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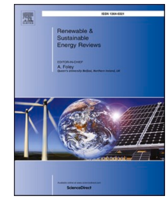

Waste heat recoveries in data centers: A review

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ABSTRACT

Data centers (DCs) uninterruptedly run 24/24 h, 365 days per year with much huge operating scale, and have the characteristics of high operation safety requirement, high heat flux density, high energy consumption and high carbon emission. They are influential energy consumers and carbon emitters in building or even global energy sectors (around 3% of global energy consumption), who are also significant waste heat producer (e.g., waste heat from year-round uninterrupted operation of IT equipment and cooling system). Huge energy consumption has increased the burden on the global energy industry, while carbon and direct waste heat emissions have also caused great damages to the outdoor environment. Thus, it is critical to improve the energy efficiency in DCs and to realize the energy conservations and environmental deterioration alleviation. Waste heat recovery technology is considered as a promising approach to improve energy efficiency, achieve energy and energy cost savings, and mitigate environmental impacts (caused by both carbon emission and waste heat discharge) at the same time. This article conducts a comprehensive review on recovering waste heat from all kind of sources (e.g., exhaust air, circulating water, and coolants) in DCs for various energy uses (e.g., heating supply, district heating supplement, cooling and electricity productions, and industrial/agricultural production process) and different application scenarios (e.g., office buildings, comprehensive energy community and residential buildings), while the future research and development proposals for DC waste heat recoveries are given through technical, energy, environmental and economic analysis.

1. Introduction

Information technologies (e.g., artificial intelligence, 5G and cloud computing) have underwent an explosive development in recent years, which emphasized the importance and high-demand and high-performance in data centers (DCs). DCs are data and energy & carbon-intensive facilities, which are comprised of not only computing and other supporting systems (e.g., storage and communication systems), but also redundant security systems (e.g., data communication connections, monitoring system, environmental control units, and security devices) [1]. As centralized repositories, DCs are required to achieve data collection, data storage, data processing, and data transmitting and exchange, whose goal is to achieve a safe, stable, efficient, and uninterrupted network environment and services [2]. The importance of DCs cannot be overemphasized, and they play a paramount role in every aspect of our lives.

DCs have the characteristics of 24/24 h, 365 days/year and globally very large scale, which annually cause much high energy use [3]. According to the statistics in 2019, DCs were responsible for approximately 3% of the electricity consumption and almost 4% greenhouse gas emissions globally [4]. It is predicted that the global energy demand for information and communication technology (ICT) things (e.g., data processing, exchange and storage, blockchain, and crypto mining) would take responsibility of around 23% of the total by 2030 [5], while the ICT-related carbon emission will explore to approximately 14% of the world total [6]. Therefore, it is paramount to improve the energy efficiency, and reduce the energy consumption in and for DCs [7].

In a typical DC, IT equipment (e.g., servers) are the biggest electricity consumers accounting for around 44% of total electricity use and are followed by the cooling system of 40% [8]. Therefore, not only the air conditioning system ensures the safe operation of the DCs, but also it greatly affects the energy consumption within the DCs [9]. To reduce DCs' energy consumption while ensuring their safe operation, two types

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Nomenclature

Abbreviations

ABC	Absorption cooling
ADC	Adsorption cooling
AHP	Absorption heat pump
CCHP	Combined cooling, heating and power
CHP	Combined heat and power
COP	Coefficient of performance
CRAC	Computer room air conditioning
CRAH	Computer room air handling
DC	Data center
DCMs	Data center microgrids
DeST	Design's Simulation Toolkit
DH	District heating
EGS	Enhanced geothermal system
GSHP	Ground source heat pump
GUI	Graphical user interface
HP	Heat pump
HPA-ORC	Heat pump assisted Organic Rankine cycle
HVAC	Heating, ventilating and air-conditioning
ICT	Information and communication technology
IDA ICE	IDA Indoor Climate and Energy
$LiBr–H_2O$	Lithium bromide-water
MURBs	Multi-unit residential buildings
NPV	Net present value
ORC	Organic Rankine cycle
PUE	Powe usage effectiveness
SH	Swimming Hall
TES	Thermal energy storage
WHR	Waste heat recovery
3 E	Energy, exergy and environmental
4 E	Energy, exergy, environmental and economic

of actions can be taken, which are to address IT load inefficiencies and to improve the cooling efficiency [10]. Enhanced semiconductor and server virtualisation was reported to effectively improve the operation efficiency of IT equipment and could reduce the corresponding electricity use [11], while enhancing the cooling efficiency is the research focus for HVAC researchers, which has been intensively investigated (e.g., airflow management, free cooling, evaporative cooling, renewable energy application) [12,13]. Cooling system optimization is mainly divided into two categories, namely cooling sources that can replace or supplement the cooling supply from conventional air conditioning system (e.g., air-side free cooling, water side free cooling, phase change cooling, and evaporative cooling) [14], and energy efficiency improvements (e.g., airflow management and waste heat recoveries, cooling equipment optimization) [15].

Due to the characteristics of the year-round uninterrupted, high-energy consumption, high heat flux density operating of DCs, Lin et al. [16] claimed that DCs could be considered as a perennial and stable heat source, which would supply continuous and large amount of waste heat, and the waste heat from DC industry has reached 56 TW h in 2016 [17]. The waste heat from DCs should be eliminated or reused, otherwise it will be directly discharged into the outdoors through CRACs, causing thermal pollution to the outdoor environment [4,18]. The waste heat from DCs belongs to low-grade heat source but has large potentials to improve the energy efficiency and achieve the sustainable energy management [19]. The current research on low-grade heat sources (e.g., solar thermal energy [20], geothermal energy [21], chips [22], and domestic hot water [23]) provides a reference and feasibility for realizing waste heat recoveries (WHRs) in DCs. Many researchers believe that waste heat utilization is one of the most promising methods for energy conservation in DCs [24,25].

However, there is a major challenge for WHRs in DCs, namely a low temperature level of waste heats due to operating temperature limitation of IT equipment [26]. In addition, the waste heat from DCs belongs to the low-grade waste heat, whose heat quality can be upgraded by heat pumps (HPs) to meet high-grade heat demands for livelihood and industry. Currently, HPs have been considered as the most promising WHR method in DCs, which can realize redundant heat removal and upgrade the waste heat quality for multiple heat supplies at the same time [27]. The use of the heat exchangers and HPs can serve a variety of uses (e.g., low or high temperature heat demands, and low-or-high grade heat demands) for the waste heat recovered from the DCs.

According to literature survey, the current available and possible WHR methods and waste heat uses in DCs include heating and district heating (DH) supply (e.g., space heating, how water supply and DH supplement) [28], cooling production in an absorption [29] or adsorption cooling [30] cycles for power need reduction, electricity production [31] utilizing the Seebek and piezoelectric effects, biomass fuel production as a catalyst [32], and clean water production through desalination [33]. The benefits of WHR are generally demonstrated through energy savings, carbon emission reduction and economic analysis. For example, Luo et al. [34] proposed applying a framework of WHR in DCs as well as a corresponding decision support tool, which can identify the compatibility of wate heat sources and sinks. They also performed energy, exergy, environmental (3 E) and economic analysis of the WHR system via the tool. They concluded that recovery indexes are needed to determine the compatibility of the waste heat sources and sinks. Furthermore, the proposed tool can be used to optimize WHR in DCs and economic payback.

In this paper, we follow the above-mentioned possible waste heat uses, and comprehensively review and analyse the possibility, feasibility and compatibility of WHR in DCs for diverse needs (e.g., heating, DH, cooling, electricity and industrial/agricultural processes, and others) and different application scenarios (e.g., office buildings, comprehensive energy community, and residential buildings) through technical, energy, exergy, environmental and economic (4 E) analysis. In addition, we also summarize their advantages and disadvantages, and applicable scenarios of various WHR methods and uses. Finally, we give recommendations for future research and development on WHR in DCs.

2. WHR for heating

2.1. Waste heat sources and potentials

Air-side cooling system is considered as the most common used technology in data centers (DCs), who can also produce the low-temperature and high-capacity and reliable waste heat [31]. However, waste heat utilization from DCs has been widely investigated, but waste heat from DCs has the characteristics of low thermal quality, which faces the challenge for a widespread use. Compared with air-side cooling, although liquid-cooling applications in DCs are limited, their waste heat temperatures are considerably higher than that in air-side cooling system, and thus have better potentials for waste heat re-utilization in DCs.

Table 1 shows the waste heat temperature levels for different source cooling system in DCs. The symbol '☆' represents the waste heat potentials, and more ☆ means more potentials. The air-side cooling system has the biggest waste heat potentials for the dominate market share, while the liquid-cooling system has the best waste heat potentials for the higher waste heat temperatures. The return hot water temperatures are between 50 and 60 °C in liquid cooling system, while the temperatures of condenser coolants are between 40 and 50 °C whether in air-side

Table 1
The waste heat temperature levels for different source cooling system in DCs.

DC cooling form		Reference	Description	Potential heat source	Temperature (°C)	Recycling potential rank	
						Waste heat Temp.	Application scope
Air-side cooling	CRACs	[35]	Room level cooling	Return warm water	15–20	☆	☆☆☆☆
				Return hot air	25–47	☆☆☆	☆☆☆☆
	CRAHs			Condenser coolant	40–50	☆☆☆☆	☆☆☆
Air to liquid	Heat exchanger		In-row & rear door cooling	Return warm water	20–30	☆☆	☆☆
				Condenser coolant	40–50	☆☆☆☆	☆☆
Liquid cooling		[36]		Return hot water	50–60	☆☆☆☆☆	☆☆

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

cooling or air-to-liquid cooling systems, which also causes much big potentials for recoveries. The return warm water in sole or hybrid air-side cooling system is as low as 15–30 °C, which has worst recovery potentials considering the waste heat temperature levels. CRACs and CRAHs are different cooling system in DCs, which are selected based on DCs' size, existing cooling infrastructure, and cooling requirements. The former ones are independent systems directly cooling and dehumidifying the air, while the latter ones belong to larger system circulating chilled air from a central cooling plant [35].

Fig. 1 shows the WHR from CRACs/CRAHs in DCs. The alternative waste heats in DCs are from both the return hot air and the coolants, which should be directly or indirectly eliminated or recycled, otherwise will be directly released to the outdoor environment causing thermal pollution.

2.2. Existing operational cases

Firstly, the waste heat from DCs can be used for the heating supply to the surrounding residential directly or after simple process (e.g., preheating and dehumidification). Stockholm Data Parks is a famous project in Sweden, which utilized the waste heat in DCs to meet the heating demand of 2500 residential apartments [37], and has proven the feasibility and economics of waste heat potentials from DCs for direct building or community heating supply. Some commercial DCs have been proven suitable for waste heat reuse in the nearby facilities. For example, the Notre Dame University (Indiana, USA) [38] and the Telehouse West (United Kingdom) [39] DCs achieve WHRs in the nearby greenhouses. Similarly, the Uspenski Cathedral (Helsinki, Finland) data center utilized waste heat to warm up water pipes for the heating demands in the nearby homes [40].

2.3. Corresponding research.

In addition, many researchers have studied the optimization and comprehensive analysis of the WHR system in DCs at the research level. Yu et al. [41] used Design's Simulation Toolkit (DeST) to simulate the dynamic AC load in the energy community with different buildings (e.g., apartment, teaching & exhibition center, fitness center, office building, and canteen) for heat and cooling load index, and took a DC in Harbin, China as a case study for feasibility of heating supply for the energy community. The results showed that the heat load in the subsidiary buildings (15.57 MW) is much smaller than the heat capacity of the cooling system in DCs (72.26 MW), and thus the thermal demand in the subsidiary buildings can be met by DC WHRs. Oró et al. [42] proposed WHR in liquid cooled DCs, and sold the excess heat to meet part of the heating demands (e.g., space heating, pool water heating) in an indoor swimming hall (SH). Through economic analysis, they found selling excess heat for heating demands in SH can bring additional income of a net present value of 330 k€ during 15-year period. In addition, the sold heat can reduce 18% heating cost for the SH as well as corresponding 60% CO_2 emission. In addition, the payback period was lower than 3 years.

More researchers utilized waste heat in DCs for the nearby residential buildings considering the relatively reasonable match between waste heat scale from DCs and the heat demand in residential buildings. For example, Antal et al. [43] considered DC as stable heat sources and developed a mathematical model to reflect the thermal energy profile in DCs to manage the expected heat demand for the nearby neighbourhoods. The results showed the utilized waste heat from DC had the potentials to meet various thermal energy demands in the nearby neighbourhoods. Murphy and Fung [44] connected the multi-unit residential buildings (MURBs) to a DC and evaluated the maximum portion of shared energy for the heating supply and cooling supply for the MURBs and DCs, respectively. They evaluated the system viability though economic and carbon emission analysis and found the optimal MURB area was 110 000 m^2 in Toronto when connected to a DC with 4 MW cooling load, and the system, with HP for heating and cooling supply for MURBs and DC respectively, was the most profitable (11.9%

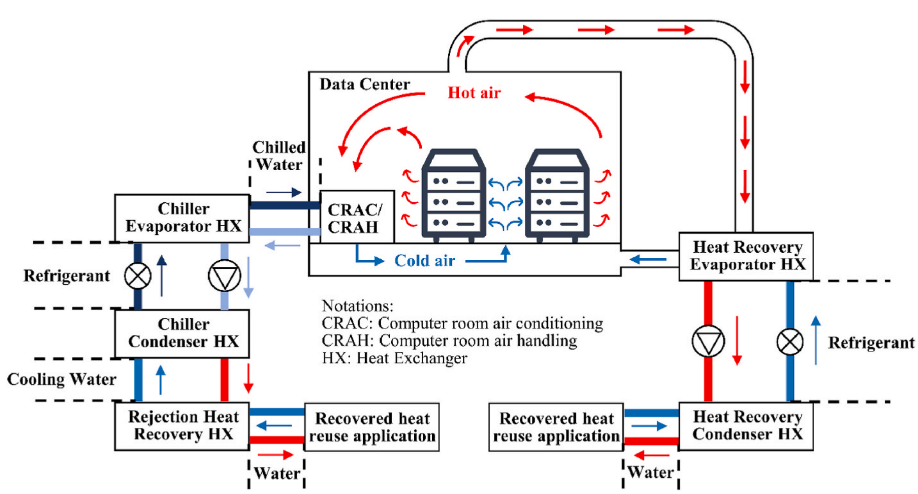

Fig. 1. WHRs in DCs with CRACs/CRAHs [27].

unlevered after-tax internal rate of return after 30 years). Then, Zimmermann et al. [45] firstly proposed an Aquasar prototype based on hot water-cooled supercomputer and analysed its energy and exergy efficiencies. Aquasar innovatively used hot water as coolant to effectively address cooling requirement in DCs, and recovered its waste heat to cover heating demand for the nearby buildings. They found that the processors could be effectively cooled by the proposal system with 60 °C hot water on the water-cooled side with only15 °C temperature differential. Under this circumstance, the waste recovery and exergetic efficiencies can reach 80% and 34%, respectively. Based on the economic analysis, using waste heat from DCs for space heating could achieve the maximum economic value. However, the temperature and quality of waste heat in DCs greatly limit its direct application.

2.3. HP application for waste heat upgrading

Fortunately, heat pumps (HPs) are widely applied to recover waste heat in DCs due to their multi-function (e.g., redundant heat removal, waste heat upgrading and residential heating provision) [27]. HPs can increase the temperatures and grades of waste heat for various heating demands (e.g., domestic hot water), which is considered as the most promising method to achieve WHRs in DCs.

Deymi-Dashtebayaz and Valipour-Namanlo [24] adopted air-source HP system for WHR in DC, and they applied the recovered heat for space heating supply in nearby office buildings. Through energy, environmental and economic analysis, they concluded that the proposed method could achieve considerable savings of natural gas, electricity energy, carbon emission and energy cost, which just needed a payback period of 2.5 years. In addition, Lin et al. [16] proposed a high-efficient method for WHR by integrating the CO_2 HP, mechanical sub-cooling cycle as well as the lithium bromide-water (LiBr–H_2O) absorption refrigeration cycle. The low-temperature waste heat in DCs is upgraded by the CO_2 HP and mechanical sub-cooling and is absorbed by circulating water for different heat demands (e.g., driving LiBr–H_2O absorption cooling unit for cooling demand in summertime, direct heat supply in wintertime and hot water supply in non-heating seasons). The hot water from the HP can be used in the surrounding office buildings in winter. They used MATLAB and REFPROP 10 to build up both energy, exergy, and economic models to analyse the system performance. They concluded that the proposed integrated system performed better in terms of both energy and exergy destruction with a short payback period (2.04–2.46 years). The application of HPs in DC WHRs has been very common and can be regarded as an indispensable part.

2.4. TES for matching supply and demand

Apart from HPs, thermal energy storage (TES) is also believed to improve WHR efficiency, which can balance the mismatch between the heat supplies from the waste heat system and the heat demands for the subsidiary buildings.

Wang et al. [46] adopted a CO_2 ground source HP (GSHP) system to establish a prosumer DC energy system to achieve WHR for the heating supply in the surrounding buildings and stored the waste heat during the non-heating seasons by a CO_2 direct-expansion GSHP. Through 3 E analysis, they found the heat-power ratio can achieve 5.7 in the prosumer DC WHR system. Compared with conventional cooling system (air-source heat pumps), the proposed system had almost the half (52.8%) of the total power consumption, and significantly improved the matching thermodynamic performance with a 3.87 improvement on exergy efficiency. In addition, the annual net profit in the proposed system is 190.34% than that in the conventional system. Besides, Dvorak et al. [47] adopted an aquifer TES (ATES) in a DC to improve the waste heat utilization efficiency for a university campus. They found that the proposed system can annually achieve 680 tons of CO_2 emission on average considering the current ATES policy, while can increase the CO_2 to 1000 tons in future scenario. Fig. 2 shows the schematic of WHR with TES systems (e.g., hot water tank, GSHP, and others).

2.5. System optimization

Except of the research on validation of different waste heat energy system based on DC and the nearby heating demand, researchers also proposed energy system management methods for better utilization of waste heat from DCs to the neighbourhoods' heating demands.

Luo et al. [48] proposed a decision support system to manage the energy system in DCs with WHR system, and the proposed system can analyse WHR conditions (e.g., opportunities, waste heat quality and quantity, and exergy and temporal availability), and used the waste heat for space heating supply in nearby buildings. They found that the proposed WHR system can recover 68% waste heat from the IT equipment, and improve 10% power usage effectiveness (PUE) in case DC, and found the proposed decision support system can be widely used in both newly-built and existing DCs for providing relatively quick deciding method on WHR investment and return strategy. In addition, Antal et al.

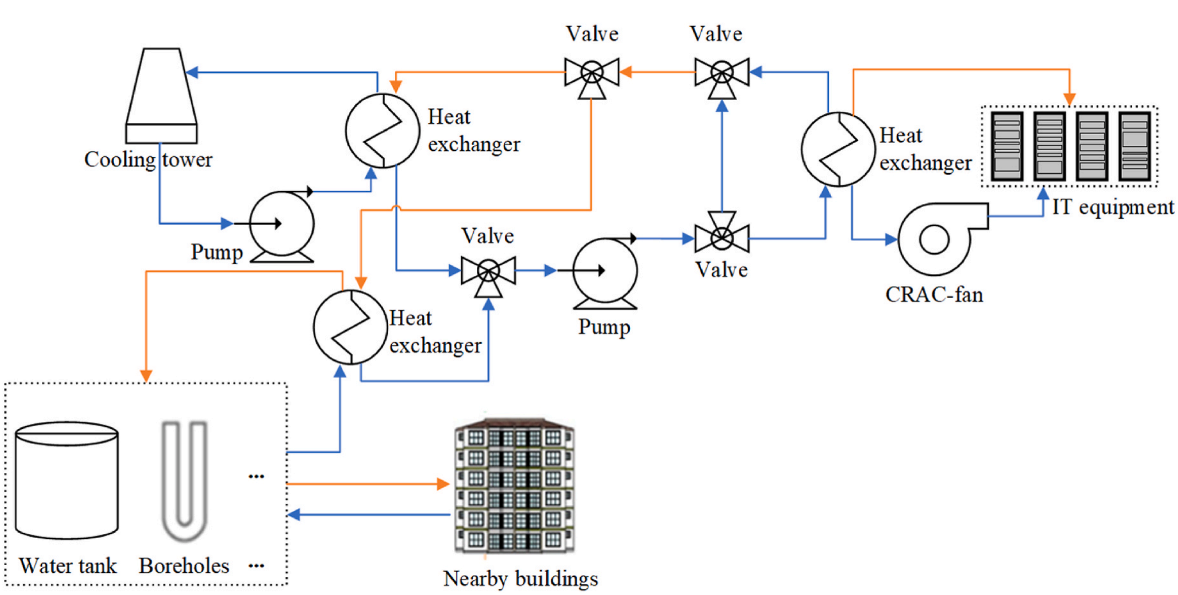

Fig. 2. Using thermal energy storage to store waste heat from DCs [47].

[49] proposed a workload scheduling for transforming waste heat from IT equipment in distributed DCs to residential homes' heating system. They found the proposed method can manage to the workload distribution, and can meet the temperature setpoint requirement and server power requirements accurately follow the heat demand.

Table 2 summarized the WHR methods and applications in DCs to meeting the heating demands in the nearby buildings directly or after pre-heating. It can be found that the feasibility of WHR for the heating demands in the nearby buildings is validated with the benefits of energy savings, carbon emission reduction, and short economic payback. The waste heat receivers are mainly residential and office buildings, while HPs are widely used in these systems for different cases with different temperature or grade-level uses. In addition, TES tank is not essential in the heating system, but can be applicable for better energy flexibility.

3. WHR for district heating networks

3.1. Background

Apart from utilizing waste heat for the heating supply in the nearby buildings directly or after pre-heating, waste heat from data centers (DCs) can also be recovered for supplementing heat loads in district heating (DH) networks. Using the waste heat for DH networks can simultaneously improve the DC operation performance and reduce carbon emission from DH. Different from waste heat recoveries (WHRs) for nearby building heating with different temperature levels (e.g., 20–55 °C), excess heat for DH networks need to meet certain supply water temperature requirements (45–55 °C) [50]. Thus, preheating is compulsory for waste heat utilization in DH networks, which requires additional heating devices and power input, and the technical, energy and economic analysis are necessary to study the WHR system feasibility. Fig. 3 shows the rough sketch of how the waste heat from DCs

Table 2
Summary of WHRs in DCs for heating the nearby buildings directly or after pre-heating.

Reference	Recovery	Application scenario	Heating type	Analysis aspects				HP	TES	Results
				En.	Ex.	Em.	Ec.			
Yu et al. [41]	Cooling-water source HP	Energy community	–DHW –Circulating water for heating system	●			●	●		–The heat load in subsidiary buildings (15.57 MW) is much smaller than heat capacity of DC cooling system (72.26 MW), –Meet the thermal demand in subsidiary buildings –Considerable economic efficiency
Oró et al. [42]	Water-to-water heat exchanger	Swimming halls	–Space heating –Pool water heating	●		●	●			–The excess heat selling bring additional income of a NPV of 330 k€ during 15-year period. –The sold heat reduces 18% heating cost for the swimming pool as well as corresponding 60% CO_2 emission. –The payback period was lower than 3 years.
Murphy and Fung [44]	Water-to-water HPs,	Multi-unit residential buildings	–Space heating	●		●	●	●		–The optimal MURB area is 110 000 m^2 connected to a DC with 4 MW cooling load –The system was the most profitable (11.9% unlevered after-tax internal rate of return after 30 years)
Zimmermann et al. [45]	Heat exchanger	Nearby buildings	–Space heating	●	●		●			–Effectively cools the processors with 60 °C hot water on the water-cooled side with only15 °C temperature differential. –The waste recovery and exergetic efficiencies can reach 80% and 34%, respectively. –Based on economic analysis, using waste heat from DCs for space heating can achieve the maximum economic value.
Deymi-Dashtebayaz and Valipour-Namanlo [24]	Air-source HP	Office buildings	–Space heating	●		●	●	●		–Achieve considerable savings of natural gas, electricity energy, carbon emission and energy cost. – Short payback period of 2.5 years.
Wang et al. [46]	CO_2 direct-expansion GSHP	Surrounding buildings	–Space heating –DHW	●	●		●	●	●	–The heat-power ratio can achieve 5.70. Compared with conventional cooling system (air-source HPs): –Almost the half (52.8%) of the total power consumption, –Greatly improve the matching thermodynamic performance, –with a 3.87 improvement on exergy efficiency, –The annual net profit reaches 190.34%.
Dvorak et al. [47]	HP	University Campus	–DHW	●		●			●	–Reduce 680 tons CO_2 emission annually considering current policy. – Reduce 1000 tons CO_2 emission annually in future scenario.
Lin et al. [16]	CO_2 HP	Office buildings	–Circulating water	●	●		●	●		–Perform better in terms of both energy and exergy destruction –A short payback period (2.0–2.5 years).

Notations: DC = Data center; HP=Heat pump; NPV= Net present value, Energy community including apartment, teaching & exhibition center, office building, canteen and fitness center; DHW = Domestic hot water; En. = Energy; Ex. = Exergy; Em. = Environmental; Ec. = Economic.

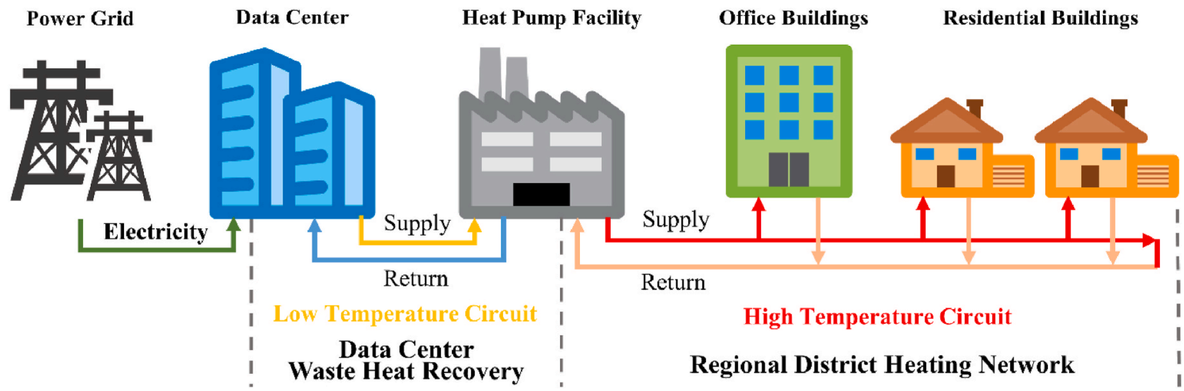

Fig. 3. WHR (low-temperature) in DCs to DH systems (high-temperature) [51].

linking to the DH networks [51].

3.2. WHR with heat pumps

Huang et al. [4] gave out the schematic of combining DC (with CRAHs) and DH networks system (with HPs), which is shown in Fig. 4. Both the waste heat from exhaust air or coolant can be recovered, whose temperature levels are upgraded by the HPs for high-grade or high-temperature heat demands (e.g., DH networks). Abdurafikov et al. [52] compared different heating energy scenarios through energy and carbon emission analysis in a typical district heated area in Finland. Here, they focused on WHR form an air-cooled DC (an industrial waste heat scenario) and achieved reductions of 32% centralized heat production and the most of 50% of carbon emission annually under the circumstance of only 20% of waste heat share in supply. In addition, Oró et al. [35] proposed implementing WHR solution in air-cooled DCs for improving energy efficiency and flexibility of DH networks, and they evaluated the energy and economic feasibility of the solution through numerical studies. According to economic analysis of the DCs with a specific 1000 kW in Barcelona, Spain, they concluded that WHR is not feasible in most conventional air-cooled DCs. However, some air-side cooling configurations, particularly rear door cooling, can achieve economic viability in terms of WHR. They mentioned that HPs were essential to increase waste heat operational temperature for the high-temperature heating demands, especially for the medium and high-temperature DH networks.

He et al. [53] incorporated a distributed cooling system and HP unit into a real Chinese DC to further raise the waste heat quality, and they found approximately 10% of the annual power could be saved due to WHR from the DC to DH networks. Besides, the DH network could annually save 18 000 tons of coal. They also mentioned two kinds of schematic of WHR for DH networks, as shown in Fig. 5. Layouts a&b all reuse the chilled water as the waste heat source, but the chillers are replaced by the HPs in layout a. In addition, the water from the evaporator of HP can also be used as the chilled water for cooling the DC.

Al-Sayyab et al. [54] put forward a novel simultaneous system with ejector-solar assisted HP for simultaneous DC cooling and further DC WHR for DH networks, and they conducted energy, exergy and environmental (3 E) analysis of the proposed system. PV/T waste heat is used via an evaporative-condenser to drive an ejector, and the generated

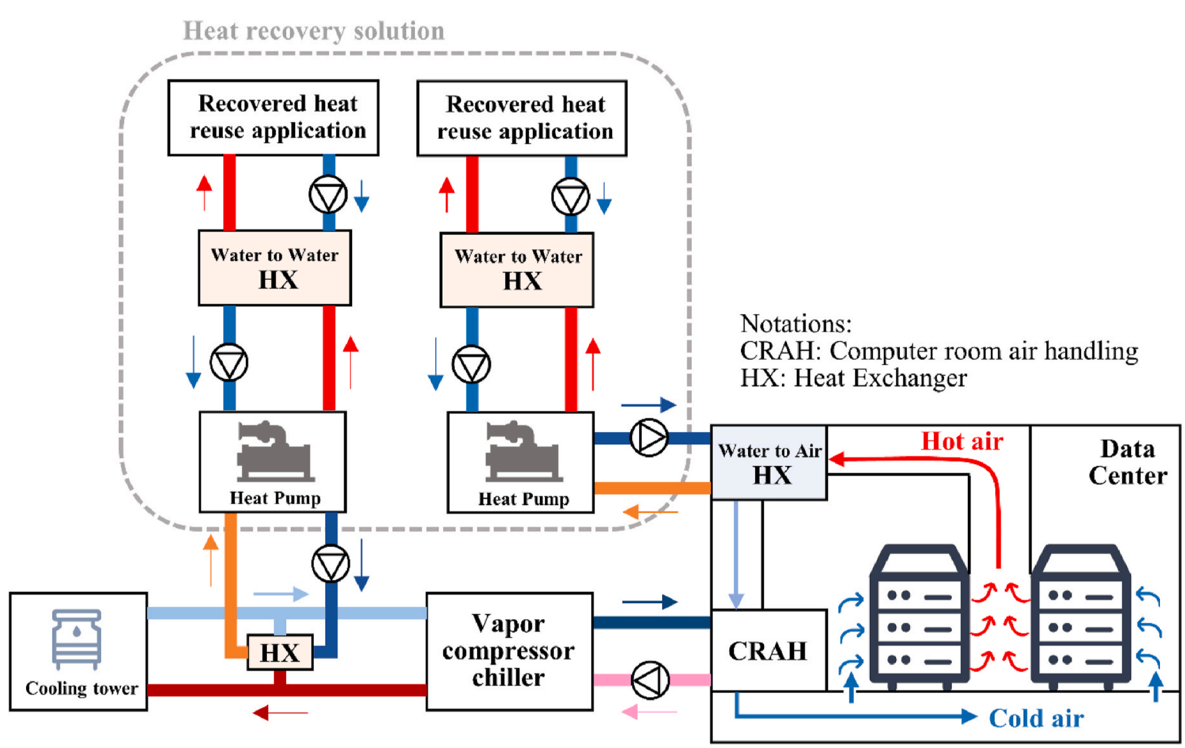

Fig. 4. Schematic of combined DC with CRAHs and DH networks system with HPs [4].

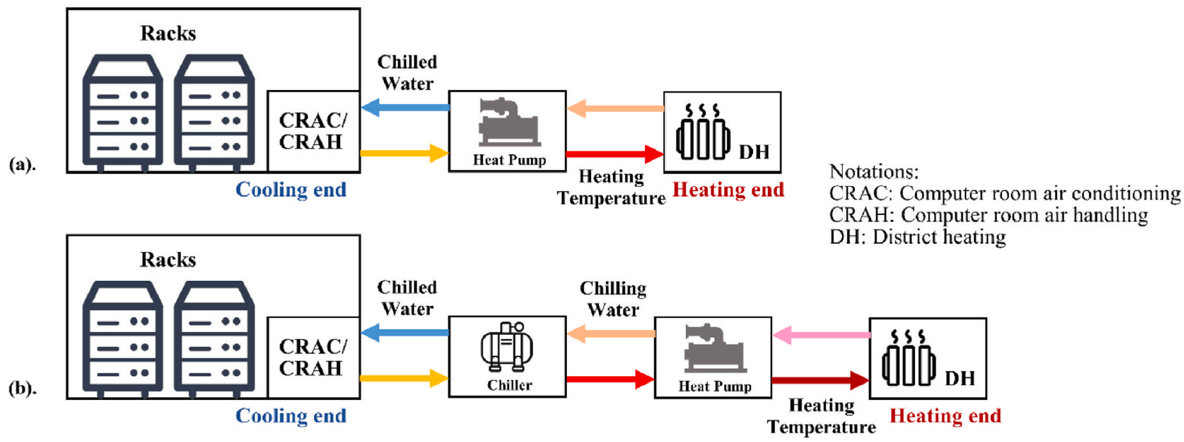

Fig. 5. Two kinds of WHR for DH networks [53].

electricity is exploited for HP compressor and pumps running. Then, the produced cooling source is for waste heat consumption and indoor air condition maintenance in DC. Finally, the waste heat can be upgraded to the functional temperature level of the compressors and used for DH networks. Existing application examples of DC waste heat recovery for DH networks was in 2020 that a Tencent DC in Tianjin, China [55] had applied a magnetic suspension HP to achieve WHR for heating demand in the residentials. According to the system operation results, they found when the waste heat was recovered by only 10%, the heating demand of the whole office buildings in the DC campus can be met. This project has achieved considerable energy savings and great economic response and has also validated the feasibility of using HP system to achieve WHRs for DH.

3.3. TES for better performance

Li et al. [56] claimed that although utilizing waste heat from DCs for DH systems is feasible, its utilization is limited by the mismatch between heat supply and heat demands from and to DCs and DH systems, respectively. In addition, the operation cost of the DH systems can be greatly affected by the high peak loads. Thus, they recommended using both short-term (e.g., water tank) and long-term (e.g., borehole) TES to balance the mismatch. They also evaluate the proposed system integrating TES into DH networks based on WHR from DCs though 3 E analysis. They found the peak load can be shaved by the water tank by 31%, which also saved 5% energy cost yearly, and the payback period was below 15 years under the circumstance of higher storage efficiency than 80%. In addition, the borehole TES can achieve WHR rate up to 96%, bringing an annual CO2 emission reduction of 8%. However, the payback period for the long-term TES was beyond 17 years. Wahlroos et al. [57] utilized the waste heat from a DC to DH networks by HPs and applied TES units to store excess heat for balancing time mismatch between heat supply and demand. They analysed its energy efficiency and potentials for the proposed low-temperature DH networks. They found waste heat use can achieve 0.6–7.3% energy cost saving from the system operational level, while it reduces the usage time of both CHP plant and heat-only boilers. In addition, the waste heat can be utilized during 95–99% of the hours regardless of electricity price and can achieved 12.2% saving of total production costs in high electricity price condition.

And Oltmanns et al. [58] proposed a direct hot-water (45 °C) cooling system and utilized the waste heat for DH networks or directly heating for nearby buildings. The WHR was achieve by both HPs and TES and achieve altogether 20–50% waste heat utilization rate for different heat uses. In addition, the proposed system can annually reduce CO_2 emission up to 720 T_{CO2} which accounts for approximately 4% of total carbon emission in the university campus. Keskin and Soykan [51] proposed a comprehensive energy cost management in a DC with combined cooling, heating, and power (CCHP) and WHR system for cooling & power supply and for DH networks, respectively. They also used a mixed integer linear programming for operational strategy selection for the overall system. They found that the combined system could annually reduce energy cost of CCHP system by 40.3%, and the payback period was about 6.6 years. Furthermore, Huang et al. [59] proposed a new WHR system in DC with HP and heat pipe based on three-fluid heat exchanger, and they also adopted TES tank for heat storage, while the system adopted three operating modes (e.g., heat recovery, heat pipe and mechanical cooling modes). They found that the comprehensive energy efficiency ratio can reach up to 4.5 in heat recovery mode under the circumstance of 50 °C heating water, which will benefit the cooling supply in DCs as well as DH. Around 9.5 MW h heat can be harvested from a 5 kW DC to successfully meet the heat demand of a residential room of 60 m^2 in Tianjin, China.

3.4. System optimization

Similar to DC waste heat for heating nearby buildings, that for DH networks is also optimized by management method and optimization model (e.g., decision support model). Ljungdahl et al. [60] developed a decision support model for waste heat system design in DCs and optimize the high-performance computing responsories with liquid-side cooling and phase change cooling, whose goal is to optimize the WHR systems considering several system parameters (e.g., coolant and DH supply temperatures, DH load coverage). The utilization of liquid coolant and latent thermal energy storage (TES) can operate at high temperature (50–60 °C) for high-temperature WHR and seasonally store the un-controllable waste heat resource, respectively, and thus the integrated system can cover larger DH loads. The proposed model is applied in a Danish DC as a case study, which can achieve 8.14–10.8% of total electricity use saving, and 85–576 MW h/year WHR potential. In addition, 8–18% operational costs saving can also achieved.

Table 3 summarized the application scenarios of waste heat from DCs for supplementing the DH networks. It can be found that all the systems adopted HPs because the waste heat temperatures are compulsory to be heated to the required temperatures (45–55 °C) for DH networks, while most of them applied different kinds of TES (e.g., hot water tank, borehole, battery storage) for balancing mismatch between heat supply and demand. The application of these two devices (HPs and TESs) greatly increases the utilization efficiency of waste heat, which also brings energy, environmental and economic benefits in combined DC and DH network system.

Table 3
Summary of utilizing waste heat from DCs for DH networks.

Reference	Cooling method	Recovery	Analysis aspects			HP	TES	Results
			En.	Em.	Ec.			
He et al. [53]	Air-side (CRACs)	–HE	●	●		●		–Annually saving 18 000 tons of coal consumption –Achieve 10% annual power saving
Abdurafikov et al. [52]	Air-cooled	–GSHP/CHP –HE	●	●		●		–Decrease the annual energy production by 32% –Reduce maximum 50% carbon emission when the waste heat share was only 20% in supply
Wahlroos et al. [61]	–Air-cooled	–HE	●		●	●	● –How water tank	–Achieve a maximum of 7.3% energy cost saving –Reduce the usage time of both CHP plant and heat boilers –The WHR system can be used during 95–99% of the hours regardless of electricity price. –Save 12.2% total production costs in high power price.
Li et al. [56]	–Air-cooled	–HE	●	●	●	●	● –Water tank –Borehole TES	For water tank: –Shave the peak load by 31%, saving 5% annual energy cost –Payback period less than 15 years For borehole TES: –WHR rate up to 96%, causing 8% CO_2 emission reduction –Payback period less than 17 years
Oltmanns et al. [58]	–How-water cooled	–HE	●	●		●	● –Buffer tank	–Achieve 20–50% waste heat utilization rate depending on heating or DH uses.
Keskin and Soykan [51]	–Air-cooled	–CCHP –HE	●	●	●	●	● –Battery storage	–Reduce 720 T_{CO2} CO_2 emission, accounting for around 4% of campus total emission. –Annually reduce energy cost of CCHP system by 40.3%. Payback period:6.6 years
Huang et al. [59]	–Air-cooled	–HP/heat pipe –Three-fluid –HE	●			●	● –How water tank	–Achieve 4.5 energy efficiency ratio with 50 °C heating water –Harvest 9.5 MW h heat from 5 kW DC for heat demand in a residential room of 60 m^2.
Ljungdahl et al. [60]	–Liquid-cooling –Phase change cooling	–HE	●		●	●	● –Latent TES	–Cover larger DH loads –Achieve operational cost savings of 8–18%

Notations: DC = Data center; HP=Heat pump; HE=Heat exchanger; TES=Thermal energy storage; DH = District heating; CCHP=Combined cooling, heating and power system; En. = Energy; Em. = Environmental; Ec. = Economic.

4. WHR for cooling supply

4.1. Absorption cooling

4.1.1. Background

Using the absorption units for low-grade waste heat utilization will not contribute to greenhouse gaze emission, and the absorption cooling system suits for the systems with all sizes (small, medium, and large), which is also simpler than other conventional cooling system (e.g., compressor refrigeration and evaporative cooling) [19]. There are two main working pairs widely used in absorption cooling system, namely the Lithium Bromide-water (LiBr–H_2O) [62] and water-ammonia [63]. Kim et al. [64] theoretically studied an absorption-based heat pump (HP) system with working pair of LiBr–H_2O for device cooling and validated its feasibility via theoretical evaluation and coefficient of performance (COP) analysis. They obtained a maximum cooling capacity up to 100 W, and a COP of 0.87. Except of LiBr–H_2O, researchers [65] also used water-ammonia as the working pair with a COP of 0.73, and they claimed that although the COP of water-ammonia based absorption cooling is lower than that of the mechanical compression system, the absorption cooling has notable advantages (e.g., high reliability, lower cost, and simple development and build processes). Fig. 6 shows the schematic of a typical absorption cooling system [66].

The above two research [64,65] have established a baseline for absorption cooling system performance, which can serve as reference for future improved absorption cooling system. Other related studies are aimed at optimizing the absorption cooling system performance via the system parameter optimization [67], hybrid cooling system (e.g., fuel cell [68], and solar energy [69], hydrophobic membrane-based adsorber/condenser [70]), combined with other media (e.g., Carrol-H_2O [71], LiCl–H_2 [72]), etc. Through literature research, it can be found that there were many and relatively comprehensive studies on the absorption cooling system.

4.1.2. Potentials for WHRs in DCs

Currently, many studies have applied absorption chiller for waste heat recoveries (WHRs) in data centers (DCs), which is usually equipped with heat pumps (HPs) for high-grade heat use. When the generator temperatures are as low as 70–90 °C, the absorption cooling system can still operate, while these low temperatures are compatible with the low-temperature waste heat ones from two-phase or liquid cooled DCs [31]. However, absorption cooling is also applicable for WHRs in air-cooled DCs with lower temperature levels (below 65 °C), which compulsorily requires an additional heat booster. Fig. 7 shows the overall system diagram of DC waste heat-driven absorption cooling system [73].

In 2010, Haywood et al. [74] come up with the idea of using waste heat from DC itself to drive a sustainable and alternative DC cooling system, which was already relatively preliminary ideas and research on

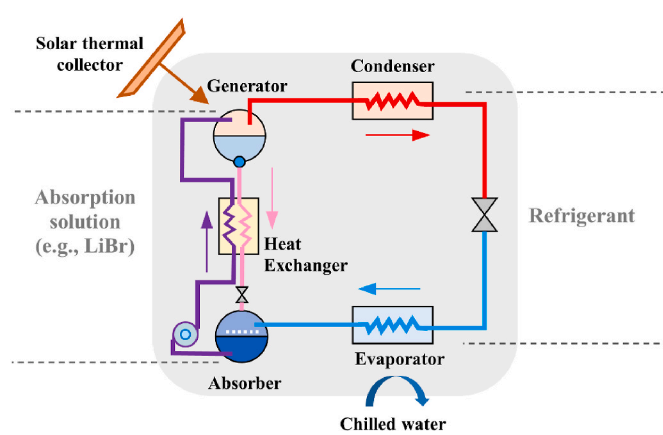

Fig. 6. Schematic of a typical absorption cooling system.

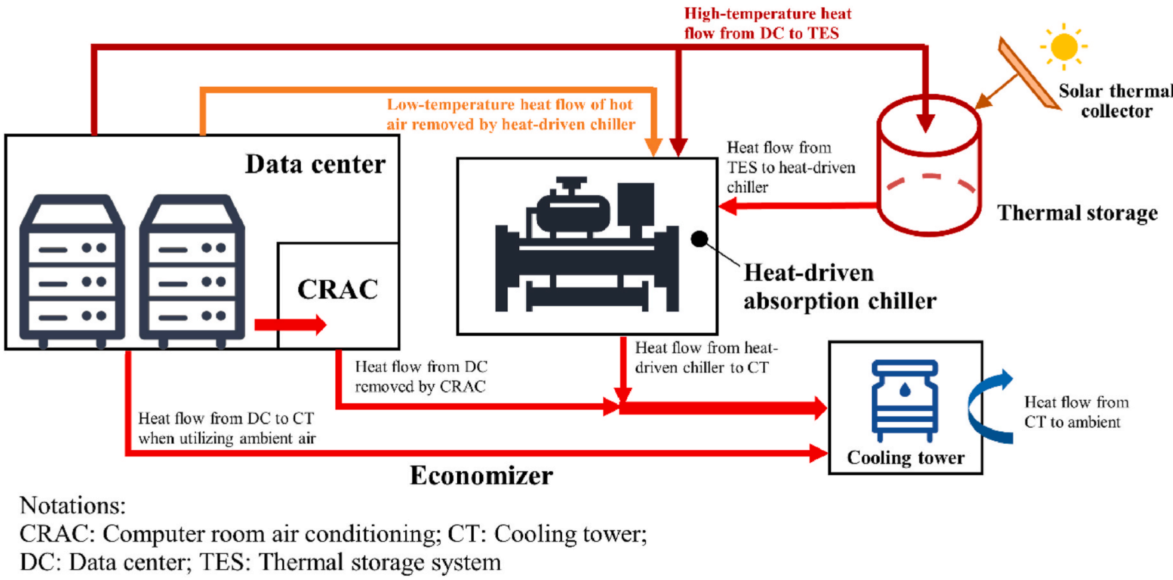

Fig. 7. he overall system diagram of DC waste heat/driven absorption cooling system.

the WHRs in DCs. The idea was challenged by providing enough exergy to drive cooling process and enough cooling for the DC under the circumstance of fluctuating thermal supply, which can be addressed by TES, multi-energy complementarity etc. The idea or research by Haywood et al. [74] is only a preliminary idea about DC WHRs but provides a reference for later related research.

4.1.3. Management methods based on workload and energy

The feasibility of absorption cooling application in DCs has been studied by many researchers as follows. Tian et al. [75] proposed an innovative energy management method combined workload and waste heat optimizations for DC microgrids, and they applied an absorption chiller to recover the waste heat from CHP units and IT equipment. Absorption chiller supplies cooling, which reduce the cooling required by conventional cooling system (e.g., CRACs), thereby improving the energy efficiency of the DCMs. The results showed that applying WHRs in both CHP unit and DC can achieve the minimum operating cost. In addition, Ding et al. [76] also proposed a WHR-based energy management method for DC microgrid, and the principle is also to used WHR for alternative cooling production, which supplement or replace the cooling from traditional CRACs. But they didn't focus on the WHR system too detailed as they focused on the two-stage stochastic programming model for optimization. Manu and Chandrashekar [19] proposed a waste heat-driven absorption HP system for chip cooling, which adopts single-stage LiBr–H_2O vapor and without solution heat exchanger, and they also used MATLAB (2008b) to develop a friendly graphical user interface (GUI) package for examination of chip heat flux effect on COP, conductance, and flow rates. They found the developed GUI for LiBr–H_2O vapor absorption heat pump had a faster and high accuracy to determine the chip temperature effect on the loads, performance, flow rates and conductance.

4.1.4. Further study with multi-energy system

In addition to research on WHR-based management platform, and workload and energy management, researchers also combine WHRs with different energy or energy storage systems to further energy efficiency improvement in DCs. Amiri et al. [77] proposed using Libr-H_2O absorption chiller system to achieve WHR in DCs and analysed its techno-economic feasibility. They found that the proposed system can achieve energy saving (up to 13.0 GW h/year) and corresponding carbon emission reduction (9208 tons CO_2) and have a relatively short payback period of 2.56–2.76 years. Furthermore, Han et al. [62] proposed using waste heat in DC to drive the Libr-H_2O absorption cooling system for further cooling to servers, and adopted an enhanced geothermal system with obsolete oil wells for TES. They also analysed the effects of some parameters (e.g., well depth, porosity, injection rate, permeability, and reservoir width) on the proposed cooling system performance. They concluded that the enhanced geothermal system could cause better LiBr–H_2O cooling system performance, and the system cooling capacity can reach 9 MW with a COP of beyond 1.0. In addition, as mentioned above, Lin et al. [16] proposed a hybrid high-efficient cooling system combining CO_2 HP, mechanical sub-cooling cycle and LiBr–H_2O absorption refrigeration cycle, which can not only upgrade the low-temperature heat by HP for heating supply in winter, but also supply cooling to the surrounding office building in summer via the absorption refrigeration cycle. The mechanical sub-cooling cycle is also used to increase the cooling capacity of CO_2 HP and decrease the required CO_2 mass flow in the cooling of DCs. Although the LiBr–H_2O absorption cooling units cost more than half of the total integrated system, the developed system has a relatively short payback period (2.04–2.46 years) with different working fluids in the mechanical sub-cooling cycle.

Chen et al. [78] integrated a spray cooling system with a waste heat driven absorption chiller in DC and adopted a chilled water storage system for peak load shifting. The hybrid system could use the cooling generated from absorption chiller to cover that from condenser of spray cooling system and stored off-peak cooling capacity of absorption chiller for on-peak cooling load supplementary. The results showed that integrating the absorption chiller with the chiller water storage unit could totally meet the on-peak cooling load, and the proposed hybrid cooling system could achieve 51%, 17% and 71% savings of energy, exergy and operation cost, respectively with a short payback period of 286 days. Like Chen et al. [78], Ebrahimi et al. also [79] also used the cooling generated from the absorption cooling cycle to replace that from condenser in the on-chip cooling system. They compared the performance between the absorption cooling systems with LiBr–water and water–ammonia working pairs in the developed model and found LiBr–water absorption system had a superiority. They also found that the proposed hybrid can improve the energy efficiency in DC, and the payback periods were 7–8 months and 4–5 months for 2 MW and 10 MW DCs, respectively.

4.2. Adsorption cooling

4.2.1. Background

Absorption refrigeration systems with LiBr–H_2O or NH_3–H_2O perform well in DCs when the waste heat temperatures range between 65 and 100 °C [73]. However, the system will shut down and have much low COP under the circumstance of lower temperatures (below 65 °C). In addition, absorption chillers have the characteristics of low power to weight ratio, which occupy a large area unsuitable for most of DCs with constrained space, and the used absorbents are environmentally unstainable and corrosive. Thus, restrictions exist in the application of absorption refrigeration in WHRs in DCs.

In addition to absorption refrigeration, adsorption refrigeration is also applicable in DC WHR as its driving temperature can be as low as 60 °C [36]. Pan et al. [36] claimed that silica gel-water performed the best among numerous working pairs in adsorption cooling system due to its low driving temperature and relatively mature technology, which had been widely adopted in solar and WHR fields. Lu et al. [80] compared two different chillers (e.g., LiBr–H_2O absorption and silica gel-water adsorption) for solar cooling system, and they found adsorption chiller performed better than absorption chiller in terms of running hours.

4.2.2. Application potentials

From 1980s on, adsorption cooling system adopting silica gel-water has been commercially used in solar cooling application [30]. To this day, the adsorption refrigeration on solar cooling application has been widely studied both experimentally and numerically. A three-stage adsorption chiller proposed Shah et al. [81] can decrease its driving temperature to about 50 °C, which facilitate the application of adsorption cooling in DC WHR. In addition, due to the characteristics of the year-round uninterrupted operation and high waste heat output in DC, DC can maintain steady, high-temperature waste heat supply, and thus has more promising application for adsorption cooling [45]. Thus, in terms of adsorption cooling, WHRs in DCs are more promising than the solar cooling due to more stable driving temperatures [30].

In DC with water-cooled servers, 50–60 °C waste hot water can be produced by some components (e.g., CPU), while the required chiller water temperature is approximately 22 °C for some other components (e.g., hard disk) [36]. Thus, it is possible to recovery the 50–60 °C waste hot water to drive the adsorption chiller for the chilled water production. Fig. 8 shows the schematic of the basic WHR system with adsorption chiller in water-cooled DC [36]. Here, adsorption chiller can achieve servers waste heat consumption and the cooling supply for servers at the same time, while cooling tower contributes to heat dissipation during adsorption and condensation in the chiller.

4.2.3. Existing studies

In Germany in 2017, Wilde et al. [82] firstly built a WHR project with adsorption cooling system in DC and proposed recovering waste heat in the high-performance computing station adopting high-temperature direct-liquid cooling system (namely CooLMUC-2 system), and used the waste heat to drive an adsorption chiller to generate cold water for other IT components cooling. Based on a case study, they found the integrated CooLMUC-2 and adsorption chiller could achieve both 95 kW heat removal from the super-computer and over 50 kW cold water production at the cost of only around 6 kW electricity consumption after optimizing the system operation parameters.

Pan et al. [36] claimed that silica gel-water performed the best in massive applications in the solar and waste heat utilization considering its lower driving temperature and mature technologies, and then proposed a silica gel-water adsorption chiller for solar cooling and DC WHR. They found that under the circumstance of using adsorption chiller, DC WHR has much shorter payback period (0.5–2 years based on the recycling system operating hours in a year) than the solar cooling application. In addition, combined with conventional cooling system without WHRs in DCs, adsorption chiller-based WHR in DCs had a short payback period of less than 1 year. Thus, they thought waste heat cooling application had more economic potential than solar cooling, which was also promising in the future.

Gupta and Puri [83] proposed a new cooling system adopting an adsorption chiller to achieve WHR in a DC with both air-side and water-side cooling, while this system can use the dissipated heat from the water-cooled racks to drive the silica gel-H_2O adsorption chiller. The chiller water generated from adsorption chiller can be used for in-row air-cooled units in the, and thus partially or fully eliminate the cooling load of the existing vapor-compression chiller, which achieve energy savings.

4.3. Other cooling

Apart from the waste heat in DCs by absorption and adsorption cooling system, that can also be used in other kinds of cooling production process (e.g., auxiliary evaporative cooling and combined cooling, heating and power system).

4.3.1. Evaporative cooling application

The waste heat can also be used for achieving evaporative cooling in DCs. In an evaporative cooling system, water evaporation process can achieve fresh-air humidification, and cooling of fresh-air by water evaporative latent heat [84]. There are also strict requirements on humidity in DCs, so this part of the cold air cannot be directly adopted to the cooling cycle. Utilization of waste heat from IT equipment can provide a warming system, which increases the fresh air temperature to some degrees and decreases its relative humidity (RH) to meet the desired server room conditions of humidity. Thus, integrating evaporative cooling with WHRs from IT equipment is theoretically feasible, and can achieve energy savings and economic benefits compared with

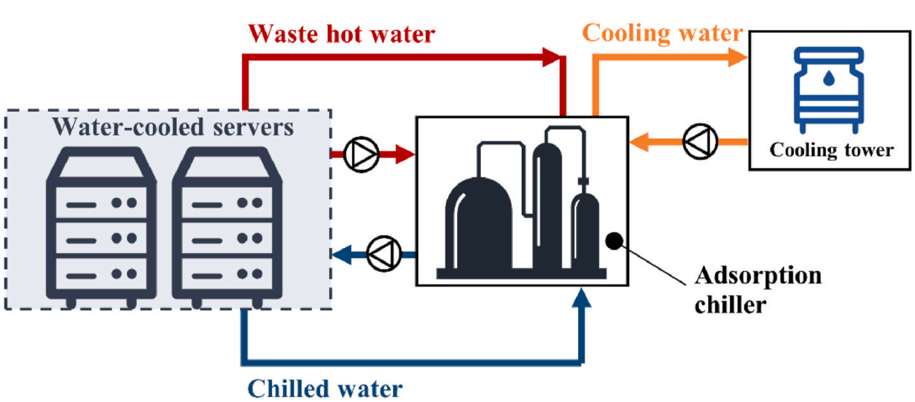

Fig. 8. Adsorption chiller based WHR system in water-cooled DC [36].

conventional CRACs.

In 2009, Chen et al. [85] proposed a waste heat-driven outdoor air system in buildings, which was integrated with evaporative cooling system and dehumidifier for fresh air cooling and dehumidification. Based on performance analysis and thermal calculation, they the proposed system can achieve energy conservation in humid and moderate climates. Their research was the initial application of the combined evaporative cooling and WHR system in buildings. While Endo et al. [84] firstly proposed a combined direct fresh-air cooling system with both evaporative cooling and WHR from IT equipment in a container DC. After one-year examination, they found that the proposed system could maintain the server environmental conditions with acceptable ranges and could annually reduce the total energy consumption by around 21% compared with container DC with CRACs.

4.3.2. Combined cooling, heating and power system application

Combined cooling, heating and power (CCHP) system is also applicable in DCs, which can produce both cooling and power for cooling system and operation respectively. CHP systems use gas turbine or fuel cell for electricity production, and produce much waste heat, which can be combined with the waste heat from IT equipment to drive refrigeration devices (e.g., absorption chillers) [86]. The cooling from the heat-driven cooling device can be used to eliminate heat from IT equipment in DCs again. As early as 2002, Herold and Radermacher [86]

Table 4
Summary of waste heat utilization for cooling production.

Reference	Scenario	Cooling system	HP	TES	Woking pair	Results and Pros & Cons
Kim et al. [64]	Chips	–ABC –Device cooling	●		LiBr–H_2O	COP: 0.87 Compared with mechanical cooing system:
Chiriac and Chiriac [65]	–High-Power electronics system	–ABC	●		Water-ammonia	COP: 0.73 –Lower cost. –High reliability. –Easier to manufacture, build and develop.
Tian et al. [75]	–CCHP –DC	–ABC –traditional CRACs			N/A	–Replace the cooling from traditional CRACs. –Improving the energy efficiency of the DCMs.
Manu and Chandrashekar [19]	–DC	–ABC –No solution heat exchanger	●		One-stage LiBr–H_2O	–Focus on a GUI package for AHP optimization. –The package can achieve faster and high accuracy to determine the chip temperature effect.
Han et al. [62]	–DC	–ABC –Enhanced geothermal system	●	●	Two-effect Libr/ H_2O	–The driven temperature of hot water from EGS can meet adsorption cooling requirement. –COP: more than 1. – The bigger the well depth and injection rate, the bigger the cooling capacity.
Amiri et al. [77]	–DC	–ABC –Traditional compression chiller			Libr-H_2O	–Energy saving (up to 13.0 GW h/year). –Carbon emission reduction (9208 tons CO_2). –Short payback period of 2.56–2.76 years.
Lin et al. [16]	–DC	–ABC –Mechanical sub-cooling cycle	● (CO_2)		Libr-H_2O	–High cost of the absorption cooling units (over the half of integrated system) –Short payback period (2.04–2.46 years)
Chen et al. [78]	–DC	–ABC –Spay cooling		●	Two-stage LiBr–H_2O	–Reduce cooling power consumption by 39% –Reduce electricity bill by 68% –During on-peak period: >Energy saving efficiency of 60.7% >exergy efficiency of 23.7% >operation cost saving of 83.3%
Ebrahimi et al. [79]	–DC	–ABC –Two-phase cooling			–LiBr–H_2O –Water–ammonia	–Payback periods were 7–8 months and 4–5 months for 2 MW and 10 MW DCs. –LiBr–H_2O had a superiority than water–ammonia.
Wilde et al. [82]	–High-performance computing station	–ADC –CooLMUC-2 system			Silica gel- H_2O	–Achieve both 95 kW heat removal. –Over 50 kW cold water production at the cost of only around 6 kW electricity consumption.
Pan et al. [36]	–DC	–ADC –Solar-driven cooling			Silica gel- H_2O	–Shorter payback period (0.5–2 years). –Better economic potential than solar cooling, promising in the future.
Gupta and Puri [83]	–DC	–ADC –Air-side cooling –Water-side cooling			silica gel-H_2O	–Partially or fully eliminate the cooling load of the existing vapor compression cooling system.
Endo et al. [84]	–Container DC	–Direct fresh-air cooling system >Evaporative cooling			N/A	–Maintain the server environmental conditions with acceptable ranges, –Reduce the total energy consumption by around 21% compared with container DC with CRACs.
Herold and Radermacher [86]	–DC	–Integrated cooling and power systems	●		N/A	Confirm the feasibility and attractive environmental benefit.

Notations: DC = Data center; DCMs = Data center grids; CHP= Combined cooling, heating and power; HP= Heat pump; GUI = graphical user interface; AHP = Absorption heat pump; TES=Thermal energy storage; EGS = Enhanced geothermal system; ABC = Absorption cooling; ADC = Adsorption cooling; CooLMUC-2 system = high-temperature direct-liquid cooling system.

has proposed integrated cooling and power systems for both cooling and power supplies in DCs, and confirmed its feasibility and attractive environmental benefit.

Table 4 summarized the waste heat utilization for cooling production. It can be found waste heat-driven cooling systems were widely studied in DCs, which can be realized by different cooling system (e.g., absorption cooling, adsorption cooling, evaporative cooling). The better working pair in absorption cooling system is LiBr–H_2O, while the absorption cooling system has a relatively low COP, but have the characteristics of lower cost, high reliability and simple development and construction processes. Adsorption cooling system can be applicable for lower waste heat temperature (below 60 °C) conditions, which causes less power input for pre-heating. The payback periods of both absorption and adsorption cooling systems are short, which deserve further study and optimization. In addition, other kinds of waste heat-driven cooling system (e.g., CCHP and evaporative cooling) is also applicable, but need more research and validation of its reliability from technical and economic perspectives.

5. WHR for electricity management and production

In addition to being used directly or indirectly for low-quality energy use (e.g., cooling and heating supply), waste heat from data centers (DCs) can also be used for the high-quality energy (e.g., mechanical energy and electricity) after conversion. Using waste heat for electricity production can be achieved by heat recovery cycles.

5.1. Power production by Organic Rankine Cycle

5.1.1. Principles

Yari et al. [87] compared the power performance in the Trilateral Rankine Cycle, the Organic Rankine Cycle (ORC), and Kalina Cycle driven by the waste heat. They found the ORC had the best economic benefits and was recommended for heat recovery-based electricity production. Thus, ORC is considered as the first choice for its flexible use of electricity production based on waste heat, which has the possibility to achieve WHR in DCs and electricity production. ORC system has the characteristics of simple and reliable system, and lower maintenance costs, which has been studied and implemented for many decades as a power cycle technique [88]. ORC system usually runs by organic fluids with lower boiling points, and requires an operating liquid temperature between 150 and 350 °C. When the working liquid temperature Nowadays, ORC system can be used for the heat sources from the geothermal and solar energy, biomass, desalination system, and WHR system [89]. Fig. 9 shows the schematic of an ORC system. The ORC system uses heat as the driving energy for electrical power generation, which is regarded as a power cycle, and the operating processes are divided into 4 parts [88].

1. Using a pump to pressurize the fluids, and pumping them into an evaporator;

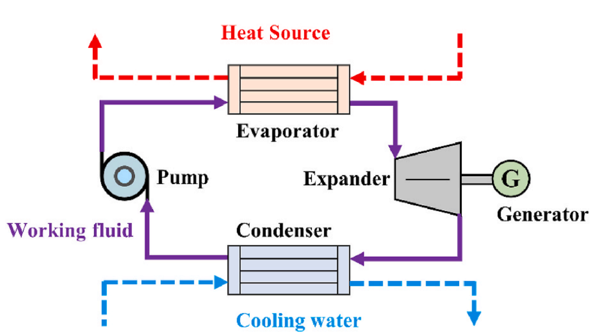

Fig. 9. Schematic of an ORC system.

2. After receiving the external heat source, the evaporator makes the ORC fluids boil;
3. The vapor fluid enters into an expander attached to a generator, and expand in the expander, where the electrical power is generated;
4. The expanded vapor enters the condenser to condense the fluid, which should be carried back to the pump.

Due to the uninterrupted waste heat production with high capacity in DCs, the generated waste heat can also be recovered and reutilized for ORC power plants for electricity production. Normally, ORC plants with HPs achieve waste heat recoveries directly from the DC equipment with refrigerant loops, or indirectly through a vapor compression cycle from a water loop connected to DC equipment [90]. As mentioned above, the typical operating temperature for the ORCs is between 150 and 350 °C, but the temperature of waste heat from DCs is normally 60–85 °C, which is far lower than the typical temperature for ORCs. However, researchers have tried many different working fluids to make OCR system more suitable for the low-grade heat sources, and they found the organic compounds (e.g., Hydrofluorocarbons) have suitable thermal properties with relatively low saturation temperatures, which are applicable for low-grade heat application [91]. In some cases that the waste heat temperatures in DCs are still lower than the required working fluid temperatures, additional electrical power is required to heat the working pair to the acceptable temperature in ORCs. Thus, thermodynamic and economic analysis should be taken into consideration in ORCs in DCs. In addition, environmental-friendly working fluid appropriate for ultra-low heat sources need be investigated.

5.1.2. Existing studies

Ebrahimi et al. [25] proposed utilizing ultra-low temperature waste heat from a dual loop DC to drive ORC system for electricity production and validated its feasibility through both thermodynamic and economic analysis. They claimed that this work firstly fully analysed the matching between ORC system and DC operating conditions. Super-heaters are always utilized in ultra-low (less than 85 °C) heat sources to boost the heat recovery temperatures, which were adopted by Ebrahimi et al. [25] as the temperatures of waste heat from DCs were below 85 °C. Through analysis, they found the super-heaters negatively impacted the overall performance due to their extra power input. In addition, the system performance is also significantly affected by increasing the waste heat temperatures (e.g., temperature differential decreasing between the chip and the micro-evaporator and increasing of chip operating temperature. They found R245fa and R134a were the optimum mediums for the ORC working fluid and the server coolant, respectively. The repayment period was 4–8 years considering the variation of regional commercial electricity cost.

Marshall and Duquette [90] tried to recover the waste heat from DC for electricity production via ORC system. They adopted a heat pump assisted ORC (HPA-ORC) and compared different low global warming potential working fluids (e.g., pentane, R161) for better thermodynamic performance and economic impact. Although the goal of their research was to better realize waste heat recovery for electricity generation, their research focuses on the impact of working fluid on the performance and economic benefits of the system. In addition, Araya et al. [88] proposed a lab scale prototype instead of modelling stage to reflect ORC-based WHR in a small DC with only two server racks at full workload of 20 kW and used a hot water cycle to stand for the waste heat from the racks. They found that the small prototype can have a maximum thermal efficiency of 3.33% and increasing the waste heat temperature by 20 °C (from 60 to 80) can increase 40% additional waste heat and increase the expander power output by 56.9%, which means the ORC can achieve significant heat recovery at ultra-low heat sources. The concluded that although there is low thermal efficiency, but its feasibility exists as the system absorbs the waste from DCs which reduces the total cooling demand and produce electricity for economic benefit back.

5.2. Power production by other technologies

In addition, Kanbur et al. [92] used fuel cells based on polymer electrolyte membrane (PEM) to effectively achieve WHR in liquid-cooled DC, and the hybrid system is composed of two-phase liquid-immersion cooling system and PEM fuel cell. The highest electricity efficiency was around 15.8%, while the efficiency would increase up to 9.16% in the case of different multi-generation. The proposed system can be considered as a combined heat and power (CHP) generation system. Combined cooling, heating and power (CCHP) and WHR systems are considered as two effective methods for energy efficiency improvement in DCs. Wan et al. [93] proposed combining CCHP and WHR in DC energy system and two strategies for energy management (namely the electrical load one with WHR (FEL-WHR) and operating cost-aware one with WHR (OCM-WHR)). They found that the combined system generally can achieve operating cost saving and are more environmentally friendly. The increase of the power generation efficiency of the CCHP system will increase the WHR rate up to 8%, and FEL-WHR performed better, and was recommended due to the better sustainability concerning the comparable operating costs compared with the OCM-WHR.

6. WHR for industrial/agricultural processes

In addition to the above-mentioned cooling, heating and power applications, DC waste heat can also be re-utilized in industrial/agricultural processes as direct heat form or converted to other forms of energy (e.g., electricity and mechanical energy), and there have been some preliminary attempts.

6.1. WHRs in desalination process

Elsaid et al. [94] claimed that waste heat utilization had been widely used in desalination causing great economic and environmental benefits (e.g., energy efficiency improvement, desalination cost saving, and lower greenhouse gases emissions). They found that wase heat can be used to drive desalination processes as direct heat form or electricity/mechanical energy forms partially or fully after conversion [95], and then comprehensively reviewed and summarized the waste heat utilization for desalination including waste heat sources and types, different desalination processes, and the benefits. They also mentioned the possibility of utilizing waste heat from DCs for desalination.

Indeed, waste heat from DCs can be used for desalination, and has been explored by some researchers. Fig. 10 shows the schematic of passive & active desalination technologies based on waste from DCs [96]. Kanbur et al. [97] proposed an improved cooling system, which adopted two-phase liquid-immersion and used waste heat from DCs for desalination, and they assessed its cooling performance by thermos-economical and thermos-dynamic multi-criteria (e.g., thermal and exergy efficiencies, capital and operation costs, the levelized product cost). Sondur et al. [96] proposed integrating the cooling system in DCs with low-temperature desalination process and applied an intelligent energy-aware control to improve energy efficiency. They tried to recover the waste heat dissipated by a modular DC with liquid-cooled rack heat exchangers and use this part of heat to drive a controlled-low-pressure desalination system for converting seawater to drinking water. The proposed system has no extra carbon cost for the desalination and can achieve significant carbon cost reduction for the DC operation. They also mentioned that for future DCs located near large bodies of brackish water, the proposed method could utilize the "free" waste heat of servers to optimally utilize low-cost cold seawater desalination to produce potable and irrigation water as by-products multivariate control scheme.

6.2. WHRs for agricultural process

Apart from industrial process, waste heat from DCs was also proposed to be utilized in agricultural process. Ljungqvist et al. [98] came up with the idea of combining the DC industry with agricultural production and investigated the feasibility of waste heat from DCs as heat sources for food greenhouse in Northern Sweden. They used IDA ICE 4.8 to build up the energy model and computed the relationship between energy supply from DC waste heat and energy demand of greenhouse production. They concluded using waste heat from DCs for self-efficiency of greenhouse food production is feasible and achievable and could achieve energy cost savings.

7. Discussions

Data and information are flooded in all aspects of our lives, and the development of the society is inseparable from the data processing, transmission, exchanging and storage. As specific device network for global cooperation, data centers (DCs) are used for data transition, calculation, acceleration, display, and data and information storage on the internet network infrastructure. Thus, the safe and efficient operation of DCs is the premise of ensuring the stability of the information society, and even everyday life.

DCs annually consume lots of energy and have direct and indirect impacts on the energy shortage and environmental impacts (e.g., greenhouse effect and global warming). IT equipment and cooling

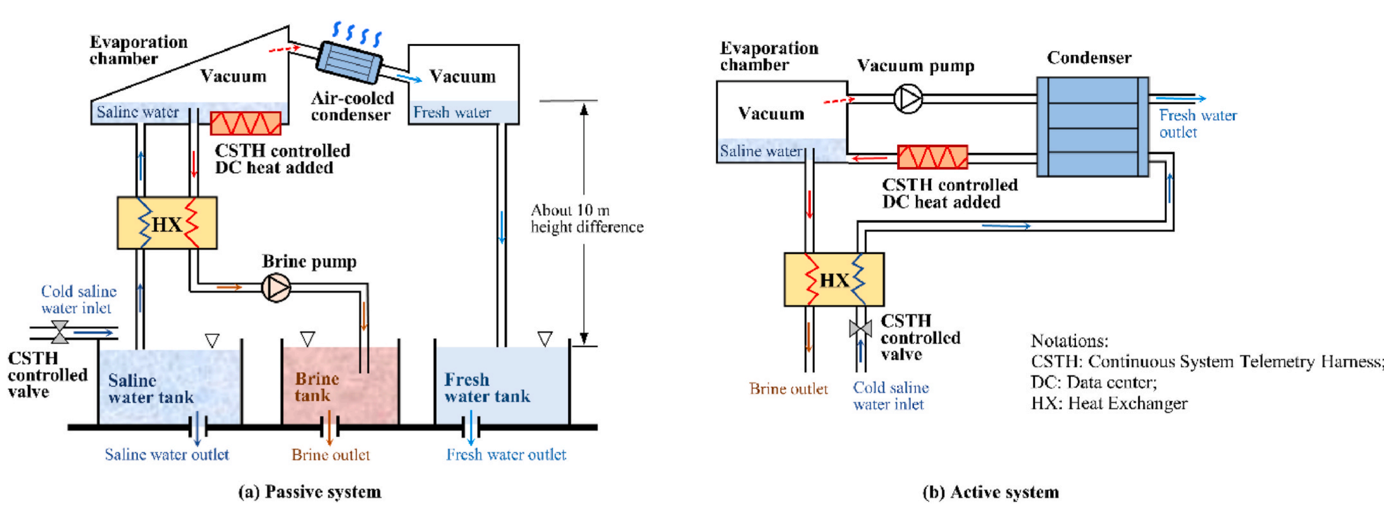

Fig. 10. The schematic of passive (left) & active (right) desalination technologies based on waste from DCs [96].

systems altogether consume approximately 84% of total energy used in typical DCs, and they are almost half-and-half. Thus, air conditioning system not only ensures the safe operation of the DCs, but also greatly affects the energy consumption of the DCs. Ensuring safe and efficient operation of DCs can be achieved by improving the IT equipment inefficiencies and enhancing the cooling system efficiency individually or simultaneously. Cooling system optimization should be the focus for HVAC researchers.

Due to the characteristic of year-round uninterrupted operation, high heat flux density, high energy consumption in DCs, there are much waste heat from exhaust air, return water, and coolants, which should be eliminate or recovered, otherwise it will be directly discharged into the outdoor environment causing thermal pollution. Waste heat recovery (WHR) technology is considered as a promising method in DCs to improve the energy efficiency, achieve energy and energy cosy, mitigate environmental impacts (caused by both carbon emission and waste heat discharge).

7.1. Waste heat sources

The possible waste heat sources from DCs are the return warm water, return hot air, and condenser coolant from air-conditioning units, while the possible WHR forms are direct heating supply, district heating (DH) supplement, cooling or electricity productions, industrial/agricultural processes. The return how water temperatures in liquid cooling system are the highest (50–60 °C) among all waste heat sources in both air-or-liquid-side cooling system, which means the biggest WHR potentials. Then, the waste heat temperatures of condenser coolants (40–50 °C) come next in air-side or air-to-liquid cooling system, which is also recommended for WHRs. In addition, the temperatures of return hot air in air-side system ranges from 25 to 47 °C, and the residual heat temperatures is sometimes high, but it is not stable for recovery. Thus, when considering WHR based on return warm air in aid-side system, its temperature stability needs to be considered.

7.2. Waste heat service objects

The serving objects of recovered waste heat include DC itself, residential buildings, office buildings, sports facilities, industry and agriculture, etc. Up to now, most studies use waste heat for the energy needs of the residential and office buildings. This is because the scale of many DCs is not very large. Although the waste heat recovered from them is uninterrupted throughout the whole year, the waste heat per unit time is limited. Thus, the waste heat is matched to the heat demand of the nearby buildings or small communities (e.g., residential building, small-scale office buildings).

7.3. Heat use form after WHRs

There are many papers on DC WHRs, with the most research on using waste heat for surrounding building heating, followed by supplement for DH networks. And there are also some cases using waste heat for cooling production and supply, more than for power generation cases. The reasons for the difference in the research heat of different forms of waste heat are as follows.

Recovered waste heat can be used for building heating system (e.g., space heating and domestic hot water) directly or after pre-heating (20–55 °C), while that for DH networks should always be preheated to 45–55 °C to the standard level. During this period, only the temperature increases, and there is no change in the form of energy. However, as the waste heat need always be heated to 45–55 °C in DH networks, its application is more energy consumed and complex than that in direct heating supply. Thus, waste heat for direct heating supply is more suitable for research and practical application with much energy saving potentials.

Apart from the waste heat for direct or indirect heating use, it can also be used for cooling production through different cooling devices (e.g., absorption chiller, adsorption chiller, evaporator cooling and CCHP system). However, waste heat-driven refrigeration process is accompanied by conversion of capacity form (e.g., the mutual conversion of thermal energy and mechanical energy). There is bound to be energy loss in the mutual conversion of high-grade and low-grade energy, and additional power is required to drive. The cooling load generated by the waste heat-driven cooling system can be reused for the cooling system of the DCs for better overall cooling effects, so it has also attracted some researchers to study. However, the waste heat utilization efficiency of heat-driven cooling system is undoubtedly lower than that of direct or indirect heat utilization system, and thus the value and number of studies on cooling system are relatively smaller than the heating system.

Furthermore, compared with the previous waste heat utilization for heating and cooling system, that for power generation is fewer, but remains possibility and feasibility. Waste heat-driven power generation is always achieved by Organic Rankine Cycle (ORC), which experiences the multiple mutual transformation of thermal energy (low temperature and high temperature), mechanical energy, and electrical energy. Thus, compared with the waste heat-driven heating or cooling system, the energy form changes the most in the electricity production process, with the most heat loss and additional electric power demand.

Last but not least, waste heat from DCs can be applicable for the industrial and agricultural processes, while the feasibility has been validated by some researchers. However, their application scope is worth considering, as only a few DCs may be built near the sea or the crops. Their findings may only apply to special cases, not general scenarios. Thus, waste heat for industrial and agricultural processes is feasible, but cannot be wide-applicable and become research hotspot.

7.4. Improving the waste heat efficiency

Heat pumps (HPs) are recommended to be used increase the waste heat operational temperature and grade for different-level heat demands, especially for medium and high-temperature DH networks. In addition, thermal energy storage (TES) is also recommended to increase the energy flexibility, which can be divided into short-term (e.g., hot water tank) and long-term (e.g., borehole) energy storage to balance the short-term and seasonal mismatch between the heat supply and demand. Finally, the use of waste heat is recommended to meet the following rules.

- Using the waste heat nearby,
- Top priority for heating supply, then DH networks, and finally cooling and power generation,
- Using HPs to increase both the heat temperature and grades,
- Using TES for mismatch balance between demand and supply,
- Using optimization methods (e.g., system management methods and multi-system optimization) and economic analysis to obtain the optimal WHR system. So far, the economic payback periods are relatively short, ranging from 2 to 8 years based on the size of DCs.

8. Conclusions

Waste heat recovery (WHR) technology is considered as a promising approach to improve energy efficiency, achieve energy and energy cost savings, and mitigate environmental impacts, whose feasibility and applicability has been studied and validated by many researchers. The uninterrupted operation of data centers (DCs) with high energy consumption and high heat flux density leads to the existence of huge waste heat, and if this part of waste heat is not eliminated or reused, it will be discharged into the outdoor environment to cause thermal pollution. Thus, recovering the waste heat from DCs seems very promising and worth investigating. In fact, the feasibility and reliability of WHR in DCs has been widely validated, and the system is continuously optimized for better operation and energy, environmental and economic sustainability. This article conducts a comprehensive review on recovering waste heat from all kinds of sources (e.g., exhaust air, circulating water, and coolants) in DCs for various energy uses (e.g., heating supply, district heating supplement, cooling and electricity productions, and industrial/agricultural processes) and different application scenarios (e.g., office buildings, comprehensive energy community and residential buildings, sports facilities).

The broad findings and recommendations are as follows.

1. DC waste heat-driven system for heating supply, district heating (DH) networks, cooling and power generation, and others have been proven feasible and applicable in terms of their technical, energy, exergy, environmental and economic (4 E) analysis.
2. The most efficient ways of reusing waste heat in DCs are for the heating supply in nearby buildings directly of after pre-heating, and for supplementing DH networks.
3. The heating system (including DH network supplement) can be further optimized and recommended by using heat pumps for the heat temperature and grade upgrading, and by adopting the thermal energy storage systems for better energy flexibility (balancing mismatch between heat supply and demand).
4. Waste heat for other purposes (e.g., cooling and power production) is also feasible, but requires conversion of energy form (e.g., conversion between thermal energy, mechanical energy, and electrical energy) causing energy loss and additional power input. Thus, their technical, 4 E performances should be taken into consideration before applications.
5. Waste heat used in industry (especially desalination) and agriculture process should be adapted to local conditions consider the location of most DCs.
6. The system optimization methods based on the existing waste heat recovery system should be the focus of future research, and the combination with other energy-efficient systems (e.g., combined cooling, heating and power system, low-temperature energy community) should also be considered in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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