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Heat pumps enabling waste heat utilization: unlocking sustainable energy from data centers

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Abstract

Driven by digitalization, AI and increasing demand for cloud services, data centers are rapidly emerging as one of the major energy consumers and thus play a crucial role in achieving sustainable energy transitions. With its input electricity converted into waste heat, their integration into circular energy systems offers substantial sustainability potential. Despite increasing pressure from legal requirements and industry-wide motivation to provide sustainable solutions, projects must still be economically viable, whereas the feasibility is highly dependent on project-specific conditions. This study investigates the techno-economic feasibility of waste heat utilization from a representative 4 MW air-cooled colocation data center in a typical district heating network in Austria, focusing on the role of heat pumps to upgrade waste heat for district heating supply. Three integration scenarios were analyzed, differing in heat pump integration configurations and the resulting temperature levels. Using defined technical and economic parameters, levelized costs of heat (LCOH) were calculated for each scenario, including sensitivity analyses for electricity price and annual operating hours. The results show LCOH values between 53.6 €/MWh and 91.7 €/MWh, strongly influenced by operational hours and electricity cost. The findings highlight that heat pump-assisted waste heat reuse from data centers can be cost-competitive with other renewable heat sources, particularly with year-round operation. Hence, data centers can evolve from pure energy consumers into local heat providers, supporting sustainable digital infrastructure and climate-neutral energy systems.

Keywords: *Data center, waste heat utilization, heat pump integration ;*

1. Introduction and Background

1.1. Data centers as important player in the energy infrastructure

Data centers (DCs) are facilities that process, store, and distribute data for diverse applications. They house IT equipment, servers, storage, and networking devices, typically arranged in racks, supported by auxiliary systems such as power supply, cooling, and fire protection to ensure reliable operation. DCs are commonly categorized as enterprise, colocation, and service-provider or cloud DCs. Enterprise DCs are operated by single organizations for internal applications and are often smaller and less efficient. Colocation DCs offer leasable "white space" and infrastructure for customers' IT. Service-provider or cloud DCs host and operate computing and storage services. Hyperscale DCs, run by technology or cloud firms, feature high computational density and efficiency, and their energy use is increasingly significant. Processing, transferring, and storing data using current transistor-based technology requires electrical energy. All of this is converted into waste heat, which must be removed to maintain stable operating temperatures for the IT equipment. Within a typical DC, the largest electricity shares are consumed by servers (on average ~60%) and cooling systems (on average ~20%), though the exact ratio strongly depends on the DC type and design [1].

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Driven by digitization trends, demand for DC services is growing rapidly. According to the IEA, DCs accounted for ~1.5 % of global electricity consumption in 2024 (≈ 415 TWh). From 2024 to 2030, electricity use in DCs is projected to more than double, reaching about 945 TWh (under 3 % of global consumption in 2030) in the base case scenario. Beyond 2030 in the base case, the IEA anticipates the consumption to reach ~1,200 TWh by 2035, whereas the maximum expects a consumption of up to 1,700 TWh. [1] In the EU, DCs are estimated to consume between 45 and 65 TWh of electricity, projections for 2030 range from 98.5 TWh to 160 TWh, the majority in hyperscale DCs, with an investment demand of 250 to 300 billion $. [2], [3] Due to their geographical concentration, DCs pose challenges for sufficient electricity supply and both intrinsic incentives and regulatory frameworks are pushing towards more sustainable and efficient DC systems.

The revised European Energy Efficiency Directive (EED) from 2023 aims to reduce overall energy consumption by establishing "energy efficiency first" principles, including relevant obligations for the DC sector. Energy performance and sustainability indicators of DCs above 500 kW are already being monitored, reported and published in a database. Power usage effectiveness (PUE) is one of the most used indicators. It compares the total power consumption of the DC with the power consumption for IT operation only. [4]

The European Commission will regularly assess the energy efficiency and sustainability of DCs based on the reported data. In the first reporting period, the first technical report evaluated 681 European DCs on the basis of PUE, reaching an EU-wide weighted average PUE value of 1.36. The average value of 1.64 for small DCs (below 1 MW) and 1.21 for very large DCs (above 10 MW) demonstrate the efficiency of scale. The second technical report proposes setting a target design PUE of 1.3 for DCs commissioned after 2027 and a threshold PUE of 1.5 to be achieved by already existing DCs until 2030. At the same time, however, only 1.8% of the total energy consumed by DCs in EU was reported to be reused. This stems predominantly from insufficient infrastructure (energy networks) and the lack of suitable heat sinks. As a result, no specific minimum performance standards aiming at waste heat reuse from DCs in EU have been set yet. [5], [6]

Germany's Energieeffizienzgesetz (EnEfG) is a pioneering legislation that paves the way for EED's implementation. In addition to reporting obligations, renewable electricity quotas and increasingly stringent requirements for energy efficiency, the law also includes mandatory quotas for waste heat utilisation for DCs (between 10 and 20%, depending on the commissioning date). [7]

Additionally, voluntary initiatives promoting energy efficiency and waste heat reuse have been established. The EU Code of Conduct aims at reducing energy consumption and increasing efficiency by showcasing best practice efficiency measures. The minimum standards include, e.g., the review of IT temperature increase, more efficient cooling (e.g., liquid cooling) and evaluations of heat reuse possibilities with and without heat pumps (HPs) [8]. The Climate Neutral Data Centre Pact suggested measures for a climate-neutrality DC sector including clean energy utilization, energy efficiency increase, water conservation and waste heat reuse. [9]

1.2. Waste heat utilization as key to sustainable DCs

Besides the more efficient cooling technologies as main non-IT electricity consumption, EED and EnEfG as well as the initiatives highlight the importance of the utilization of unavoidable waste heat to achieve high overall system energy efficiencies. For the successful utilization of waste heat, the heat source temperature is a key factor, as it determines the quality of the recovered heat. It is largely influenced by the type of cooling system employed in the DC. Most DCs rely on air-based cooling, utilizing cold air streams, which are conditioned via passive or active cooling, to maintain the operational temperatures of IT equipment. They support power densities of up to 50 kW per rack [10], dissipating heat as warm air or water at temperatures ranging from 15°C to 50°C [11], with 20 °C to 30 °C being most common [5]. For higher power densities, liquid cooling is increasingly favoured, offering several advantages, including higher efficiency and waste heat temperatures of up to 60°C, thereby enhancing the potential for heat recovery. There are two primary liquid cooling technologies: Direct-to-chip cooling, where a cooling medium is circulated to cold plates attached to IT components, and immersion cooling, in which the servers are submerged in a dielectric liquid.

The waste heat temperature must match with the heat sink temperature for the successful reuse. For heat from DCs, the application potential is limited to low-temperature heat processes such as drying and preheating, utilization in greenhouses and the direct integration of efficient building's heating systems. Upgrading the heat quality to supply temperatures above 200°C with a HP enables broader utilization in industrial processes and thermal networks such as district heating. However, from a PUE perspective only, integrating waste heat utilization, especially via HP, is not expedient, as it can increases non-IT power consumption.

Finally, the successful implementation of waste heat utilization depends not only on technical feasibility but also on favourable economic conditions for both stakeholders, the DC operator and the heat off-taker. As highlighted in [12], a range of factors must be considered when assessing the economic feasibility of such projects, including temperature levels, available heat and its annual profile, flexibility of demand and supply and energy prices (alternate energy sources as well as electricity prices in case of HP utilization). Consequently, general conclusions about the economic viability of waste heat utilization of DCs are difficult to draw. Instead, each project requires a case-specific assessment based on individual technical and economic parameters as well as the evaluation of different technical configurations, especially when a temperature lift via a HP is necessary to unlock the waste heat potential for relevant heat demands. For this purpose, the aim of the here presented research is the exemplary evaluation of the techno-economic feasibility of an exemplary use case, considering different scenarios and sensitivities, to illustrate the technical options and relevant factors.

2. Approach

To evaluate the techno-economic feasibility of waste heat utilization, a representative case study was defined. It reflects a typical configuration of an air-cooled colocation DC (4 MW installed IT load) connected to a district heating network (DHN) in a major Austrian city, where the supply temperature is controlled by ambient conditions. This setup was chosen to ensure practical relevance and replication potential. The setup of the DC includes air conditioning for the IT equipment with cold water, which is cooled, depending on ambient temperatures, via passive cooling using ambient air or via active cooling, where an adiabatic cooling unit is used to dissipate heat to ambient air via water evaporation (see Figure 1 (a)). Due to the setup, different scenarios for the implementation of a HP in the cooling system are conceivable. Figure 1 (b) to (d) illustrate the assessed integration scenarios. The detailed, technical assumptions are summarized in Table 1. In Scenario 1 (S1), the cooling water used for air conditioning is utilized as a heat source directly, whereas Scenario 2 (S2) utilizes the existing active cooling unit and its temperature lift to harvest waste heat at higher temperatures. In Scenario 3 (S3), an alternative active cooling unit is installed, which provides waste heat at higher temperatures, which can feed directly into the DHN at times of lower network temperatures (summer).

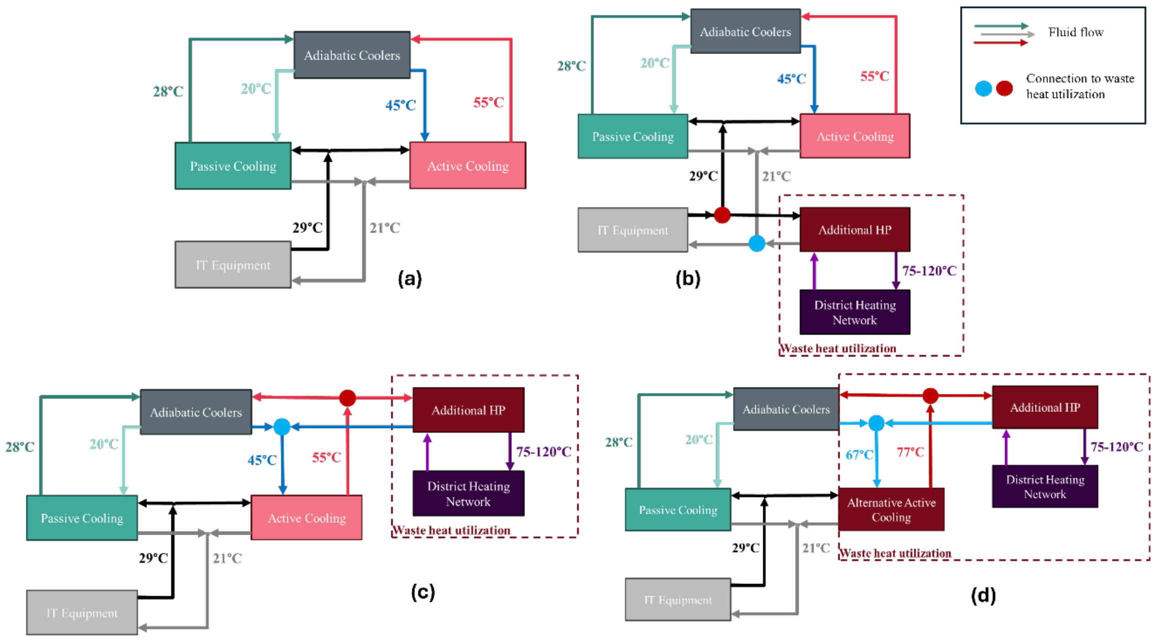


Figure 1. Illustration of the considered integration scenarios; (a) Setup of use case DC without waste heat utilization; (b) Scenario 1 - Utilization of IT cooling circuit; (c) Scenario 2 - Utilization of active cooling circuit; (d) Scenario 3 - Alternative active cooling aggregate with higher temperature lift to utilize active cooling for a direct heat supply to DHN in summer.

To calculate the coefficient of performance (COP), the Carnot COP formula with an efficiency factor of 0.55 was used, along with the heat source (waste heat) and heat sink (district heating with seasonal supply temperature) temperature and a temperature difference of 2 K over each heat exchanger in the HPs. The obtained COPs displayed a satisfactory fit with the COP values of applicable HPs reported in [13], [14].

For the economic evaluation, the levelized costs of heat (LCOH) were calculated for the different scenarios as sum of capital expenditures (CAPEX) and operational expenditures (OPEX) over the lifetime of the heat upgrade. The costs were adjusted with the discount factor in each year of operation, and the sum then divided by the sum of heat upgraded for utilization over this period.

The assumptions can be found in Table 1, whereas CAPEX costs were estimated based on specific costs for HPs in a suitable range of size and temperature levels, as reported in [13], multiplied by the necessary capacity, which was determined from the waste heat potential using the calculated COP. Costs covering the DHN connection and other auxiliaries were not considered because they are site-specific. OPEX include electricity for the heat pump based on COP calculations as well as maintenance costs (based on branch insights). Due to the annual heat demand profile and other base-load providing heat sources (e.g. waste incineration plants, industrial waste heat) as well as renewable heat from, e.g., solar thermal, it is likely that the district heating system's capacity is already reached in warmer periods of the year, leading to the assumption of 4,000 operating hours per year during the colder periods, when the heat can be utilized in the district heating system due to increased heating demand.

Table 1. Technical information and economic assumptions for the assessed use case (base case)

Aspect	Assumption
DC type	Colocation, air-cooled, active and passive cooling
IT load / waste heat potential	4/3.2 MW
Heat sink type	District heating network (supply)
Heat sink supply temperature	Ambient temperature-controlled supply temperature (75°C at 12°C/120°C at -12°C)
Annual weather profile	4 seasons (2°C/10°C/20°C/10°C) - each 25% of the year
Investment costs for HP	S1: 600 €/$kW_{TH;}$S2: 400 €/kW_{TH}; S3: 75 €/kW_{TH} (upgrade), 300 €/kW_{TH} (second stage)
Electricity costs	100/150/200 €/MWh
Operating hours waste heat utilization	2,000/4,000/6000/8,000 h/a
Discount rate	5%
Lifetime	10 years
Other operational expenditures	Maintenance: 15,000 €/a (existing chillers), 2.5%/a CAPEX (heat upgrade equipment)

The sensitivity of the resulting LCOH on two significant factors, the operating hours and the electricity price, was analysed for S2. For the electricity price, the range of industrial prices according to [15] were chosen. To consider the heat demand of the DHN, the lower bound of the annual operating hours represents the heating period in winter, where the demand will always be high enough for the DC to provide heat to the DHN. The upper bound on the other hand represents year-round heat demand in the DHN, considering maintenance downtime. These values were then inputs for the same LCOH estimation method used in the base case.

3. Results and Discussion

The comparison of the three integration scenarios is summarized in Table 2. LCOH between 71.1 and 77.4 €/MWh can be observed, while S3 leads to the lowest costs of heat. In all three scenarios, operational expenditures (OPEX) contribute the major part of the costs, with an increasing trend from S1 to S3, which in turn increases sensitivity to electricity price. The achievable thermal rating ranges between 19.9 and 20.5 GWh/a, the difference resulting from different efficiencies of the HPs based on temperature levels. The total COP of S1 is the highest, as this system is dedicated to heat recovery only, and as such, is more integrated than the other scenarios. This is, however, reflected in the increased investment cost, as well as final LCOH.

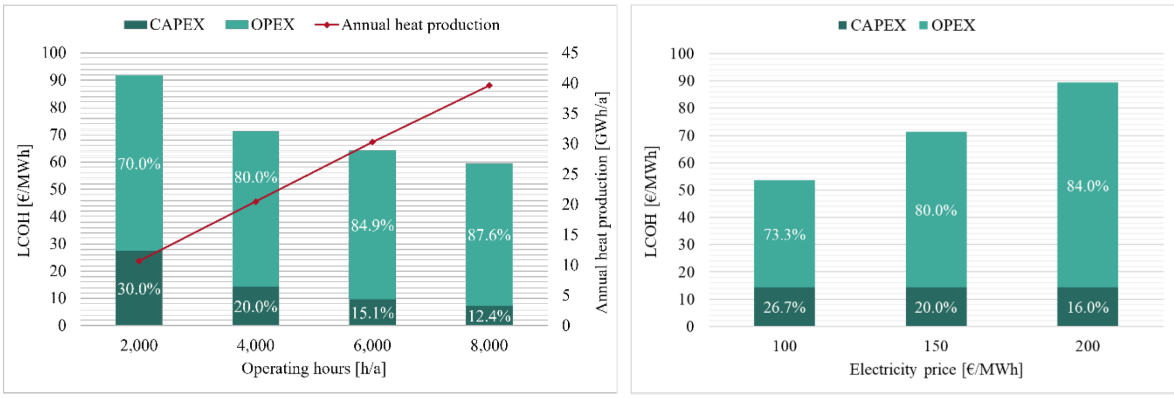
Table 2. Results for different scenarios

		Scenario 1	Scenario 2	Scenario 3
Operating hours	[h/a]	4,000	4,000	4,000
Electricity price	[€/MWh]	150	150	150
LCOH	[€/MWh]	77.4	71.5	71.1
CAPEX contribution	[€/MWh]	20.2	14.3	12.7
OPEX contribution	[€/MWh]	57.2	57.1	58.4
Thermal rating to DHN	[MW]	5.16	5.67	5.46

	[GWh/a]	19.9	20.5	20.3
Total COP	[-]	2.63	2.30	2.41

The resulting sensitivity of LCOH on annual operating hours and electricity price and the percentage contribution of CAPEX and OPEX is illustrated in

Figure 2. Waste heat utilization for only peak-load coverage (2.000 h/a) results in a significantly higher LCOH of 91.7 €/MWh, whereas for all-season operation with annual operating hours of 8.000, an LCOH of 59.5 €/MWh can be achieved with a reduced contribution of CAPEX and proportionally increased total thermal energy delivered to the DHN. The reduction of electricity price by a third results in LCOH of 53.6 €/MWh, with 26.7% of that being CAPEX contribution, whereas at the higher electricity cost a LCOH of 89.3 €/MWh is achieved. Similar trends were observed for S1 and S3.



(a) (b)

Figure 2. LCOH sensitivity to (a) annual operational hours; (b) electricity price of Scenario 2.

The LCOH range obtained by the scenario and sensitivity analysis is comparable to other calculations as presented in [12], ranging from 34 to 143 €/MWh. These costs are competitive with conventional heat sources such as natural gas (44-161 €/MWh) and biomass (66-109 €/MWh) [12]. Additionally, the obtained costs are reasonable in comparison to district heating working prices, ranging between 30 and 167 €/MWh, with a median of 99 €/MWh [16], where additional costs, like those for the operation of the thermal network, have to be covered by consumer prices.

4. Conclusions and Outlook

Waste heat reuse in DCs is an important contribution to efficient and sustainable digital infrastructure and, due to its large energy consumption and resulting amount of waste heat, a relevant source of low- to medium-temperature heat for different processes and space heating. The utilization of HPs to lift the available temperature unlocks great application potential, enabling the integration into, e.g., thermal networks.

The performed analysis showed that, based on the specific assumptions, an LCOH between 53.6 and 91.7 €/MWh can be achieved, depending on integration scenario, operating hours and electricity price. The analysis shows that cost-wise, the most favourable integration is S3. However, since it requires modifications in the classic DC setup by establishing alternative active cooling aggregates, S2 with a higher LCOH is the most likely for implementation in existing DCs. Furthermore, the aim should be to use the heat in all seasons as much as possible, as covering only the peak demand in winter leads to higher heat costs.

The achievable costs of heat at usable temperature levels are comparable with conventional heat sources and can be competitive under specific conditions in regard of Austrian district heating price levels.

Nevertheless, for a more detailed assessment for specific projects, several additional aspects must be considered to obtain the accurate heating price. For example, transport pipelines, heat exchangers to DHN and other auxiliary units will contribute to higher CAPEX, and, especially in combination with autonomous renewable electricity sources, the electricity price might vary over the course of the year, potentially changing the sensitivity to operating hours.

When projecting future available waste heat and its reuse options, certain uncertainties, such as how widespread the use of liquid cooling will be, and their effect on waste heat supply and utilization, must be considered. According to [1], this advanced cooling approach will be very likely adopted in 2030 by more and more DCs, and the 2024 survey of colocation operators also revealed that planned sustainability measures include liquid cooling adoption in the next two years [17]. Furthermore, new technological solutions bear the potential to further enhance waste heat utilization, for example innovative ways of integrating HPs into cooling systems of DC [18].

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