Optimizing Data Center Waste Heat Reuse: Case Studies and Environmental Implications

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ABSTRACT

As data centers (DCs) are the backbones of information and communications technology (ICT), internet and big data, the utilization of energy by DCs has increased exponentially, which presents a significant impact on the environment. To simultaneously solve the dilemma of DC huge amount of electricity used for cooling on the one hand and a large amount of waste heat that is converted from nearly all the consumed electricity on the other hand, better use of low-grade waste heat from DCs represents a significant source of energy savings for both future fourth generation of district heating (DH) networks and reducing environmental impact. This study presents an innovative waste heat reuse approach and develops a generalizable methodology that employs a simple dynamic estimate of the potential for reutilising DC waste heat in the heat demand in DH for buildings. Brief economic calculations for building operators are also provided. The proposed modeling method is a two-stage approach for calibration and validation based on two real DCs in Finland. After validation, the model is then applied for investigating the potential environmental impacts of a real DC in its design phase. The analysis demonstrates that reusing waste heat from an 18 MW data center to heat 400,000 m^2 greenhouse and buildings results in a substantial reduction of 603,366 tons of carbon dioxide (CO_2) emissions over a 25-year period. From the building owners' perspective, the payback time is remarkably short, spanning only five years. The results highlight the feasibility and effectiveness of the DC waste heat recovery to tackle the energy and environmental problems.

Keywords: *Data center, Power consumption, Waste heat reuse, Simulation, Case studies.*

1. INTRODUCTION

As urban areas grow increasingly larger, cities have turned to ‘smart city’ concepts by embracing the ICT and big data driven approach to urban sustainability which the UN is drawing particular attention to [1]. Since data centers (DCs) are an essential part for handling ICT and massive data applications, the utilisation of energy by DCs has increased exponentially, which presents a significant impact on urban infrastructures, energy consumption and greenhouse gas (GHG) emissions. A research study predicted that the growth speed could directly result in one fifth of Earth’s electricity consumption by 2025 and the biggest polluter in just seven years [2]. Therefore, cutting the power consumption of DCs has become an urgent and major issue, China in particular needs such a special concern due to its explosive growth in DC construction, which is up 29.8% year-on-year [3].

One opportunity to save energy and to improve efficiency of DCs is to reuse waste heat from DCs. Because on the one hand, DCs consume vast amounts of cooling electricity, on the other hand, nearly all the consumed electricity is converted into heat, which, in most cases, is rejected and wasted. If the waste heat were utilised, it would make a huge contribution to energy savings and preservation of the environment. However, economic and technical challenges exist because of the low-grade heat, typically below 40ºC temperature, and the high risk of DC investments that the benefit of payback time for waste heat reuse is not easily justified [5].

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Despite the challenges, DC waste heat utilisation has gradually gained its recognition and is mostly used in Nordic countries. The extracted waste heat is commonly utilised in the district heating (DH) networks. According to [5], for example, Bahnhof operates four DCs (Pionen, Thule, St Erik, Elementica) in Stockholm with waste heat recovery for DH. In Finland, many IT companies (e.g. Telia Company, Ericsson Telecity Group, Yandex) supply DC waste heat to DH for space heating. We believe in the vast potential of DC waste heat reuse, also owing to the coming fourth generation DH networks that provide the heat supply with low DH temperature requirements.

This paper aims at introducing a novel DC waste heat reuse strategy and developing a generalizable methodology that employs a simple dynamic estimate of the potential for recycling the waste heat from DC to DH for buildings. Noting that we do not address the detailed business model due to non-transparent business practices, we will however provide brief economic calculations for DC owners and operators. The proposed modeling method is a two-stage approach for calibration and validation of two real DCs in Finland where the first stage uses one DC to obtain generalised dynamic model and model-calibration estimation while the dynamic model is validated using another real DC in the second phase. The model is then applied to investigate the potential of environmental impacts of DC waste heat reuse in DH in China using a real case study. We emphasize the technological and economic possibilities and report our initial elaboration of these technologies in China. The results highlight the feasibility and the effectiveness of the DC waste heat recovery to tackle the energy and environmental problems in China.

2. MODEL FORMULATION

A dynamic model power consumption of a DC is proposed based on a subsystem model and each subsystem has associated model for the power consumption regarding its dynamic behaviour. For more details, see [6-8]. This approach presents physical modelling for heat flow and model parameters needed to be determined by experimentation. A real DC from Finland is used to calibrate the parameters. Figure 1 conceptually illustrates the model. The data center with heat recovery unit is shown in Figure 2.

Theoretically, only heat pump is needed. Both heating and cooling generated from heat pump can be utilized to DC and HD networks. As shown in Figure 2, DC's waste heat enters to the water-to-water heat pump to increase its temperature to 70-90°C. The heat is then supplied to the DH networks. Simultaneously, the produced cooling energy can be applied to cool DC. DC employs a dry cooler or a hybrid type for emergency cooling. The generated cooling energy from the heat pump can satisfy the cooling need of the DC. The energy consumption consists of the power used by the major subsystems, such as servers that consist of all the relevant equipment for processing and storing data, cooling infrastructure that includes CRAH (computer room air handler), CRAC (computer room air conditioner), chillers and pumps, UPS (uninterruptible power supply), PDU (power distribution unit), and others that consumes power. The power consumption of the subsystems are modeled as follows.

$$E_{total} = E_{server} + E_{cooling} + E_{PDS} + E_{UPS} + E_{unknown} \quad (1)$$

where

- E_{total}: total electric energy consumption [W]
- E_{server}: server electric energy consumption [W]
- $E_{cooling}$: cooling consumption [W]
- E_{PDS}: power consumption by PDU [W]
- E_{UPS}: power consumption by UPS [W]
- $E_{unknown}$: unknown power consumption [W]
- $E_{unknown}$: additional and uncertainty power associated with the derivation of the model Equation (1).

$$E_{cooling} = \frac{E_{cooling}}{COP_{cooling}} \quad (2)$$

where

- $COP_{cooling}$: coefficient of performance (COP) for cooling of heat pump

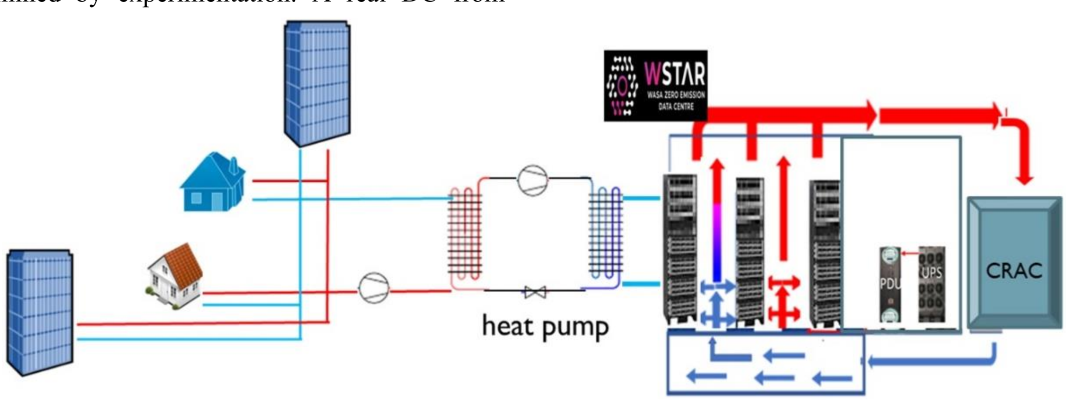

Figure 1 Schematic representation of the DC modeled in this paper.

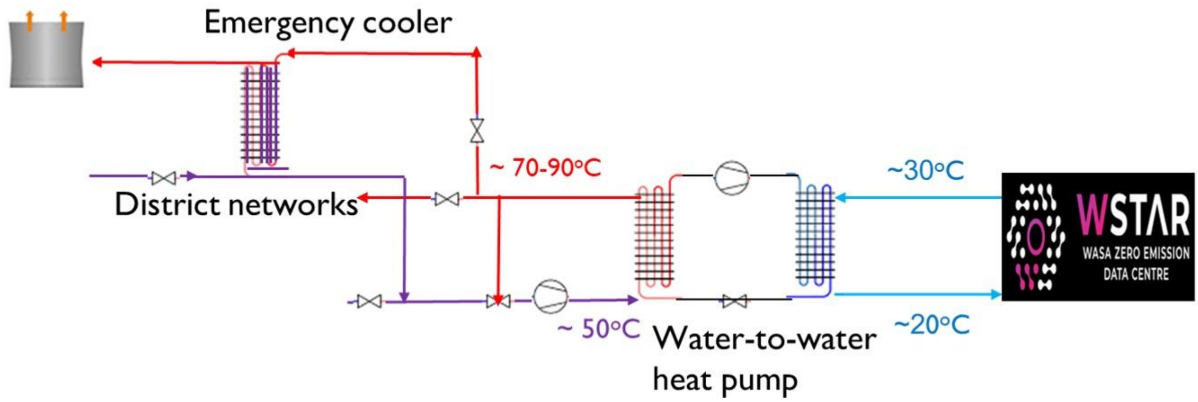

Figure 2 DC heat reuse solution.

3. CALIBRATION AND VALIDATION DATA CENTERS

Two calibration and validation test DCs are used.

3.1. Calibration

The model is calibrated through a real DC located in southern Finland. The design IT power is about 1 MW but run about 500 kW when measurement data were collected [9], see Figure 3.

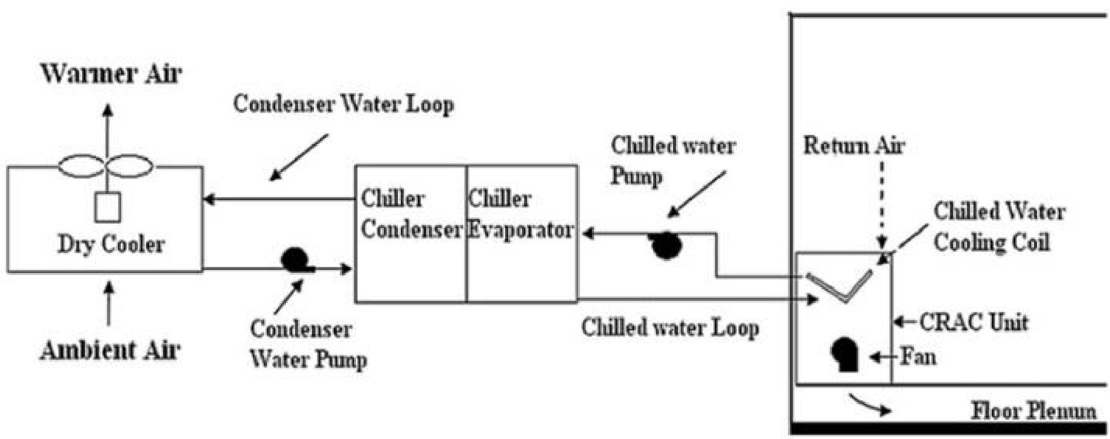

Figure 3 Cooling system of the calibration DC [10].

Using the dynamic model, the power breakdowns are estimated as [10]

- servers: 494 kW
- cooling infrastructure: 53 kW (CRAC)+149 kW (chiller) = 202kW
- other subsystem: 17.4 kW (pump) + 28 kW = 45.4kW

Calibration aims to find the unknown parameters of the model which gives the best fit to the experimental data.

3.2. Validation

Validation was conducted using a campus DC in Finland with about 1 MW capacity IT capacity is a bit over 1 MW and the waste heat is reused in the nearby DH. Figure 4 shows the DC-DH network.

Two heat pumps were adopted with coefficient of performance (COP) about 3.6. The heat pumps efficiently decrease the water temperature from 15°C to 10°C in the DC. The extracted heat is supplied into the DH return line, elevating the temperature to 60-70°C. This heated water is mixed with the return water in order to minimise the temperature difference between the supply and return lines of the local DH network. This process significantly enhances the overall energy efficiency of the entire DC-DH networks. Averagely, the heat pumps provided about 11000 MWh heat to the local DH network with temperatures ranging from 55 to 70°C during the period of January-October.

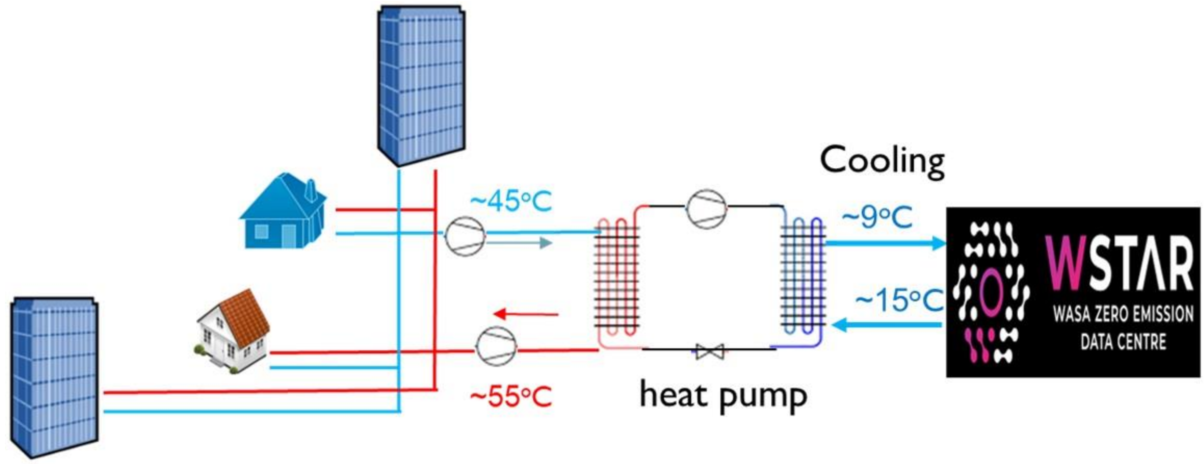

Figure 4 Utilizing DC waste heat in district heating.

4. CASE STUDY

The heat recovery strategy is implemented in the design of an actual data center, with the goal of assessing its potential for reducing carbon emissions. The DC is located in a Digital Hub that covers about 220,000 m^2 area where DC area is about 3,0000 m^2. There are 400 racks and IT runs the capacity at 18 MW. The DH networks include 200000 m^2 office buildings and 200000 m^2 greenhouse that have annual heating demand around 158600 MWh. Buildings are classified as office, dormitory, exhibition center, and facilities, see classification in Table 1.

Table 1. Building types and classifications

Exhibition center	winter heating
Dormitory	24 hours hot water + winter heating
Office	winter heating
Facilities	winter heating
Greenhouse	seasonal heating

The meteorological data is obtained and shown in Figure 5.

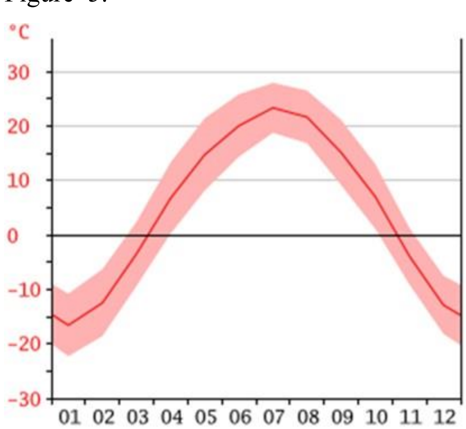

Figure 5 Local weather data.

The DC waste heat is recycled by water-water heat pump and then supplied to heat the buildings in the Digital Hub. Given a coefficient of performance (COP) of 4.5 for the heat pump, and considering that the cooling water from the data center's refrigerating unit is conveyed to the heat pump via a pipeline with a 10% heat loss. Table 2 outlines key parameters essential for conducting a life cycle cost (LCC) analysis spanning 25 years, focusing on the viewpoint of building owners.

Table 2. Input parameters for LCC analysis

	Value	
Discount rate	5%	
Inflation rate	2%	
Electricity price for the first year	57,25 €/MWh	
Electricity inflation rate	2%	
District heating price for the first year	3,94 €/m^2	
District heating inflation rate	3%	
Electricity CO_2 emission factor for the first year	531 gCO_2/kWh	
DH CO_2 emission factor for the first year	378 gCO_2/kWh	
Initial cost of the DC waste heat recovery system	Heat pump (20 MW)	6,106,870 €
	Other costs	1,014,790 €
	Total cost	7,121,660 €

We assume a yearly reduction of 2.5% in both the electricity and DH CO2 emission factors. Additionally, the annual maintenance cost is fixed at 2% of the total investment cost, focusing solely on the investment related to the data center waste heat recovery system from the perspective of building owners.

The simulation results are shown in Figs. 6 and 7.

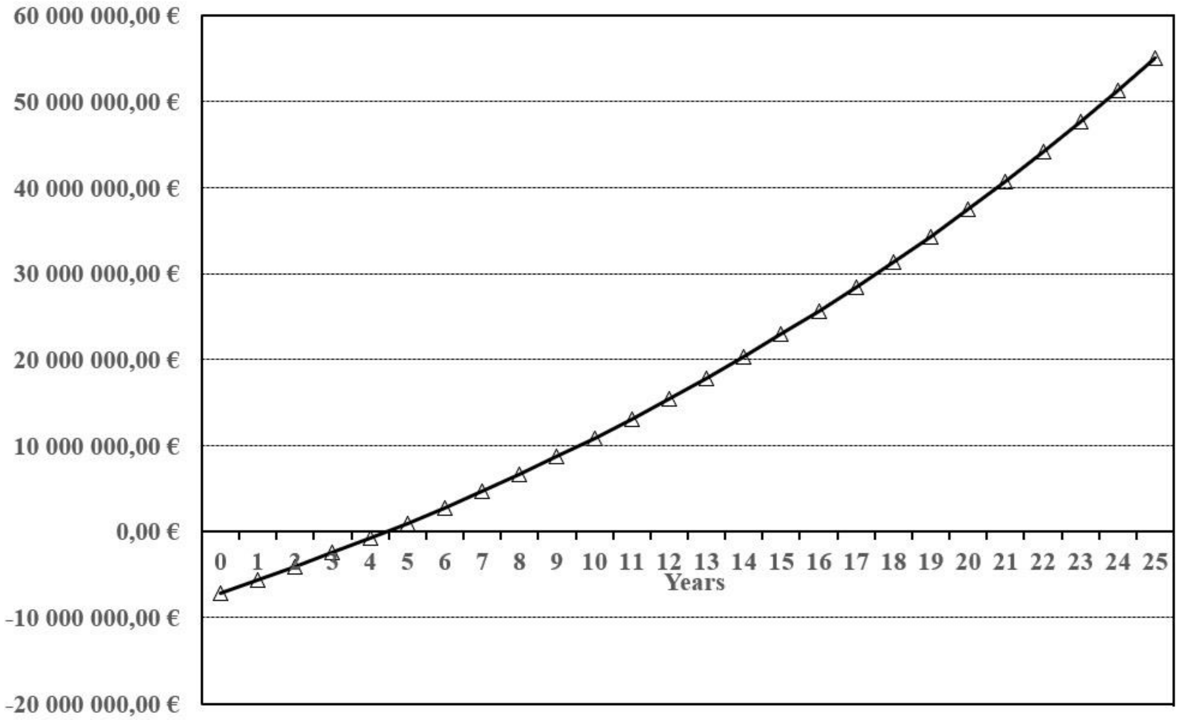

Figure 6 The net present value (NPV) for life cycle cost savings

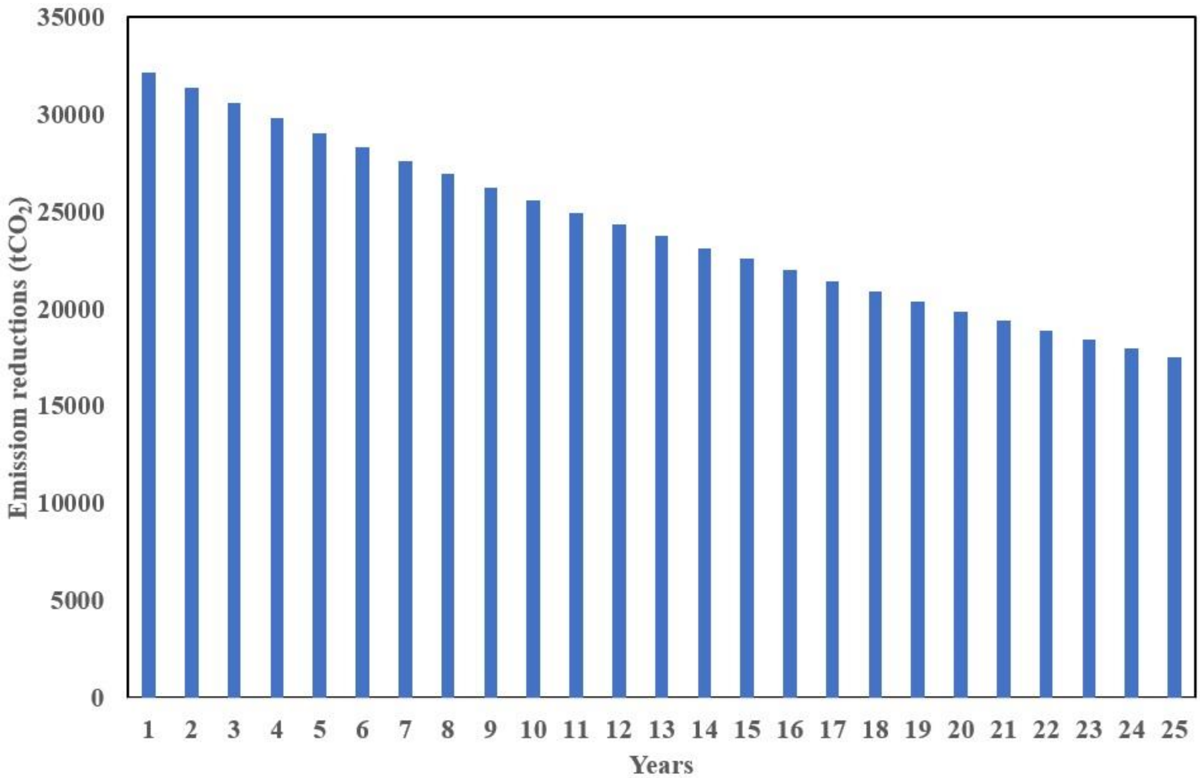

Figure 7 Life cycle CO_2 emission reductions.

In contrast to the scenario where DC waste heat is not recovered, and district heating is utilized for heating a 400,000 m^2 greenhouse and buildings, the DC waste heat recovery scheme demonstrates a substantial reduction in DH consumption by 123,708 MWh annually, representing a remarkable 71% reuse of DC waste heat. Over a 25-year period, this recovery scheme results in savings of €55,036,997 in heating costs (see Figure 6) and a reduction of 603,366 tons of CO2 emissions (see Figure 7). The payback period is approximately five years, as illustrated in Figure 6.

5. CONCLUSIONS

This paper presents a DC power consumption model and a novel heat recovery strategy, aiming at reducing DC's carbon emissions. Three real DC cases were adopted for calibration, validation and investigation of the proposed solutions. The investigation is conducted for an 18 MW DC located in the Digital Hub. The results reveal that approximately 71% of data center waste heat can be effectively utilized to provide heating for a combined area of 400,000 m^2, encompassing both greenhouses and buildings. Consequently, the data center cooling load can be diminished by as much as 71%. Implementing the data center waste heat recovery strategy leads to substantial reductions in district heating consumption and CO2 emissions, amounting to 55,036,997€ and 603,366 tons, respectively, over a 25-year period. In summary, the district heating network offers advantageous conditions for harnessing waste heat from data centers, presenting a significant potential for carbon reduction.

AUTHORS' CONTRIBUTIONS

Xiaoshu Lü: Writing – original draft, Methodology, Conceptualization. **Tao Lu:** Writing – review & editing, Methodology, Conceptualization, Simulation. **Qunli Zhang**: Writing – review & editing.

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