems. Moreover, the high peak loads in DH systems can significantly impact operational costs as they require supplementary heat sources beyond the stable waste heat supply from DCs, increasing overall costs. To mitigate this, they recommended using both short-term (e.g., water tanks) and long-term (e.g., borehole) TES to balance the mismatch. They evaluated the integration of TES into DH networks using energy, economic, and environmental (3E) analysis and found that the water tank could shave 31 % of the peak load, saving 5 % of energy costs annually, with a payback period below 15 years at storage efficiencies above 80 %. Furthermore, borehole TES achieved a WHR rate of up to 96 %, resulting in an annual CO_2 emission reduction of 8 %, though the payback period exceeded 17 years for long-term TES.

In summary, as the demand for more sustainable and efficient energy solutions grows, the integration of DC WHR into DH systems has emerged as a promising approach. This integration not only aims to optimize energy use but also addresses critical challenges associated

Table 4
Summary of research on DC WHR in DH networks from energy, economic and environmental perspectives.

Reference	Cooling method	Analysis aspects			HP	TES	Region	Results
		En.	Em.	Ec.				
He et al. [75]	Air-side (CRACs)	☆	–	–	☆	–	China	– Reduces coal consumption by 18 000 tons each year – Attains a 10 % yearly energy savings
Huang et al. [74]	Air-side	☆	–	–	☆	–Hot water tank	China	– Achieves an energy efficiency ratio of 4.5 with 50 °C heating water – Recovers 9.5 MWh of heat from a 5 kW DC to meet the heating needs of a 60 m^2 residential room.
Hou et al. [71]	All applicable	☆	☆	–	☆	-Short-term hot water tank	Norway	– Monthly reduce energy cost by 3.2 %
Du et al. [73]	All applicable	☆	–	–	☆	–	Australia	– The average COP of HP is 2.2 – Reduces DH energy use by 35 % during heating seasons – Cuts DH energy consumption by 50 % during non-heating seasons
Petrovic et al. [77]	Air-side (CRAHs)	☆	☆	–	☆	–	Denmark	– Cover 4 % and 27 % of DH heating demand – Reduce the DH price by1–2 %
Keskin and Soykan [78]	Air-side (CRAHs)	☆	☆	–	☆	–Battery storage	Turkey	– Reduces the annual energy cost of CCHP system by 40.3 % – The payback period is 6.6 years
Ljungdahl et al. [79]	–Liquid-cooling –Phase change cooling	☆	☆	–	☆	–Latent TES	Denmark	– Accommodates larger DH loads – Achieves operational cost savings ranging from 8 % to 18 %
Wahlroos et al. [66]	– Air-side (CRACs)	☆	☆	–	☆	–Hot water tank	Finland	– Achieves up to 7.3 % in energy cost savings – The WHR system operates 95–99 % of the time, independent of electricity prices – Reduce total production costs by 12.2 % during periods of high electricity prices
Khosravi et al. [18]	All applicable	☆	☆	–	☆	–	Finland	– Cover 30.25 % of DH energy use – LCOE is 3.192 ¢/kWh
Abdurafikov et al. [41]	Air-cooled	☆	–	☆	☆	–	Finland	– Lower annual energy production by 32 % – Reduce carbon emissions by up to 50 % when waste heat contributes only 20 % to the energy supply
Coyne et al. [80]	All applicable	☆	–	☆	☆	–Hot water tank –Electricity storage	Ireland	- Achieve a 26 % decrease in energy consumption - Produce 12.40 TWh of hot water – Decrease the renewable electricity generation requirements by 6.92 % – Lower total system emissions by 3 %
Oltmanns et al. [81]	–How-water cooling	☆	–	☆	☆	–Buffer tank	Germany	– Achieve a waste heat utilization rate of 20–50 %, depending on heating or DH uses. – Reduce CO_2 emissions by 720 tons, which accounts for approximately 4 % of the campus's total emissions.
Adamski et al. [82]	All applicable	☆	☆	☆	☆	–	Poland	– Achieve a heat reuse efficiency of 89.5 %. – Reduce carbon emissions by 58 %. – Reduce capacity by 23 %. – Save approximately €450,000 in annual energy costs. – With an initial capital investment of €3 million, the estimated Return on Investment was 6.7 years.
Li et al. [83]	Air-side (CRACs & CRAHs)	☆	☆	☆	☆	–	China	– Increase in COP by 18.2 %–28.9 % – Reduction in system investment costs by 4.2 %–10.2 % – Lower energy costs by 23.0 %–75.0 % – Reduce annual CO_2 emissions by 12 880 tons – Drop in annual ERE from 1.296 to 0.902 over 121 heating days
Li et al. [72]	All applicable	☆	☆	☆	☆	–Water tank –Borehole TES	Norway	For the water tank: – Reduce peak load by 31 %, – Save 5 % of annual energy costs - Payback period of less than 15 years For borehole TES: – Achieve a WHR rate of up to 96 % – An 8 % reduction of CO_2 emissions - Payback period of less than 17 years

Notations: DC = Data center; HP=Heat pump; TES=Thermal energy storage; DH = District heating; COP=Coefficient of performance; LCOE = Levelized cost of energy; CCHP=Combined cooling, heating and power; En. = Energy; Em. = Environmental; Ec. = Economic; ERE = energy reuse effectiveness.
The studies listed are based on differing data sources and modeling assumptions, and are therefore not strictly comparable. Storage types are labelled according to function. "Buffer tank" and "water tank" are jointly referred to as thermal storage tanks in this table.

with energy management and environmental impact. Table 4 summarize the current research on DC WHR in DH networks from energy, economic and environmental perspectives. Understanding the intricacies of this process, ranging from technological adaptation to energy, economic and environmental considerations, is essential for evaluating its effectiveness.

The application of DC WHR in DH systems offers significant economic and environmental benefits. In the optimization of DC WHR within DH systems, technologies (e.g., HPs, energy storage devices, and demand response) play a positive role, which significantly enhance energy efficiency, reduce energy costs, and mitigate the environmental impact related to carbon emissions. Their integration contributes to more effective and sustainable energy management, demonstrating substantial benefits across various aspects of energy use and environmental protection.

5. Discussion

Integrating DC WHR into DH networks is a promising approach for enhancing energy efficiency, reducing carbon emissions, and supporting sustainable development. Significant amounts of waste heat are produced by the DCs, especially with the rapid expansion of high-density DCs driven by increasing demand for artificial intelligence, big data, and IoT. The cooling systems in modern DCs (e.g., air-cooling, liquid-cooling, and two-phase cooling) offer diverse waste heat sources. Among these, liquid-cooling systems produce higher temperature waste heat, while air-side cooling produce numerous waste heat, both making them ideal for recovery. This discussion focuses on evaluating the feasibility, challenges, and future prospects of this integration from 3Eperspectives.

Integration with low-temperature DH systems, especially 4GDH and5GDH networks, is key to achieving energy efficiency. These low-temperature systems reduce heat loss, making WHR more economically viable as lower heat losses mean more recovered waste heat is effectively utilized, reducing operational costs and improving overall system efficiency. The use of HP further boosts the usability of low-temperature waste heat by upgrading it to the temperature levels required for DH systems. This approach has already been implemented in several countries, proving its technical feasibility.

5.1. Energy perspective

The energy potential of DC WHR is significant, primarily due to the continuous and reliable nature of waste heat generated by DCs. DCs operate 24/24 h, 365 days/year, consuming vast amounts of electricity and consequently producing a substantial amount of low-grade waste heat [23]. As highlighted in the introduction, approximately 30–50 % of the electricity consumed by DCs is converted into heat, providing an enormous opportunity for recovery and reuse [26]. The lower supply temperatures required by 4GDH and 5GDH make it technically feasible to integrate this waste heat, especially when coupled with HP technology [9,45]. HPs can efficiently upgrade the low-grade waste heat from DCs to meet the temperature requirements of DH systems [15,46,58], as demonstrated by multiple case studies across Europe and China [1,62,64].

However, the efficiency of WHR depends on several factors, including the type of cooling system used in DCs, the proximity of the DC to the DH network, and the operational characteristics of both the DC and the DH system. For instance, liquid-side cooling systems, though less commonly used than air-side cooling, generate higher temperature waste heat (50–60 °C), which is more suitable for direct use in DH networks [15,34,41]. The use of HPs is essential for upgrading the lower temperature waste heat (15–50 °C) generated by air-side cooling systems, which dominate the market [15,46,58].

The adoption of advanced technologies such as heat exchangers, thermal energy storage (TES), and smart control systems can further optimize the integration of DC WHR into DH networks [64,65,71]. TES, in particular, plays a crucial role in balancing the mismatch between heat supply and demand, thereby improving the overall efficiency of the system. As demonstrated in existing studies, TES can store excess heat generated during low-demand periods and release it when demand is high, ensuring a stable and efficient heat supply [64,72].

5.2. Economic perspective

From an economic standpoint, the integration of DC WHR into DH networks offers considerable cost-saving opportunities. The reuse of waste heat not only reduces the need for additional heat production but also lowers operating costs for DCs and DH operators. For DCs, the reduction in cooling requirements translates to lower electricity consumption and operational costs. For DH operators, the availability of a reliable and continuous heat source can reduce dependency on fossil fuels and other expensive heat sources.

Several studies have highlighted the economic benefits of DC WHR, with payback periods ranging from 6 to 15 years, depending on the specific setup and local energy prices [72,78,82]. For instance, the integration of WHR systems in Espoo, Finland, has shown that using a 100 MW HP can meet up to 32 % of the city's heating demand, significantly contributing to the decarbonization efforts of the DH network [1,18,43]. Similarly, in Tianjin, China, certain air-side cooling setups have been found to make WHR economically viable, especially when combined with HPs to meet the high-temperature demands of medium and high-temperature DH networks [69].

However, the economic feasibility of DC WHR is influenced by several factors, including the initial capital investment, operational and maintenance costs, and the availability of government incentives or subsidies, as well as factors such as heat demand fluctuations, distance to heat consumers, efficiency of integration technologies, and prevailing energy prices [64,65]. The initial investment in HPs, TES, and other required infrastructure can be substantial, making the financial viability of such projects dependent on the availability of supportive policies and market conditions [1,67,77]. Additionally, the operational differences between the rapidly evolving DC industry and the long-term stability required by DH infrastructures pose a challenge in terms of contractual agreements and risk management [53].

5.3. Environmental perspective

The environmental benefits of integrating DC WHR into DH networks are substantial, particularly in terms of reducing carbon emissions and enhancing energy efficiency. By recovering and reusing waste heat, the overall carbon footprint of both DCs and DH systems can be significantly reduced. This is especially relevant in the context of increasing global energy consumption and the urgent need to mitigate climate change.

Studies have shown that WHR can lead to substantial reductions in carbon emissions. For example, the reuse of waste heat from a DC in London was estimated to reduce CO_2 emissions by over 4000 tonnes annually [44], while similar projects in Finland and Denmark have reported reductions of up to 50 % [41]. The integration of DC WHR into DH networks also supports the transition towards low-carbon and renewable energy systems, as it reduces the need for fossil fuel-based heat production [55,58,61].

Moreover, the environmental benefits extend beyond carbon reduction. The recovery of waste heat can also alleviate thermal pollution in the surrounding environment and reduce the cooling demands of DCs, further lowering their environmental impact [15]. The implementation of WHR technologies aligns with the goals of sustainable development, promoting the efficient use of resources and the reduction of waste [15,49,50].

However, the environmental impact of DC WHR is also influenced by the efficiency of the recovery process and the sustainability of the HP technology used. The use of high-efficiency HPs, smart control systems, and TES can maximize the environmental benefits by ensuring that the waste heat is recovered and used in the most effective manner [71,72,74]. Additionally, the integration of renewable energy sources into the DH network can further enhance the sustainability of the system [12].

5.4. Challenges and future prospects

While the potential benefits of DC WHR are clear, several challenges must be addressed to realize its full potential. These include technical challenges related to the integration of WHR systems with existing DH networks, economic challenges related to the initial investment and operational costs, and environmental challenges related to the sustainability of the recovery process.

One potential technical challenge is the temporal mismatch between the relatively constant heat supply from DCs and the fluctuating heat demand in DH systems. While this mismatch is not always significant, particularly when DC WHR represents a small fraction of the total heat supply, it can become a limiting factor in high-integration scenarios or during seasonal load variations [1]. This challenge can be mitigated through the use of TES, advanced control systems, and scalable HP solutions that adapt to changing demand levels [71].

Economic challenges include the need for substantial initial investment in WHR infrastructure and the uncertainty related to the long-term stability of DC operations [13,71,72]. Government incentives, subsidies, and supportive policies can play a crucial role in overcoming these challenges by making WHR projects more financially viable.

From an environmental perspective, the main challenge is ensuring that the recovery process is as sustainable as possible. This requires the use of high-efficiency technologies, the integration of renewable energy sources, and the careful management of resources to minimize waste and reduce the overall environmental impact [13,72,74].

Looking ahead, the future of DC WHR holds great potential, especially in the context of rising energy demand and the global push toward decarbonization [13,18,19]. With the introduction of smart control systems, TES technologies, and innovative heating models, WHR technology is expected to be further optimized. The low-temperature operation and decentralized design of 5GDH systems enable the integration of diverse low-grade heat sources (e.g., data centers and ambient geothermal) offering greater source-side and spatial flexibility [8,12,13]. However, this can reduce access to centralized thermal storage, potentially limiting demand-side flexibility [13]. In both 4GDH and 5GDH, advanced control systems and data-driven optimization technologies, including smart sensors, predictive algorithms, and automated control, play an important role in improving efficiency and responsiveness. These tools enhance the intelligent operation of modern DH systems, regardless of generation [71,72,74]. Moreover, with government policy support and advancements in industry technology, the integration of DC waste heat into DH networks is likely to become standard practice in many regions, particularly in Europe [29–33]. Additionally, future DC developments will further enhance WHR potential. Trends such as the adoption of high-efficiency liquid cooling, AI-driven heat management, and modular DC designs will improve waste heat quality and utilization [15,41,64]. The increasing demand for edge computing and decentralized DCs may also create new opportunities for localized WHR applications [13,18], reducing transmission losses and enabling more efficient heat reuse. WHR is expected to see broader global adoption, not only improving the energy efficiency of DCs and DH systems but also contributing to global efforts to combat climate change and promote sustainable development [24,27,28].

6. Conclusion

This study highlights the significant potential of DC WHR to enhance DH networks from technical, energy, economic, and environmental standpoints. The key findings are as follows.

1. Technical feasibility: Integrating DC WHR with low-temperature DH systems, especially 4th and 5th generations of DH, is technically viable. Heat pumps (HP) effectively upgrade low-grade waste heat for DH use, while liquid-cooled systems, though less common, offer higher-temperature waste heat suitable for direct DH integration.
2. Energy efficiency: DCs operate continuously, providing a stable source of waste heat. WHR can greatly improve DH energy efficiency and reduce reliance on primary energy sources. Technologies like thermal energy storage (TES) further optimize the balance between heat supply and demand.
3. Economic viability: WHR offers cost-saving potential for both DCs and DH operators by lowering cooling demands and reducing fossil fuel dependence. Payback periods typically range from 6 to 15 years, with financial viability strengthened by government incentives.
4. Environmental impact: Integrating WHR into DH systems significantly reduces carbon emissions and supports decarbonization efforts. By using waste heat that would otherwise be lost, WHR helps transition DH networks to low-carbon energy sources.
5. Challenges and future prospects: Key challenges include technical mismatches between heat supply and demand, high initial investment costs, and the need for stable, long-term operation. Additionally, the evolution of DC infrastructure, including improved cooling technologies and AI-driven energy management, will further enhance WHR feasibility and efficiency, enabling more widespread application across different geographic regions and heating systems.

In conclusion, DC WHR presents a valuable opportunity to boost energy efficiency, reduce environmental impact, and support sustainable development in heating systems. Challenges can be addressed through technological innovation and policy support, making DC WHR a critical part of future energy systems.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xiaolei Yuan reports financial support was provided by Business Finland. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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