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Developing an active heat recovery system to boost data centre waste heat utilization: a novel and cost-effective solution for building decarbonisation

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ABSTRACT

Data centre (DC) waste heat recovery for district-heated buildings often relies on costly heat pumps. However, the rise of liquid-cooled distributed/edge DCs driven by increasing computational demand offers new potential for cost-effective onsite recovery. These systems produce higher-temperature waste heat, making heat exchanger-only solutions more feasible. Yet full recovery remains challenging due to high return water temperatures in building heating networks and the passive nature of such systems. To overcome these limitations, this paper proposes an active DC waste heat recovery system (AHE-DCWHR) that enhances heat exchanger-only solutions through an innovative heating demand reallocation strategy. This strategy utilizes a small heat pump (1) to precool the return water of one heating network before entering the heat exchanger, increasing the inlet temperature difference to enable near-complete waste heat recovery, and (2) to reuse the extracted precooling energy to heat another network, minimizing losses. AHE-DCWHR was validated in TRNSYS through 25-year life-cycle cost (LCC) and emission analyses for a liquid-cooled DC suppling 25 kW of waste heat to a district-heated building. During the 5-month winter, AHE-DCWHR consumed only 7.5 MWh of electricity for the heat pump (average COP = 4.75), enabling the heat exchanger to recover 98.4 % of the waste heat (~90 MWh), a 16 % improvement over the heat exchanger-only system (75.1 MWh). Based on 25-year LCC and emission analyses, it saves €123,431 heating costs (vs. €106,501 for the heat exchanger-only system), cuts CO_2 emissions by 167,087 kg (vs. 134,711 kg), and achieves a two-year payback. AHE-DCWHR cost-effectively outperforms heat exchanger-only and heat pump systems.

1. Introduction

Based on the 2023 report by the International Energy Agency, buildings represent 30 % of the world's final energy consumption and 26 % of energy-related emissions, with CO_2 being the predominant emission in this sector [1]. Concurrently, with the exponential growth of artificial intelligence and ChatGPT, energy consumption in data centres (DCs) is skyrocketing. Vinson & Elkins survey shows that DCs constitute approximately 2.5 % of U.S. electric demand, a figure projected to increase to 20 % by 2030. Cryptocurrency mining, consuming about 0.4 % of global annual electricity, has seen an electricity demand growth of 2300–3500 % from 2015 to 2022 [2]. A recent analysis by The Guardian claims that DC emissions could be 662 % higher than reported by major tech companies. With the surge in energy demand in DCs, liquid cooling is expected to dominate in the future, which benefits waste heat recovery due to the relatively higher temperatures compared to the conventional air-cooled DCs [3]. This offers a significant decarbonisation pathway for both the building sector and DCs, presenting a win-win solution for combating climate change. As Nordic countries are pioneers in energy transition, Finland, for example, aims to achieve carbon neutrality and become the first fossil-free welfare society by 2035 [4]. DCs in Nordic countries have emerged as important heating resources for buildings decarbonisation [3].

1.1. Literature review

District heating (DH) systems are regarded as a key technology and

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Nomenclature

C_0	initial investment cost in euros (€)
$C_{coolant}$	heat capacity rate of the coolant (kW/^{o}C) on the secondary side of the CDU (cooling distribution unit)
$c_{hx,ld}$	liquid specific heat capacity on the source side of WHR_HX (kJ/kg/^{o}C)
$c_{hx,src}$	liquid specific heat capacity on the source side of WHR_HX (kJ/kg/^{o}C)
C_n	annual cash flow in euros (€)
C_n^{DH}	cost savings from district heating used for both space and ventilation heating networks (€)
$C_n^{electricity}$	electricity cost for operating the heat pump (€)
$C_n^{maintainance}$	maintenance cost associated with both C_n^{DH} and $C_n^{electricity}$ (€)
$E_{CO2,red}$	annual CO_2 emission reduction (kgCO_2/MWh)
$\dot{m}_{hx,ld}$	mass flow rate on the load side of WHR_HX (kg/s)
$\dot{m}_{hx,src}$	mass fluid rate on the source side of WHR_HX (kg/s)
$\dot{m}_{vh}$	total mass flow rate of the ventilation heating network (kg/s)
N	total number of years
$\dot{q}_{server}$	power dissipated by servers (25 kW)
$\dot{q}_{waste}$	heat transfer rate through the heat exchanger (kW)
$\dot{q}_{waste,avg}$	the average recovered waste heat (kW) during simulation period (01.11.2023–31.03.2004)
$\dot{Q}_{sh}$	current space heating demand (kW)
$\dot{Q}_{vh}$	current ventilation heating demand (kW)
$Q_{DH,sv}$	saved district heating energy (MWh)
Q_{HP}	electricity consumption for the heat pump (MWh)
r	discount rate
$T_{coolant,in}$	rack inlet coolant temperature (°C)
$T_{coolant,out}$	rack outlet coolant temperature (°C)
T_{waste}	waste heat temperature on the primary side of CDU (°C)
T_{rtn}	return water temperature for a heating network (°C)
$T_{rtn,avg}$	the average return water temperature of the ventilation heating network during the simulation period (01.11.2023–31.03.2004) (^{o}C)
$T_{rtn,h}$	heated return water temperature after WHR_HX (°C)
$T_{sh,r}$	return water temperature for the space heating network (°C)
$T_{TV3Mixing}$	return temperature of the ventilation heating network at the TV3Mixing point (°C)
$T_{vh,r}$	return water temperature for the ventilation heating network (°C)
ε_{DH}	emission factor for district heating (kgCO2/MWh)
$\varepsilon_{electricity}$	emission factor for electricity (kgCO2/MWh)
ε_{waste}	effectiveness of the heat recovery heat exchanger
φ_{sh}	mass flow rate ratio of return water from the space heating network to the load-side flow of WHR_HX
φ_{vh}	mass flow rate ratio of return water from the ventilation heating network to the load-side flow of WHR_HX

Abbreviations

AHE-DCWHR	active heat exchanger data centre waste heat recovery
CDU	cooling distribution unit
CDU_HX	CDU liquid-to-liquid heat exchanger
CHP	Combined heat and power
CO_2	carbon dioxide
COP	coefficient of performance
DC	data centre
DH	district heating
HOB	heat only boiler
LCC	life cycle cost
NPV	net present value

policy in the EU for decarbonising the building sector [5]. In Nordic nations, DH networks are extensively utilized for warming buildings. In Finnish cities, for example, more than 90 % of apartment buildings and 70 % of other structures rely on DH [6]. Each building is equipped with a DH substation featuring heat exchangers that separate the primary DH network from the secondary water networks [7]. DH is then circulated through these secondary networks to provide hot water and heating to buildings. CO_2 emissions in DH-heated buildings can be reduced through both direct and indirect approaches. The direct approach involves retrofitting secondary side networks to reduce DH demands by integrating additional renewable sources such as geothermal, solar energy, and building waste heat into the heating networks [3,8]. The indirect approach utilizes renewable energy, and industrial and building waste heat within DH networks to lower CO_2 emissions [3,9–13]. Both direct and indirect methods can be applied in DCs to reduce CO_2 emissions. Harnessing waste heat from DCs can also diminish their cooling demands, further contributing to CO_2 emission reductions. In both methods, heat pumps are commonly adopted to upgrade liquid-cooled DC waste heat for local DH networks, nearby and onsite building heating networks.

Hiltunen et al. [14] examined the potential of DC waste heat in the DH network of Espoo, Finland, as a substitute for fossil-based heat production. In 2016, the DH network had a production capacity exceeding 1200 MW_{th} and met about 2.4 TWh of annual heat demand, including distribution losses. The plan aimed to achieve 85 % carbon-neutral heat by 2026 by replacing an 80 MW_{th} coal-fired HOB (heat only boiler) and a 160 MW_{th} coal-fired CHP plant with two wood-chip-fired HOBs and wastewater and DC heat pumps. The study focused on a 100 MW_{th} DC heat pump with a COP (coefficient of performance) of 5.5, recovering liquid-cooled DC waste heat at 44 °C and supplying 70 °C water to the DH network. EnergyPro simulations confirmed that integrating DC waste heat could enable 85 % carbon-neutral heat production, reducing the average production cost from €34.89/MWh to €33.34/MWh and annual CO_2 emissions from 168.1 ktonCO$_2$ to 128.5 ktonCO$_2$. Oltmanns et al. [15] proposed using a 360 kW liquid-cooled DC on a university campus to supply heat to campus buildings. The campus heat and power station provided heating for these buildings, while the DC waste heat at 45 °C was upgraded by a heat pump, raising the station's return line temperature from 55-70 °C to 60-75 °C-an increase of about 5 °C. Simulations using IDA ICE indicated that roughly 50 % of the waste heat (about 1600 MWh annually) could be recovered, reducing annual CO_2 emissions by around 720 tons (≈4.2 %). The high waste heat temperature enabled the heat pump to achieve an average COP of 6.8.

Despite the reduction in CO_2 emissions and alignment with the EU's climate targets, the higher upfront cost of heat pumps has hindered their deployment [16]. Recently, the rapid increase in server power densities has driven the adoption of liquid-cooled distributed/edge DCs, which may offer a solution to this challenge by using cost-effective heat exchangers alone, eliminating the need for heat pumps [3]. In particularly, the direct-to-chip cooling has gained great popularity. It employs cold plate technology to cool high-heat electronic components like CPUs, GPUs, and memory modules [17–22]. It can produce waste heat of 50 °C upward [23], making it compatible with the maximum supply water temperature of certain low-temperature building heating. Commercial buildings typically have two heating networks for warming buildings in their DH substations: one for space heating and one for ventilation heating. Space heating networks are usually connected to radiators, while ventilation heating networks supply heat to air handling units to warm outdoor air to the desired temperatures. The supply water temperature for the secondary side networks of two heating networks can be as low as 45 °C for radiator heating and 35 °C for underfloor heating [3, 8]. Consequently, this high-quality waste heat could be directly reused without the need for a heat pump for both heating systems.

Zimmermann et al. [19] tested Aquasar, a DC prototype cooled with hot water and designed for waste heat reuse. The system housed both water- and air-cooled IBM BladeCentre servers with a total load of 7–8 kW. About two-thirds of the servers used direct-to-chip liquid cooling, while the rest were air-cooled. The cooling system consisted of three loops: a primary loop that cooled the electronic components, transferring heat to an intermediate loop via a heat exchanger, and then to the building heating grid through another heat exchanger. A three-way valve in the intermediate loop could also supply additional cold water to prevent overheating. Results showed that about 80 % of the waste heat from the liquid-cooled components was successfully recovered for the building heating grid.

Lu et al. [3] investigated the use of direct-to-chip cooling and the distributed/edge DC concept to recover waste heat from a single liquid-cooled rack for an office building's secondary heating network, aiming to reduce DH consumption. The DC, located inside the building, had a total capacity of 50 kW–30 kW for direct-to-chip cooling of one rack and 20 kW for free air cooling. A steady 25 kW of heat was recovered from the liquid-cooled rack. The office building's annual space heating demand was 285,662 kWh, with maximum secondary network temperatures of 45 °C (supply) and 30 °C (return). Two heat exchanger configurations were analysed: Configuration 1, connected to the secondary side of the cooling distribution unit (CDU), and Configuration 2, connected to the primary side. Life cycle cost (LCC) and CO_2 emission reductions were evaluated over 25 years using TRNSYS 18 simulations. Both configurations achieved payback periods of less than one year. Configuration 1 performed better in DH savings, electricity savings for the dry cooler and CDU pump, and CO_2 emission reduction. Annually, it utilized about 71 % of the waste heat compared with 63 % in Configuration 2. Over 25 years, Configuration 1 reduced CO_2 emissions by 291,996 kg, while Configuration 2 achieved a reduction of 258,192 kg. Similar studies using only heat exchangers for waste heat recovery from liquid-cooled DCs include [15]. Despite advancements, the use of heat exchangers alone faces challenges because, although the return water temperatures in these networks are lower than the waste heat temperatures, they are not low enough for full waste heat recovery, leading to inefficient DC waste heat recovery.

1.2. Challenges for state-of-art liquid-cooled DC waste heat recovery solutions

In summary, the literature indicates that DC waste heat can be utilized for local DH networks or for nearby and onsite buildings. Distributed/edge DCs, typically located within buildings, are particularly suited for supplying waste heat to onsite heating systems, effectively serving as data furnaces [3]. Two primary types of liquid-cooled DC waste heat recovery systems have been identified: (1) heat pump-based systems [14,15] and (2) heat exchanger-only systems [3,15], which rely solely on heat exchangers for heat recovery. Due to the supply water temperature requirements of energy companies, heat pump systems are typically preferred for DH networks. Both suffer from either economic or technical limitations. For example, for a 100 kW liquid-cooled DC, since DC waste heat is commonly used directly as a heat pump's heat source in a heat pump system, this requires a heat pump with at least 100 kW heat absorption capacity, leading to high investment and operation costs.

In commercial buildings, ventilation heating networks typically have higher demand and lower return water temperatures than space heating networks, making them more suitable for DC waste heat recovery through heat exchangers-especially in small distributed/edge DCs, where near-complete heat recovery is achievable and highly beneficial during cold winters. However, current heat exchanger-only systems [3, 15]-particularly those recovering waste heat from the primary side of liquid cooling systems (e.g., internal CDUs integrated within racks [24])-face limitations due to their passive nature, as they depend on the return water temperatures of building heating networks for full DC waste heat recovery. Although enlarging the heat transfer area of the heat exchanger in a heat exchanger-only system may enhance its effectiveness, it does not ensure complete recovery of DC waste heat. Even with a theoretical effectiveness of 1, a sufficient temperature difference between the DC waste heat and the return water of the building heating network remains essential for full recovery. In many practical cases, the return water temperature of the ventilation heating network is not low enough to provide this required temperature difference, resulting in partial rejection of the available waste heat. Increasing this temperature difference can indeed enable full waste heat recovery in the heat exchanger; however, achieving this requires extracting energy from the return water of building heating networks, and efficiently reusing this energy to minimize losses remains a challenge.

Therefore, a clear research gap exists in developing cost-effective and scalable solutions for decarbonizing heating in DH-supplied buildings. Specifically, there is a need for systems that can achieve near-complete waste heat utilization than heat exchanger-only systems while remaining more economically viable than conventional heat pump systems.

1.3. Innovations and contributions

This study addresses the identified research gaps by developing an active heat exchanger DC waste heat recovery (ACH-DCWHR) system, which enhances heat exchanger-only systems.

The goal of the ACH-DCWHR system is to provide a solution that enables existing heat exchanger–only systems reported in the literature to achieve potential full DC waste heat recovery with minimal electricity consumption. Unlike existing conventional heat exchanger–only systems, the ACH-DCWHR system combines a heat exchanger for direct DC waste heat recovery with a small heat pump that lowers the return water temperature of the building heating network. This increases the temperature difference between the source and load inlet temperatures, thereby enabling complete DC waste heat recovery with minimal electricity consumption. The system is designed to recover waste heat from small liquid-cooled distributed/edge DCs and supply it to the onsite building's heating networks.

The key contributions are.

- The AHE-DCWHR system is based on a novel concept of heating demand reallocation, which employs a compact, low-power heat pump to transfer heat from the ventilation heating network's return line to that of the space heating network. This reallocation of heating demand between the two heating networks offers the following advantages for achieving complete DC waste heat recovery:

1. **Enhanced temperature difference for the heat exchanger**: The return water of the ventilation heating network is precooled before entering the heat exchanger, increasing the temperature difference needed for nearly complete recovery of the available waste heat from the liquid-cooled DC.
2. **Energy reuse:** The precooling energy extracted from the ventilation heating network's return water is reused to heat the space heating network. This is the core of the heating demand reallocation concept. Without it, increasing the temperature difference across the heat exchanger would require considerable energy. In practice, implementing this process via a small heat pump requires minimal electricity, as the heat pump's COP is typically near 5 due to return water temperatures exceeding 20 °C. Thus, only about 25 % of the precooling energy input is needed to achieve full DC waste heat recovery.
3. **A small-capacity heat pump used.** In the AHE-DCWHR system, the heat pump's role is limited to precooling the return water of the

ventilation heating network to increase the temperature difference between the source and load inlets, enabling full recovery of DC waste heat by the heat exchanger. Essentially, the heat pump assists the heat exchanger in recovering only the portion of waste heat that the heat exchanger alone cannot recover—typically a much smaller amount than the total waste heat. Consequently, compared with conventional heat pump systems where large heat pumps are required to recover all DC waste heat, the AHE-DCWHR system achieves full recovery using a significantly smaller and more energy-efficient heat pump.

4. **Efficient waste heat utilization:** Due to the heat transfer (i.e., heating demand reallocation) from the ventilation heating network to the space heating network, the ventilation heating demand increases, ensuring that DC waste heat is always reused through the ventilation heating network-even when the available waste heat exceeds its demand. In such cases, the recovered waste heat is able to be shared across both heating networks without flow mixing, thereby simplifying hydraulic control. In contrast, conventional heat exchanger-only systems must mix the return water flows from the two heating networks to enable waste heat utilization across them.

By intelligently reallocating heating demand, the AHE-DCWHR system overcomes the limitations of passive systems and reduces reliance on large, high-capacity heat pumps. The result is a highly efficient, cost-effective, and scalable solution for DC waste heat recovery that surpasses conventional heat exchange-only and heat pump systems in both performance and economic viability.

- The AHE-DCWHR system was validated using the TRNSYS commercial simulation package, based on a real-world liquid-cooled DC developed under the EU-funded WSTAR project, demonstrating an efficient and scalable solution for DC waste heat recovery.

Overall, the key innovation of the AHE-DCWHR system lies not merely in improving existing heat exchanger-only systems, but in enabling them to achieve complete DC waste heat recovery with minimal electricity consumption through the innovative concept of heating demand reallocation using a small auxiliary heat pump.

The paper is organised as follows.

- Section 2 introduces the building's space and ventilation heating networks and the liquid-cooled rack used in the study. It also presents the state-of-the-art heat exchanger-only system and provides a detailed comparison between the heat exchanger-only and AHE-DCWHR systems within the context of the case study.
- Section 3 describes the TRNSYS models developed for the heat exchanger-only and AHE-DCWHR systems. It also outlines the LCC and CO_2 emission reduction methodologies, along with investment, installation, and maintenance cost assumptions for both systems.
- Section 4 presents and analyses the results from Section 3, with a focus on DH savings, LCC performance, and CO_2 emission reductions of the AHE-DCWHR system compared to the heat exchanger-only system.
- Section 5 concludes the paper and outlines directions for future research.

2. Methodology

This study aims to present a proposed DC waste heat recovery system capable of fully utilizing waste heat from distributed/edge DCs to supply the onsite building's heating networks. Specifically, the goal is to significantly enhance the performance of current state-of-the-art heat exchanger-only systems that rely solely on heat exchangers. To achieve this, we will first provide a detailed description of the distributed/edge DC facility and the onsite building's space and ventilation heating networks. Next, we will present the existing heat exchanger-only systems, highlighting their limitations. Finally, the proposed AHE-DCWHR system is introduced as a cost-effective solution that overcomes the limitations of existing systems to enable complete DC waste heat recovery.

2.1. Facility description

2.1.1. Building heating networks

Fig. 1 illustrate layouts of typical building space and ventilation heating networks.

In this study, the building heating networks refer to the secondary networks of the building systems, which are directly connected to the heat emitters (e.g., radiators, heating coils), rather than the primary networks linked to the local DH networks managed by the energy company. Waste heat recovery systems, such as those examined here, are typically permitted to connect only to the secondary networks. In Fig. 1, the control centre regulates TV1 and TV2 in the primary networks to control the DH flow to heat exchangers 101 and 102, maintaining the secondary supply water temperature at the set value based on outdoor temperature. This regulation does not affect the operation of a waste heat recovery system on the secondary network. Consequently, only measurements from the secondary networks are available (see Fig. 1), while supply and return water temperature data from the primary network are not measured and are therefore not illustrated in Fig. 1.

The real case study of Fig. 1 represented in this paper is located in an office building in Vaasa, Finland (63°06′N, 021°37′E), with a gross floor area of 3268 m^2. Both heating networks are fully supplied by DH. In 2023, measured heating energy consumption was 95.8 MWh for space heating and 178.1 MWh for ventilation heating, with the latter exhibiting significantly higher demand. This study focuses on the winter months (January, February, March, November, and December), which account for over 70 % of the building's annual heating consumption. Utilizing DC waste heat during this period presents strong potential for CO_2 emission reductions and cost savings, given the elevated DH pricing in winter.

During winter, the return water temperature of the ventilation heating network ranges from 22 °C to 33 °C (average 27 °C), while that of the space heating network ranges from 26 °C to 44 °C (average 34 °C). Due to its approximately 7 °C lower average return temperature, the ventilation network is more suitable for recovering high-grade DC waste heat via heat exchanger-only systems.

Although based on real case data, the network configurations in Fig. 1 are representative of typical configurations in modern commercial buildings, for example post-2000 ones in Northern Europe, where ventilation heating networks generally exhibit higher heating demands and lower return water temperatures than space heating networks.

2.1.2. WSTAR data centre

The case study DC is the distributed/edge WSTAR DC, which allocates 30 kW for direct-to-chip liquid cooling in a single rack and 20 kW for free air cooling [3]. Waste heat from the 30 kW liquid-cooled rack is recovered to supply the onsite building heating networks (Fig. 1). The liquid-cooled rack (Fig. 2) is situated within the building, adjacent to the DH substation, which houses the primary piping, equipment (e.g., heat exchangers, pumps), and sensors for the space and ventilation heating networks depicted in Fig. 1.

In a self-contained liquid-cooled rack (see Fig. 2), the CDU is typically integrated within or positioned adjacent to the rack [24]. In such configurations, the secondary side of the CDU is located inside the rack, making access difficult. Therefore, in this study, waste heat recovery is carried out from the primary side of the CDU, which is more accessible and common in practice.

Because the liquid cooling system shown in Fig. 2 has been thoroughly detailed in Ref. [3], we only provide a brief overview here. A steady 25 kW of heat is assumed to be captured from this 30 kW rack. All liquid-to-liquid heat exchangers in this study are assumed to have a constant effectiveness of 0.7 [3,25–27]. Commercial CDU products from

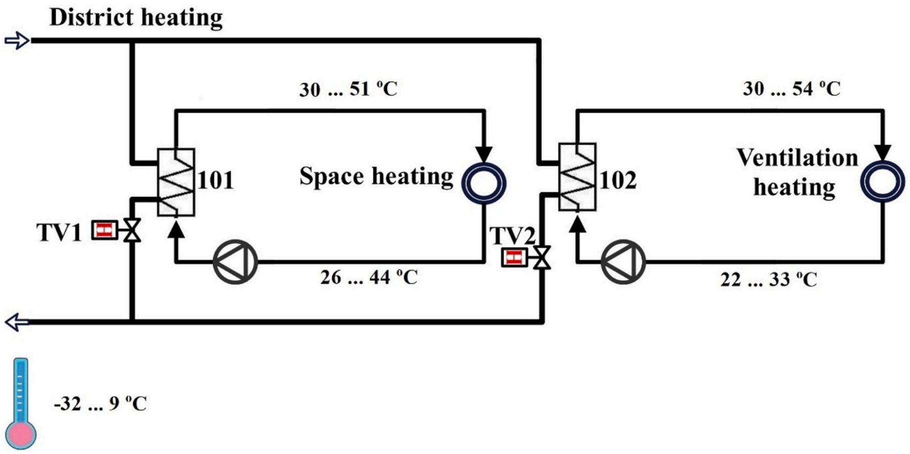

Fig. 1. Building space and ventilation heating networks.

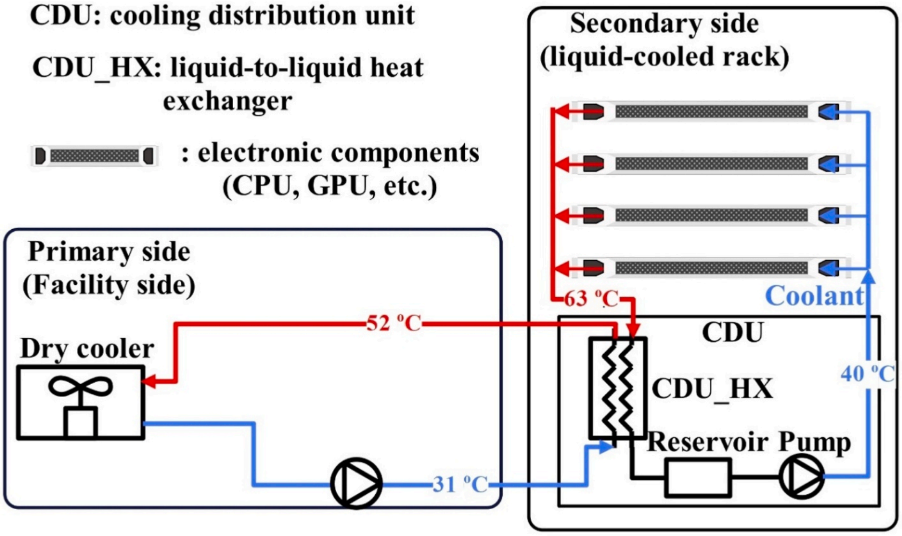

Fig. 2. The layout of the liquid-cooled rack.

Asetek [27], nVent [28], and CoolIT [29] typically have a liquid-to-liquid heat exchanger effectiveness ranging from 0.5 to 0.8 [3]. Therefore, an effectiveness of 0.7 is a realistic and commonly adopted value for modeling DC waste heat recovery systems in the literature, particularly in TRNSYS-based studies [3,25,26].

All relevant input data for the CDU are sourced directly from Ref. [3]. The resulting input data are shown in Table 1. Details about the dry cooler and circulation pumps (see Fig. 2) are omitted here as they are not significant for this study (see Table 1 in Ref. [3]).

The coolant inlet temperature (40 °C in Fig. 2) is maintained at approximately 40 °C in this study, which is close to Asetek's experimental value of 41 °C [27]. The coolant outlet temperature on the secondary side (63 °C in Fig. 2) is calculated using the following formula [3]:

$$T_{coolant,out} = T_{coolant,in} + \frac{\dot{q}_{server}}{C_{coolant}} \tag{1}$$

where $T_{coolant,out}$ and $T_{coolant,in}$ are coolant outlet and inlet temperatures respectively (°C), $\dot{q}_{server}$ is the power dissipated by servers (25 kW) and $C_{coolant}$ is the heat capacity rate of the coolant (kW/°C) on the secondary side. In practice, the power dissipated by servers ($\dot{q}_{server}$) is not constant and increases as the coolant inlet temperature ($T_{coolant,in}$) decreases. However, in this case study, the coolant inlet temperature is nearly constant at 40 °C, so the formula remains valid and the coolant outlet temperature is kept near 63 °C. Asetek's experimental coolant inlet and outlet temperatures are reported as 41 °C and 65 °C on the secondary side, respectively [27], which are close to the values used in this study.

Table 1
Some important input data for modelling the case liquid-cooled rack.

CDU (coolant distribution unit)	
Heat exchanger effectiveness (CDU_HX as well as other heat exchangers)	0.7 [3, 25, 26, 27]
Secondary side	
Coolant specific heat capacity (kJ/kg.°C)	3.91 (water mixed with propylene glycol) [3]
Mass flow rate (kg/h)	1000 [3]
Primary side	
Fluid specific heat capacity (kJ/kg. °C)	3.53 (water mixed with propylene glycol) [3]
Mass flow rate (kg/h)	1200 [3]

2.2. State-of-the-art DC waste heat recovery systems and limitations

State-of-the-art DC waste heat recovery systems include heat pump systems and heat exchanger-only systems, as discussed in Section 1. In the case of heat pump systems [30], the heat pump must have a minimum heat absorption capacity of 25 kW to fully recover 25 kW of waste heat from the DC, which are associated with high capital, operational, and maintenance costs. Therefore, they are excluded from consideration from cost-effective perspective. Instead, the focus is placed on the more economical heat exchanger-only systems illustrated in Fig. 3.

Fig. 3 depicts the layout of the heat exchanger-only system design for the liquid-cooled rack.

2.2.1. *Governing equations for the heat exchanger-only system*

As shown in Fig. 3, when using waste heat to raise the return water temperatures of the heating networks through a liquid-to-liquid heat exchanger (WHR_HX), the heat transfer rate ($\dot{q}_{waste}$, kW) is determined by the following formula, provided the liquid heat capacity rate on the load side of the heat exchanger is greater than that on the source side:

$$\dot{q}_{waste} = \varepsilon_{waste} c_{hx,src} \dot{m}_{hx,src} (T_{waste} - T_{rtn}) \tag{2}$$

where $c_{hx,src}$ and $\dot{m}_{hx,src}$ are the liquid specific heat capacity (kJ/kg/^{o}C) and mass fluid rate (kg/s) on the source side of the heat exchanger, T_{waste} is the waste heat temperature on the primary side (52 °C in Fig. 3), T_{rtn} is the return water temperature from the heating networks (28 °C in Fig. 3) and ε_{waste} is the effectiveness of the heat exchanger (0.7 in this study). The multiplication of mass flow rate and specific heat capacity is also called liquid heat capacity rate (kW/^{o}C). According to Eq. (2), Table 1, and Figs. 2 and 3, the return water temperature T_{rtn} must be reduced to 22 °C, namely the temperature difference between load and source inlet temperatures must be greater than 30 °C for WHR_HX, to enable full recovery of 25 kW of DC waste heat.

The load flow rate is set to constant 1080 kg/h (see Fig. 3), ensuring that the heat capacity rate on the load side of the heat exchanger WHR_HX is greater than that on the source side, even at full load (1200 kg/h). This way, according to Eq. (2), the recovered waste heat is determined entirely by the flow rate on the source side of WHR_HX, which can be regulated by the three-way valve TV4.

The load-side fluid of WHR_HX is a mixture of return water from both the space and ventilation heating networks, determined by the following mass flow rate ratios:

$$\varphi_{vh} = 1, \varphi_{sh} = 0 \; when \; \dot{Q}_{vh} \geq 25 \; kW,$$

$$\varphi_{vh} = \frac{\dot{Q}_{vh}}{\dot{Q}_{vh} + \min\left(\dot{Q}_{sh}, \left(25 - \dot{Q}_{vh}\right)\right)}, \varphi_{sh} = 1 - \varphi_{vh} when \; \dot{Q}_{vh} < 25 \; kW \tag{3}$$

where φ_{vh} and φ_{sh} represent the mass flow rate ratios of return water from the ventilation and space heating networks, respectively, to the load-side flow of WHR_HX. $\dot{Q}_{vh}$ and $\dot{Q}_{sh}$ denote the current ventilation and space heating demands (kW), with 25 kW corresponding to the DC waste heat capacity. According to Eq. (3), DC waste heat is first allocated to the ventilation heating network due to its lower return water temperature. Any surplus is then directed to the space heating network. For instance, Fig. 3 shows a case where all recovered DC waste heat is used solely for heating the ventilation heating network, as its heating demand exceeds 25 kW.

The load inlet temperature of WHR_HX, denoted as T_{rtn} in Eq. (2) and represented by the mixed temperature at the TV3TV5Mixing point in Fig. 3, is calculated as:

$$T_{rtn} = T_{vh,r} \varphi_{vh} + T_{sh,r} \varphi_{sh} \tag{4}$$

where $T_{vh,r}$ and $T_{sh,r}$ are the return water temperatures (^{o}C) from the ventilation and space heating networks, respectively.

The load outlet temperature of WHR_HX, i.e., the warmed return water after heat recovery ($T_{rtn,h}$, ^{o}C), is calculated as:

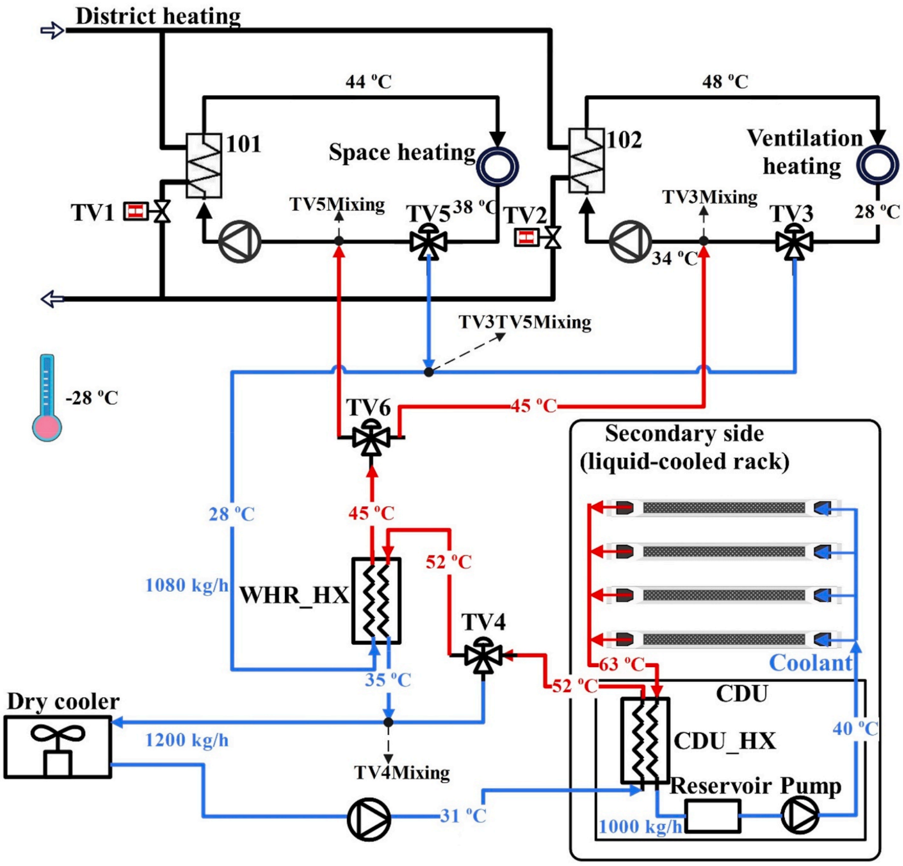

Fig. 3. The layout of the heat exchanger-only system for the liquid-cooled rack (WHR_HX: waste heat recovery heat exchanger).

$$T_{rtn,h} = T_{rtn} + \frac{\dot{q}_{waste}}{c_{hx,ld}\dot{m}_{hx,ld}} \tag{5}$$

Where $c_{hx,ld}$ is the specific heat capacity (4.186 kJ/kg/°C for water), and $\dot{m}_{hx,ld}$ is the mass flow rate (kg/s) on the load side of WHR_HX.

The final return temperature of the ventilation heating network at the TV3Mixing point (Fig. 3), $T_{TV3Mixing}$ (^{o}C), is given by:

$$T_{TV3Mixing} = T_{rtn,h}\frac{(\dot{m}_{hx,ld}\varphi_{\ vh})}{\dot{m}_{vh}} + T_{vh,r}\left(1 - \frac{(\dot{m}_{hx,ld}\varphi_{\ vh})}{\dot{m}_{vh}}\right) \tag{6}$$

where $\dot{m}_{vh}$ is the total mass flow rate of the ventilation heating network (kg/s) (Note: $\varphi_{\ vh} = 1$ for the AHE-DCWHR system when using this equation, see Section 2.3).

Eqs. (2) and (5)–(6) are fundamental to modelling both the heat exchanger-only and AHE-DCWHR systems. The temperature $T_{TV3Mixing}$ is monitored in both systems to regulate DC waste heat flow to WHR_HX. Given the ventilation heating network's lower return temperature and higher heating demand, prioritizing its use for DC waste heat recovery is essential. Therefore, monitoring $T_{TV3Mixing}$ is sufficient, even when the return flow to WHR_HX includes mixed return water from both heating networks (as described in Eq. (3)).

The heat exchanger-only system operates as follows in this study.

- When the ventilation heating demand is $\geq$ 25 kW, the three-way valve TV4 is fully opened to maximize DC waste heat recovery through WHR_HX.
- When the ventilation heating demand is $<$ 25 kW, TV4 modulates the source flow to WHR_HX, ensuring that the warmed return water temperature of the ventilation heating network (TV3Mixing in Fig. 3) approaches the current supply temperature setpoint, based on measured data.

2.2.2. Limitations

As low-temperature DH networks gain attraction globally, new regulations aim to reduce return water temperatures on the secondary side of building heating systems. For instance, Finnish regulations for new buildings and major renovations recommend return temperatures not exceeding 30 °C [8]. Low-carbon policies support wider application of heat exchanger-only systems as state-of-the-art waste heat recovery solutions, given their advantages of low capital, operational, and maintenance costs.

However, as detailed above, the systems cannot ensure complete DC waste heat recovery, primarily due to their inherent limitation, their passive nature. They are unable to actively adjust operating conditions such as the temperature difference between source and load inlets, which significantly limits the potential for full waste heat recovery.

2.3. New solution: active heat exchanger DC waste heat recovery (AHE-DCWHR) systems

To address the limitations of the state-of-the-art waste heat recovery systems, we propose a new system, AHE-DCWHR system, designed to overcome the passive nature of the heat exchanger-only system and enable near-complete DC waste heat recovery at minimal costs. The system diagram is shown in Fig. 4.

As shown in Figs. 3 and 4, both systems utilize heat exchanger WHR_HX for waste heat recovery. The key difference is that the AHE-DCWHR system incorporates an additional heat pump, based on an entirely new technical concept. This concept will be explained in detail in the following sections, where the system's performance advantages are assessed. Further advantages of the proposed system, particularly in comparison to heat exchanger-only systems, will also be presented below.

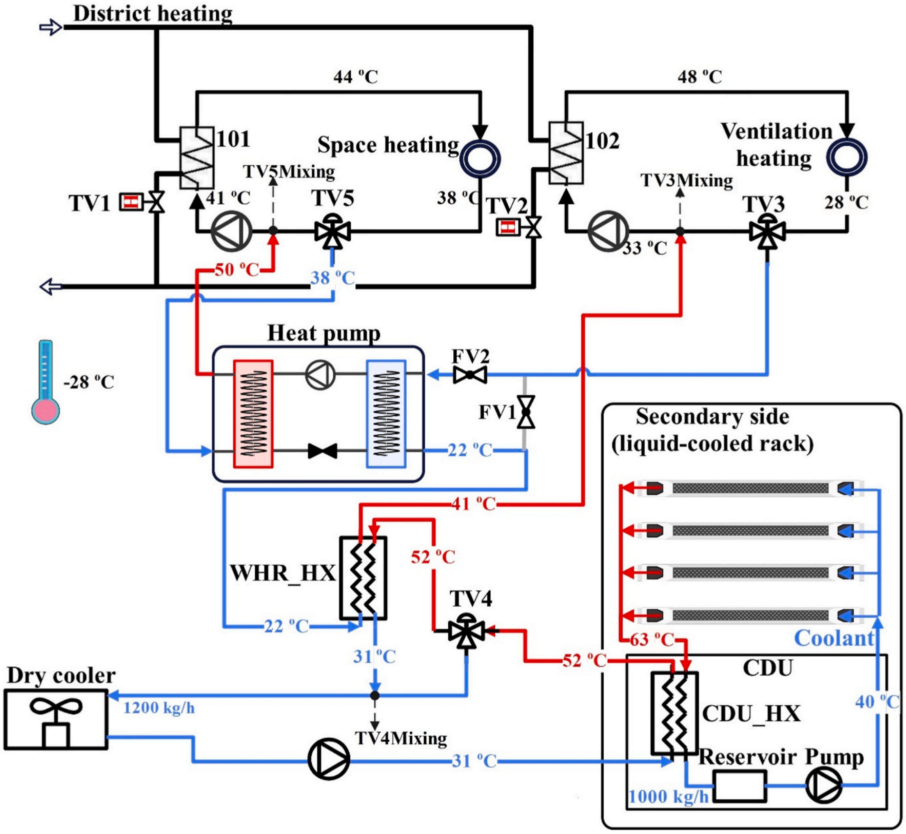

Fig. 4. The proposed AHE-DCWHR system for the case building space and ventilation heating networks and liquid-cooled rack (the heat pump is on when the valve FV2 is opened, and valve FV1 is closed).

2.3.1. *New concept: active reallocation of building heating demands*

To demonstrate the proposed concept, we utilize data from our case study (see Figs. 3 and 4 for temperature data). The performance advantages observed can be easily scaled to more general applications. Fig. 5 illustrates the energy flows from Figs. 3 and 4 that demonstrate how the proposed active AHE-DCWHR system overcomes the passive limitations of the heat exchanger-only systems. The figure highlights the fundamental difference between the active operation of the AHE-DCWHR system and the passive nature of heat exchanger-only systems. Further detailed analysis and discussion validating the superior performance of the proposed AHE-DCWHR system are presented below.

For the given design outdoor temperature of −28 °C in Vaasa region in winters, as shown in Figs. 3 and 4, the ventilation heating demand significantly exceeds 25 kW, meaning that the maximum possible waste heat recovered from both systems is required to supply the ventilation heating network only. In this study, the effectiveness–NTU method [31] (Eq. (2)) is used to analyze the amount of recovered DC waste heat for both systems, as the heat exchanger's effectiveness (assumed constant), mass flow rates, and inlet temperatures on both sides are known, while the outlet temperatures are unknown. For example, in the case shown in Fig. 5, Eq. (2) indicates that the recovered waste heat — the primary focus of this study— primarily depends on the temperature difference between the DC waste heat and the return water from the ventilation heating network (i.e., the inlet temperature difference across the heat exchanger). Therefore, this inlet temperature difference is used instead of the logarithm mean temperature difference (LMTD) to illustrate how the AHE-DCWHR system increases it to achieve full waste heat recovery and outperform the heat exchanger-only system. The LMTD method is well suited for sizing a heat exchanger to achieve specified outlet temperatures when the mass flow rates and the inlet and outlet temperatures of both hot and cold fluids are known [31]. Since this study focuses on achieving full DC waste heat recovery rather than equipment sizing, the effectiveness–NTU method, based on the inlet temperature difference, is adopted instead of the LMTD approach to better support the analysis in Fig. 5.

The results show that the AHE-DCWHR system fully recovers 25 kW of waste heat, compared to only 20 kW by the heat exchanger-only system—a 20 % increase. This 20 % more waste heat recovery is achieved by a small-capacity heat pump, which lowers the return water temperature from 28 °C to 22 °C, corresponding to 7.5 kW of extracted heat from the ventilation heating return flow. This 7.5 kW of extracted heat is not wasted; instead, it is intelligently redirected to the space heating network, raising the return temperature from 38 °C to 41 °C. The small-capacity heat pump requires only 2 kW of electricity input.

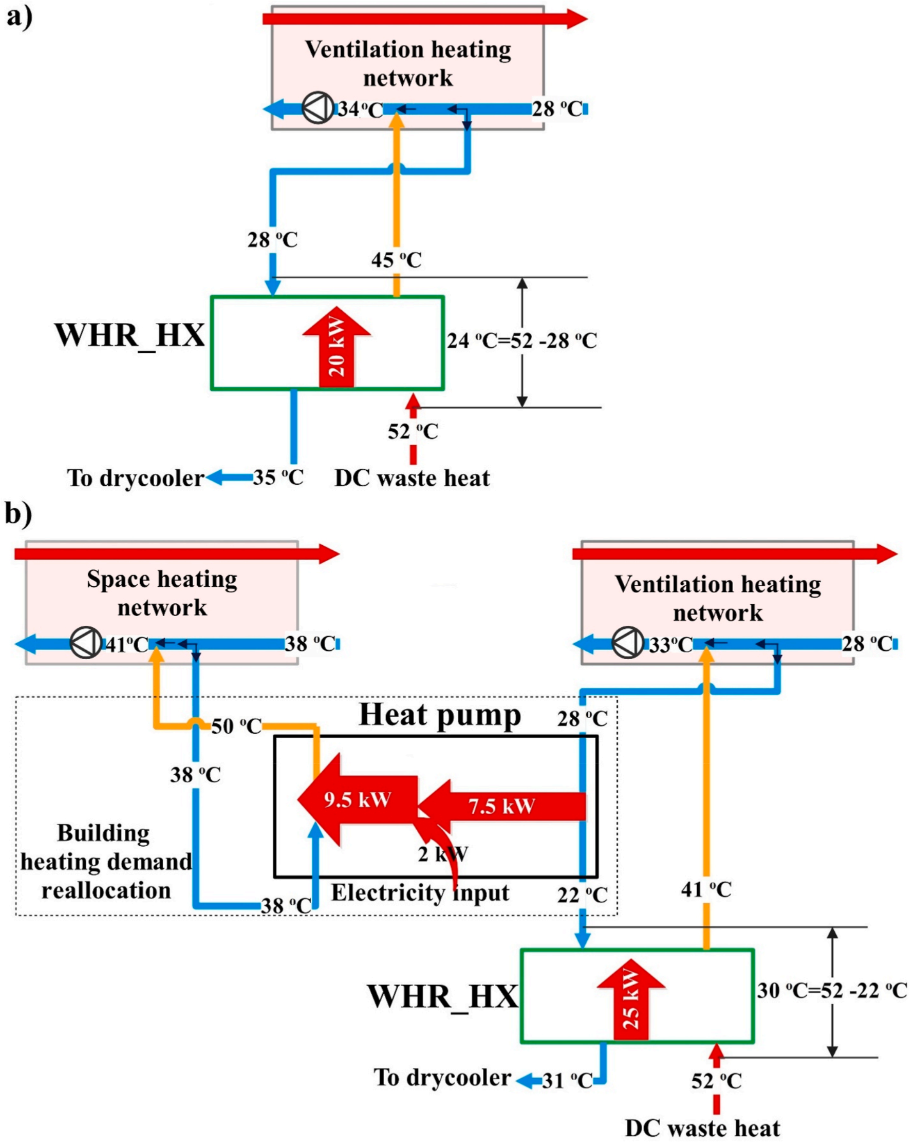

Fig. 5. DC waste heat recovery situations in a) the heat exchanger-only system, and b) the AHE-DCWHR system (energy flow from Figs. 3 and 4).

2.3.2. Superior performance of the AHE-DCWHR system

To highlight the superior performance of the AHE-DCWHR system compared to the state-of-the-art heat exchanger-only system, it can recover 20 % more waste heat by reallocating 7.5 kW of heating demand from the ventilation to the space heating network, achieving complete waste heat recovery. This reallocation increases the temperature difference between the hot and cold fluids at the heat exchanger (WHR_HX) from 24 °C to 30 °C, while requiring only 2 kW of electricity input (see Fig. 5b). In other words, 2 kW of electricity enables recovery of an extra 5 kW of waste heat, making the process highly cost-effective—especially given that Finland's electricity-to-district heating price ratio is typically below 1.5.

This innovative approach forms the basis of the building heating demand reallocation concept, which involves transferring heat between the return lines of the space and ventilation heating networks. For example, 7.5 kW is transferred from the ventilation to the space heating network in Fig. 5b. This enables effective redistribution of heating demand between the two heating networks without any energy waste. Therefore, unlike the single-stage heat exchanger-only system, the AHE-DCWHR system operates as a two-stage solution: it first reallocates building heating demand using a heat pump to improve the conditions for full DC waste heat recovery at the heat exchanger, and then recovers the DC waste heat through a conventional heat exchanger.

A heat pump is well suited for implementing heating demand reallocation due to its ability to: (1) absorb energy on the source side by lowering the return water temperature, enabling near-complete DC waste heat recovery in many heating networks; (2) reuse the extracted energy to supply, for example, the space heating network; and (3) operate with a high COP of around 5, because return water temperatures in typical building heating systems are generally above 20 °C, ideal for heat pump operation.

Finally, it is worth mentioning that the state-of-the-art full scale heat pump solution requires a heat absorption capacity of 25 kW, which is 3.3 times higher than the 7.5 kW capacity of the small heat pump used in the AHE DCWHR system, resulting in significantly higher investment costs and carbon emissions.

2.3.3. Practical implementation of the AHE-DCWHR system

Importantly, the AHE-DCWHR system's practical implementation is simple. The two-way valves FV1 and FV2 in Fig. 4 control the heat pump's operation. The heat pump is active when FV2 is open and FV1 is closed, and inactive when FV2 is closed and FV1 is open. The heat pump is switched off only when the heat exchanger alone can meet the total heating demand of both networks. However, during the winter season, this is rare due to relatively high return water temperatures in the ventilation heating network. To simplify the analysis, when the heat pump is off, the recovered waste heat is directed solely to the ventilation heating network. Nonetheless, the AHE-DCWHR system can be easily configured to supply both space and ventilation networks, similar to the heat exchanger-only layout shown in Fig. 3.

The AHE-DCWHR system can be controlled using a relatively simple strategy.

- The load-side flow rate of the heat pump—connected to the return line of the space heating network (Fig. 4)—can be set to its minimum allowable value to avoid overheating.
- Valve TV4 remains fully open to allow the full DC waste heat flow through the source side of WHR_HX. Valve TV3 is modulated to regulate the return water flow from the ventilation heating network through the heat pump. When the ventilation heating demand exceeds 25 kW, the control aims to fully recover the available DC waste heat. When the demand is below 25 kW, the control maintains the warmed return temperature at TV3Mixing (Fig. 4) as close as possible to the supply temperature setpoint and terminates once either the waste heat is fully recovered or the setpoint is reached.

3. Case study

The building's space and ventilation heating networks, along with the self-contained liquid-cooled rack used in the case study, are described in Sections 2.1.1 and 2.1.2, including key input data and the fundamental modelling equation (Eq. (1)). The heat exchanger-only and AHE-DCWHR systems are detailed in Sections 2.2 and 2.3, respectively, in relation to the building heating networks and the liquid-cooled rack. Control strategies and relevant modelling equations for the heat exchanger-only and AHE-DCWHR systems (Eqs. (2)–(6)) are also provided in Section 2.2.1.

In the case study, the baseline scenario consists of the building's space and ventilation heating networks operating without DC waste heat recovery. The performance of the heat exchanger-only and AHE-DCWHR systems is then evaluated during the winter months (January, February, March, November, and December), focusing on their effectiveness in reducing DH demands and associated CO_2 emissions relative to the baseline.

All modelling and simulations are conducted using TRNSYS 18 in the case study, a widely used transient system simulation tool for renewable energy and building performance analysis, including DC waste heat recovery [3], with a time step of 1 h.

To facilitate the following discussion, the TRNSYS components used in the study are summarized in Table 2.

3.1. Modeling of the building's space and ventilation heating networks, and the self-contained liquid-cooled rack

Hourly measurements of mass flow rates, supply and return temperatures, and heating demands for the building's space and ventilation heating networks were collected during the winter period (November 1, 2023–March 31, 2024). These data were stored in a file and used to model the heating networks in TRNSYS using two Type 9 components—*VentilationHeatingNetwork* and *SpaceHeatingNetwork*—which read the input data directly (see Fig. 1).

The cooling system of the self-contained liquid-cooled rack, including waste heat characteristics, was modeled based on the model in Ref. [3]. The system includes the following TRNSYS components: *DryCooler* (Type 511), *CirculationPumpRejection* and *CirculationPumpServer* (Type 114), *CDU_HX* (Type 91), and *LiquidCooledRack* (Type 682), representing the dry cooler, primary and secondary circulation pumps,

Table 2
Important TRNSYS components used in the study.

Type of component	Function
Equation	It can handle expressions outside the standard components, define constants, and evaluate conditions [32].
Type 9	It can read data from a text-based file [32].
Type 22	It is an iterative feedback controller, utilizing the secant method to model a real feedback controller (e.g., PID) that calculates the control signal, minimizing tracking error [32].
Type 91	It models a sensible fluid-to-fluid heat exchanger with constant effectiveness using Eq. (2) [32].
Type 114	It models a fixed-speed pump designed to deliver a constant fluid outlet mass flow rate [32].
Type 511	It models a dry cooler as a single-pass, crossflow heat exchanger [33].
Type 647	It models a diverting valve that distributes an incoming liquid mass flow into multiple outlet flows based on specified fractions [34].
Type 649	It models a mixing valve that merges up to 100 separate liquid streams into one unified outlet mass flow [34].
Type 682	It applies a user-defined load to a flow stream and determines the resulting outlet fluid temperature based on Eq. (1) [35].
Type 927	It models a single-stage water-to-water heat pump using user-provided data files that contain catalogue information on capacity and power consumption as functions of entering load and source temperatures [33].

CDU heat exchanger, and the server rack, respectively. Outdoor temperatures for the *DryCooler* (Type 511) are provided by the *FinlandWeather* component (Type 9), which reads a weather data file.

These components form the foundation of the TRNSYS models for both the heat exchanger-only and AHE-DCWHR systems.

3.2. Modeling of the heat exchanger and AHE-DCWHR systems

Since the space and ventilation heating networks are modeled using measured data and the DC waste heat supply is assumed constant, the modelling of both the heat exchanger-only and AHE-DCWHR systems is straightforward. The focus is on determining the amount of DC waste heat recovered by heat exchanger WHR_HX ($\dot{q}_{waste}$), governed by Eq. (2). WHR_HX is modeled using the Type 91 component in TRNSYS. The following two subsections describe TRNSYS modelling in each system.

3.2.1. TRNSYS model for the heat exchanger-only system

Fig. 6 shows the TRNSYS model for the heat exchanger-only system which is largely on the TRNSYS model in Ref. [3].

The detailed operation procedures, key settings, and equations are presented in Section 2.2.1. This section provides a brief overview of the TRNSYS model.

- *TV3Diverting*, *TV4Diverting*, *TV5Diverting*, and *TV6Diverting* (Type 647): Model the diverting valves TV3, TV4, TV5, and TV6, respectively, as shown in Fig. 3.
- *TV3Mixing*, *TV3TV5Mixing*, *TV4Mixing*, and *TV5Mixing* (Type 649): Simulate the mixing of flow rates and temperatures at the corresponding mixing points indicated in Fig. 3.
- *SettingCtrl* (Equation) and *WasteHeatController* (Type 22):
    - *SettingCtrl* computes flow ratios between the space and ventilation heating networks using Eq. (3), based on input data from *VentilationHeatingNetwork* and *SpaceHeatingNetwork*, and applies them to *TV3Diverting* and *TV5Diverting*.
    - *WasteHeatController* regulates DC waste heat flow to *WHR_HX* by controlling *TV4Diverting*, by monitoring the mixed return water temperature from *TV3Mixing* (i.e., the warmed return temperature of the ventilation heating network).
    - When ventilation heating demand is ≥ 25 kW, *SettingCtrl* overrides *WasteHeatController* and sets *TV4Diverting* to full DC waste heat flow. Otherwise, it passes the controller's signal through.

3.2.2. TRNSYS model for the AHE-DCWHR system

In the AHE-DCWHR system, a heat pump's mass flow rate should ideally match the range of the secondary side of the ventilation heating network to operate efficiently across its full capacity. As the maximum return water temperature of the ventilation heating network is 33 °C, a water-to-water heat pump with a higher maximum source inlet temperature than 33 °C is preferable. Since the heat pump in the system does not directly use waste heat as its source, estimating its heat absorption capacity requires AHE-DCWHR simulations. Based on these factors, we select a heat pump model with the following key specifications [36].

- Flow rates range from 0.19 L/s to 0.57 L/s for both source and load sides.
- The allowed source inlet temperature ranges from −1 °C to 43 °C, and the load inlet temperature ranges from 16 °C to 49 °C.
- The heating capacity is 6.6 kW when the source and load inlet temperatures are 0 °C and 40 °C, respectively, with both source and load flow rates at 0.57 L/s.
- The maximum outlet load temperature is 58 °C.

Based on these specifications, the load flow rate is set to a constant 0.19 L/s for the heat pump, while the source flow rate varies between 0.28 L/s and the minimum of either the current flow rate of the ventilation heating network or 0.57 L/s. The *HeatPump* component (Type 927) is used to model the heat pump using catalog data from the manufacturer [36]. TRNSYS employs an empirical equation-fit model—rather than a thermodynamic model—which uses catalog data (typically performance at different entering/leaving water temperatures and flow rates) to fit two non-dimensional polynomial equations for heating capacity and power input. This equation-fit approach is commonly used in EnergyPlus [37] and TRNSYS Type 927 [33]. The TRNSYS model for the system is shown in Fig. 7.

Since the heat pump's load-side flow rate is fixed, valve TV5 and mixing point TV5Mixing (see Fig. 4) are not included in the case study model. Components *TV3Diverting*, *TV3Mixing*, *TV4Diverting*, and *TV4Mixing* are modeled identically to those used in the heat exchanger-only system (see Fig. 6 and Section 3.2.1).

The TRNSYS implementation of the AHE-DCWHR system in the case study differs from the control strategy discussed in Section 2.3.3., as TRNSYS lacks a controller component capable of managing multiple setpoints. Therefore, the TRNSYS modelling of the AHE-DCWHR system follows a two-stage approach: building heating demand reallocation and DC waste heat recovery.

- **Heating demand reallocation**: The *VHReturnWaterController* (Type 22) controls *TV3Diverting* to regulate the return water flow from the ventilation heating network to the *HeatPump*, maintaining its source outlet temperature as close as possible to 22 °C—identified as the maximum allowable *WHR_HX* load inlet temperature for full DC waste heat recovery (based on Eq. (2)). The *HXContrlSet* (Equation) sets the minimum and maximum control signals (i.e., allowable heat pump source flow rates) based on the current mass flow rate from *VentilationHeatingNetwork*. It also checks for overheating in the space heating network by comparing the heat delivered to load by the *HeatPump* with the space heating demand from *SpaceHeatingNetwork*.
    - If no overheating occurs, the *HeatPump* source flow rate and outlet temperature are passed to *WHR_HX* to simulate active operation.
    - If overheating is detected, *HXContrlSet* passes the flow rate (1080 kg/h) and the current return temperature of

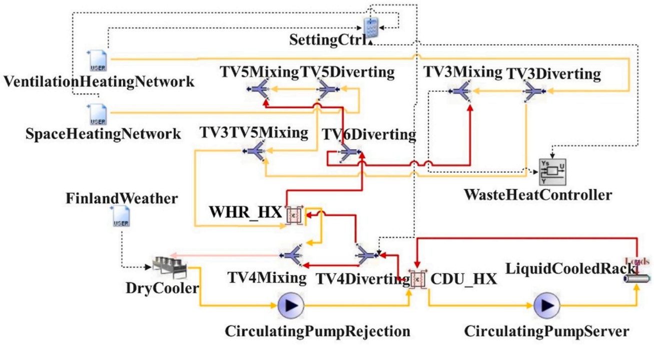

Fig. 6. TRNSYS model for the heat exchanger-only system.

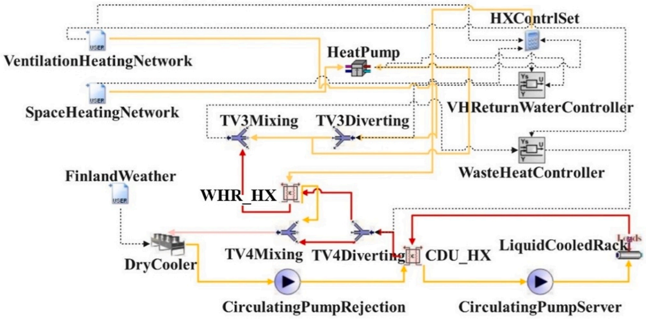

Fig. 7. TRNSYS model for the proposed AHE-DCWHR system in the case study.

VentilationHeatingNetwork to *WHR_HX*, simulating heat pump shutdown.

- **DC Waste Heat Recovery**: The *WasteHeatController* (Type 22) regulates *TV4Diverting* to adjust DC waste heat flow to *WHR_HX*, ensuring that the warmed return water temperature of the ventilation heating network (i.e., the outlet temperature of *TV3Mixing*) closely matches the current supply temperature setpoint of *VentilationHeatingNetwork*.

It is important to note that the above paragraph describes TRNSYS implementation algorithms for the AHE-DCWHR system rather than real-world control strategies (see Section 2.3.3. for practical operations of the AHE-DCWHR system).

3.3. Life cycle cost for the heat exchanger-only and AHE-DCWHR systems

The life cycle cost (LCC) approach evaluates the overall expenses involved in operating a project throughout its duration. A common method within LCC for assessing the profitability of different alternatives is the net present value (NPV), which computes the present value of future cash flows. The NPV is calculated as follows [38]:

$$NPV = -C_0 + \sum_{n=1}^{N} \frac{C_n}{(1+r)^n} \tag{7}$$

where C_0 denotes the initial capital cost in euros (€), C_n stands for the annual cash flow in euros (€), N indicates the total number of years, and r signifies the discount rate. The annual cash flow C_n is calculated as [3]:

$$C_n = C_n^{DH} - C_n^{maintainance} - C_n^{electricity} \tag{8}$$

where C_n^{DH} represents the DH cost savings for both space and ventilation heating networks by utilizing DC waste heat, $C_n^{electricity}$ is the electricity cost for operating the heat pump in the AHE-DCWHR system, and $C_n^{maintainance}$ is the maintenance cost associated with both C_n^{DH} and $C_n^{electricity}$. All costs, C_n^{DH}, $C_n^{maintainance}$ and $C_n^{electricity}$ are adjusted for inflation to reflect the true value of the initial expenses.

3.3.1. Investment, installation and maintenance costs

Figs. 3 and 4 highlight the required components for the heat exchanger-only and AHE-DCWHR systems. The heat pump used in the AHE-DCWHR system has dimensions of 64.8 cm (depth) × 66.8 cm (height) × 45.7 cm (width) [36] and is installed on the first floor in the building's DH substation.

The estimated length of additional heat distribution piping for the AHE-DCWHR system is approximately 60 m. Installation costs are assumed to be 35 % of the total investment, covering delivery, setup, automation, and commissioning. Cost estimates for investment, installation, and maintenance are primarily based on values reported in Ref. [3] (see Table 2 in Ref. [3]) for the heat exchanger-only system. Table 3 summarizes the investment cost breakdown for both systems, with price data sourced from internet resources and company consultations, reflecting above-average market prices.

The annual maintenance cost is assumed to be 2 % of the total investment [3]. Table 4 outlines the key inputs used in the NPV analysis.

DH energy savings and heat pump electricity consumption during the five winter months are assumed to represent consistent annual savings and costs over a 25-year period for both systems. Although heating demands in buildings may decrease by 5–10 % over 25 years [42], it is conservatively assumed that annual heating demands will not drop below that observed during the five winter months, accounting for potential climate change effects.

As the WSTAR DC, housing heat exchanger WHR_HX in both systems, is located adjacent to the DH substation, it is assumed that the existing water pumps are sufficient to support circulation, eliminating the need for additional pumps. This assumption also simplifies the modelling process.

Table 3
Investment and installation costs of the heat exchanger-only and AHE-DCWHR systems.

Component	Unit cost	Quantity (heat exchanger-only)	Quantity (AHE-DCWHR)
Heating pipes	€ 70.4/m	60	60
Plate heat exchanger	€ 850	1	1
Actuated three-way valve	€ 600	4	3
Siemens PLC (Programmable logic controller)	€ 350	1	1
Waterproof DS18B20 digital temperature sensor	€ 10	2	4
Wiring and connectors	€ 40	2	4
Heat pump	€ 4150 [39]	0	1
Flow sensor	€ 300	4	3
Two-way valve	€ 300	0	2
Total investment (€)		9124	13074
Installation cost (35 % investment, €)		3193.4	4575.9
Capital cost (€)		12317.4	17649.9

Table 4
Input parameters for NPV calculations.

Cost factor	Value
Number of years	25 [40]
Discount rate	7 % [40]
Inflation rate	2 % [3]
Electricity price for the first year	€ 121/MWh [41]
Electricity inflation rate	2 % [3]
District heating price for the first year	€ 105/MWh [41]
District heating inflation rate	3 % [3]

3.3.2. CO_2 emission reductions over 25 years for the heat exchanger-only and AHE-DCWHR systems

The annual reduction in CO_2 emissions ($E_{CO2,red}$, kgCO_2) is calculated as follows:

$$E_{CO2,red} = \varepsilon_{DH} Q_{DH,sv} - \varepsilon_{electricity} Q_{HP} \tag{9}$$

where ε_{DH} is the emission factor for DH (kgCO_2/MWh), $\varepsilon_{electricity}$ is the emission factor for electricity (kgCO_2/MWh), $Q_{DH,sv}$ denotes the saved DH energy (MWh) and Q_{HP} indicates the electricity consumption for the heat pump (MWh). The Finnish Ministry of the Environment has published emission factors for future years to evaluate the life cycle CO_2 emissions [43]. Fig. 8 shows the CO_2 emission factors for electricity and DH over the 25-year period considered. Eqs. (7)–(9) are implemented in

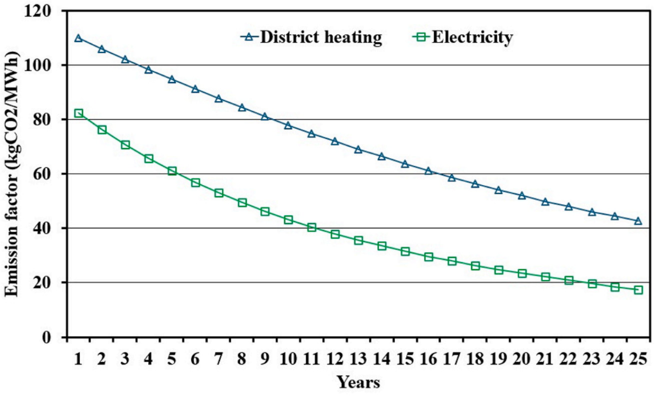

Fig. 8. CO_2 emission factors (kgCO_2/MWh) [43].

Excel.

4. Results and discussion

Section 4.1 presents the DC waste heat recovery performance of the AHE-DCWHR system, comparing it with state-of-the-art heat exchanger-only system. Section 4.2 presents the LCC and CO_2 emission reduction results, along with a discussion of the AHE-DCWHR system, including its comparison with conventional heat pump system and assessment of its applicability.

4.1. Data centre waste heat recovery performance comparison

This section highlights the superior performance of the proposed AHE-DCWHR system by comparing its DC waste heat recovery with state-of-the-art heat exchanger-only system. Although these systems also save electricity by lowering dry cooler cooling loads, these savings are minimal compared to the DH savings from DC waste heat recovery, particularly in winter.

Fig. 9 compares the waste heat recovered by the AHE-DCWHR system to that of the heat exchanger-only system. Fig. 10 highlights the heating demands for the space and ventilation heating networks, along with the DH energy savings achieved by both systems. Fig. 11 shows the comparison of the recovered waste heat by the AHE-DCWHR system against the heating demands for both the space and ventilation heating networks.

First, several assumptions and verifications were made to facilitate discussion and validation of the simulation results.

- DC waste heat load through the heat exchanger (WHR_HX): During the simulation period (01.11.2023–31.03.2024), the combined space and ventilation heating demand generally exceeded 25 kW. Therefore, a full-load condition (1200 kg/h; see Figs. 3 and 4) was assumed for the waste heat on the source side of WHR_HX. Simulation results support this assumption for both systems.
- Return water temperature at the load side of WHR_HX: In the AHE-DCWHR system, this temperature originates from the ventilation heating network. In the heat exchanger-only system, it represents the mixed return flow from the space and ventilation heating networks. Since the ventilation heating demand (typically >25 kW) dominates the total return flow, the resulting temperature is close to that of the ventilation heating network. Thus, the return water temperature entering the load side of WHR_HX was assumed to be the return water temperature of the ventilation heating network for both systems.
- Temperature difference across WHR_HX: The term HX temperature difference refers to the difference between the source and load inlet temperatures throughout the rest of Section 4. Based on the above assumptions, it is calculated as the difference between the DC waste heat temperature (52 °C) and the ventilation return water temperature. According to Eq. (2), the recovered DC waste heat (kW) is directly proportional to this difference, and full waste heat recovery requires an HX temperature difference of 30 °C.

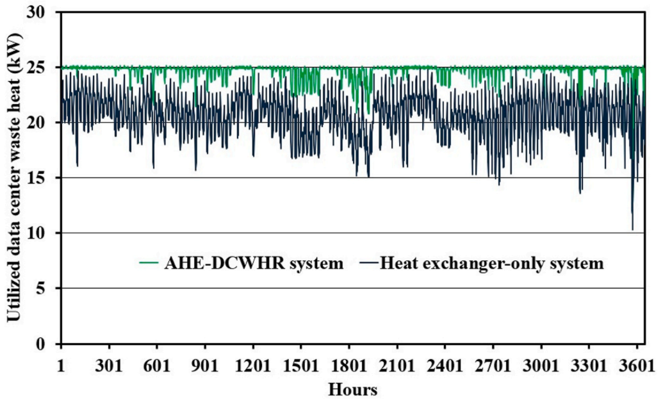

Fig. 9. Comparison of recovered waste heat between the AHE-DCWHR system and the heat exchanger-only system.

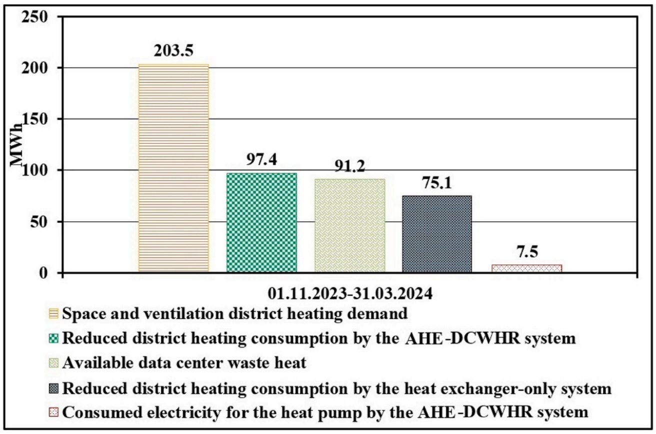

Fig. 10. Total heating demand of space and ventilation heating networks and saved DH energy by the AHE-DCWHR system and the heat exchanger-only system.

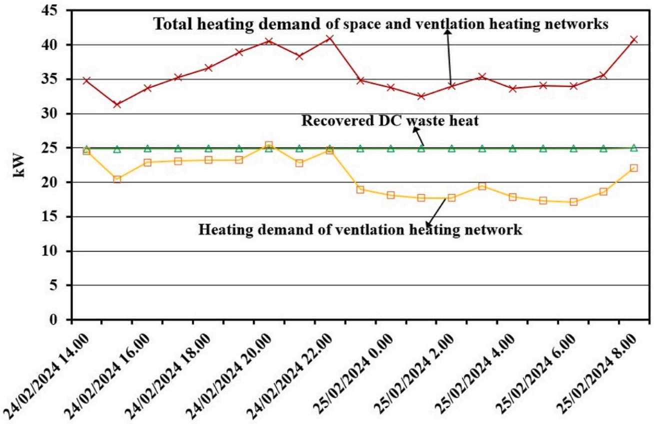

Fig. 11. Recovered waste heat by the AHE-DCWHR system against the heating demands for space and ventilation heating networks from 14:00, February 24, 2024 to 8:00, February 25, 2024.

- Average recovered waste heat: The average recovered waste heat (kW) is defined as the arithmetic mean of hourly recovered DC waste heat over the simulation period. The total recovered waste heat (MWh) equals this average multiplied by the total number of simulation hours. DH savings equal the total recovered waste heat in the heat exchanger-only system, and the sum of this value and the heat pump's total electricity consumption (MWh) in the AHE-DCWHR system. The indicator of average recovered waste heat is essential for validating and interpreting the simulation results.

Therefore, to interpret and validate the TRNSYS simulation results, Eq. (2) can be simplified using as:

$$\dot{q}_{waste,avg} = 25 \times \frac{(52 - T_{rtn,avg})}{30} \tag{10}$$

where $\dot{q}_{waste,avg}$ is average recovered waste heat (kW) during simulation period (01.11.2023–31.03.2024), 25 kW is the full DC waste heat, 52 °C is the waste heat temperature, $T_{rtn,avg}$ is the arithmetic mean of hourly return water temperature of the ventilation heating network during the simulation period (^{o}C) and 30 °C is the required HX temperature difference for full recovery.

In the heat exchanger–only system (Fig. 3), the average return temperature of the ventilation network (27 °C, measured from November 01, 2023 to March 31, 2024) is substituted into Eq. (10), giving $\dot{q}_{waste,avg} = 25 \times (52\text{-}27)/30 = 20.83$ kW, which closely matches the TRNSYS simulation result of 20.6 kW, confirming the validity of the simulation.

In the AHE-DCWHR system (Figs. 4 and 5), $T_{rtn,avg}$ denotes the reduced return water temperature from the ventilation heating network, cooled by the heat pump. It was expected to be around 22 °C to achieve an HX temperature difference of approximately 30 °C, enabling nearly complete waste heat recovery. The TRNSYS simulation results show that $T_{rtn,avg} \approx 22.14$ °C, confirming that the AHE-DCWHR system effectively maintains the HX temperature difference required for full waste heat recovery, thereby validating the model. The simulated COP ranges from 4.2 to 5.47, with an average of 4.75—consistent with the manufacturer's catalog data [36], confirming that the TRNSYS model aligns with the specified performance.

Substituting the reduced return water temperature (22.14 °C) into Eq. (10) yields $\dot{q}_{waste,avg} = 25 \times (52\text{-}22.14)/30 = 24.9$ kW, which closely matches the TRNSYS simulation result of 24.6 kW, further validating the simulation accuracy.

Based on the above validated simulation results, we provide a summary analysis to demonstrate the innovative features of the proposed AHE-DCWHR system compared with the state-of-the-art heat exchanger–only system.

- **Heat exchanger–only system (see** Figs. 3 and 5**)**: This passive system relies solely on the HX temperature difference. However, the return water temperature (averaging 27 °C) is insufficient to provide the ∼30 °C HX temperature difference required for complete DC waste heat recovery (see Eq. (10)). As a result, only 82.4 % of the waste heat (20.6 kW out of 25 kW) was recovered, corresponding to 75.1 MWh of DH savings from November 1, 2023 to March 31, 2024 (see Fig. 10).
- **AHE-DCWHR system (see** Figs. 4 and 5**):** Before the return water of the ventilation heating network enters the load side of the heat exchanger, the heat pump consumes total 7.5 MWh of electricity from November 1, 2023 to March 31, 2024 to transfer 28 MWh of thermal energy from the ventilation network's return water to that of the space heating network through the heating demand reallocation concept. This reallocation yields three major benefits:
  - **Increased temperature difference:** On the source side of the heat pump, the ventilation heating network's return water temperature decreases from 27 °C to 22.14 °C on average. This reduction increases the HX temperature difference from 25 °C to 29.86 °C (=52–22.14 °C), enabling nearly complete DC waste heat recovery (98.4 % or 24.6 kW), which is 16 % higher than that of the heat exchanger-only system (98.4 % vs. 82.4 %, 24.6 vs. 20.6 kW).
  - **Energy reuse:** On the load side of the heat pump, the extracted 28 MWh of thermal energy, together with the 7.5 MWh of electrical input, is reused to raise the space heating network's return water temperature from 33.5 °C to 36.3 °C on average. This energy reuse is the key innovation of this study. Without it, if the 28 MWh of recovered heat and 7.5 MWh of electricity were discarded, the DH savings of the AHE-DCWHR system would decrease from 97.4 MWh to 61.9 MWh (=97.4–28 – 7.5 MWh)-lower than the heat exchanger-only system (61.9 MWh vs. 75.1 MWh; see Fig. 10). This innovation enables the AHE-DCWHR system to achieve greater DH savings (97.4 MWh vs. 75.1 MWh; see Fig. 10).
  - **Smaller heat pump requirement:** Since the heat exchanger alone recovers 82.4 % of the waste heat (20.6 kW), the heat pump only needs to raise the HX temperature difference by about 5 °C (from 25 °C to ∼30 °C) to recover the remaining 4.4 kW (=25–20.6 kW) and achieve full recovery. This can be accomplished with a compact 6.6 kW-capacity heat pump (see Section 3.2.2), significantly reducing equipment size and cost.

Overall, the AHE-DCWHR system consumes only 7.5 MWh of electricity to operate the heat pump (average COP = 4.75), enabling the heat exchanger to recover nearly 90 MWh of DC waste heat from November 1, 2023 to March 31, 2024 (=97.4–7.5 MWh; Fig. 10). This results in 22.3 MWh greater DH savings compared with the heat exchanger-only system (97.4 vs. 75.1 MWh). Economically, the AHE-DCWHR system remains more cost-effective than the heat exchanger-only system when the electricity-to-DH price ratio is below 2.97 (=22.3/7.5). In Finland, this ratio has typically remained below 1.5 and has never exceeded 2 between 2010 and 2023, confirming the superior cost-effectiveness of the proposed AHE-DCWHR system.

Another advantage of the AHE-DCWHR system is its ability to distribute recovered waste heat between the space and ventilation heating networks without flow mixing (Fig. 4), simplifying system operation. As shown in Fig. 11, from 14:00 on February 24, 2024 to 08:00 on February 25, 2024, the utilized waste heat remains nearly constant at around 25 kW (indicating full recovery), even though the ventilation heating demand is below 25 kW. This demonstrates that the system can supply waste heat to both networks through heating demand reallocation, with the heat pump transferring the excess heat to the space heating network. This reallocation also prevents return water mixing between the two networks—a limitation of the heat exchanger–only system (Fig. 3). Similar behavior is observed at other times, further highlighting the benefit of heating demand reallocation. Over the full simulation period (01.11.2023–31.03.2024), both heating networks utilized the recovered waste heat for approximately 26 % of the time in the AHE-DCWHR system.

Moreover, since the emission factor for electricity is lower than for DH (Fig. 8), the AHE-DCWHR system reduces CO_2 emissions for the space and ventilation heating networks by much greater than 44.2 % during the winter season (November 1, 2023, to March 31, 2024) ((97.4-7.5)/203.5, Fig. 10). In comparison, the heat exchanger-only system reduces CO_2 emissions by 36.9 % (75.1/203.5, Fig. 10).

4.2. *Life cycle cost (LCC), CO_2 emission reductions and practical considerations of the AHE-DCWHR system*

Comparisons between the AHE-DCWHR and heat exchanger-only systems are shown in Figs. 12 and 13 for LCC and CO_2 emission reductions, respectively.

The AHE-DCWHR system has a payback time of near two years, making it a profitable investment with a short payback period. Over 25

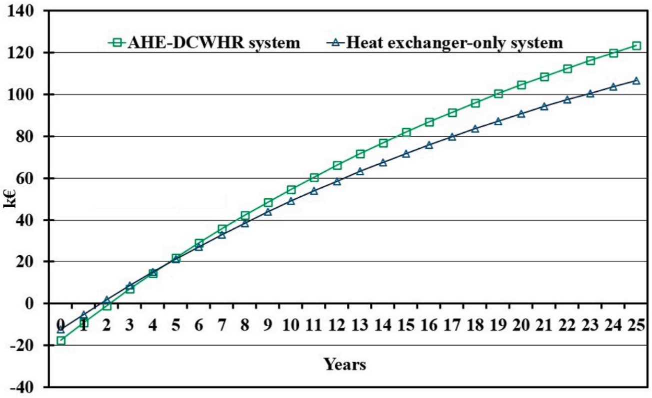

Fig. 12. NPV comparison between the AHE-DCWHR system and the heat exchanger-only system.

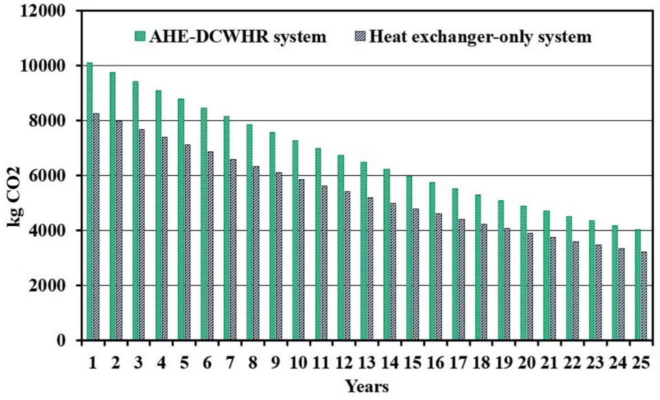

Fig. 13. Life cycle CO_2 emission reduction comparison between the AHE-DCWHR system and the heat exchanger-only system.

years, it is projected to save approximately €123,431 heating costs (€106,501 for the heat exchanger-only system) and reduce CO_2 emissions by 167,087 kg (134,711 kg for the heat exchanger-only system). Additionally, after five years, the AHE-DCWHR system saves more heating costs than the heat exchanger-only system (see Fig. 12).

This study focuses on comparing the heat exchanger-only system and the AHE-DCWHR system, as the conventional heat pump system clearly entails higher investment, maintenance, and operating costs. According to the manufacturer's catalog [36], achieving full waste heat recovery in a conventional heat pump system requires selecting a model with approximately double the heating capacity of that used in the AHE-DCWHR system. Specifically, when the source and load inlet temperatures are 0 °C and 40 °C, respectively, the heating capacity of the suitable heat pump model is 13.3 kW, compared to 6.6 kW in the AHE-DCWHR system. In typical configurations, a liquid-to-liquid heat exchanger is installed between the heat pump's source side and the CDU's primary side to maintain inlet temperatures within the operating range [30] and enable full recovery of DC waste heat. Additionally, a circulation water pump is required between the heat exchanger's load side and the heat pump's source side. Consequently, compared with the AHE-DCWHR setup (Fig. 4), a conventional heat pump system demands both a larger-capacity heat pump (13.3 kW vs. 6.6 kW) and an additional circulation pump, resulting in substantially higher capital cost. Based on return water conditions from the space and ventilation heating networks during the simulation period (01.11.2023–31.03.2024), the average COP of the selected heat pump ranges between 6 and 8 [36]. As discussed earlier, the AHE-DCWHR system achieves near-complete waste heat recovery—24.6 kW on average over the same period. To recover an equivalent amount of heat, the conventional heat pump system would at least consume approximately 3.5 kW of electricity (=24.6/(8−1)), compared to 2.05 kW for the AHE-DCWHR system. Overall, the AHE-DCWHR system clearly outperforms the conventional heat pump system in terms of investment, maintenance, operational costs, and electricity consumption.

In this case study, the average heat transfer during the winter period (November 1, 2023–March 31, 2024) was 7.67 kW for the AHE-DCWHR system. This led to a reduction in the return water temperature of up to 10 °C in the ventilation heating network. According to Finnish regulations on DH substations [8], the maximum return temperature on the secondary side should remain below 30 °C for new buildings and 40 °C for older buildings, with some flexibility in very old buildings. The space and ventilation heating networks in this study represent typical conditions found in post-2000 buildings, where a reduction of up to 10 °C is sufficient to enable near-complete recovery of DC waste heat in ventilation heating systems, due to their higher heating demands and lower return water temperatures.

Increasing the heat transfer area of the heat exchanger in a heat exchanger-only system (see Fig. 3) to improve its effectiveness may recover more DC waste heat, but this does not guarantee full recovery of DC waste heat. According to Eq. (2), even if ε_{waste} is increased to 1 (which is not achievable in practice) for the case study, the temperature difference ($T_{waste} - T_{rtn}$) must exceed 21.25 °C (=25 kW/(1 × 3.53 kJ/kg/^{O}C × (1200/3600) kg/s, where 1200 kg/h is full load of waste heat) to recover the full 25 kW of waste heat. This means T_{rtn} must be below 30.75 °C (52 °C − 21.25 °C). Even in modern buildings, such as the present case study, return water temperatures can exceed 30.75 °C (see Fig. 1), and in older buildings, they are typically much higher. For example, consider an older building where the ventilation heating network has an average return water temperature of 35 °C (quite common in old buildings) and where the ventilation heating demand exceeds 25 kW during the three coldest months (January, February, and December). If the same 52 °C DC waste heat was used for this older building, a single heat exchanger (i.e., a heat exchanger–only system) could at most recover 19.98 kW (=1 × 3.53 × (1200/3600) × (52 − 35), where $\varepsilon_{waste} = 1$) on average, corresponding to only 79.92 % of the total 25 kW waste heat. Therefore, to achieve full recovery, the temperature difference ($T_{waste} - T_{rtn}$) must be increased to 21.27 °C, corresponding to an average 4.27 °C reduction in return water temperature (from 35 °C to 30.73 °C), which is comparable to the case study presented in Section 4.1 (approximately 5 °C reduction).

Thus, the AHE-DCWHR system is designed to complement an existing heat exchanger-only setup, providing full DC waste heat recovery in a cost-effective manner. However, if a conventional heat exchanger-only system already achieves near-complete recovery for a given building, an AHE-DCWHR system is unnecessary. It should be noted that the AHE-DCWHR system still benefits from a higher heat exchanger effectiveness, as a larger ε_{waste} reduces the required temperature difference and thus the electricity demand of the heat pump. For older buildings with higher return water temperatures, combining a larger heat exchanger with a small heat pump is an effective strategy for achieving full DC waste heat recovery.

As shown in Fig. 11, the AHE-DCWHR system can recover DC waste heat for both space and ventilation heating networks simultaneously. However, it is primarily designed for small distributed/edge DCs, where waste heat can be fully utilized by a single heating network during cold winter conditions, and shared between both networks as outdoor temperatures rise.

The practical design of the AHE-DCWHR system in this case study (Fig. 4) includes an option to disable the heat pump when the space heating demand is very low. In such instances, DC waste heat is directed solely to the ventilation heating network by opening valve FV1 and closing FV2. This simplification is justified, as the heat pump is inactive for only 1 % of the winter period (November 1, 2023–March 31, 2024), during which the ventilation heating demand is significantly higher than that of the space heating network. In practice, the system can be configured to distribute DC waste heat to both networks when the heat pump is off (see Fig. 3). Additionally, during non-heating seasons, the system can operate as a pure heat exchanger-only system by switching off the heat pump to save electricity consumption.

5. Conclusions and future work

Heat exchanger-only systems have attracted considerable attention for recovering waste heat from liquid-cooled DCs due to their low investment, maintenance, and operating costs, as well as their negligible electricity consumption. During cold winters, maximizing DC waste heat recovery is highly desirable to reduce DH consumption and CO_2 emissions, particularly for small distributed/edge DCs typically located within buildings. However, the main limitation of heat exchanger-only systems lies in their passive nature: they rely on a sufficient temperature difference between the source and load inlets to drive heat transfer for full DC waste heat recovery, regardless of the heat exchanger's efficiency.

This paper proposes a novel AHE-DCWHR system that overcomes this limitation by integrating a small heat pump with a heat exchanger to dynamically increase the temperature difference across the heat exchanger, enabling complete DC waste heat recovery. Its performance is evaluated through a case study on the WSTAR DC and an onsite district-heated building, comparing it with the state-of-the-art heat exchanger-only system in terms of DH savings, LCC, and CO_2 emission reduction. Extensive TRNSYS 18 simulations are conducted, with space and ventilation heating networks modeled using measured data. The results of this case study are thoroughly presented and discussed in Section 4, where the innovative features of the AHE-DCWHR system are also demonstrated, leading to the following key conclusions.

- When reusing DC waste heat to raise the return water temperature of a building heating network via a heat exchanger, a natural approach is to precool the return water to increase the temperature difference between the waste heat and return water. However, precooling requires extracting energy from the return water, and managing this extracted energy efficiently is crucial to avoid losses. The heating demand reallocation concept addresses this challenge by transferring heat between the return lines of two heating networks. It precools one network's return water to enhance the temperature difference for full waste heat recovery, while reusing the extracted cooling energy to heat the other network—thus avoiding energy loss. This concept serves as the core principle of the AHE-DCWHR system and key innovation in this study.
- Although the inclusion of a heat pump was initially expected to lengthen the payback period of the AHE-DCWHR system, simulation results indicate a payback time of about two years, and after five years the system becomes more profitable than the heat exchanger-only system. As discussed in Section 4.1, modern heat exchangers already recover a substantial portion of high-grade liquid DC waste heat; assisting them with a small heat pump to recover remaining waste heat, as in the AHE-DCWHR system, requires minimal additional electricity. Consequently, the performance of the AHE-DCWHR system also depends on the efficiency of the heat exchanger.
- The AHE-DCWHR system is particularly suited for small distributed/edge DCs, where the available waste heat can be fully utilized by building heating networks for most of the time, as demonstrated in this study. Conversely, if a DC consistently generates more waste heat than the building's heating demand, a heat exchanger-only system may be a more economical solution, since full waste heat recovery is unnecessary.

The main limitation of the AHE-DCWHR system is that the heating demand reallocation concept requires two heating networks, which most residential buildings lack. Therefore, the AHE-DCWHR system is best suited for commercial buildings and is most effective for distributed/edge data centres located within buildings.

Alternative configurations, such as placing a heat pump downstream of a heat exchanger to recover the remaining DC waste heat, may potentially achieve similar performance to the AHE-DCWHR system. However, such setups typically involve more complex and costly piping, as both the heat pump and heat exchanger may need to interface with both the space and ventilation heating networks. Nevertheless, future research comparing this configuration with the AHE-DCWHR system would be valuable.

CRediT authorship contribution statement

Tao Lu: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Xiaoshu Lü:** Writing – review & editing, Supervision, Methodology. **Derek Clements-Croome:** Writing – review & editing, Investigation. **Yanping Yuan:** Writing – review & editing, Investigation. **Birgitta Martinkauppi:** Investigation.

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.

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Data availability

Data will be made available on request.

References

[1] International Energy Agency (IEA). Buildings. https://www.iea.org/energy-system/buildings (accessed on 21 May 2024).
[2] International Energy Agency (IEA). Data centres and data transmission networks. https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks (accessed on 21 May 2024).
[3] Lu T, Lü X, Välisuo P, Zhang Q, Clements-Croome D. Innovative approaches for deep decarbonization of data centres and building space heating networks: modeling and comparison of novel waste heat recovery systems for liquid cooling systems. Appl Energy 2024;357:122473. https://doi.org/10.1016/j.apenergy.2023.122473.
[4] Finland Ministry of the Environment. Government's climate policy: climate-neutral Finland by. https://ym.fi/en/finland-s-national-climate-change-policy. [Accessed 21 May 2024].
[5] Euroheat & Power. Euroheat & power summit 2024 - Euroheat & power.https://www.euroheat.org/events/euroheat-and-power-summit-2024 (accessed on 15 September 2024)..
[6] Vainio T, Lindroos T, Pursiheimo E, Vesanen T, Sipilä K, Airaksinen M, Rehunen A. High-efficiency CHP, district heating and district cooling in Finland 2010-2025. 2015. STUDY REPORT VTT-R-04071-15.
[7] Sipilä K, Nuorkivi A, Pietiläinen J. The building level substation – the innovation of district heating system. VTT TECHNOLOGY 2015;231.
[8] Publication K1/2021. Rakennusten kaukolämmitys-määräykset ja ohjeet-julkaisu K1/2021(District heating of Buildings-Regulations and Guidelines-Publication K1/2021), Energiateollisuus. https://energia.fi/wp-content/uploads/2016/08/JulkaisuK1_2020_Energiateollisuus_ry_paiv._20201119-1.pdf (accessed on 21 May 2024). [in Finnish)].
[9] DataCentreKnowledge.Sea-Cooled data Centre heats homes in Helsinki. https://www.datacentreknowledge.com/archives/2011/09/06/sea-cooled-data-centre-heats-homes-in-helsinki#close-modal (accessed on 22 May 2024).
[10] Motiva. Energy efficiency of data centres in Finland, Reoprt. 2022.
[11] Fortum.Fortum and Microsoft's data centre project advances climate targets. https://www.fortum.com/data-centres-helsinki-region (accessed on 22 May 2024)..
[12] Fortum.Two-way district heating. https://www.fortum.com/media/2018/06/two-way-district-heating (accessed on 22 May 2024)..
[13] Fortum. Tietoa hukka-lämmön ostohin-noista (information on waste heat purchase prices). https://www.fortum.fi/yrityksille-ja-yhteisoille/lammitys-ja-jaahdytys/kaukolampo/avoin-kaukolampo/avoin-kaukolampo-ostohinnat?vtab=accordion-item-49576. [Accessed 22 May 2024] (in Finnish).
[14] Hiltunen P, Syri S. Low-temperature waste heat enabling abandoning coal in Espoo district heating system. Energy 2021;231:120916. https://doi.org/10.1016/j.energy.2021.120916.
[15] Oltmanns J, Sauerwein D, Dammel F, Stephan P, Kuhn C. Potential for waste heat utilization of hot-water-cooled data centers: a case study. Energy Sci Eng 2020;8:1793–810. https://doi.org/10.1002/ese3.633.
[16] IEA. The future of heat pumps. World Energy Outlook Special Report.November 2022. https://www.iea.org/reports/the-future-of-heat-pumps (accessed on 15 September 2024)..
[17] Douchet F, Nortershauser D, Le Masson S, Glouannec P. Experimental and numerical study of water-cooled datacom equipment. Appl Therm Eng 2015;84:350–9. https://doi.org/10.1016/j.applthermaleng.2015.03.030.
[18] Nada SA, El-Zoheiry RM, Elsharnoby M, Osman OS. Experimental investigation of hydrothermal characteristics of data centre servers' liquid cooling system for different flow configurations and geometric conditions. Case Stud Therm Eng 2021;27:101276. https://doi.org/10.1016/j.csite.2021.101276.
[19] Zimmermann S, Meijer I, Tiwari MK, Paredes S, Michel B, Poulikakos D. Aquasar: a hot water cooled data centre with direct energy reuse. Energy 2012;43:237–45. https://doi.org/10.1016/j.energy.2012.04.037.

[20] Khalaja AH, Halgamuge SK. A review on efficient thermal management of air- and liquid-cooled data centres: from chip to the cooling system. Appl Energy 2017;205: 1165–88. https://doi.org/10.1016/j.apenergy.2017.08.037.

[21] Hnayno M, Chehade A, Klaba H, Bauduin H, Polidori G, Maalouf C. Performance analysis of new liquid cooling topology and its impact on data centres. Appl Therm Eng 2022;213:118733. https://doi.org/10.1016/j.applthermaleng.2022.118733.

[22] Coles H, Greenberg S. Direct liquid cooling for electronic equipment. Berkeley Lab: US: Report; 2014.

[23] Wahlroos M, Pärssinen M, Rinne S, Syri S, Manner J. Future views on waste heat utilization – case of data centers in Northern Europe. Renew Sustain Energy Rev 2018:1749–64. https://doi.org/10.1016/j.rser.2017.10.058.

[24] ASHRAE. Liquid Cooling Guidelines for Datacom equipment centers. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers; 2014.

[25] Taddeo P. Waste heat recovery from urban data centres and reuse to increase energy efficiency of district heating and cooling network. Spain, Barcelona: Universitat Polit`ecnica de Catalunya; 2017. Master thesis.

[26] Oró E, Allepuz R, Martorell I, Salom J. Design and economic analysis of liquid cooled data centres for waste heat recovery: a case study for an indoor swimming pool. Sustain Cities Soc 2018;36:185–203. https://doi.org/10.1016/j.scs.2017.10.012.

[27] Asetek. Installation operation & maintenance guide InRackCDU (4U-V2). Asetek manual; 2019.

[28] Rack nVent. Level high density liquid cooling. White paper; 2019.

[29] CooLIT. Rack DCLC-Reliable Direct Liquid Cooling for the world's most demanding Data Centers. CooLIT manual; 2023.

[30] Yuan X, Liang Y, Hu X, Xu Y, Chen Y, Kosonen R. Waste heat recoveries in data centers: a review. Renew Sustain Energy Rev 2023:113777. https://doi.org/10.1016/j.rser.2023.113777.

[31] Cengel Y, Yunus A. Heat and mass transfer - fundamentals and applications. sixth ed. New York, NY: McGraw-Hill Education; 2020. fiveable library. Heat and Mass Transfer Unit 5 Review. https://fiveable.me/heat-mass-transfer/unit-5/effectiveness-ntu-method/study-guide/kz42EsEzE0KkHv4t. [Accessed 21 October 2025].

[32] TRNSYS 18 documentation, mathematical reference. University of Wisconsin-Madison; 2019.

[33] TESSLibs 17 documentation. HVAC Library mathematical reference. University of Wisconsin-Madison; 2019.

[34] TESSLibs 17 documentation. Hydronics Library mathematical reference. University of Wisconsin-Madison; 2019.

[35] TESSLibs 17 documentation. Loads and structures Library mathematical reference. University of Wisconsin-Madison; 2019.

[36] WaterFurnace. EW series specification catalog. WaterFurnace International, Inc.; 2008.

[37] EnergyPlus™ Version 22.1.0 Documentation. Engineering Reference. U.S. Department of Energy; 2022.

[38] Gluch P, Baumann H. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Build Environ 2004;39:571–80. https://doi.org/10.1016/j.buildenv.2003.10.008.

[39] Helsinki Hot Heart. Decarbonising the city—And making a global attraction. White paper; 2021.

[40] Pulakka S. Life-cycle cost methods and tools. In: Proceedings of 9th international conference on durability of building materials and components. Australia: Brisbane; 2002.

[41] Statistics Finland. Tilastokeskus 2023. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_ehi/. [Accessed 15 May 2023].

[42] Jylhä K, Jokisalo J, Ruosteenoja K, Pilli-Sihvola K, Kalamees T, Seitolaa T, et al. Energy demand for the heating and cooling of residential houses in Finland in a changing climate. Energ Buildings 2015;99:104–16. https://doi.org/10.1016/j.enbuild.2015.04.001.

[43] The Ministry of the Environment of Finland. Method for the whole life carbon assessment of buildings. Publications of the Ministry of the Environment; 2019.