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Potential of solar photovoltaics and waste heat utilization in cold climate data centers. Case study: Finland and northern Japan

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ABSTRACT

As countries worldwide seek to reach net zero emissions within the coming decades, data center sustainability measures are becoming increasingly important as these facilities consume substantial amounts of electricity to support globally expanding digital infrastructure. Yet, local renewable energy production and waste heat utilization are still rarely used in data centers, even though recent high electricity prices have considerably increased the economic value of self-generation and energy efficiency investments. The benefits and cost-effectiveness of data center sustainability measures have also not yet been thoroughly researched in cold-climate regions, where the data center industry is currently growing rapidly. Thus, this paper assesses how solar photovoltaics (PV) and waste heat utilization can effectively be integrated into different cold climate data centers, with a case study analyzing data centers in Finland and northern Japan. The modelled results indicate that solar PV systems can cost-effectively be used to provide renewable electricity to data centers in both Finland and northern Japan, with electricity prices having the largest influence on economic performance. The use of larger external PV systems is shown to be cost-effective at the higher electricity prices seen in 2022, whereas smaller rooftop PV systems and grid electricity provide more economic benefits at 2019 price levels. Selling surplus PV electricity to the grid and using waste heat for district heating is also shown to be effective in data centers located in Finland, whereas battery storage and snow melting are better suited to utilize surplus PV electricity and data center waste heat in northern Japan.

Nomenclature

Abbreviations	
COP	Coefficient of performance
CRAC	Computer room air conditioning
DC	Data center
DH	District heating
EU	European Union
GHG	Greenhouse gas
HP	Heat pump
HVAC	Heating, ventilation and air conditioning
I(C)T	Information and communications technologies
LIB	Lithium-ion battery
PF	Power factor
PV	Photovoltaic

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Abbreviations	
PPA	Power purchase agreement
PUE	Power usage effectiveness
Variables	
COP_i	Hourly COP
$COP_{theoretical}$	Theoretical COP
LCC	Life cycle cost (€/MW)
$LCOE$	Levelized cost of energy (€/MWh)
P_i	Hourly electricity consumption (MW)
$Q_{WH,i}$	Hourly energy of recovered waste heat (MWh/h)
$Q_{DH,i}$	Hourly energy of produced DH (MWh/h)
RF	Renewable fraction
$T_{high,m}$	Mean DH temperature (K)

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(*continued*)

Abbreviations	
$T_{low,m}$	Mean cooling air temperature (K)
Parameters	
C_{Inv}	Investment cost (€/kW)
$C_{O\&M}$	Operation and maintenance cost (€/kW/year)
E_{disch}	Discharged energy (kWh)
r	Discount rate
t	Lifetime (years)
$T_{sink,in}$	DH supply temperature (K)
$T_{sink,out}$	DH return temperature (K)
$T_{source,in}$	DC cooling air supply temperature (K)
$T_{source,out}$	DC cooling air return temperature (K)

1. Introduction

Data centers (DCs) are facilities designed to enable the concentrated and efficient usage of software and hardware in one place. Besides equipment used for data processing, data storage, and communications, DCs typically include specialized power conversion and backup equipment to maintain a reliable power supply, proper temperature and humidity for information and communications technology I(C)T equipment [1]. As the world continues to digitalize and the global amount of internet traffic increases every year [2], it is clear that DCs are an instrumental part of the digital infrastructure modern societies depend on and form the platform where cyberspace and physical space meet. As data processing operations can vary considerably between different DCs, previous studies have categorized DCs into enterprise, co-location, cloud, and hyperscale data centers, that besides their size i.e., commissioned power, differ from each other in several other ways, such as ownership, purpose, and revenue model [3]. Enterprise DCs are usually owned and operated by the company they support and can be located close to the company's other facilities. Co-location DCs instead rent readily equipped data center space to multiple customers who bring in their own IT equipment, whereas cloud-based DCs are owned and operated by companies selling on-demand cloud services to various clients. Recently, the development of hyperscale DCs have attracted the greatest attention [4], as these large-scale facilities with typically over 20 MW and 5000 servers are becoming more popular in locations with abundant power supply and good fiber-optic connectivity.

As data centers become an ever more vital part of our digital infrastructure, it draws further attention to both their sustainability and energy use [5]. According to the International Energy Agency, global DC electricity use was 220–320 TWh in 2021, which equals to 0.9–1.3 % of global final electricity demand, not including energy used for cryptocurrency mining (100–140 TWh in 2021) [2]. Although the DC industry has been continuously expanding to support global digital infrastructure in recent years, the increase in overall DC energy consumption has remained moderate over the last decade, despite earlier projections suggesting that data center and ICT-related energy consumption will increase drastically by 2030 [6]. Some studies have accredited this development to improvements in IT energy efficiency [7], while others have highlighted how computing power in DCs has become more concentrated into larger units [8]. Nevertheless, as large consumers of electricity, DCs still contribute substantially to global greenhouse gas (GHG) emissions [9], and further improvements are needed in DC energy efficiency, renewable energy use, and waste heat recovery in order to decarbonize global digital infrastructure. While current legislation regulating DC energy use is still lenient in most regions, the European Union (EU) has recently taken the first steps in making DCs operations climate neutral in Europe. Notably, the EU has recently introduced mandatory reporting of energy use, energy efficiency, and emissions for DCs over 500 kW through the new EU Energy Efficiency Directive [10], supplemented by further reporting requirements mandated by the EU Corporate Sustainability Reporting Directive [11]. Additionally, company sustainability targets and industry initiatives have also recently become driving forces for emission reduction measures throughout the global DC industry, with for instance, numerous DC operators recently signing the Climate Neutral Data Center Pact aimed at making DCs climate neutral already by 2030 [12].

Currently, the most common method of increasing renewable energy use in DCs is to purchase renewable electricity through the electricity grid, which usually includes premium on top of market prices and distribution costs. Another alternative, which has gained much attention recently, is to acquire electricity directly from producers by means of bilateral hedging (usually from a wind power operator if purchasing renewable energy) using power purchase agreements (PPAs) [13]. The use of on-site solar photovoltaic (PV) electricity generation has also been recognized as another capable option to acquire clean energy for DCs [14], an approach which could be especially beneficial for DC operators at the high electricity prices seen in many countries in recent years. Nevertheless, especially in northern regions, many DC operators have been hesitant to implement PV systems at their facilities, even though the cost of utility-scale PV systems have decreased over 80 % since 2010 [15]. While this kind of reluctancy or lack of interest may be due to scepticism about limited solar irradiation at higher latitudes, it is also certain that more research is needed on how PV systems can cost-effectively be implemented in cold climate DCs in order to facilitate evidence-based decision making.

Waste heat recovery and re-use is another topic gaining increasing attention in many studies. While outside the core business of DCs, low-grade heat, typically between 25 and 50 °C in DCs with air-side cooling [5], can be considered as an industrial-scale side-stream with significant value depending on the surrounding conditions [16]. However, the effective recovery of heat necessitates that there are applications and processes (such as district heating (DH) networks or local low-temperature solutions connected with warming of indoor air, greenhouse farming, fish farming, biomass drying or snow melting) where low-grade heat can be used [1]. Simultaneously, waste heat utilization would also need to be affordable enough (even after the possible use of heat pumps (HPs) to reach higher temperatures) to compete against other sources of heat [17]. Additionally, as the effectiveness of energy efficiency in DCs is mainly measured using the power usage effectiveness (PUE) indicator, which shows how overall electricity consumption compares to IT-related electricity use, the value of waste heat utilization is often overlooked when comparing DC performance metrics [18]. Recent studies have thus also suggested a broader adaptation of new indicators to measure DC performance, such as the Energy Reuse Factor (ERF), which could facilitate sustainability measures and waste heat re-use more effectively in DCs [8].

Notably, prior research has also emphasized the importance of energy efficiency already in the site-selection phase of new DC projects. I(C)T equipment has been shown to consume approximately 45 % of total electricity demand in conventional DCs, closely followed by the cooling system at 40 % [5], with remaining power being used by power distribution systems, uninterruptible power supplies, chillers, and lighting, etc. [19]. Placing new DCs in northern regions has also become an attractive alternative for DC operators, as cold climate conditions have been documented to substantially reduce the electricity consumption of heating, ventilation, and air conditioning (HVAC) systems in DCs when paired with open-air cooling [8]. For instance, Rong et al. (2016) estimates that proper DC site selection can reduce computer room air conditioning (CRAC) electricity consumption in DCs by up to 30 % [20]. And although the location of a DC may be insignificant in the dematerialised space of data, locational questions are of paramount importance to DC operators, with several factors affecting site-selection decisions [8]. In addition to climate conditions, factors including the availability of a reliable power supply, international data connectivity, low energy prices, political stability, a business-friendly environment, a competent workforce, and a natural disaster-free climate have all been shown to greatly influence DC site selection [4]. Hence, in recent years, many northern regions have become especially attractive locations for new data centers due to a combination of favourable conditions, with for instance the Nordic countries developing into the largest European DC hub outside the Frankfurt, London, Amsterdam, Paris, and Dublin area, with an estimated live capacity of 600 MW [8]. Similar advantages have also lately been recognized in northern Japan [21], where a cold climate, access to renewable energy, and developments in arctic submarine cable infrastructure are advancing the planning and construction of several new DCs. Nevertheless, few studies have assessed the economic performance and emission reduction potential of local renewable energy generation and waste heat re-use in DCs located in different cold climate regions [9], although the data center industry and demand for sustainability measures is rapidly growing in these locations.

Consequently, this study aims to assess how solar PV systems, energy storage, and waste heat can be effectively utilized in cold climate DCs located in different regions in terms of economic performance and system operation. For this purpose, this study presents a case study assessing the use of these technologies in different sized data centers in both Finland and in northern Japan, as both of these locations share a cold climate and many of the competitive advantages identified as key criteria for the DC industry, however, with distinct differences in solar PV effectiveness, electricity supply, and uses for waste heat. Notably, the generation profile of solar PV systems, with its peaks in the summer, could complement the cooling demands of DCs located in northern regions [22,23], while aiding DC operators in reducing the considerable carbon emissions linked to the high electricity consumption of DCs [23]. Likewise, the existing DH networks in Finland could allow recovered waste heat to be utilized effectively for the heating of buildings after increasing the temperature with HPs [18], providing both environmental benefits from displacing fossil fuel-based heat production and an additional revenue stream to DC operators. In northern Japan there is also a high demand for more efficient ways of removing snow during the winter, with the city of Sapporo spending over 150 million € annually on snow removal [24], a cost that is increasing every year [25]. Waste heat utilization from DCs for snow melting could thus provide significant social and economic value also in this region, depending on the location and surroundings of the DC.

2. Material and methods

The potential of solar PV systems and waste heat utilization in cold climates was in this research assessed by modelling DCs in two different locations, Helsinki in southern Finland and Sapporo in northern Japan. For each location, several scenarios were created to assess the system operation, economic viability, and environmental impact of differently sized and configured solar PV systems, with certain scenarios including the battery storage or the option to sell excess PV electricity to the grid. For DCs modelled in Finland, DH was evaluated as the primary application for waste heat re-use due to pre-existing DH infrastructure, whereas snow melting and space heating were considered as the primary applications for waste heat from DCs located in northern Japan. The study design employed in this work is depicted in Fig. 1, illustrating how solar PV systems, grid electricity, energy storage, and waste heat utilization interact with each other in the different scenarios.

2.1. Modelling of solar PV and energy storage usage

MATLAB was used as the primary modelling tool and computing environment for the simulations and economic analysis performed in this study. The employed modelling approach was adapted from a computing algorithm developed in previous research [23], where MATLAB was shown to an effective simulation tool for the modelling of solar PV and energy storage systems in buildings, providing sufficient flexibility to analyze both the operation and economic performance of diversely configured renewable energy systems in detail. Fig. 2 illustrates the model logic of the employed MATLAB model, showing a block diagram of how the used input data, model functions, output data, and modelled results are connected with each other. As can be seen in Fig. 2, the model uses hourly timeseries data for solar PV generation and data center energy consumption to calculate the net electricity demand of the DC and the amount of surplus electricity generated by the PV system. The results are subsequently used to calculate the capacity of possible energy storage systems, simulate energy supply and demand between different components, and to attain the achieved renewable fraction of the system. These technical outputs are then together with economic input data used to analyze the economic performance of the modelled energy system. Notably, the storage need function illustrated in Fig. 2 assumed that all surplus electricity is stored until the first possible dischargeable timestep within technical constraints, including a limit to the maximum energy storage capacity at twice the rated power of the modelled PV system. The energy flows and costs parameters in the model were all simulated with an hourly resolution, resulting in 8760 timesteps for each assessed year. Case-study specific assumptions are presented in further detail in Chapter 3.

In the economic analysis, life cycle cost (*LCC*) and levelized cost of energy (*LCOE*) were used to assess the financial feasibility of the modelled solar PV configurations. *LCC* was selected as it is a frequently

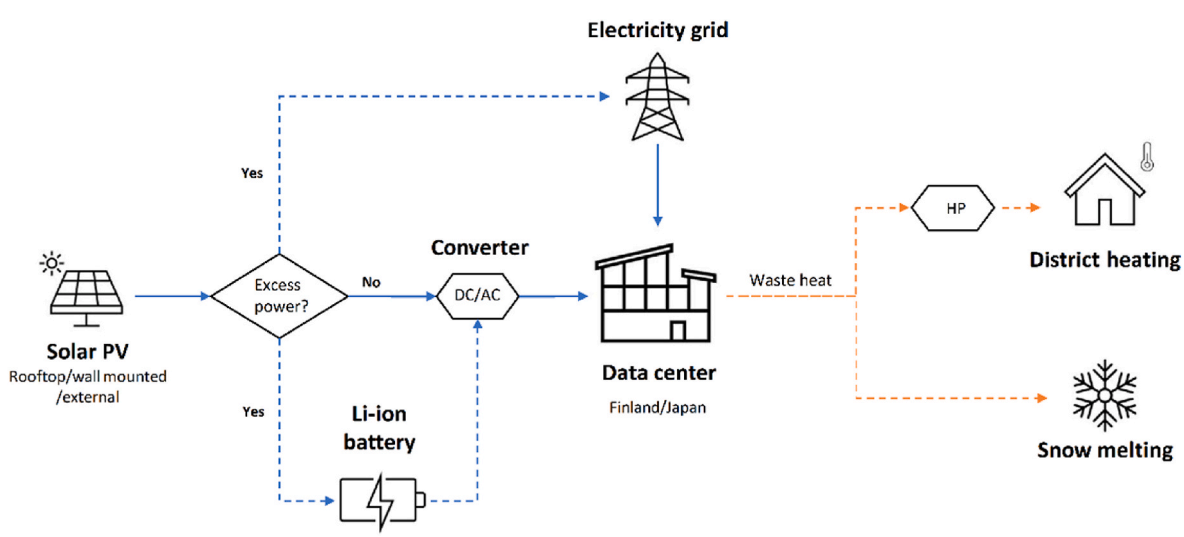

Fig. 1. Flowchart illustrating the employed study design.

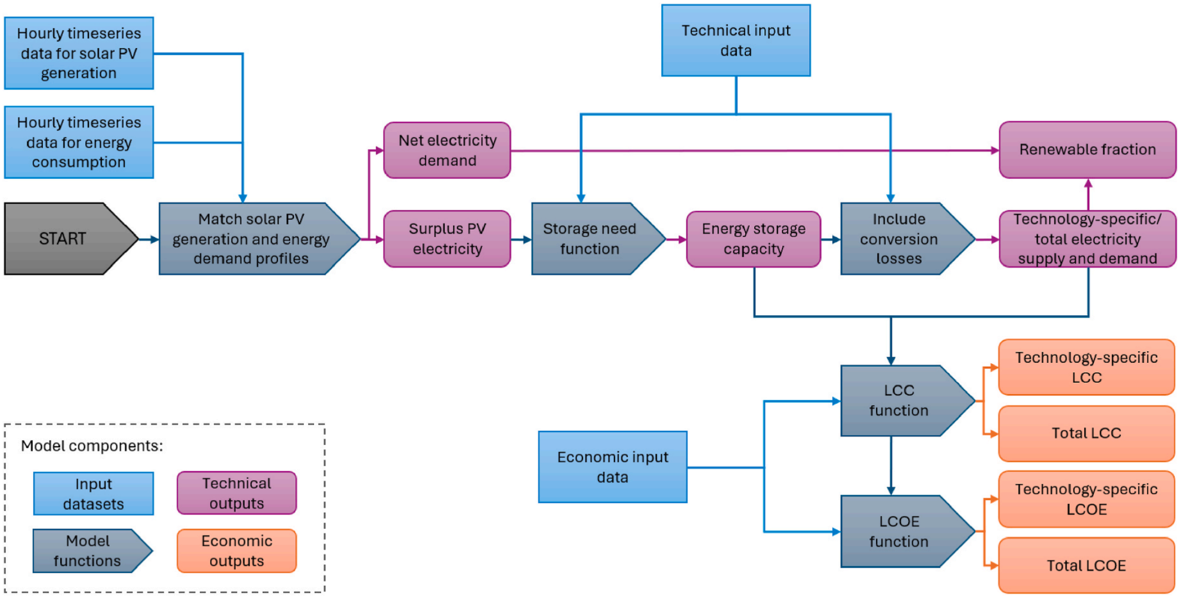

Fig. 2. Inputs, functions, and outputs of the employed MATLAB energy system model.

used cost-indicator in several academic disciplines, which depicts the entire discounted cost of a given system over its lifetime [26]. Additionally, *LCOE* was also selected as a complementary economic indicator, as it depicts the discounted cost per unit of employed in a system and can be used to compare the costs of local renewable energy generation with the costs of using grid electricity. Equation (1) and Equation (2) depict how the *LCC* and *LCOE* were calculated in the economic analysis of this study. In these equations, C_{Inv} is the initial investment cost, $C_{O\&M}$ the annual operation and maintenance costs, E_{disch} the annual amount of produced or discharged electricity, r the used discount rate, and t the system lifetime. Notably, end-of-life costs are excluded in these equations.

$$LCC = C_{Inv} + \sum_{t=1}^{T} \frac{C_{O\&M}}{(1+r)^t} \tag{1}$$

$$LCOE = \frac{C_{Inv} + \sum_{t=1}^{T} \frac{C_{O\&M}}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_{disch}}{(1+r)^t}} \tag{2}$$

2.2. Modelling of waste heat utilization

In addition to simulated operation and modelled costs of using solar PV systems in DCs, the benefits of DC waste heat re-use in DH production were evaluated based on the annual operating costs and achieved revenue from the point of view of a DC operator. This work assumed that approximately 67 % of the modelled DC's electricity consumption can be recovered as useable waste heat, as prior research has shown that IT-related electricity consumption is around 70 % of total electricity demand in open-air cooled cold climate DCs [18], and that up to 97 % of this electricity consumption can be recovered as waste heat [27]. In DCs with open-air cooling, this waste heat would be recovered from the warmed-up outlet air from servers and IT-equipment at an estimated temperature of 35 °C, corresponding to an inlet temperature of 25 °C [28]. In Finland, where waste heat can be utilized for DH, HPs are needed to raise the waste heat temperature to the supply temperature of the DH network. This supply temperature is defined using a control curve and varies between 75 °C and 120 °C according to outdoor temperatures [29]. However, as technical limitations prevent HPs producing very high temperature heat, the maximum output temperature of the HPs was limited to 90 °C in the modelling [30], while the return temperature of DH water was assumed to be a constant 50 °C.

Furthermore, in order to model the hourly DH production from DC waste heat throughout the year, as well as to estimate the electricity consumption of the HPs, this study calculated the seasonally changing coefficient-of-performance (COP) of the HPs using hourly resolution temperature data for the year 2022. To accurately define the COP of the HPs in DH production, a theoretical COP of the HP was first calculated based on the used design parameters. Equation (3) presents the calculation method for the theoretical COP ($COP_{theoretical}$), in which the mean temperatures $T_{high,m}$ and $T_{low,m}$ were calculated using Equations (4) and (5). In Equation (4), the DH supply temperature is $T_{sink,out} = 343.15\,K$ and return temperature $T_{sink,in} = 323.15\,K$, in accordance with the design of Finnish DH networks. In Equation (5), the temperature of the warm returning cooling air in the data center is estimated at $T_{source,in} = 308.15\,K$, while the temperature of the cold cooling air is estimated at $T_{source,out} = 298.15\,K$.

$$COP_{theoretical} = \frac{T_{high,m}}{T_{high,m} - T_{low,m}} \tag{3}$$

$$T_{high,m} = \frac{T_{sink,out} - T_{sink,in}}{ln\left(\frac{T_{sink,out}}{T_{sink,in}}\right)} \tag{4}$$

$$T_{low,m} = \frac{T_{source,in} - T_{source,out}}{ln\left(\frac{T_{source,in}}{T_{source,out}}\right)} \tag{5}$$

Based on these equations, the HP efficiency was then calculated using the theoretical COP and the assumed design conditions of the actual COP. Here, the actual COP was assumed to be 4.1 in the same design conditions [31], which results in a HP efficiency of 36.8 %. However, as the COP differs on every hourly time step due to the varying supply temperature, the COP was calculated on every hour by multiplying the theoretical COP on each timestep with the HP efficiency. After defining the COP on every hour, electricity consumption was then calculated using Equation (6) and the produced DH load using Equation (7), where P_i is the hourly electricity consumption, $Q_{WH,i}$ hourly energy of the recovered waste heat, COP_i hourly coefficient-of-performance, and $Q_{DH,i}$ hourly energy of the produced DH load.

$$P_i = \frac{Q_{WH,i}}{COP_i - 1} \quad (6)$$

$$Q_{DH,i} = Q_{WH,i} + P_i \quad (7)$$

2.3. Used data

This study used hourly timeseries data to model the electricity consumption of the data center, spot electricity prices, PV generation, and outdoor temperatures. The electricity consumption data was based on recorded values for an operational DC in southern Finland, as well as modelled consumption profiles for a DC located in northern Japan. This data was acquired from companies operating data centers in these regions and is not publicly available. The electricity consumption profile of the modelled DC was assumed to be comparable for all DC sizes, with the electricity consumption data scaled to a chosen size in each scenario. The electricity demand data for Finland was also linearly adjusted to account for observed growth in the capacity of the DC in the source data, with a seasonal projection used to fill in missing data points. The used solar irradiation and PV generation data was acquired from the public PVGIS tool, developed by the European Commission, and its corresponding dataset [32]. Outdoor temperature data for Finland and Japan was obtained from the Finnish Meteorological Institute and the Japan Meteorological Agency, respectively [33,34]. Hourly electricity spot price data for Finland was acquired from the Nord Pool data service [35], whereas electricity price data for northern Japan was acquired from the Hokkaido Electric Power Company [36].

3. Case study: data centers in Finland and northern Japan

As mentioned in Chapter 1, there are considerable differences in the size and operating conditions between various types of data centers, which can also impact the effectiveness of both solar PV systems and waste heat re-use. For this reason, this study selected to model both a medium sized DC (average load of 2.5 MW) and a hyperscale DC (average load of 25 MW) in two different cold climate locations – Helsinki in southern Finland and Sapporo in northern Japan – resulting in four scenarios as shown in Table 1. Each scenario (S1–S4) assessed the effectiveness of both rooftop solar PV systems (PV-R) and external solar PV systems (PV-E), with the option to either sell surplus solar PV electricity to the power grid (PV-ES) or store it to meet demand in the following hours using LIBs (PV-EB). In S1 and S2, DC waste heat was used to produce DH in the Helsinki region, whereas S3 and S4 assessed the possibility of using waste heat for snow melting in the Sapporo region. Open-air cooling was assumed to be the default cooling method of the modelled data centers in all the scenarios. The system size of the data center, solar PV system, and LIB storage in each scenario are illustrated in Table 1.

Table 1
System size of the modelled data centers, solar PV, and LIB systems.

System size	Unit	Helsinki		Sapporo	
		S1	S2	S3	S4
Data center					
Location		Helsinki, Finland		Sapporo, Japan	
Coordinates		60.17 °N, 24.94 °E		43.06 °N, 141.35 °E	
Avg. electricity usage	MW	2.5	25	2.5	25
Rooftop surface area	m^2	6000	60 000	6000	60 000
Rooftop surface area for PV	m^2	4800	48 000	2400	24 000
Solar PV and LIB system					
Rated power – rooftop	MW	0.96	9.6	0.48	4.8
Rated power – external	MW	5	50	5	50
LIB storage capacity	MWh	10	100	10	100

3.1. Solar PV and battery storage

The size of the modelled rooftop solar PV system was selected by estimating the available rooftop surface area of each modelled DC, as shown in Table 1. In Helsinki, it was assumed that 80 % of the total rooftop area could be used for PV panels. In Sapporo, it was estimated that only 40 % of the rooftop area could be used for this purpose, due to heavy snowfall and structural limitations to contend with seismic activity. While limited space, high land prices and higher annual solar irradiation can make wall-mounted solar PV systems attractive options in Sapporo, wall-mounted PV systems were not modelled or included in the scope of this study as their effectiveness varies greatly according to the location, surroundings, and design of each building.

In addition to the modelled rooftop solar PV system, an external solar PV system with a rated capacity two times higher than the average electricity consumption of the DC was modelled. This resulted in a 5 MW external PV system in S1 and S3, and a 50 MW PV system in S2 and S4. As the modelled external PV system would generate a considerable surplus of electricity while operating at full capacity during hours with high solar irradiation, both selling electricity to the grid and the use of energy storage were assessed as options to recover excess power in these scenarios. The size of the modelled LIB was set at 10 MWh in S1 and S3, and 100 MWh in S2 and S4, as can be seen in Table 1.

For the purposes of this research, all the modelled PV systems were assumed to have the properties of crystalline silicon (c-Si) PV panels, as it is the most common commercial solar PV panel technology with a 95 % market share as of 2020 [37]. The solar PV system was also assumed to be fixed mounted with an optimal 44-degree slope in Finland, and an optimal 40-degree slope in Sapporo, which would maximize the annual electricity generation of the PV system [32]. It was also assumed that the DC rooftop or surroundings would allow the PV system to be installed with a zero-degree azimuth angle, and that the overall system losses (accounting for nameplate losses, mismatch, as well as light-induced degradation over the lifetime of the PV system) would be approximately 14 %. In the modelled scenarios with battery storage, the properties of a 4-h duration LIB with a 90 % round-trip efficiency was used, as most solar PV installations with battery storage employ Li-ion batteries [38].

The modelled cost estimates for solar PV and LIB systems are presented in Table 2 and are representative of crystalline silicon PV panels and 4-h duration LIB storage systems based on US cost projections from 2021 and converted to euros using a 1.1 USD/EUR exchange rate [15, 37–39]. The cost estimate for PV systems ranges from commercial scale 0.5 MW fixed tilt rooftop PV systems to utility-scale 100 MW fixed tilt ground-mounted PV systems, while the cost estimate for battery storage depicts the market price of utility-scale LIB systems. Any possible subsidies were excluded in these estimates [40]. The modelling was performed using the selected values presented in Table 2, which are equal to the median values found in the cited literature, adjusted upwards to account for the higher equipment and labor prices in Finland and Japan. Likewise, the solar PV and LIB system costs were assumed to be comparable for all the scenarios both in Finland and Japan, even though price differences may occur depending on the DC location and system size. To account for these differences, the modelling included sensitivity analysis on the economic viability of the solar PV and LIB system with the low- and high-end cost estimates presented in Table 2. Additionally, the modelling used a 4 % discount rate with a 20-year project lifetime in the *LCC* and *LCOE* calculations.

3.2. Waste heat utilization

The primary application for data center waste heat in the modelling was DH production in Helsinki (S1 and S2), and snow melting in Sapporo (S3 and S4). In S1 and S2, it was assumed that the DC operates the HP at maximum capacity every hour, producing DH according to the availability of the waste heat source, which leads to an increase in

Table 2
Estimated costs, lifetime and efficiency of solar PV and Li-ion battery systems in commercial and utility scale applications.

Parameter	Unit	Solar PV system [15,37]		Unit	Li-ion battery system [38,39]	
		low - high	*selected*		*low - high*	*selected*
Investment cost	€/kW	750–1330	1100	€/kWh	230–680	500
O&M cost	€/kW/year	13–16	15	€/kWh/year	0–32	30
Lifetime	years	25 +	25	years	7–20	15
Efficiency	%	17–23	20	%	80–93	90

electricity consumption for the DC and results in higher electricity costs. As electricity consumption makes up the majority of the HP operating cost, no other operating and maintenance costs were considered in this analysis. It was presumed that the local DH operator pays a variable buy-in price between 14.3 and 50 €/MWh for the produced DH, depending on outdoor temperatures. The full buy-in price list is presented in Table 3 and corresponds to the price offered by Forum for heat sold to the Espoo DH network [41].

As little research exists on the large-scale use of DC waste heat for snow melting purposes [42], the benefits and costs of snow melting systems in S3 and S4 were based on existing installations in other applications. These snow melting systems typically have an energy use ratio between 200 and 1600 W/m^2, depending on both climate and the design of the snow melting system [42]. Assuming that the 35 °C waste heat from the DC would be directly used for snow melting without priming or the need for HPs, this study used this energy use ratio estimate to determine the size of the potential snow melting system.

3.3. Grid electricity

The cost of grid electricity was based on spot electricity prices from the Nord Pool electricity market for the modelled DCs in Finland, as most end-consumers of electricity either use fixed or spot-based prices in Finland and northern Europe [35]. In northern Japan, grid electricity prices were based on fixed rates from the regional power company, as the majority of private and commercial end-consumers in Japan purchase electricity at fixed rates, with options including separate day and night prices, as well as weekday and weekend prices, often available [36]. While an open electricity market also exists in Japan, with 45 % of electricity in the country being traded at variable prices on the JEPX platform, spot electricity prices are mostly used for wholesale trading and rarely by end-consumers. It is also common for large electricity consumers, such as DCs, to negotiate their electricity price directly with power companies, and not disclose this information publicly. Moreover, Fig. 3 illustrates how electricity prices in Finland and northern Japan have shifted considerably in recent years, with factors such as the Covid-19 pandemic, energy crisis in Europe, and geopolitical uncertainty affecting global energy prices, making it challenging to accurately estimate future price levels. For this reason, this work opted to use electricity prices for multiple years in the modelling, using 2019 and 2023 spot prices for Finland (in S1 and S2), and fixed prices for Japan (in S3 and S4), depicting both the stable and low electricity prices seen in 2019, as well as the volatile and high electricity prices seen in more recent years.

Table 3
Waste heat buy-in-price by Fortum for the Espoo DH network in Finland starting January 1, 2023 [41]. Prices are intended for waste heat producers with a capacity below 5 MW.

Outdoor temperature (°C)	Buy-in price (€/MWh)
≤ −8	50
−7.9 … −7	47.5
−6.9 … −4	45
−3.9 … −3	42.5
−2.9 … −2	40
−1.9 … −1	35
−0.9 … 4	30
4.1 … 6	24
6.1 … 7	21.5
7.1 … 16	19
≥ 16.1	14.3

The grid connection voltages, electricity prices, and electricity transfer costs used in the modelled scenarios are presented in Table 4, showing distinct differences between grid electricity in Finland and Japan. For instance, electricity transfer costs are typically included in the fixed electricity prices offered to end-consumers in Japan, whereas electricity transfer and distribution costs in Finland are separated from electricity market prices. In Japan, DCs are also connected to the grid at different voltages compared to Finland, while differences in electricity taxation also exist between the countries. Notably, electricity tax is levied on all end-consumers in Finland, however, a lower electricity tax class is available to industrial applications and DCs over 5 MW that meet certain sustainability criteria [43]. The electricity prices presented in Table 4 are average annual spot prices for Finland in S1 and S2, and fixed prices including electricity transfer costs for northern Japan in S3 and S4.

The option to sell surplus electricity to the power grid was also assessed in the modelled scenarios with larger solar PV installations [23, 26]. In the modelled DCs in Finland, surplus electricity was sold to the grid at spot prices, including transmission fees [44]. In northern Japan, selling surplus renewable electricity is mostly not encouraged or supported by electricity companies and grid infrastructure, or only available at lower sellback prices, and subsequently the sellback price for electricity in Japan was set to be 50 % of the purchase price in the modelling.

4. Results

This Chapter presents the results of the modelling performed in this research. Section 4.1. presents the system operation of the simulated PV and waste heat re-use systems in the different scenarios, followed by economic analysis in section 4.2.

4.1. Data center energy use and system operation

Fig. 4 illustrates the electricity demand and supply of the 2.5 MW data center modelled in S1 and S3, showing the annual share of electricity which would be produced by a rooftop solar PV system (PV-R), a larger external PV system (PV-E), in addition to any annual PV surplus sold to the grid or stored using Li-ion batteries. The PV surplus illustrated in Fig. 4 is presented without including additional electricity consumption from HP system. Furthermore, Fig. 4 shows the amount of waste heat that can be recovered from a 2.5 MW DC in both Finland and Japan, and the subsequent amount of DH that can be produced after priming the waste heat with HPs to increase its temperature.

As can be observed, the share of solar PV generation in the annual electricity demand of the DC is still minor, even with a comparably large 5 MW solar PV installation in the vicinity of the DC. Most of the electricity demand of the DC is still met using grid electricity, making the purchase of low carbon grid electricity a necessity for reducing overall CO_2 emissions. Conversely, Fig. 4 also illustrates how a 2.5 MW DC could produce around 15 GWh of useable waste heat from the cooling of IT equipment, which could be primed into over 20 GWh of high temperature heat for DH or used locally for the heating of office space or for

Fig. 3. Historical electricity price in Helsinki, Finland and Sapporo, Japan from 2018 to 2023. The electricity price for Finland is the weekly average of Nord Pool day ahead spot prices, and the electricity price for Japan is the electricity charge (including transfer costs) used by the Hokkaido Electric Power Company.

Table 4
Electricity prices and electricity transfer costs for the modelled DCs in Finland and Japan.

Grid electricity	Unit	Helsinki		Sapporo	
		S1	S2	S3	S4
Contract type		Spot	Spot	Fixed	Fixed
Grid connection voltage	kV	20	110	30	60
Electricity prices [35,36]					
Flat price, 2019	€/year	–	–	28 211	280 500
Flat price, 2022	€/year	–	–	36 997	368 358
Energy price, 2019	€/MWh	44.0	44.0	125.5	125.2
Energy price, 2022/2023	€/MWh	154.0	154.0	221.7	221.4
Electricity transfer costs [36,43–45]					
Annual transfer fee, intake from network	€/year	112 500	0	–	–
Transfer fee, intake from network	€/MWh	8.25	4.975	–	–
Electricity tax	€/MWh	2.253	0.063	–	–
Electricity sellback price [36,44,45]					
Sellback price	€/MWh	Spot	Spot	50 %	50 %
Transfer fee, output to network	€/MWh	0	0.62	–	–

snow melting. Additionally, Fig. 4 shows the additional electricity consumption required by the HP from priming the waste heat, illustrating how DH production from waste heat increases the overall energy use of the DC by around 25 %.

Furthermore, Figs. 5 and 6 illustrate the seasonal electricity demand profile, solar PV generation profile, and corresponding outdoor temperatures of the modelled medium-sized DC in Helsinki (S1) and Sapporo (S3), respectively. As can be observed, the daily electricity consumption profiles of the modelled data centers partially correlate with both the generation profile solar PV systems in cold climate regions, as well as follow outdoor temperatures at warmer temperatures, suggesting PV systems be effectively used to provide DCs with renewable electricity. The observed correlation between the energy consumption and surrounding climate conditions of DCs is further highlighted in Figs. 7 and 8, which use second degree polynomial trendlines and regression analysis to illustrate the statistical correlation between the outdoor temperature and data center electricity consumption based on recorded values for a DC in Helsinki (S1) in Fig. 7, and modelled values for a DC in Sapporo (S3) in Fig. 8.

Notably, the regression analysis presented in Figs. 7 and 8 show how there is a statistically significant correlation ($R^2 = 0{,}55$) between outdoor temperatures and the recorded total daily electricity consumption of a medium-sized DC in Helsinki (S1), and a statistically strong correlation ($R^2 = 0{,}98$) between outdoor temperatures and the modelled total daily electricity consumption of a medium-sized DC in Sapporo (S3). These results thus highlight how DC electricity consumption increases and has a strong correlation with outdoor temperatures at 10 °C and above, which validates the modelled data used in this study with similar findings presented in prior research [18]. Notably, the results presented in Figs. 5–8 are given using outdoor temperatures (and not e.g. cooling degree days) due to the more detailed hourly resolution of the timeseries data used in this study, but also to validate the modelled data more

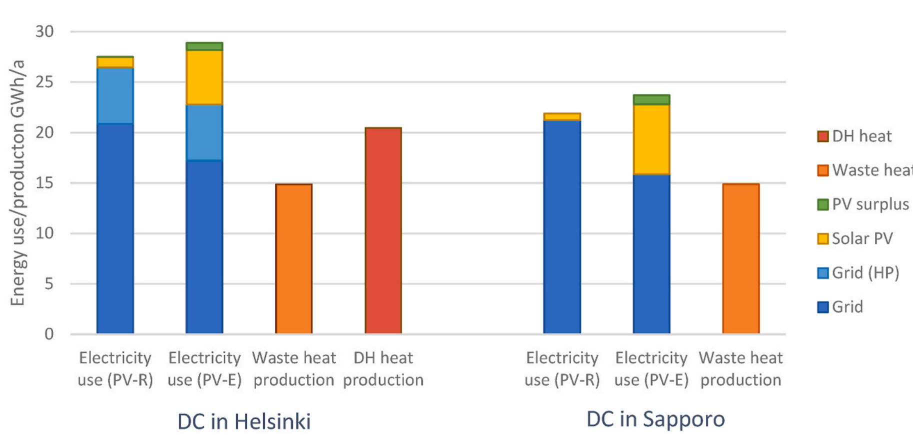

Fig. 4. Electricity use, solar PV electricity surplus, available waste heat, and DH production for the modelled 2.5 MW DCs in Helsinki (S1) and Sapporo (S3).

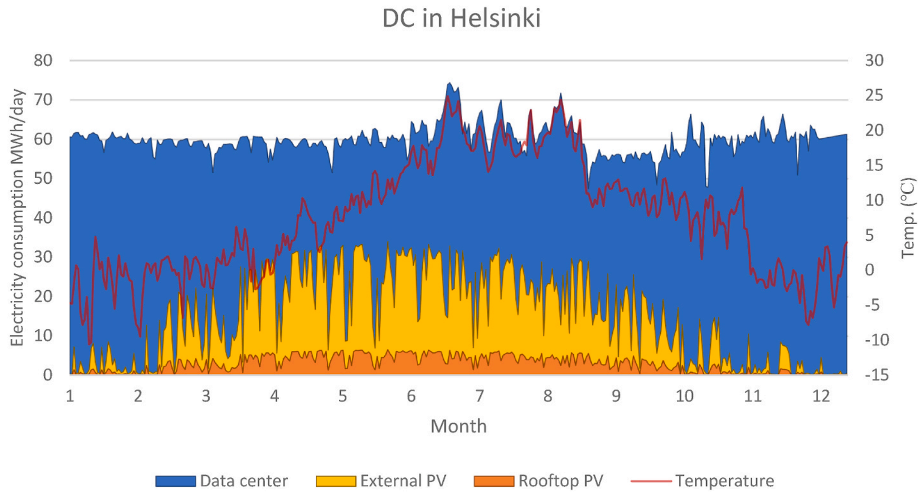

Fig. 5. Daily electricity consumption, solar PV generation, and average outdoor temperature for the modelled 2.5 MW DC in Helsinki (S1). The DC electricity consumption is based on historical data.

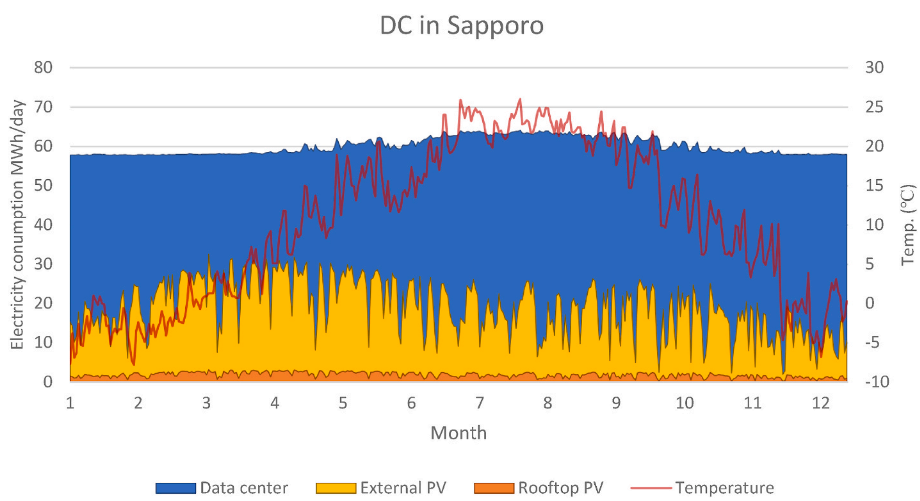

Fig. 6. Daily electricity consumption, solar PV generation, and average outdoor temperature for the modelled 2.5 MW DC in Sapporo (S3). The DC electricity consumption is based on modelled data.

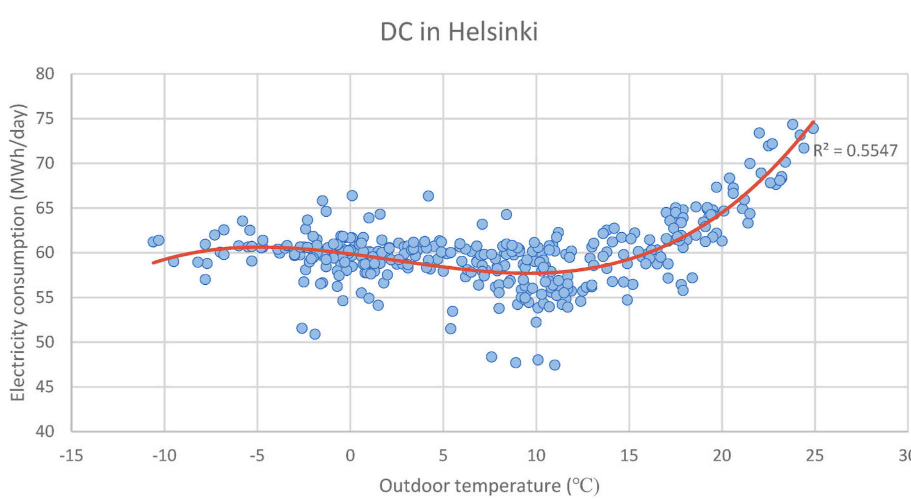

Fig. 7. Correlation between daily electricity consumption and average daily outdoor temperature of the modelled 2.5 MW DC in Helsinki (S1).

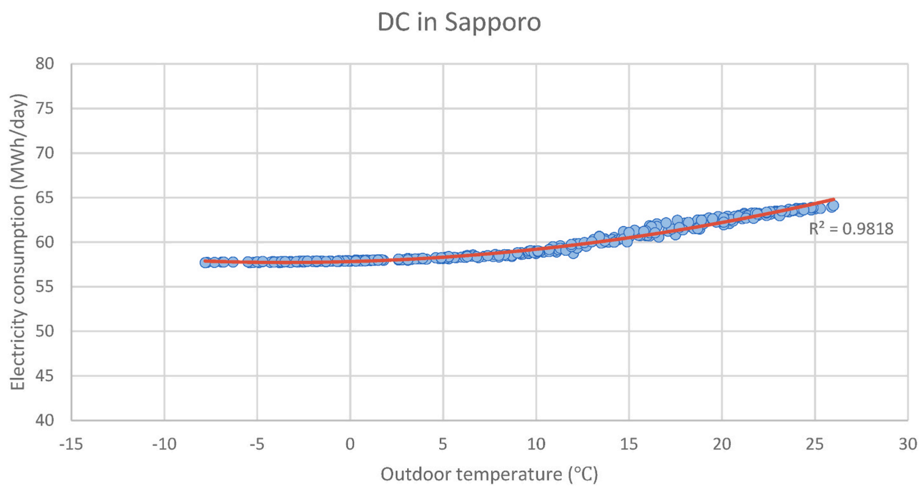

Fig. 8. Correlation between daily electricity consumption and average daily outdoor temperature of the modelled 2.5 MW DC in Sapporo (S3).

accurately with similar results presented in prior studies.

4.2. Economic performance of solar PV systems

Table 5 and Table 6 present the results of the economic analysis conducted in this study, illustrating the financial feasibility and economic impact of the different solar PV installations modelled in S1–S4. The results compare the use of only grid electricity (G), a rooftop solar PV system (PV-R), a large external solar PV system where surplus electricity is sold to the grid (PV-ES), and a large external solar PV system where surplus electricity is stored for later use using LIBs (PV-EB), with both historically average (2019) and recently seen higher (2022/2023) electricity prices.

As can be observed from Table 5, integrating a rooftop solar PV system in both 2.5 MW and 25 MW data centers would have a *LCC* of around 1.30 M€/MW in both Finland or Japan, whereas a larger PV system able to sell surplus electricity to the grid would cost between 0.96 and 1.21 M€/MW over its lifetime in Finland, or between 1.03 and 1.12 M€/MW in Japan, depending on electricity prices. In comparison, a PV system with battery storage would instead have a *LCC* of around 2 M€/MW, as utility scale energy storage systems are still relatively expensive. Together, these results show how solar PV installations are often considerable investments for DC operators, emphasizing the need for cost-effective and optimal system design.

In addition to the *LCC*, Table 5 presents the *LCOE* of the modelled scenarios, illustrating the economic performance of PV systems in comparison to the cost of grid electricity. As can be observed, the modelled rooftop solar PV system would have an *LCOE* of 89.1 €/MWh in Finland, compared to the cost of grid electricity at 59.7 €/MWh in 2019 and 171 €/MWh in 2022. Likewise, the cost of the larger PV system varies between 74.8 and 94.9 €/MWh depending on electricity prices, making the cost of grid electricity the determining factor when calculating the economic viability of PV system. With 2019 prices, the *LCOE* of grid electricity is consistently lower than the price of PV electricity in Finnish DCs, whereas with 2022 prices both rooftop and larger PV systems have the lowest costs by a clear margin. These results thus show how both smaller and larger solar PV installations are cost-effective approaches to acquire local renewable electricity in Finland at the high electricity prices seen in recent years. Additionally, the results also show how supporting solar PV systems with battery storage increases the *LCOE* for DCs in Finland, even at the high electricity prices of 2022.

In contrast, the higher overall electricity prices and better solar performance in Japan make both rooftop and larger solar PV systems profitable in most scenarios, as the LCOE of PV electricity is only between 62.9 and 70.1 €/MWh compared to the LCOE of grid electricity at 126.8 €/MWh in 2019, and 223.2 €/MWh in 2023. Similarly, the higher

Table 5
Life cycle cost (LCC) and levelized cost of energy (LCOE) of the modelled scenarios.

Scenario	Unit	2.5 MW DC				25 MW DC			
		G	PV-R	PV-ES	PV-EB	G	PV-R	PV-ES	PV-EB
Finland									
System *LCC*									
2019	M€/MW	–	1.30	1.21	2.00	–	1.30	1.21	2.00
2022	M€/MW	–	1.30	0.96	2.00	–	1.30	0.96	2.00
System *LCOE*									
2019	€/MWh	59.7	89.1	94.8	227.7	49.1	89.1	94.9	227.7
2022	€/MWh	171.3	89.1	74.8	227.7	160.7	89.1	74.9	227.7
Impact on DC *LCOE*									
2019	€/MWh	–	+1.4	+7.4	+41.1	–	+1.6	+8.6	+42.4
2022	€/MWh	–	−5.1	−26.2	+8.2	–	−4.8	−25.0	+9.5
Japan									
System *LCC*									
2019	M€/MW	–	1.30	1.15	2.00	–	1.30	1.15	2.00
2023	M€/MW	–	1.30	1.03	2.00	–	1.30	1.03	2.00
System *LCOE*									
2019	€/MWh	126.8	69.1	70.1	176.9	126.5	69.1	70.1	176.9
2023	€/MWh	223.2	69.1	62.9	176.9	223.1	69.1	62.9	176.9
Impact on DC *LCOE*									
2019	€/MWh	–	−1.7	−15.3	+16.1	–	−1.7	−15.2	+16.2
2023	€/MWh	–	−4.6	−43.8	−14.1	–	−4.6	−43.7	−14.0

Table 6
Renewable fraction (RF) and emission reduction potential of the modelled scenarios.

Scenario	Unit	2.5 MW DC				25 MW DC			
		G	PV-R	PV-ES	PV-EB	G	PV-R	PV-ES	PV-EB
Finland									
Renewable fraction	%	0 %	4.7 %	24.6 %	24.4 %	0 %	4.7 %	24.6 %	24.4 %
Emission reduction	$tonCO_2/a$		62	324	320		621	3240	3200
Japan									
Renewable fraction	%	0 %	3.0 %	31.7 %	31.4 %	0 %	3.0 %	31.7 %	31.4 %
Emission reduction	$tonCO_2/a$		358	3730	3700		3580	37300	37000

amount of solar irradiation available in northern Japan also makes battery storages more effective in Japan, with a *LCOE* of 176.9 €/MWh, making it a viable option at current electricity prices. The system *LCOE* presented in Table 5 also shows how the solar PV and electricity costs of medium and hyperscale DCs are quite similar, with the largest difference being the markedly lower electricity prices available for large DCs in Finland. The overall impact of the solar PV investment on the total *LCOE* of the DC can also be seen in Table 5, clearly indicating the economic viability of each scenario.

In addition to the cost analysis presented in Table 5, the integration of local solar PV systems would also present significant environmental benefits to data centers, considering that the emission factor of used electricity in Finland was 60 $kgCO_2/MWh$ in 2022 [46], and 538 $kgCO_2/MWh$ in Japan during the 2021 fiscal year [47]. Notably, Table 6 depicts how a rooftop solar PV installation in a 2.5 MW sized DC has an emission reduction potential of 62 $tonCO_2/a$ in Finland, and 358 $tonCO_2/a$ in Japan, which is increased to 621 and 3580 $tonCO_2/a$ for a 25 MW sized DC, respectively. Additionally, Table 6 shows how larger external solar PV installations increase the emission reduction potential of data center energy use even further, by up to 3240 $tonCO_2/a$ and 37300 $tonCO_2/a$ for 25 MW sized DCs in Finland and Japan, respectively.

Besides the potential emission reductions achieved by solar PV systems in DCs, Table 6 also presents the renewable fraction (*RF*) of the different solar PV systems modelled in this study, assuming grid electricity is not fully renewable. As can be observed, a rooftop PV system would generate enough renewable electricity to cover 4.7 % of the data centers total electricity consumption in the Helsinki DC, or 3.0 % in Sapporo, mainly limited by the available rooftop surface area. In comparison, the large PV systems modelled in this study would instead increase the renewable fraction up to 24.6 % in Finland, or 31.7 % Japan, as space is not a limiting constraint in these scenarios. Notably, the renewable fraction of a solar PV system selling surplus electricity to the grid is slightly higher than a PV system with a battery utilizing most of its surplus locally, due to sold electricity also being counted towards the renewable fraction.

Furthermore, to more accurately display how the cost of solar PV investments related to the achieved environmental benefits, as well as to the installed PV system size, this study modelled the *LCOE* for a solar PV system as a function of the attained renewable fraction. For this purpose, Figs. 9 and 11 present the *LCOE* of a solar PV system and a solar PV system with battery storage in comparison to the *LCOE* of grid electricity for 2019, whereas Figs. 10 and 12 illustrate the same relationship with year 2022 electricity prices. Additionally, Figs. 9–12 also include sensitivity analysis on the modelled solar PV and battery storage costs presented in Table 2, illustrating the economic impact of both low-end and high-end system cost estimates.

As can be observed from the figures, with 2019 electricity prices, the *LCOE* of a stand-alone solar PV system increases with its size in both Finland and Japan, as increasingly more electricity would be sold to back to the grid at rates lower that the price of purchased electricity. However, as grid electricity prices in Japan are higher than Finland, also larger solar PV systems would be economically viable in Japan, making it an effective option to reduce carbon emissions if sellback of surplus PV electricity is possible at the DC location. With 2022 electricity, as presented in Figs. 10 and 12, solar PV installations become highly profitable with a negative *LCOE* at higher *RF* values, as selling surplus electricity to the power grid would be profitable.

In contrast, the *LCOE* of solar PV installations supported by battery storage systems increases rapidly with the renewable fraction in all scenarios after the solar PV size surpasses the data center electricity consumption, seen in Figs. 9–12 at approximately at a 20 % renewable fraction, as surplus solar power is generated at this point and onwards. Notably, in order to limit the overall costs and increase the effective use

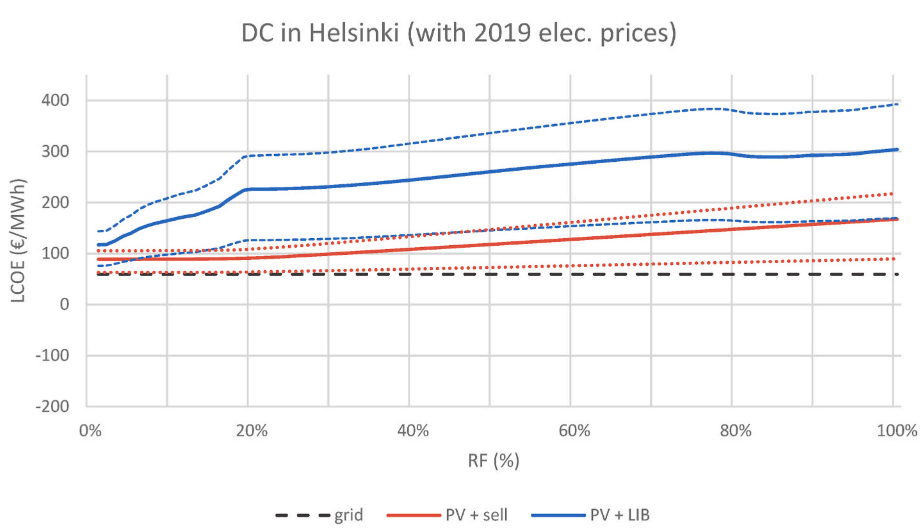

Fig. 9. Levelized cost of energy (LCOE) of the modelled PV systems in S1 (Helsinki) as a function of the attained renewable fraction (RF) with year 2019 electricity prices. The dashed lines showcase the sensitivity analysis on solar PV and LIB system costs, according to the lower and upper values presented in Table 2.

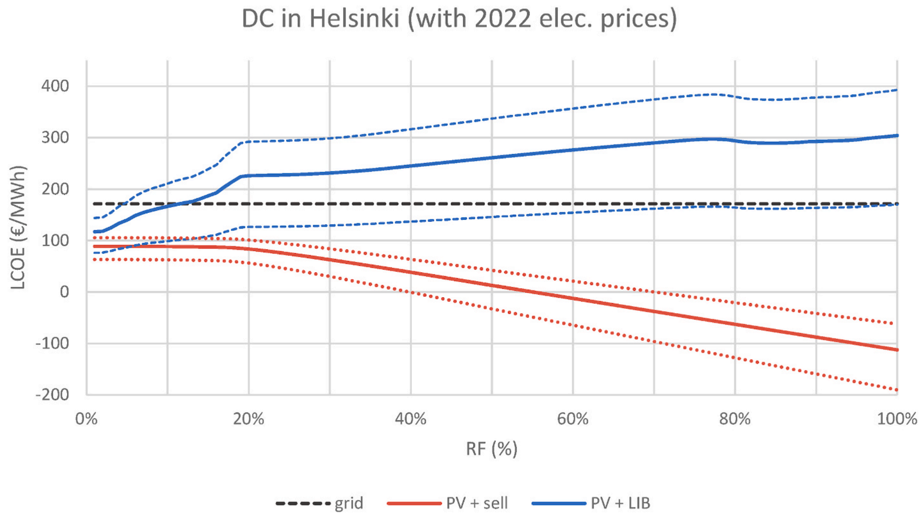

Fig. 10. Levelized cost of energy (LCOE) of the modelled PV systems in S1 (Helsinki) as a function of the attained renewable fraction (RF) with year 2022 electricity prices. The dashed lines showcase the sensitivity analysis on solar PV and LIB system costs, according to the lower and upper values presented in Table 2.

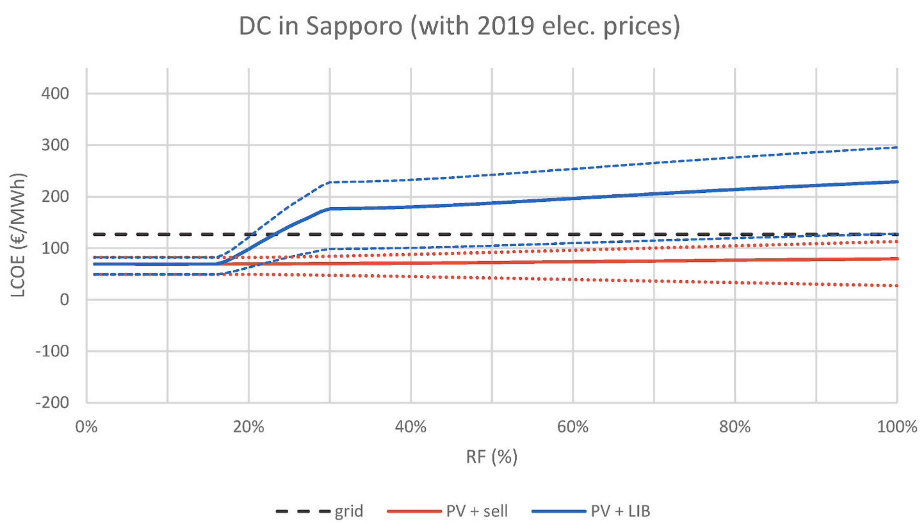

Fig. 11. Levelized cost of energy (LCOE) of the modelled PV systems in S3 (Sapporo) as a function of the attained renewable fraction (RF) with year 2019 electricity prices. The dashed lines showcase the sensitivity analysis on solar PV and LIB system costs, according to the lower and upper values presented in Table 2.

of the battery, the total storage capacity of the LIB is limited according to the solar PV capacity shortly after, causing the slope of the graph to decrease. The sensitivity analysis in Figs. 9–12 also shows the scale at which current price estimates for both solar PV and battery storage systems differ, and how continued development towards lower cost photovoltaics and batteries might could considerably improve the cost effectiveness of integrating renewables in the near future, enabling larger PV systems to be installed and utilized effectively in data centers, as well as other buildings.

4.3. *Cost-effectiveness of waste heat utilization*

Furthermore, Table 7 presents the modelled results of regarding waste heat utilization, including annual waste heat and DH production, HP electricity consumption, emission reduction potential, as the economic viability of utilizing waste heat for DH in Finland. As can be observed, the use of waste heat for DH could reduce annual CO_2 emissions by 3720 or 37200 tons in 2.5 MW and 25 MW data centers, respectively, assuming the produced waste heat is considered renewable. Thus, these results clearly highlight the considerable emission reduction potential of implementing waste heat utilization in DCs in cold climate regions where DH infrastructure is available. Notably, the high emission reduction potential of waste heat utilization is mainly due to the high emission factor for DH in Finland, which was 182 $kgCO_2$/MW for generated heat in Helsinki in 2021 [48], as DH is mainly produced with combined heat and power plants using fossil fuels or biomass in Finland.

The results in Table 7 also indicate that DH production would make a significant profit annually for the DC operator when modelled with 2019 electricity prices, between 298000 and 303500 € for a 2.5 MW DC, or 3416000–3445000 € for a 25 MW hyperscale DC, with scenarios with an existing solar PV surplus being the most profitable. However, the results also show how the unusually high electricity prices seen in 2022 severely increase HP operating costs, resulting in overall operating losses for the DC. Figs. 13 and 14 further illustrate the seasonal cost effectiveness of waste heat utilization for DC operators in Finland, showing the deviation between weekly DH revenue and HP operating costs with both 2019 and 2022 electricity prices.

As can be observed, the revenue from selling DH is the highest during the winter months, as the price of DH is calculated based on the outdoor temperature. Likewise, as HP operating costs directly depend on the used electricity price, Fig. 14 also illustrates how the HP operating costs

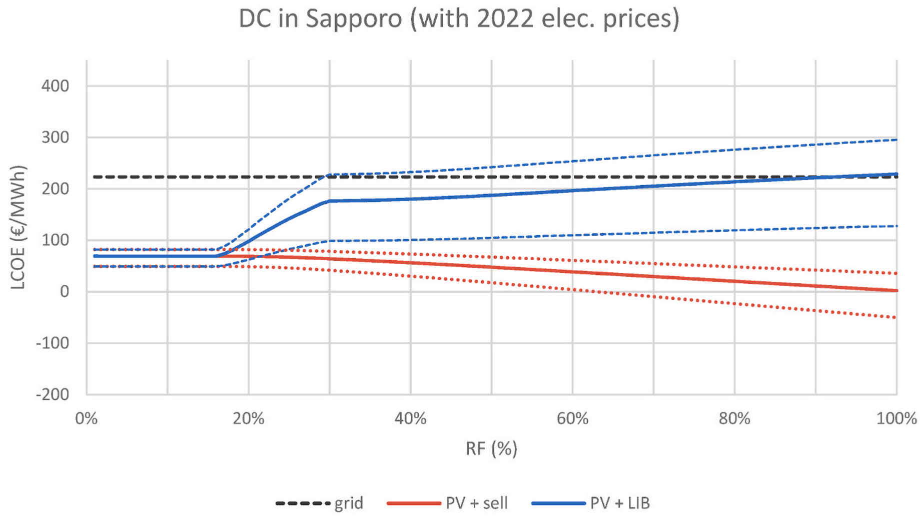

Fig. 12. Levelized cost of energy (LCOE) of the modelled PV systems in S3 (Sapporo) as a function of the attained renewable fraction (RF) with year 2022 electricity prices. The dashed lines showcase the sensitivity analysis on solar PV and LIB system costs, according to the lower and upper values presented in Table 2.

Table 7
Estimate of the annual available waste heat in the modelled DCs in Helsinki and Sapporo, as well as DH production and operating profit for the DC operator in Finland with 2019 and 2022 electricity prices.

Scenario	Unit	2.5 MW DC		25 MW DC	
		G/PV-R	PV-E	G/PV-R	PV-E
Waste heat	GWh/a	14.9	14.9	148.7	148.7
DH heat	GWh/a	20.5	20.5	204.5	204.5
HP electricity	GWh/a	5.6	5.6	55.8	55.8
Emission reduction	tonCO_2/a	3720	3720	37200	37200
2019					
HP operating cost	€/a	304 800 €	300 400 €	2 742 500 €	2 719 000 €
Revenue from selling heat to DH operator	€/a	513 400 €	513 400 €	5 133 700 €	5 133 700 €
Operating profit for DC	€/a	208 600 €	213 000 €	2 391 200 €	2 414 700 €
2022					
HP operating cost	€/a	929 200 €	924 800 €	8 987 000 €	8 963 500 €
Revenue from selling heat to DH operator	€/a	513 400 €	513 400 €	5 133 700 €	5 133 700 €
Operating profit for DC	€/a	−415 800 €	−411 500 €	−3 853 300 €	−3 829 800 €

for the DC operator far exceed the attained revenue from DH production using waste heat during periods with high electricity prices in 2022. Notably, as these figures only present the weekly average operating costs and revenue, individual hours with high electricity prices are not showed in the figure. Additionally, Table 7, Fig. 13, and Fig. 14 do not present HP or potential DH network investment costs, which should also be considered to accurately determine the overall economic feasibility producing DH from DC waste heat in Finland.

Additionally, the use of waste heat for snow melting in Sapporo is also assessed in S3 and S4. As earlier shown in Table 7, approximately 14.9 GWh/a and 148.7 GWh/a of waste heat can be recovered from 2.5 MW to 25 MW DCs, respectively. Using a heat requirement of 200–1600 W/m^2 to estimate the size of the snow melting system, the DC waste heat could enable snow melting in a 1000–8500 m^2 area for a 2.5 MW medium-sized DC, or in a 10600–84900 m^2 area for a 25 MW hyperscale DC, with benefits reaching an even larger area considering that only roads and pavements would be counted towards the estimated surface area. Using an investment cost estimate of 35–70 €/m^2 for snow melting systems in Sapporo, the overall cost to implement the proposed snow melting system would thus be between 37 000–600 000 € in 2.5 MW DCs, and 0.37–5.94 M€ in 25 MW DCs. While these initial investment costs are substantial, the minimal operating and maintenance costs over the lifetime of the system would simultaneously negate reoccurring snow removal expenses near the DC.

5. Discussion

The results and analysis presented in this study highlight how both solar PV systems and waste heat re-use can provide substantial environmental, economic, and social benefits to data centers located in different cold climate regions. Notably, the modelled results emphasize how both rooftop and larger external solar PV systems can be effectively implemented to increase the share of renewable energy in cold climate DCs, and how DCs are a valuable source of low temperature waste heat in cold regions with and without existing DH infrastructure. Additionally, the economic analysis presented in this work suggests that both solar PV systems and waste heat utilization can bring substantial economic benefits to both smaller and larger DCs in various cold climate regions, especially at the high electricity prices recently seen in many countries. Moreover, the modelled results highlight how regional conditions greatly influence the optimal size, design, and cost-effectiveness of emission reduction measures in DCs, with electricity prices, local energy infrastructure, climate conditions, and available solar irradiation having a notable impact on the effectiveness and operation of solar PV, energy storage, and waste heat re-use systems in data centers.

Although this study emphasizes how solar PV systems can effectively provide cold climate DCs with a valuable source of renewable electricity, the results also highlight how the use of external renewable electricity will be a necessity to make the energy use of DCs fully carbon neutral. This is evident from the achieved renewable fraction of all the different PV configurations modelled in this study, as these systems only generate enough electricity to supply DCs with a fraction of their annual electricity demand. While larger external PV systems can be utilized to reach higher shares of renewable electricity generation in DCs, these systems typically necessitate the use of battery storages or selling excess electricity to the power grid to be technically effective, lowering the economic performance of larger PV systems in most scenarios at normal electricity prices. Notably, the high initial investment cost of LIB systems is a considerable limiting factor for the cost-effectiveness of large-scale battery storage systems in cold climate DCs, especially in Northern

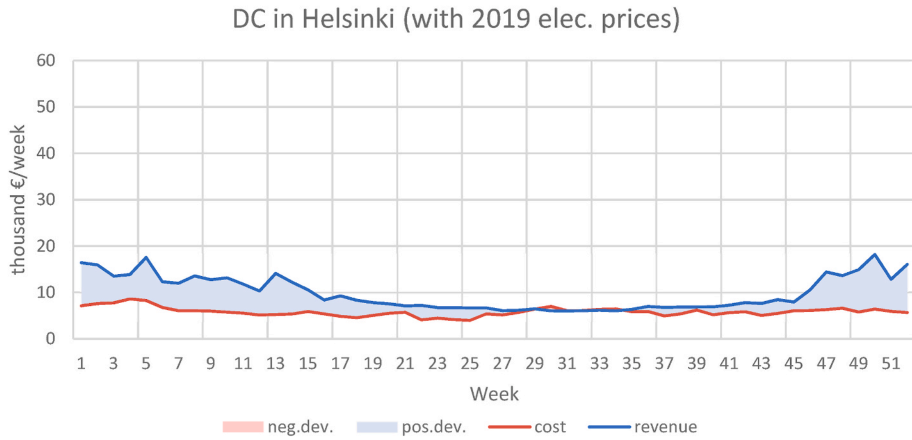

Fig. 13. Weekly revenue and HP operating costs from converting waste heat to DH in Helsinki (S1) with 2019 electricity prices. Values are presented in thousand euros/week, with profits and losses shown as positive deviation (pos.dev.) and negative deviation (neg.dev.), respectively.

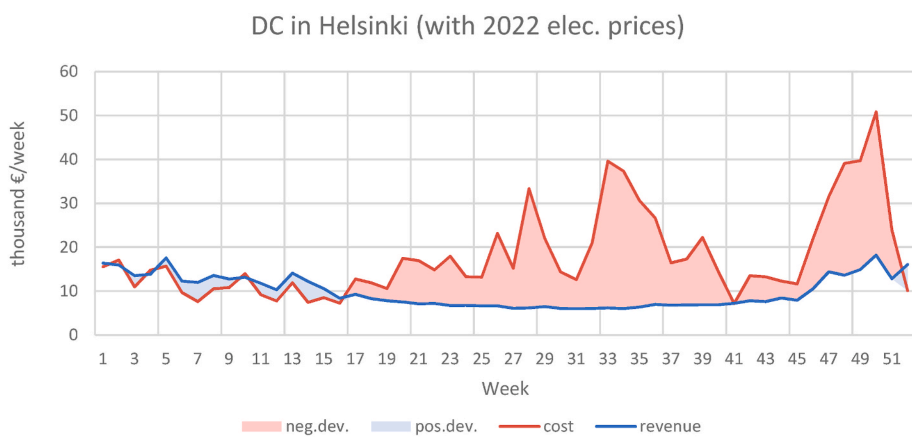

Fig. 14. Weekly revenue and HP operating costs from converting waste heat to DH in Helsinki (S1) with 2022 electricity prices. Values are presented in thousand euros/week, with profits and losses shown as positive deviation (pos.dev.) and negative deviation (neg.dev.), respectively.

Europe and at higher latitudes where the annual operation hours of solar PV and battery storage systems are lower. Yet, in cold climate regions located at lower latitudes, such as northern Japan, battery storage can be an effective approach to support PV systems in DCs as more solar irradiation is available annually. Additionally, in northern Japan, higher electricity prices and limited access for end-consumers to sell electricity through the power grid also notably improve the technical and economic benefits of both solar PV and energy storage systems in data centers.

Furthermore, the modelled results in this study also demonstrate how HP electricity consumption is a crucial factor affecting the operating costs and economic performance of DC waste heat utilization in DH networks in Finland. Thus, the use of DC waste heat for DH necessitates a stable supply of affordable grid electricity, or alternatively optimization of DH production according to hourly electricity prices, in order to be economically viable throughout the year. Additionally, as DCs are considerable producers of low temperature waste heat, this research indicates that DH production using DC waste heat will require close collaboration and coordination between DC and DH network operators, which could present both practical and organizational challenges for many DCs aiming to increase energy efficiency in their facilities. Yet, if implemented, DC waste heat re-use for DH could also enable a pathway to deeper sector coupling between electricity and heating networks, increasing overall energy efficiency in both applications. In cold climate regions where DH infrastructure is unavailable, such as northern Japan, the potential benefits of using DC waste heat for snow melting is also evident for DCs located in proximity of densely populated urban areas, where the economic and social benefits of snow melting systems could outweigh their high initial investment costs.

Consequently, the research and analysis presented in this study provides novel insights on the technical and economic performance of PV installations and waste heat re-use applications in different types of DCs located in cold climates. The presented work is especially relevant for DC operators aiming to improve renewable energy use and energy efficiency in both existing and upcoming facilities to make DCs climate neutral by 2030, as few DCs today have installed PV systems and re-use low temperature waste heat. Notably, a key strength of this study is its use of real-life recorded energy consumption data to model DCs located in Finland, which allowed this research to conduct a more detailed and accurate analysis of solar PV installations and waste heat re-use in DCs compared to prior studies. Nevertheless, the scope of this work is also limited in terms of the assessed technologies, as the presented research does not consider all of the different DC cooling methods, solar PV technologies, and energy storage types available for DCs, nor all possible applications where low temperature DC waste heat can be utilized. Additionally, this study did not optimize the size of the analyzed PV and energy storage systems, nor the production of DH from DC waste heat, which could be a potential source of error in the presented research. Nevertheless, the study does adequately address the main sources of uncertainty identified in the analysis, both by modelling multiple scenarios with different projections for future electricity prices, as well as by including a sensitivity analysis on the used cost parameters in the economic analysis.

Overall, the future outlook for sustainability measures in DCs is promising. As ICT companies strive to decarbonize their operations and make DCs climate neutral by 2030, and with countries continuously introducing stricter legislation limiting carbon emissions in different sectors, DCs could substantially benefit from solar PV systems to provide local renewable energy and waste heat utilization to improve energy efficiency, also in cold climate regions where the DC industry is growing at a fast pace. This study also suggests that the use of rooftop or smaller external solar PV systems are already very lucrative options for DC operators in many different regions, as all the renewable electricity in smaller PV systems can be utilized locally and initial investment costs are relatively low. Simultaneously, remaining electricity demand in DCs can be met through the power grid using renewable electricity acquired from both electricity markets and bilateral contracts with large electricity producers. This work also suggests that waste heat utilization could provide many DCs with an additional revenue stream and even become an integral part of DCs operations in cold climate regions in the long term, especially in countries where DC waste heat can be utilized in DH networks. Nevertheless, this work also shows that more research is still needed on the adaptation of technically feasible, cost-effective, and regionally suited sustainability measures in DCs in order to fully decarbonize global digital infrastructure.

6. Conclusions

This study assessed the potential of solar PV systems and waste heat utilization in cold climate DCs, with a case study analyzing the costs and benefits of these technologies in different sized DCs located in both Finland and northern Japan. The modelled results highlight how the use of both solar PV systems and waste heat re-use can provide substantial environmental and economic benefits to DCs, with future electricity prices having the largest impact on the economic performance of the assessed emission reduction measures in DCs.

The research also emphasizes key differences between DCs located in different cold climate regions. For instance, selling surplus electricity through the power grid can be an effective approach to support PV systems in regions with large seasonal variation in solar irradiation and developed power grid infrastructure, such as Finland. In contrast, battery storages can effectively provide demand-side flexibility for PV systems in regions located at lower latitudes with more annual sunlight hours and where excess PV electricity cannot be sold through the grid, such as northern Japan.

The analysis presented in this study also shows that primed waste heat from DCs can be cost-effectively used in DH networks in locations where existing DH infrastructure is available, such as Finland, as long as DCs are able to acquire electricity at a stable and affordable price. In regions where DH is not widely used, such as northern Japan, the use of low temperature DC waste heat for snow melting and local indoor space heating can provide substantial economic and social benefits to areas in the vicinity of the DC, however, at high initial investment costs.

Overall, the findings of this study highlight the importance of sector coupling and co-operation between DC operators, energy companies, and grid operators in order to effectively implement sustainability measures in data centers. Additionally, this work indicates that there is a clear need for supplementary renewable grid electricity to make DCs fully carbon neutral within the coming decade. The analysis and conclusions presented in this study are also applicable to DCs located in other cold climate countries with similarities in energy infrastructure or climate conditions, and especially in many northern regions where the DC industry is rapidly growing.

Nevertheless, as most DC operators are yet to invest in solar PV systems, and waste heat utilization is still not widely practiced in the DC industry, further research on renewable energy use and regional energy efficiency measures in DCs is also needed, as the effectiveness and costs of both solar PV systems, energy storages, forms of waste heat re-use, and electricity market conditions regularly change and differ between countries. Additionally, alternative and optimized means of operating energy systems in DCs should be studied in further detail. For instance, future research could analyze how solar PV battery storages and existing reserve power in DCs can be operated to provide ancillary services to the electricity grid and participate in balancing markets, as this could both improve the cost-effectiveness of energy storage systems in DCs, as well as become an additional source of revenue for DC operators.

CRediT authorship contribution statement

Johannes Hyvönen: Conceptualization, Methodology, Writing – original draft. **Taro Mori:** Conceptualization, Investigation, Writing – review & editing. **Juha Saunavaara:** Investigation, Writing – original draft. **Pauli Hiltunen:** Methodology, Writing – original draft. **Matti Pärssinen:** Investigation, Writing – review & editing. **Sanna Syri:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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