ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Future views on waste heat utilization – Case of data centers in Northern Europe

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ARTICLE INFO

Keywords:
Data center
Waste heat recovery
District heating
Energy efficiency
Metrics
Change process

ABSTRACT

In this study the potential for data center waste heat utilization was analyzed in the Nordic countries. An overview of upcoming data center projects where waste heat is utilized is presented. Especially in Finland data center operators are planning to reuse waste heat in district heating. However, business models between the district heating network operator and data center operator are often not transparent. The implications of economics and emissions on waste heat utilization in district heating were analyzed through life cycle assessment. Currently the biggest barriers for utilizing waste heat are the low quality of waste heat (e.g. low temperature or unstable source of heat) and high investment costs. A systematic 8-step change process was suggested to ensure success in changing the priority of waste heat utilization in the data center and district heating market. Relevant energy efficiency metrics were introduced to support rational decision-making in the reuse of waste heat. Economic calculations showed that the investment payback time is under the estimated lifetime of the heat pump equipment, when waste heat was utilized in district heating. However, the environmental impact of waste heat utilization depends on the fuel, which waste heat replaces.

1. Introduction

The issue of energy efficiency in data centers (DC) is an emerging concern, as more and more data is saved, processed and transferred to offer a multitude of digital services. It has been suggested that centralized DCs are more energy efficient than individual and distributed information technology (IT) [1]. It is estimated that DCs already accounted for 1.1–1.5% of the world's total electricity consumption in 2010 [2]; and in 2013, the IT sector represented 10% of the world's electricity consumption [3]. In addition to direct electricity consumed by the information and communication technology (ICT) hardware and basic infrastructure, DCs require vast amounts of cooling energy, typically produced with air conditioning units. The electricity consumed in a DC almost completely converts to heat. However, the heat is mostly not utilized, even though various solutions already exist.

Modern DCs can contain thousands of server racks, and the nominal power of DCs can be over 400 MW. This also means that the floor area of DCs is increasing, and the computing power of DCs continues to grow, resulting in increased energy consumption in DCs. The United States has had the highest electricity consumption worldwide (with a share of 25–35% of the total power consumption [2]) in the DC industry, but as the demand for data and energy efficiency in DCs keeps growing, more suitable locations for DCs are searched for.

There are several prerequisites for DC location. DCs require both cheap and reliable energy, a stable political environment, and a location near where the data is consumed in order to keep data transfer delays low. For remote areas (e.g., the Nordic countries), it is essential that telecommunication links are adequate for allowing efficient data transfer to other parts of the world.

The cold climate in the Nordic countries is extremely suitable for

Abbreviations: ALCA, attributional life cycle assessment; CAPEX, capital expenditure; CFD, computational fluid dynamics; CHP, combined heat and power; CLCA, consequential life cycle assessment; COP, coefficient of performance; CPU, central processing unit; CRAC, computer room air conditioner; CRAH, computer room air handler; CSF, critical success factor; DC, data center; DCeP, data center energy productivity; DH, district heating; DSC, dynamic smart cooling; DWPE, data center workload power efficiency; ERE, energy reuse effectiveness; ERF, energy reuse factor; FVER, fixed-to-variable energy ratio; GRI, global reporting initiative; HOB, heat-only boiler; HP, heat pump; HPC, high-performing computing; ICT, information and communication technology; IT, information technology; NPUE, network power usage effectiveness; NZEB, net-zero energy building; OPEX, operating cost; PDE, power density efficiency; PPW, performance per watt; PUE, power usage effectiveness; RHI, return heat index; RTI, return temperature index; SHI, supply heat index; SLA, service level agreement; sPUE, system power usage effectiveness; TCO, total cost of ownership; WPE, workload power efficiency

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https://doi.org/10.1016/j.rser.2017.10.058
Received 21 December 2016; Received in revised form 8 July 2017; Accepted 22 July 2017
1364-0321/

DCs by providing natural and cheap cooling energy. Furthermore, there is a high demand for heat in these countries and industrial waste heat is already utilized in different processes and district heating (DH) on a large scale, especially in Finland and Sweden. Waste heat in DH was 3.3% in 2015 [4] in Finland and 8% in 2014 in Sweden [5]. DH with highly efficient combined heat and power (CHP) is exceptionally common in Finland and Sweden. As the housing stock is becoming better insulated, DH networks are striving towards lower temperatures, which would enable feeding lower quality heat to the DH network. Therefore, there may be even more potential to utilize the waste heat from DCs in the future.

In this study, the current solutions and technologies in existing Nordic DCs and potential in the future were analyzed. The target was to give an example of an adequate solution for waste heat recovery and utilization both economically and technically, in the Nordic countries. In Finland, many DCs are built close to an existing DH network. Thus it is proposed that utilizing waste heat in DH networks would be economically the most viable solution. In Finland, the DH networks and DCs are owned by separate utilities. Therefore the benefits for both parties were evaluated and how the investments should be concluded between the parties were discussed. An 8-step systematic change process to overcome barriers is suggested. Available energy efficiency metrics were reviewed, and a subset of relevant metrics that provide data to support investment decision-making for both, DC operators and DH operators were suggested.

2. Literature review

Many studies concerning facility energy efficiency in DCs have been conducted recently. Most of the studies on the energy efficiency of facilities are related to efficient cooling systems, electricity consumption and integrating renewable electricity with DCs. Instead, reusing waste heat from DCs is studied less. But in recent years, research has become more topical and some case studies have been conducted.

To have a green and sustainable image, DC operators have different strategies for procuring renewable electricity. DC operators can produce their own electricity on-site or off-site, for example by solar or wind power, or they can purchase the electricity certified as green energy (green certificates, guarantee of origin, power purchase agreements, etc.). Goiri et al. [6] studied the scheduling of power demand with variable renewable generation to minimize the use of an electrical grid to supply power by implementing solar panels with DCs. Oro et al. [7] studied strategies for integrating renewable energy in DCs and suggested that electricity consumption in DCs should be dynamically modeled to truly understand the potential for increased energy efficiency.

One key question considering new DCs is the effect of location on DC energy efficiency. Depoorter et al. [8] studied the electricity generation portfolio, on-site generation, and cost of electricity in different locations. The results showed that implementing direct free air cooling could save from 5.4% to 7.9% of the consumed electricity depending on the location. In Sweden the electricity is considerably cheaper than in Germany, and a DC could save up to 42.5% in energy costs. The study also demonstrated that due to the high share of hydro power and nuclear power in Sweden, a DC in Stockholm would emit more than 30 times less CO_2 than a DC located in London, according to the calculations. However, due to international electricity transmission connections, comparing emissions of national electricity production mixes is questionable.

There is not a single method for reusing waste heat, and different applications and scales of utilization have been investigated. Marcinichen et al. [9] showed that low temperature waste heat from a DC could be used in preheating feed water of a power plant. Utilization would lead to fuel savings in the power plant and increase the efficiency of the power plant by up to 2.2%. Ebrahimi [10] studied waste heat utilization through absorption cooling machines. The study showed that the payback time for retrofitting an absorption system can be as low as 4–5 months in a 10 MW DC.

Lu et al. [11] evaluated energy efficiency in real DCs in Finland and the potential for capturing waste heat. The study showed that 97% of the power consumption could be captured as waste heat. The study concluded that waste heat at a 1 MW DC, operating at half of its nominal load, could fulfill the heat demand for over 30,000 m^2 of non-domestic buildings annually. Sorvari [12] studied waste heat reuse in heating a spa and rental cottages in Northern Finland. The results suggested that the DC waste heat would satisfy the heat demand almost completely for over 60,000 m^2. Kupiainen [13] compared two different cooling options for a DC in the Futura building in Jyväskylä in Central Finland. The combination of free cooling with heat pumps (HPs) resulted in €280,000 lifetime savings in 20 years compared to a free cooling and refrigeration machine.

Stenberg [14] simulated a 3 MW DC in Helsinki, Finland. An optimal set-up for temperatures for utilizing the waste heat in a computer room air handler (CRAH) cooled DC was studied. The results of the study showed that utilizing the waste heat could result in lifetime savings of millions of euros with a lifetime of 20 years. The most cost-efficient system would be a HP priming the waste heat to 75 °C and selling heat to either the supply or return side of a DH network depending on the outside temperature. Investment costs for HPs which increase the temperature up to 75 °C (coefficient of performance (COP) 3.5) are €420,000 higher than in the reference case where the cooling of the server room is conducted by free cooling and waste heat is not utilized. As the HPs were used for cooling the server room, it increases the annual electricity consumption by over 4 GWh compared to the reference case, which increases the costs. Nonetheless, the annual revenue from selling the waste heat to a DH network would be close to €600,000 in this case. All in all, the study suggests that the payback time of the cooling equipment investment would be less than 2 years, as the revenues from selling the heat are larger than the additional electricity costs, investment costs, and operational and maintenance costs.

Davies et al. [15] studied the possibilities of DH networks in London and the potential for waste heat utilization. The possible savings of waste heat reuse in a DH were calculated assuming that the waste heat would replace natural gas based heat production. The study showed that using liquid cooling in DCs would generate the most savings in energy as well as in carbon savings. The cost savings in this case could be over £875,000 in the case of a 3.5 MW DC. In the UK, the DC heat could be categorized as waste heat and could in that case be eligible for the Renewable Heat Incentive, thus further encouraging the use of DC waste heat.

Based on the literature review, both technical solutions for waste heat utilization and case studies have been conducted. But commercialization of waste heat has hardly been done, even though the studies that have been made show that waste heat reuse results in significant savings in energy costs with considerably low payback periods. Real-life pilots and the amount of waste heat based on real data have hardly been discussed in the media, making it especially difficult to analyze the true utilization rate of the waste heat. Finnish DCs are beginning to increase transparency by bringing out the volumes of heat captured in an actual DC. Thus in this study, some of the most interesting new projects in the Nordic countries and their plans for utilizing waste heat were presented.

3. Methodology

The potential for waste heat utilization from DCs was analyzed by conducting a literature review on cooling technologies and solutions for waste heat utilization. In addition, some of the most interesting projects currently related to DC waste heat utilization in the Nordic countries are analyzed through available online sources and literature. Furthermore, the methodology behind analyzing energy efficiency metrics, the economic and emission analysis, and systematic change process for adapting to waste heat utilization are presented in the subsections below.

3.1. The method for selecting relevant energy efficiency metrics for decision making

A recent study [16] investigated the most relevant metrics with the highest impact on energy efficiency for a modern large scale DC. The evaluated metric set was gathered from 45 scientific articles; 37 different metrics were selected in total. The evaluation of the metrics has been done by investigating four different orthodox dimensions in relation to each of the metrics. The selection addresses the most energy-consuming domains in a DC. Metrics were categorized into two dimensions. Energy efficiency metrics is the first category. It includes six different energy-efficiency domains with consumption: (1) physical infrastructure, (2) communication elements, (3) computing elements, and (4) network, (5) general energy efficiency and (6) CO_2 and renewables use. A second category is the DC technology. It includes seven technology domains: (1) servers, (2) network, (3) storage, (4) cooling, (5) air movement, (6) uninterruptable power supply, and (7) general. The last domain includes overlay metrics. Metrics were rated from four relevant dimensions. The dimensions were: (1) impact, (2) relevance, (3) complexity, and (4) coverage. The result was that there were 20 metrics that outperformed the rest in many or all of the dimensions. From these, 13 metrics matched the scope of this paper. The aim of the selected metrics is to give holistic visibility to the impacts of any changes in DC topology or technology, including waste heat utilization. Data-based decision-making requires relevant metrics.

3.2. The method for economic and CO_2 analysis

Economics of waste heat utilization in DH are evaluated by assuming that utilizing DC waste heat will replace both solid fuel CHP and heat-only boiler (HOB) production in the DH network. This situation was compared to the reference system where DC waste heat would not be utilized at all. Variable costs of heat production were calculated by taking into account the increased costs of electricity consumption due to HP, reduction in fuel utilization for CHP and HOB and the investment costs for HPs. The decreased amount of income from sold electricity from CHP was also considered.

The emissions of waste heat utilization are counted in two ways, namely using consequential life cycle assessment (CLCA) and attributional life cycle assessment (ALCA) [17–20]. CLCA gives an answer to what happens if consumption (or production) changes a little. The emission factor for electricity is quite high as the first plants to react to the changes are those that have the highest marginal cost (i.e., traditional condensing power plants) or sometimes CHP plants. As far as there are those kinds of plants running “enough” (not, for example, 1% of the total production at the time), the CLCA method gives the right value to estimate the short-term impact. If the power plant portfolio remains constant in the sense that there is at least a moderate amount of condensing or CHP plants running, the CLCA method also provides the right resources for future prospects.

ALCA in turn answers the question about the total emissions of the certain activity over a certain time period. It usually does not describe the effects of changes in consumption because the production portfolio is generally composed of more expensive plants, with minor variable costs, to handle the base load. Variable generation, such as wind and solar, is also in this category. The cheaper plants, which have higher operating costs, in turn take care of balancing the production and consumption. These plants typically burn some fuel, which should be avoided for the sake of the environment.

3.3. The method for implementing systematic change

In order to overcome various barriers against waste heat utilization, a systematic approach ensures that changes are made. According to Kotter article [21] in the Harvard Business review, most major change initiatives intended to boost quality, improve culture, execute disruptive change, or create high profits fail miserably. Many managers do not realize that transformation is a process, not an event. A process has eight stages, which build on each other, and it can take years to complete. Pressured to accelerate the process, managers tend to skip stages. But shortcuts do not work. Highly capable managers make critical mistakes by declaring victory too soon, resulting in loss of momentum, reversal of hard-won gains, and devastation to the entire transformation effort. Kotter argues that by understanding the eight stages of the change process and the unique pitfalls in each stage, one increases the chances of a successful transformation. The eight stages are: (1) establish a sense of urgency, (2) form a powerful guiding coalition, (3) create a vision, (4) communicate the vision, (5) empower others to act on the vision, (6) plan for and create short-term wins, (7) consolidate improvements and produce more change, and (8) institutionalize new approaches. Kotter´s full model is used in Section 8.5.

4. Energy consumption and energy efficiency in data centers

DC cooling is the second largest power consumer in the DCs after servers. The required cooling energy in a DC varies between different cooling methods. In the most efficient DCs the cooling energy might be only 10% of the total energy consumption, compared to closer to 45% in the air-cooled DCs [9]. Increasing the efficiency of the server's power consumption is a challenge. The amount of data grows faster than server processing develops. Increasing the efficiency of cooling systems is the easiest option to improve DC energy efficiency.

4.1. Measuring energy efficiency

A demand for managing energy efficiency and the use of renewable energy sources is emerging [17–19]. The aim of GreenIT is to improve energy efficiency, use clean energy, and reduce CO_2 emissions.

An energy-efficient DC maintains inlet air at a constant temperature level. Hot air is driven to air conditioning units and is not allowed to mix with incoming cold air. Air conditioning also delivers a proper mass flow for a given geometric distribution of heat loads. An energy-efficient DC requires a network of hundreds of temperature sensors at the rack inlets and outlets. A DC management system with thermo-fluids policies enable: (1) automated dynamic provisioning of air-conditioning resources, (2) distribution of computing workloads for power management, and (3) a DC's balance with heat loads [25].

The DC industry is lacking a standard method to categorize installed hardware and software resources and workloads into measurable groups for power usage calculations [22]. Commonly known metrics do not distinguish the energy efficiency of a DC communication system from computing servers; both are IT equipment [26]. The Green Grid has specified an effective DC energy-efficiency metric: (1) intuitive name, (2) definition and purpose, (3) measurable, (4) scales to technological, economic, and environmental changes, (5) scientific and precise usage, and (6) granularity to analyze individual aspects and provide data-driven decisions.

Measurement methods for energy efficiency and the desired objectives should be regulated and standardized by an authority in charge of sustainability, on a global level. A service level agreement (SLA) should complement the measuring values. A metric should be cost-effective and should consider: (1) DC diversity, (2) segmenting DC prior to applying a metric, (3) security and constraints, (4) usability and motivation for businesses and users, (5) provision of numerical information, and (6) evaluation of cooperative efforts for energy-efficiency improvement [22].

Fast decisions on thermal performance require advanced optimization of DC computational fluid dynamics (CFD) together with an abstract heat flow model. Integration with thermal aware scheduler models strengthens the impact on energy efficiency and the results can be verified with CFD simulation [27]. The first step is to evaluate the energy consumption in a DC in a holistic manner [23]. Measuring energy efficiency and performance holistically enables tracking improvements, estimating the impact of the changes, and benchmarking. Determining effectiveness in terms of reporting, targets, education, analysis, and decision support is needed.

The energy consumption of a DC is a problem. A good objective for a DC is to become a net-zero energy building (NZEB). In NZEB, servers are included in the overall energy plan of the building. DC energy contributes to the energy demand in advanced energy efficient buildings. DC operators should establish project targets for energy reuse effectiveness (ERE). Better ERE reduces the renewable energy requirements of the building [28].

4.2. Recommendations for metrics

ERE and power usage effectiveness (PUE) are not sufficient for engineering analysis purposes. To complement ERE and PUE, suggested [16] metrics include power density efficiency (PDE), return temperature index (RTI), supply heat index (SHI), return heat index (RHI), performance per watt (PPW), workload power efficiency (WPE), network power usage effectiveness (NPUE), system power usage effectiveness (sPUE), data center workload power efficiency (DWPE), fixed-to-variable energy ratio (FVER), and data center energy productivity (DCeP). These metrics create a holistic view of DCs energy usage and thermodynamic performance. This data is used for energy efficiency optimization and waste heat reuse equipment investment decision-making. DH operators gain actual data for forecasting available waste heat as a function of time.

4.2.1. Generic energy efficiency metrics

PUE is the most popular benchmark metric. It is defined as the total annual energy divided by the total annual energy used in the IT [28]. PUE-based metrics are not useful for DC energy analysis. The PUE variables are difficult to measure and calculate when facilities or primary equipment are shared. With energy reuse, the PUE value could go below 1.0, but this is not allowed, which is contrary to PUE definition [22]. PUE ignores IT load changes, and it does not address the DC utilization level [26].

PUE equation is [28];

$$PUE = \frac{TotalEnergy}{IT\,Energy} = \frac{Cooling + PowerDistribution + Misc + IT}{IT}; 1.0 \leq PUE \leq \infty \tag{1}$$

ERE includes the reuse of energy from a DC to PUE. Energy must be reused outside the DC to affect ERE. Energy Reuse Factor (ERF) can be used to calculate ERE from the site PUE [28]. The ERE and ERF equations are;

$$ERE = \frac{TotalEnergy - ReuseEnergy}{IT\,Energy} = \frac{Cooling + PowerDistribution + Misc + IT - Reuse}{IT}; 0 \leq ERE \leq \infty \tag{2}$$

$$ERF = \frac{ReuseEnergy}{TotalEnergy}; 0 \leq ERF \leq 1.0 \tag{3}$$

$$ERE = (1-ERF) \times PUE \tag{4}$$

PDE is also a variation of PUE. PDE takes into account improvements in the IT and the cooling system. The impact of the physical changes on energy efficiency can be measured with PDE. The PDE metric reflects inefficiencies in the air flow thermal management. PDE allows a comparison of DCs on different scales. The PDE metric enables a more holistic assessment of DC energy efficiency [23].

The DCeP metric correlates the DC throughput with the consumed power. DCeP indicates how much work IT equipment performs in a DC facility. A DC should define DCeP parameters according to the workload and business model [29]. NPUE defines the power consumed by the network IT equipment [26]. Network is an essential part of a DC and its energy efficiency is significant. FVER is a metric measuring DC energy efficiency. FVER defines part of the energy as a useful work function of the IT services. FVER demonstrates the improvements in the modern design of a facility and existing facilities using more efficient systems. FVER provides an understanding of changes and determines the energy use at the electrical input to the DC for any specified device or group of devices within the DC [30].

4.2.2. Heat flow based metrics

RTI is used in air management effectiveness measurement. It evaluates cooling air bypassing the rack equipment and air recirculation within the racks. Bypassed air does not contribute to rack cooling, and it lowers the temperature of the air returning to the air cooling system. RTI is a measure of the net bypass air or net recirculation air. SHI and RHI measure the level of separation of cold and hot air streams. SHI is a ratio of heat in the cold aisle to the heat at the rack. RHI is the ratio of heat extracted by a cooling system compared to the heat at the rack exit. RTI and SHI are tools to understand convective heat transfer to improve energy efficiency [23]. WPE is a metric measuring the power consumption of all participating subsystems. WPE is a performance/W metric for a high-performing computing (HPC) system [31].

4.2.3. Specific energy-efficiency metrics

sPUE measures the effectiveness of a specific HPC system for a specific DC. sPUE depends on factors like the cooling power used and the power consumed by the IT equipment. sPUE will change, if the current HPC system is replaced. DWPE is a metric for a specific workload, running on a specific HPC system. DWPE makes a connection between workload energy efficiency and the DC infrastructure. It combines the performance/W metric with the PUE. PPW measures the actual energy efficiency of a device and how it is used. The PPW uses a relative performance indicator for each individual asset. This indicator is calculated by the types of hardware and capabilities learned from an asset inventory of that device. PPW enables a global evaluation [31].

5. Cooling technologies in data centers

DC cooling is an essential part of DC efficiency. In order to secure efficient use and to prevent the malfunction of processors in DCs, the temperature of the air in the servers should be kept in the range of 18–27 °C [32]. The cooling of DCs is a highly sensitive issue. Keeping the DC as cool as possible has been the traditional way, but because the cooling consumes huge amounts of energy, the cooling system should be designed to an optimal level for each DC individually.

In DCs, the servers are placed in racks that can draw the cooling energy from the front and reject the hot air from the back. Racks are commonly arranged back-to-back to create cold and hot aisles to maximize the efficiency of the cooling systems by avoiding the mixing of hot and cold. Fig. 1 explains the configuration of a waste heat recovery system for a remote air-cooled DC, where waste heat is utilized in a DH network. The chilled water is supplied to the computer room air conditioner (CRAC) or CRAH. CRACs produce the cool air that is pushed to the cold aisle via a perforated and raised floor. Waste heat is recovered from the hot aisles to the ventilation system or directed back to the CRAC. The collected waste heat can go through different stages, e.g., an evaporator and condenser and subsequently a HP to be able to be used in the reuse application (e.g., the DH network).

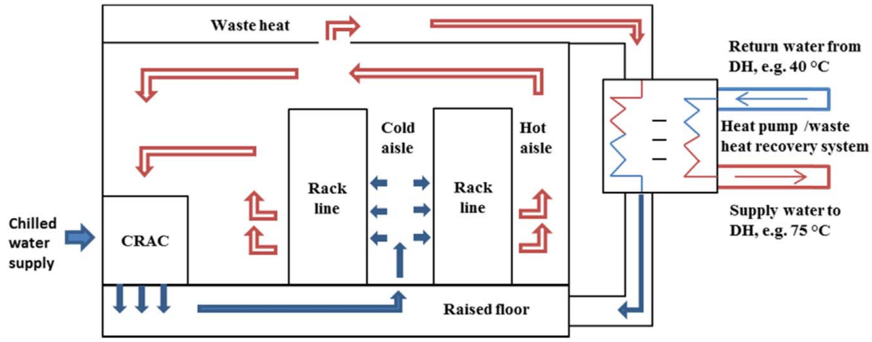

Fig. 1. Configuration for a waste heat recovery system for a remote air-cooled data center, which utilizes waste heat in DH. Reproduced from a figure in [15].

Various solutions for DC cooling exist. Cooling can be conducted by free cooling, mechanical refrigeration, or a combination of both (the most common method). Mechanical refrigeration consumes high amounts of energy, thus free cooling is typically more profitable.

In free cooling, the cooling capacity of ambient air, seawater, or ground is capitalized by chilled water to be used in cooling the DC. Free cooling is not always possible, as the ambient temperature may be too high, and therefore mechanical refrigeration can be used to produce the additional cooling energy, for example when the outdoor temperature is over 15 °C. Free cooling is very common in Nordic DCs because in the best situations, outside temperatures are high enough for most of the year, allowing direct free cooling of the server room.

For the DC server room, air cooling has been the most common method for cooling in the past. Air cooling has its limitations and cannot be used as effectively in more modern DCs [9]. Emerging technologies for cooling include liquid cooling, two-phase cooling, free cooling, and district cooling.

Liquid cooling can be conducted by different methods. Coolant liquid can be brought to the racks by pipes rather than providing the coolant to chill the air. There is also the on-chip cooling solution, where the coolant is brought right up to the processors. The benefits of liquid cooling are notable especially for waste heat utilization. The coolant liquid can be of a higher temperature, thus making it possible to capture waste heat in higher temperatures. In on-chip cooling, the waste heat is also easier to capture, as the heat can be captured directly from the local chip [9].

District cooling is an extremely intriguing cooling solution for DCs in the Nordic countries. District cooling can be distributed in the same distribution network as district heat. The cooling energy is mainly produced by the district heat network operator, and it is distributed to customers through a pipeline. Cooling energy can be produced, for example, by HPs, by absorption refrigerators, or even by free cooling. The supply temperature in district cooling is typically between 7 and 10 °C [33]. For the DC operator, district cooling is also a good option because it does not require as much space as in the case where cooling energy is produced in the DC.

6. Solutions for waste heat recovery and utilization

Cooling systems are developing as discussed in the previous section. Modern cooling technologies increase the profitability of capturing waste heat. Nonetheless, waste heat could also be utilized from air-cooled DCs. Some of the DCs are already capitalizing on the waste heat, but the scale of utilization is still small considering its economic profitability shown by the case studies in the literature. In this section, the possibilities of how and where waste heat could be utilized are discussed.

The two most important issues in waste heat utilization are heat demand and profitability. There must be a certain demand for heat in the near vicinity. Heat cannot be distributed long distances as efficiently as electricity. Thus there must be local heat demand in the vicinity of the DC. The amount and quality of waste heat, and consequentially the profitability of waste heat, depend a lot on the cooling technologies used in DCs.

Almost all of the waste heat can be recovered, as suggested in [11] and [9]. The best locations for capturing waste heat have been discussed in [10] and [15]. In air-cooled servers the best locations are at the return air flow to the CRAC/CRAH. In air-cooled DCs waste heat can generally be captured between 25 °C and 35 °C, while liquid cooling would allow capturing the waste heat at 50–60 °C. In liquid cooling systems the heat can be captured closer to the central processing units (CPUs) and other components, where operating temperatures are higher. (Typically, the upper operating temperature limit is 85 °C for processors.) Due to the more efficient heat transfer of liquid compared to air, the temperature of the circulating liquid can be higher, and therefore the waste heat can be captured as higher quality. In water-cooled systems, the circulating water temperature can be in some cases be set close to 60 °C while still maintaining temperatures of the components below the limits. Liquid cooling decreases the need for chillers and CRACs, potentially making them unnecessary in the liquid-cooling systems [34]. Ellsworth and Iyengar have found that water-cooled systems can in fact increase processor performance by 33% compared to the air-cooled systems [35]. Waste heat could also be captured in the chilled supply water where the temperature is only 10–20 °C [15].

As the biggest question in waste heat is the temperature, this is where HPs could come into action. HPs can be used in DCs to produce the cooling energy for the server room; but in addition, HPs can be used to improve the quality of heat up to 95 °C and above, which would allow heat to be utilized in many other processes (including DH networks). HPs can be used in different cycles if there are, for example, heat loads at different temperatures. In order to make the most out of the low quality heat, can be used to transform low-grade heat to higher temperatures. HPs in DCs typically have COP values around 2–7, depending on the number of cycles and at which temperature waste heat is upgraded [15]. In principle, an alternative heat source for HP could be solar heat stored in the bedrock, from boreholes. The advantage of using DCs as a heat source instead of this is the higher heat source temperature (increases COP) and probable lower investment costs. Increased electricity consumption due to the HPs also decreases the PUE value of the system; but if the waste heat will be utilized, it will decrease the ERE value and improve the energy efficiency of the DC.

There are many types of different utilization methods for waste heat. Small-scale and location-specific solutions (e.g., heating swimming pools and self-heating facilities) typically do not require heavy investments compared to large-scale installations such as investing in a connection to a DH network. Different applications for waste heat have been studied comprehensively, for example, in [34]. Table 1 presents different applications where DC waste heat could be utilized. The applications have been categorized in two categories (although some of the applications work in both categories): consuming waste heat in

Table 1
Applications for waste heat utilization.

Own consumption	External processes
• Space heating and floor heating • Domestic hot water • Melting snow • Producing cooling energy through absorption refrigeration	• Drying biomass • Preheating water in power plants • District heating • Water desalination • Electricity production (Organic Rankine cycle, Piezoelectricity, thermoelectric generator)

one's own premises or distributing heat to other processes. In one's own consumption, waste heat could be utilized in heating one's own premises with simple solutions like space heating, domestic hot water and melting snow (e.g. for pedestrian safety around the premises) to more complex solutions, i.e., absorption refrigeration. Space heating is the most common solution, and it can be easily conducted without significant investment costs. But space heating demand is seasonal, while domestic hot water demand is generally more constant throughout the year. Nonetheless, as studied in [10], absorption refrigeration has the potential to produce the much required cooling energy from waste heat.

External processes include different applications from case-specific solutions, e.g., from drying biomass, to more universal heating use. Waste heat reuse in DH and economic evaluation is discussed in detail in Section 7. Biomass drying requires a lot of energy but it increases the fuel conversion efficiencies of biomass. Waste heat temperatures are high enough for drying (~60 °C is suitable), especially when utilizing HP, but biomass drying should be conducted next to the DC. Biomass drying with the waste heat from a CHP plant has been studied in [36]. Electricity production from waste heat is possible by several applications, but the conversion efficiencies are very low, especially when the waste heat is very low quality, and therefore they are not considered in detail.

6.1. Barriers for waste heat utilization

There are different barriers slowing down the utilization of waste heat. Barriers for waste heat utilization have been studied in [10] and [37]. In general, barriers can be roughly categorized as follows:

- Low-quality heat and lack of heat demand
- Need for ancillary heat production
- High investment costs and inconvenient infrastructure
- Differing financial outcome expectations of DC and DH operators
- Information security and reliability
- Business models and mutual contracts
- Comprising factors
- Optimization of thermodynamics

If the heat demand exists nearby the DC, in most cases the main reason for not utilizing the waste heat is the low quality of heat. Captured waste heat is usually below 85 °C due to temperatures in the components, thus temperatures are too low for many applications and processes to exploit by conventional methods [34].

Investments in heat recovery equipment can be expensive, even though repayment periods can be only a few years. In the case of DH, the network must exist close to the DC because the connection fees increase substantially as the distances increase. If DC is built in a region with no existing DH network, DH can be considered as a lost chance. When it comes to waste heat utilization, the best locations for DCs would be next to a DH production unit and near a heat consumption center. For example, TeliaCompany's large DC (24 MW) is built inside the city of Helsinki [38]. On the other hand, in big Nordic cities like Helsinki, the DH production system has different kinds of plants for different situations, which makes it less profitable to feed excess heat to the DH network. The best profitability for using excess heat is in the networks that have only separate heat production with expensive fuel, e.g. natural gas in Finland.

DC operators and DH operators are not operating with the same business logic or model. Ownership of these operators varies inside the same business domain but especially between the business domains. All companies expect a different rate of return. The required rate of return is dependent on the risk level of the project. The higher the risk, the higher is the expected rate of return. In addition, between projects the highest rate of return is selected when the owners' appetite for risk and potential higher returns is high [39]. This might create unbalanced expectations between DC and DH operators. The DC operator business is investment-intensive and economies of scale dominate as a generic business strategy. Ownership is usually dominated by private investors. The DH operator business is also investment-intensive but usually rests on a natural monopoly inside the network position. Ownership is private and public. Rate of return is company-internal information. It has been estimated that the rate of return of a DC is significantly higher than that of a DH operator due to regulation.

Information security is a critical issue in DCs. DC operators try to limit access to premises and DC information as much as possible. DC markets are highly competitive, and thus DC operators try to keep corporate secrets to themselves as much as possible; and therefore DCs tend to limit the data available to the public from the DCs. The lack of data and transparency is a major factor slowing down the commercialization of waste heat utilization.

Business models for waste heat utilization are in many cases missing. Especially smaller DCs may not be owned by the DC operator, but the premises have been rented. In this case, the question is for what and how the DC operator pays. It is common that DC operators pay rent by floor area rather than paying separately for electricity, space heating, and cooling. In these cases, incentives for investing in waste heat recovery systems might seem pointless. The problems in waste heat utilization in DH networks are discussed in the upcoming sections.

According to [40], the economics of operating a DC are comprised of four main factors that contribute to the total cost of ownership (TCO): (1) resiliency, (2) downtime, (3) financial considerations, and (4) vertical scalability. The same four main factors comprise energy efficiency as well.

From thermodynamic perspective, heat dissipation and energy efficiency can be optimized for an isolated system. DCs are not isolated systems and are therefore difficult to optimize for the following reasons: (1) mixing cooling streams and heat sources at different temperatures complicates heat transference and fluid mechanics, (2) overprovisioning is a consequence of applying closed-system methods to an open-system design, leading to excess cooling capacity, (3) airflows are in a dynamic interconnection in an open system [25], 4) demand for more and faster computing resources, as well as higher uptimes, (5) risk avoidance is forcing the overprovision of cooling resources when designing new DCs [41], and (6) resources are overprovisioned to cover for the worst-case scenario [42]. In a DC, air conditioners are the largest consumers of power for cooling purposes. Thermal distribution implicitly correlates with the energy cost of a DC, and it is essential to optimize it [23,27]. A global management system is required for dynamic deployment of cooling resources in a DC. It should be based on a dynamic heat load distribution, and deployment of heat loads or computing workloads, based on the most energy-efficient cooling configuration in a room [25]. According to [43], an insufficient or a malfunctioning cooling system can lead to overheating, thus reducing system reliability and device lifetime.

7. Case of data centers in the Nordic countries

As previously suggested, DC location can have a huge impact on overall energy efficiency. The Nordic countries boast several suitable assets benefiting not only energy efficient but also secure DCs. In Finland, DCs have become more attractive since the data network was enhanced by linking Finland and Germany with a high capacity submarine cable in the beginning of 2016 [44]. The benefits of the Nordic countries for DCs include:

- Cold climate
- Cheap electricity
- High level of information security and know-how in the IT sector
- Stable political situation
- Efficient electrical grid
- Share of renewables in the electricity portfolio

The Nordic countries have a high share of renewables in their DH network due to the use of wood fuels. Large hydro, CHP, and nuclear capacity enable low electricity prices in the liberalized electricity markets. The Nordic countries are well suited for DCs due to the cold climate, cheap electricity for industries, and in many locations free cooling can be efficiently adopted not only by the cold outdoor temperature but also due to the possibility of implementing sea or lakes as a source of cooling. For instance, on average 58% of the hours in a year in Jyväskylä, Finland, are below 5 °C, while in Budapest, Hungary, the corresponding value is only 31% [45]. This makes the climate extremely suitable for utilizing free cooling or even district cooling that utilizes free cooling. Helsinki, Finland, has world's largest HP that produces both DH and district cooling. The capacity of the Katri Vala HP is 90 MW district heat and 60 MW district cooling. The Katri Vala HP uses purified wastewater to produce DH; and in wintertime, cooling energy can be derived from the sea via heat exchangers [46].

In Finland, DH produces approximately 90% of the total heat demand of the largest cities [47]. Most DH networks in Finland have several heat production units, including CHP and HOBs with different fuels, HPs, solar heat collectors, and industrial waste heat. Heat production plants may also have the ability to switch to an alternate fuel, e.g., from natural gas to fuel oil, which increases system stability enormously in case of exceptional fuel shortages.

DH has gone through many generations since the first steam-based DH networks. Current medium-temperature DH networks, which are considered 3rd generation, are utilized in many regions, but the Nordic countries have been the most competitive in implementing DH. In the current DH networks, supply temperatures are typically around 75–120 °C, depending on the outside temperature [48]. Waste heat can typically be utilized in the current networks in the supply side if the waste heat temperature is over 70 °C (at least in summer) and in the return side if the temperature is over 55 °C [14]. In the Nordic countries, waste heat is already utilized, as there are many energy-intensive industries, including forest, chemical, and steel industries. The waste heat from these processes is typically higher quality; but as the DH networks are improving, lower temperature waste heat can be utilized in the network. Finnish DH utilities have estimated DCs as the second most potential source for waste heat, after the forest industry, while the main barriers are high investment costs and low quality of the heat [49]. Also the location of the waste heat may not be close enough compared to that of heat demand.

7.1. Economical and CO_2 impacts of using heat from data centers in a district heating network

Waste heat utilization with HPs in a DH network affect the economics of the DC. Utilization requires investments in HP equipment, piping, and connection to the DH network. In addition, HP uses electricity to prime the heat, and thus it increases electricity consumption, which further increases the operational costs. In addition there are operation and maintenance costs related to HPs. However, selling the waste heat to a DH operator brings revenue to the DC operator. This section presents a rough outline and a very general example of how to estimate the cost and emission effects of using DC heat in a DH network.

It is assumed that a DC produces a constant amount of heat throughout the day and also seasonally. Obviously, without seasonal heat storages or very low heat demand compared to the DC heat supply, the heat from a DC can replace only a base part of the heat load in a northern climate. On the other hand, since the heat from a DC can be supplied also during the peak heat demand, it decreases the need for peak load boilers. CHP added with DC heat together can handle a larger part of the DH supply than CHP alone. The same applies to the summertime, when CHP plants tend to have a maintenance break for a month (for example). A DC can replace an oil boiler during that time, and in the best case, it can replace it completely.

So if heat from a DC replaces DH heat, probably produced mostly with a CHP or a solid-fuel HOB, supplemented with a peak boiler using oil as fuel, the effect on system cost and emissions depends on the share of the DC heat. The more the replaced DH production is oil-based during peak demand or during solid fuel boiler downtime in the summertime, the better the result.

To have at least a very approximate estimate of how much heat from DCs could be recovered, it is estimated that in the future, DC power consumption in Finland would be 5 TWh, i.e., about 5% of the total future electricity consumption in Finland. This is 3–5 times more than the world average in 2010 [2], but the consumption is increasing and Finland is a favorable place for servers in the future.

Most of that 5 TWh can be used as a heat source for HPs, producing DH. Supposing HP COP of 2.6, the heat output would be 7.5–8 TWh, spread quite evenly over the year. The DH supply in Finland is about 35 TWh [4], so in theory with these preconditions about 20% of the total DH production could originate from DCs.

In Finnish climate conditions, this means that the heat effect of HP using DC as a heat source produces about 5% output compared to the peak heat demand. About 2/3 of the summertime oil use during a solid fuel boiler maintenance break can be avoided. This is based on the summertime heat demand of 5–10% (in effect) of the peak heat demand [4]. As a relative amount, the saved oil is about 1.5% of the total annual heat supply.

In wintertime, DC heat use of this magnitude could cut about 1/3 of oil use in peak boilers. This is based on the usual DH system dimensioning in Finland, i.e., 90–95% of the annual energy is supplied from a solid fuel boiler (CHP or HOB) and the rest from oil boilers. In terms of output effect, the solid fuel boilers cover about 50% of the peak demand and the oil boilers the rest. As a relative amount in this case, the saved oil is about 2.5% of the total annual heat supply.

Altogether, supplying 20% of the total heat demand in DH network, oil use is reduced from 10% of the total heat supply to 4%. Furthermore, heat from a solid fuel boiler (CHP or HOB) share drops from 90% to 76%. These figures are of course only directional, depending on the system dimensioning and annual weather conditions.

DC can be seen as one possible HP heat source for, among some others. The alternatives are at least ambient air, sea/lake/river water, ground source heat, sewage water, exhaust air from buildings, and heat from space-cooling or industrial processes. Compared to natural sources, the advantage of excess heat from human activities (including DC) is the higher temperature. This in turn leads to a higher COP. For example, the COP for a 70 °C temperature lift is about 3, which for a 40 °C lift is round 4.3, that is, the electricity consumption of HP in the low temperature lift-case is 30% less than in the high temperature lift case [50]. Also, the heat harvest cost may be lower when not using the natural streams but rather those that are already more concentrated in the first place, e.g., those from buildings.

On the other hand, increasing the condensing temperature of HP above the ambient temperature (as when not using a DC as a heat source for DH) decreases the HP COP. Also, the cooling effect may be reduced when an increased output temperature is wanted. Thus, the net costs of upgrading DC cooling heat to DH are the differences between the HP COP and the cooling effect, between cooling to ambient air and to DH temperatures.

The HP (or cooling machine) output effect decreases when the condensing (i.e., heat sink) temperature is increased. In the DC case, it can be assumed, for simplicity's sake, that the required extra HP equipment should be able to raise the temperature from about 20 °C to about 75 °C. Here, 20 °C is the approximate maximum temperature of the cooling air or water from the DC and 75 °C is the required minimum DH water temperature [4]. The HP COP for this 55 °C temperature lift is about 3.5.

But in addition to increasing the temperature mentioned of 55 °C, it must be noted that the electricity consumption of cooling also increases when not cooled straight into the ambient air. In the winter, the cooling electricity consumption may get close to the zero because free cooling can be adopted. In other words, when the heat from DC cooling is used, it is as if the ambient temperature was 20 °C (for example) year-round. Thus, the electricity consumption in non-summer months is increased.

The amount of this increase in non-summer months depends on the actual properties of the equipment. It has been estimated that if free cooling is utilized and not upgrading DC heat to DH, DC uses 15% of its total energy for cooling. In the other case, DH is made and an average of 23% of the total energy is used for cooling, the result is a high enough source temperature for HP to further raise the temperature and produce DH. So, if servers and other uses of electricity (other than cooling) take, e.g., 55 GWh/a in the first case, cooling accounts for 10 GWh. In the other case, it is estimated that the servers have the same 55 GWh, etc. So, cooling takes in that case 16 GWh, i.e., 23% of the total consumption.

Further on, Table 2 shows the essential, estimated example values for DCs with heat use as DH and without that possibility. Note that this is only a rough estimate for an average system in Finland. If DH system properties, plant portfolio, climate conditions, etc., are different, the result can also be very different.

As there are uncertainties concerning the availability of DC heat, the investment in peak/reserve (oil) boilers probably cannot be avoided or reduced as a possible consequence of using DC heat. Oil boiler capacity is cheap to invest in, but expensive to use. Thus, to be on the safe side, no reductions in oil boiler investments are assumed here.

Solid fuel is supposed to be a mix of wood fuels, peat, and coal that was actualized in Finland in 2015. It gives an average CO_2 emission factor of 50 g/MJ. This is about half of the value that coal or peat would have alone, corresponding to the situation where 50% of the fuel in some plant would be wood and another 50% peat. This is quite a common case in Finland nowadays and thus can be representative for the time being. The average price of this mix is round 20 EUR/MWh, fluctuating over the years due to carbon trade price variations, for example. The 20 EUR/MWh here also includes the variable maintenance cost of the plant, which is 1–2 EUR/MWh_{fuel}.

The wood fuel emission factor is here assumed to be 0. If the wood is branches, tops, small trees from thinnings, and byproducts of forest industries, in practice they would have been decomposed in about 10 years in any case and would have released the carbon to the atmosphere. Thus it is on solid ground to hold the emission factor as zero. But it must be remembered that even in Finland, wood is a scarce resource and it must not be wasted. However, CHP and HP are both good system-efficient solutions. So the above-mentioned calculation example is still on a sustainable basis in that sense.

One consequence of using an emission factor of 0 for wood is that if the alternative DH production is done using 100% (or almost 100%) wood, the DC heat use clearly increases the emissions. This is the case for both CHP and heat only boilers. For CHP heat, the effect is even more drastic, since CHP power replaces other electricity. Electricity however has the fossil component in it, i.e., some part of electricity is

Table 2
Economic and emission evaluation of waste heat utilization.

	DC heat cooled to ambient air, not utilized as DH	DC heat utilized as DH	
Electricity for servers and other DCs	55	55	GWh/a
Electricity for cooling	10	16	GWh/a
Electricity for HPs, upgrading heat from 20 °C to 75 °C	–	29	GWh/a
Electricity use in DC, total	65	101	GWh/a
Heat recovered from DC to be upgraded to DH	–	71	GWh/a
DH output from DC, constant effect	–	12	MW
Estimated extra investment for upgrading DC heat to DH	–	5	MEUR
DH production from DC, including electricity to run HPs	–	100	GWh/a
DH production, CHP, solid fuel	450	380	GWh/a
DH production, heat-only-boiler, oil	50	20	GWh/a
Electricity production CHP	225	190	GWh/a
Solid fuel use	800	670	GWh/a
CO_2 emissions from solid-fuel boiler	144	121	1000 t/a
Neg. CO_2 emissions due to the power production in CHP plant, calculated with CLCA method (avoided, thus neg.)	−113	−95	1000 t/a
CO_2 emissions from oil boiler	16	7	1000 t/a
CO_2 emissions of electricity use in DC cooling and HPs, calculated with CLCA method	5	23	
Net emissions of DH production, calculated with CLCA method	**94**	**102**	**g/kWh_{heat}**
Neg. CO_2 emissions due to the power production in CHP plant, calculated with ALCA method (avoided, thus neg.)	−45	−38	
CO_2 emissions of electricity use in DC cooling and HPs, calculated with ALCA method	2	9	
Net emissions of DH production, calculated with ALCA method	**230**	**194**	**g/kWh_{heat}**
Solid fuel cost	16	13.4	MEUR/a
Income from CHP electricity (negative “cost”)	−9	−7.6	
Oil cost	4.1	1.6	
Electricity cost (extra cost, compared to “no DH” case)	–	2.7	
Net variable cost of DH production	**22**	**20**	**EUR/MWh_{heat}**
Direct investment payback time. Investment = heat from DC cooling upgraded to DH, using HPs.	–	**5**	**Years**
Net cost of CO_2 emission reduction, CLCA method	(HP investment increases emissions)		
Net cost of CO_2 emission reduction, ALCA method	–	**28**	**EUR/t_{CO2}**

Table 3
Data center projects considering waste heat utilization in the Nordic countries.

Data center operator	Location	IT load capacity	Cooling technology	Waste heat reuse	Estimated amount of recovered waste heat
Apple	Viborg, Denmark	Unknown, (floor area 166,000 m^2)	Free cooling	District heating	Unknown
Bahnhof (3 operational + 1 under construction)	Stockholm, Sweden	~3 MW (21 MW under construction)	Heat pumps	District heating	600 kW (Pionen) + 500 kW (St Erik) + 1500 kW (Thule)
CSC	Kajaani, Finland	2.4 MW	Free cooling	Other processes	Unknown
TeliaCompany	Helsinki, Finland	24 MW	Unknown	District heating	200 GWh/a
TelecityGroup (5 locations)	Helsinki, Finland	7 MW (2 MW reusing waste heat)	District cooling (+free cooling)	District heating	4500 block apartments + 500 detached houses
Tieto	Espoo, Finland	2 MW, (floor area 1000 m^2)	Heat pumps	District heating	~30 GWh/a (~1500 detached houses)
Yandex	Mäntsälä, Finland	10 MW	Free cooling	District heating	~20 GWh/a (~1000 detached houses)

produced by fossil fuels. The fact that CHP produces the most in the wintertime when it is economically (or for natural reasons) often difficult to have enough available low-emission production (solar, wind, nuclear), still underlines the CHP advantages. More, DC heat use increases DC electricity use especially in the wintertime when free cooling and (therefore very low electricity consumption for cooling) would be an alternative. However, the situation is not that bad for a DC, as discussed later.

The electricity price (40 EUR/MWh) is the average in Finland during the 2010s. This is a market price in Nord Pool Spot, without taxes or transmission costs. The electricity tax is 7 EUR/MWh for the manufacturing industry (DCs included) and 23 EUR/MWh for the rest (HPs, for example). The transmission cost for a large-scale user like it is here is about 10 EUR/MWh. In addition, there is a power charge for transmission. This varies between electricity distribution companies, but is generally about 20 EUR/kW/a. All the prices mentioned here are without value-added tax.

The basic values (prices, technical properties) are rounded a little to represent general averages in Finland. Using more accurate numbers would not make sense since there are uncertainties that are far more important than variations in some basic values. For example, CO_2 emission factors for electricity (500 g/kWh for the CLCA method and 200 g/kWh for the ALCA method) are roughly rounded [17,20]. They indicate the approximate level of the emissions in Finland in the 2010s. But as seen from the difference between the values, there are more important issues than if the ALCA emission factor were 10% more or less.

About these uncertainties, fuel and electricity prices are not well-known more than 5 years or so in the future. Fuel prices are generally dependent on global politics and (in more detail) how seriously the targets to cut down CO_2 emissions and decrease dependency on fossil fuels are taken. Especially the price of coal can vary a lot, e.g., somewhere between 6 and 40 EUR/MWh, depending on the degree of these ambitions.

Moreover, the investment in HPs and other devices may vary. A rather low 500 EUR/kW_{heat} is used here, which is based on the assumption that a DH network with large enough pipeline is very near to the DC. The cost level is taken from experience in collecting heat with HPs from sewage water in Finland. Even if the application is different, the basic HP equipment, temperature levels, and size class (> 10 MW heat) are about the same.

The electricity price is also difficult to predict. Fuel prices, with their variability, surely have an effect on the price of electricity, but so does the share of renewables (and nuclear) with very low marginal production costs. The higher the share of renewables is, the lower the electricity price gets. This is because the price is defined hourly after the most expensive (concerning marginal cost) running or near-to-run production method. Low cost is nice in the short term for consumers, but it leads (and has already led) to a situation where it is not profitable to invest in any electricity production if the income is based only on the market price. Furthermore, this can lead to power shortages or a socially and economically unsustainable forced limitation of electricity use.

Some subsidies or perhaps, more sustainably, some compensation for flexible production capacity (=dispatchable production) and socially sustainable (=voluntary from the consumer's point of view) demand-side management, should be in place to encourage an economically sustainable situation. All in all, these concerns mean that the electricity price and its fluctuations are decided, e.g., by political decisions and the future behavior of consumers. As they are not exactly known, it is not easy to have an idea about future electricity prices. This of course remarkably increases the unpredictability

Notably, the situation on the economic level remains the same even if there were smart grids, energy storages, etc. Following the variable consumption and especially handling the peaks is nearly always more expensive than the base load production or the production regardless of the consumption.

7.2. Data center projects in the Nordic countries

Some of the most interesting DC projects and built DCs that utilize waste heat on different scales in the Nordic countries are presented in this section (see Table 3). The purpose of this overview is to study how much information on the DCs can be derived from public sources. As Linna [37] studied in his thesis, many DCs reveal very little information and data on the actual load or reused waste heat. Few large-scale DCs have been built in Finland, e.g., Google in Hamina, which does not utilize waste heat as it has chosen free cooling as a cooling option rather than connecting to a DH network. However, Google has been effectively promoting its integration of renewable electricity by purchasing wind power.

Apple is building a 166,000 m^2 DC in Vyborg, Denmark, scheduled to start operations in 2017. Apple chose Denmark as its location mainly because of the prospect of satisfying the entire energy demand with wind power. Waste heat has been planned to be utilized in the DH. However, utilizing waste heat is under scrutiny, as it has been suggested that Vyborg city is reluctant in investing the proposed sum of 250 million Danish Crowns (~33 million euros) [51].

Bahnhof is operating three DC units (Pionen, Thule, St Erik) in Stockholm, which all feed the waste heat to Fortum's DH network. Currently operating units have projected a return on investment between 3 and 5 years for the heat recovery. Bahnhof is planning to build a modern, 21 MW, DC (Elementica) in Stockholm, which would start operating in 2018 or 2019 and it is estimated that Elementica could annually feed 112 GWh of heat to the DH network [52]. HPs are also used to produce cooling energy for the DCs, and waste heat is typically fed to the supply side with temperatures over 68 °C.

The largest mobile operator in the Nordics, TeliaCompany, is building a new large-scale DC in Helsinki that should be operating at the end of 2017. The new and modern DC is estimated to have the IT capacity of 24 MW in the first phase, which can be enlarged up to 100 MW in the later phases. Fortum announced in October 2016 that they have a letter of intent for purchasing the DH to be utilized in the Espoo DH network. It has been estimated that 200 GWh of waste heat could be captured annually, which would fulfill 10% of the total heat demand in Espoo [38,53]. Alongside the TeliaCompany DC, Fortum announced at the end of November 2016 that they will utilize waste heat from Ericsson's DC. At the moment, Ericsson's DC is producing between 15 and 20 GWh waste heat, and the amount is expected to double when the capacity of the DC will be increased in 2017 and 2018. In this case Fortum will make the investment in the HPs, and they will be installed on Ericsson's premises. In addition, HPs will produce the cooling energy for Ericsson's DC [54].

British TelecityGroup bought the Finnish DC companies Tenue and Academica. Currently TelecityGroup operates five DCs in Finland, and three of the DCs utilize waste heat in the DH network by producing annual DH for a total of 4500 block apartments and 500 detached houses. Tieto DC in Espoo, Finland, won an Uptime Institute 2011 Green Enterprise IT Beyond The Data Center award granted by U.S. Uptime Institute for waste heat reuse in 2011, the year it started operating. Tieto DC supplies Fortum's DH network with 30 GWh of waste heat annually in the first phase. However the DC has the potential to be enlarged from 1000 m^2 up to 6000 m^2. [55]

The Russian IT company Yandex built its DC in Mäntsälä, Finland, in 2015. The first DC unit in Mäntsälä is operating at a capacity of 10 MW, but Yandex has planned to increase the total IT capacity of the DC up to 40 MW. Yandex is selling waste heat to Nivos, which operates in the electricity, heat, and water management sectors. The first unit of Yandex is estimated to supply approximately 20 GWh with a 3.6 MW load of waste heat to the DH network of Nivos. When the DC expansions are completed, it is estimated that Yandex could fulfill almost the entire DH demand for the city of Mäntsälä [56]. Only the peak production would be covered by natural gas, biogas, or wood pellets. The COP of the invested HPs varies between 2.7 and 4 when the waste heat is primed to 85 °C before being fed to the DH network. The total investment costs for the heat production and connection to the DH network were approximately 3.5 MEUR, according to the CEO of the Nivos corporation, Esa Muukka [57].

8. Findings and recommendations

8.1. Roles of individual parties in utilizing waste heat in district heating

As Stenberg studied in [14], utilization of waste heat in DH networks seems to be one of the most efficient methods of utilizing waste heat. However, the business models are currently not clear, and as the DC owners typically do not act in the energy sector, the lack of know-how may keep them from taking the risk of investing in DC. Certainly, waste heat utilization might not come into question if the premises are not owned by the DC operator and the incentives for investments may not be clear enough.

The negotiation process with the DH and DC operators should be as transparent as possible, with both parties understanding both the technical and economic limitations in the process. In Finland, DH is a natural monopoly inside the network, but the business is open and based on mutual contracts between the parties. However, DH network operators are not obligated to implement waste heat in their network. In the negotiations, a win-win situation should be obtained between the DC operator and the DH network operator. Table 4 shows the requirements and benefits of the waste heat utilization of DH for both parties.

Table 4
Requirements and benefits for separate parties in utilizing waste heat in DH.

DH network operator	DC operator
• Stable source of heat and long-term contracts	• Ease of use
• Quality of heat (temperature and timing)	• Transparency in pricing and investments
• Less fossil fuels required to fulfill the DH demand	• Green image (higher ERF)
• Decreasing DH production costs	• Possibility to utilize district cooling
• Possibility to replace DH peak production or remove the need for new capacity investments	

As mentioned in the waste heat utilization section, the first priorities for waste heat utilization are profitability and quality of heat. If the DC operator invests in waste heat utilization, the sales from the heat must cover the costs of the investments within a reasonable time. From the DH network operator's point of view, the heat bought from the DC must be cheaper than the marginal production costs of the replaced heat. Depending on the quality of heat it should be distributed either to the supply or return side in the DH network.

Therefore the supply of waste heat from DCs must be stable and available when heat demand is highest. On a daily schedule, the demand for data typically correlates with the demand for DH. However DH has huge seasonal variance, especially in the Nordic countries. In wintertime the heat demand is high, while in summertime the heat demand is approximately one tenth of the peak load. Therefore, DH is generally more valuable in wintertime. Because of this, DH network operators tend to pay for waste heat on dynamic pricing, where prices fluctuate depending on the outside temperature, for example on a monthly basis. In addition, if the quality of heat is not enough for the supply side of the DH network, DH network operators need to improve the quality, and thus waste heat supplied to the return side has a much cheaper value.

Waste heat also benefits the green image of both parties. DCs compete on green branding and utilizing waste heat decreases ERE and improves total efficiency as long as the waste heat is measured. For the DH network operator, the greatest benefit comes from avoiding the building of new heat production capacity or reducing the need for expensive peak production, which in most cases is either natural gas or oil-based HOBs. Replacing peak production decreases the emissions of heat production; and in addition, peak production is the most expensive to produce. So for the DH network operator, the largest savings would come particularly from replacing peak production. However, it must be noted that utilizing waste heat may not decrease the need for ancillary production capacity, but utilizing waste heat will decrease the operational hours of the peak production units. Peak production could be cut by demand-side management measures and thermal storage. Thermal storage could be applied to DCs to supply waste heat when the demand is higher.

It has been assumed that DCs can provide waste heat on a continuous basis. However, there are certain issues that affect the waste heat production. First is the need for cooling energy. DCs produce more waste heat when more cooling energy is required, and therefore waste heat will be slightly more available in summertime, but this is also tightly linked to the cooling technology. Second and more critical is the fluctuation in the IT load, both intraday and on longer time frames. On longer time frames, stability of the load depends on customer activity. New and departing large customers change the IT load in both directions. Fortunately for waste heat production, the IT hardware is quite inelastic as a function of the departing IT load.

The key question in the business for both parties is who pays for the investment in heat recovery equipment. In [14] both alternatives are studied, and although the results suggest that if the DC operator makes the investment it is more beneficial for the operator, the difference in the total lifetime cost is not tremendous. It must be noted that the win-

win situation may actually be further exploited if the DC is cooled by district cooling and the infrastructure is already built-in. Therefore the decision on investing in the waste heat recovery should be conducted in the planning phase of the DC construction because retrofitting the equipment may be unfeasible.

8.2. Assessing the emissions and risks of waste heat utilization in a district heating network

As a guiding principle, the CLCA method seems to be a better tool to assess the impact on CO_2 emissions in a DH network than ALCA [17–20]. CLCA also reflects the price of electricity, since in the Nord Pool market the electricity price is the marginal cost of the most expensive production method running at a certain hour. Thus, trying to minimize the electricity cost by using electricity when it is cheapest and at the same time minimizing the emissions generally. And consequently it makes the most sense to use CHP when electricity is most expensive. Thus, DC heat and CHP together enhance the flexibility of the energy system, which can have a large share of the variable wind and solar power.

This applies also in the case of DC heat upgrading. The best result for operation costs and environmental impact is obtained when HP use is directed to the moments of cheap electricity. Heat storage can help balance the mismatch between heat production and consumption. There is in good cases also the possibility for free cooling and cooling to ambient air using HPs as air conditioning units, using less electricity than when producing DH to a higher temperature. In this way, there is a good possibility to use DC as an easy-to-collect heat source for a flexible energy system.

From the investment point of view, there is a risk that the equipment for upgrading DC heat is left without a use. The DC operation can be run-down or there may be disagreements concerning the price of extracted heat. Thus the system owner can require a quick payback for the DC heat upgrading system. The DC heat system can be owned by the DC or DH utility, but both face the risks. If the owner is the DC operator, one potential risk is that the DH operator invests in some other production, which is at least occasionally cheaper than would be heat from a DC. The DH operator would not be willing to pay more for heat than the cost of buying it from a new, cheaper source. As stated before, the DC operator may also seek a higher rate of return than the DH operator.

This risk can be made at least smaller, or in other words the allowed payback time could be lengthened, if there are possibilities to use the same equipment somewhere else and it can be easily moved. This in turn is easier if the design is modular, i.e., the same basic compressor with heat exchangers, etc., can be used for different purposes with minor modifications. Also, the more there are similar installations, the easier it is to find a new place for used equipment.

As a general conclusion, as it seems that the investment payback time is under the estimated lifetime of the equipment (here 5 years vs. > 15 years), heat recovery from a DC seems to be a profitable investment. From an environmental point of view, it is questionable whether or not DC utilization decreases CO_2 emissions. HP is needed to increase the temperature level of the cooling fluid, and it consumes electricity. If the alternative heat is produced by CHP, the emissions may be even higher with DC heat. This is especially true when wood is a high proportion of the CHP, as it often is in Finland. On the other hand, if the alternative is HOB using fossil fuel, DC heat use is environmentally beneficial.

Delivering waste heat to the DH network will affect the operation of other DH production units. However, pushing more low-cost heat to the DH network will decrease utilization of more expensive production, as DH network operators operate plants on the basis of short-term variable costs. This will in addition decrease the marginal production costs of DH, which will provide system-level savings [58]. However, as DH is currently not dynamically priced, this will hardly have a direct effect on the consumer prices. On the other side, in the longer term the producer advantage is also the consumer advantage if there is competition, goodwill, or other forces to share the benefit.

Improving the energy efficiency of buildings is at least a European-wide trend, and it also has strong political support. In Finland, new buildings also consume roughly 20–70% less energy for space heating, compared to otherwise similar older ones. However, the renewal of building stock is slow (around 1.5% per year), not all old buildings are torn down, and the building area per person tends to increase when the standard of living gets higher. Also, hot tap water consumption may not decrease remarkably, since the technical improvements in that sense are mostly done (e.g., one-grip armature) and the desired level of comfort is increasing rather than decreasing. People also still move to larger cities, which favors DH systems. All in all, energy efficiency may decrease DH consumption a bit, but the general level probably stays constant. However, the success of competing alternatives in the heat market may change the usage share of different heating methods. To maintain its high share in Finland, DH operators should also strive to be open in communications, offer pricing alternatives, etc.

8.3. Characteristics of a successful new data center project

Many DC operators, e.g., Yandex and TeliaCompany, are pursuing environmental certificates such as ISO 14001. Global Reporting Initiative (GRI) is an international independent organization that helps businesses, governments, and other organizations to understand and communicate the critical impact of businesses on sustainability. The main cornerstones of GRI are: (1) multi-stakeholder process and inclusive network, (2) transparency as a catalyst for change, (3) informed decision-making, and (4) global sustainability perspective. Of the top 250 largest corporations in the world, 92% report on their sustainability performance in accordance with GRI [59]. Public promises create positive pressure to succeed in achieving sustainability objectives, and Yandex and TeliaCompany have chosen to take this path.

In order for a DC to perform a global sustainability act, DC operators are encouraged to globally release transparent data regarding their efforts. However, such data is usually confidential in nature but although required when further researching waste heat utilization. There are three reasons that might result in information being claimed as confidential: (1) Actual data is not known exactly, (2) data is not measured, or (3) fear of reverse engineering. Another challenge according to the Fujitsu study [60] is the ICT sustainability does not have high priority for most ICT departments. Chief information officers (CIOs) are interested in sustainability, but it is a balancing act between many competing priorities. The single most important reason ICT managers and leaders do not prioritize sustainability or have a compelling reason to do so is the lack of visibility of power consumption. Only one in seven managers include the cost of ICT power consumption in their ICT budgets. The Fujitsu report reveals that the lowest awareness index score comes from the energy-efficiency metrics [60].

A DC is a large capital expenditure (CAPEX). When particularly considering a DC investment and TCO of a DC, operating cost (OPEX) is as an essential factor as the actual investment. A simple miscalculation can cost DC providers millions of euros annually. The design phase preceding a new DC investment is the most crucial phase from an energy-efficiency perspective. Critical success factors (CSFs) when designing DC energy efficiency are: (1) location based on the availability of renewable energy sources, (2) favorable climate for cooling, (3) a partnership with a local municipality or company for waste heat utilization, (4) effective risk and project management practices and (5) use of an external specialized consultant [61].

One of the most important issues in the projects that have succeeded has been the proactive attitude of the energy company, e.g., Fortum in both Finland and Sweden. Fortum aims for a carbon-neutral DH supply in Finland by 2030, and therefore they are actively looking for new business concepts for DH, e.g., an open DH network and hourly marginal cost based pricing [52,58] and DH demand-side management [62]. Fortum has taken waste heat utilization in their branding portfolio by advertising waste heat utilization in TV commercials. In Sweden, Fortum Värme is promoting a simple concept for DCs for utilizing waste heat in an open district heating network [63]. Fortum Värme will invest in the connection to the DH network, and DC will be responsible for the waste heat recovery equipment. HP will be used to produce cooling energy for the DCs. Fortum Värme is bringing up long-term contracts for DCs with a 10 + 5-year time span. In Sweden, Fortum Värme is also operating a district cooling network, thus making it possible to utilize excess cooling energy in the district cooling network. It has been suggested that sales of waste heat could save 29% of the DC electricity costs in Sweden [64].

DH network operators typically seek long-term solutions to replace conventional heat production (especially HOBs). In some cases, investing in waste heat utilization may save the energy company from the need to invest in new DH production capacity. This was one of the reasons for the cooperation between Yandex and Nivos, as the alternative option would have been investing in a new wood-chip HOB in Mäntsälä. Mäntsälä is a small city with about 21,000 inhabitants, and in small cities, DH production typically consists of only a few production units. Therefore in smaller cities and municipalities, it is necessary to have close cooperation with the DH network and DC operator and city planning if new DCs will be built.

8.4. Considerations regarding legacy data centers

Companies are limited in the amount of CAPEX, therefore, revenue-generating investment activities are preferred. IT is managed to minimize its cost, which is why IT reports to the Chief Financial Officer (CFO) in many companies [65].

According to a 2008 Gartner report, 50% of DCs have insufficient power and cooling capacity to meet the demand of high-density equipment in the near future [66]. An existing DC provider with out-of-date equipment and poor energy efficiency has four strategic alternatives: (1) modernize the existing DC, (2) invest in a new DC, (3) migrate workloads to a large DC operator, or (4) do nothing. Modernization of the existing datacenter is a valid option if there are obstacles to transforming workloads into a large DC operator. Possible obstacles include: (1) security and privacy when using a public cloud shared infrastructure serving many customers, (2) challenges to assess the costs involved in variable pay-as-you-go pricing models, (3) SLAs for the cloud service do not guarantee availability and scalability, and (4) integration into on-premise IT creates a natural lock-in [61]. Migrating workloads to a large DC operator is an option unless cloud costs are significantly higher than current DC costs. A better strategy would be to identify decision criteria whether a given application is hosted internally or moved to a cloud environment [65]. DCs operating with economies of scale have three key benefits compared to smaller competitors: (1) server, networking, and administration costs are 5–7 times lower compared to the average private provider, (2) the actual costs of power and cooling servers are 34% of the TCO compared to the amortized 10-year lifetime server, with 54%, (3) switching off a server is not as economically prudent as using the server at full capacity at all times [40]. Waste heat recovery can be utilized in the first three strategic alternatives. In the first two alternatives, a destination for the waste heat must be sought. An environmentally wrong decision is the fourth alternative: to continue with the existing energy consuming DC and do nothing.

Different technologies are employed in non-energy-proportional DCs to reduce energy costs and power density, including: (1) load-balancing evenly between different servers to distribute the workload per server and achieve uniform power density, and (2) server consolidation to assign incoming tasks to the minimum number of active servers [66]. Depending on the PUE value, one watt saved in DC power consumption saves at least one watt in cooling [29].

8.5. A systematic approach to overcome barriers

Kotter introduced an effective eight-step change process [21], and this framework is used to suggest ways to overcome obstacles systematically.

8.5.1. Step 1: Create a sense of urgency

A sense of urgency is created around the need for change. If people start talking about the change, the urgency can build and feed on itself. The magnitude of energy consumed is a function of an exponentially growing demand outstripping the energy-efficiency gains made by the IT industry. According to a Greenpeace report, numerous small- and medium-sized DCs consume the majority of energy, yet are energy-inefficient [67]. These DCs typically do not capture waste heat. A recent survey of 120 + DCs submitting information for the Energy Star program had an average PUE of around 1.9 [28]. High energy consumption results in large electricity costs and high carbon emissions. Reports from DC operators indicate servers run between 10% and 50% of their maximum utilization levels to avoid high loads and to meet SLA targets [67,68]. The challenges mentioned above constitute the core of a sense of urgency that needs to be communicated to society.

The CSFs for Step 1 are: (1) clear communication regarding potential threats, opportunities, and possible future scenarios, (2) honest discussions in a society with dynamic and convincing reasons as input, (3) support from stakeholders to strengthen the argumentation, and (4) actual results from working solutions to strengthen the message.

8.5.2. Step 2: Form a Powerful Coalition

Step 2 aims to convince people that change is necessary. It requires strong leadership and visible support from regulatory authorities, academia, and organizations. The power comes from a variety of sources; job title, status, expertise, and political importance. The change coalition needs to work as a team to build urgency and momentum around the need for change [21].

The change coalition is required for overcoming barriers and obstacles. According to the Energy Star November 2012 study “Understanding and Designing Energy-Efficiency Programs for Data Centers”, there are barriers in implementing energy efficiency: (1) lack of knowledge and risk-aversion, (2) reliability targets for power and cooling systems are creating much uncertainty towards implementing projects that could affect reliability, (3) misperception of the tradeoff between energy efficiency and performance, (4) vendors may have a disincentive to encourage energy efficiency [69], (5) program administrators face challenges in ensuring that an investment generates actual energy savings, and (6) split incentives between a decision-maker and an entity directly benefiting from the project.

A split incentive between an IT manager and a facility manager occurs when the IT manager makes financial decisions based on available CAPEX regardless of power usage or its associated costs [69]. The result is a situation where the IT manager seeks to stretch the CAPEX budget as much as possible with energy-inefficient, low-cost IT equipment. This leads to a cooling system, power delivery, and capacity shortfall . Another split incentive might be between the DC and DH operators’ expected payoff from the joint venture. The change coalition needs to build consensus between parties by seeking common targets, such as a reduction in CO_2 emissions. For DC operators, waste heat is a cost issue; for DH operators, it is a business opportunity. Common ground does exist.

Understanding market conditions and program implementation obstacles is important for effective program planning and for developing reasonable forecasts of energy savings. Obstacles for DC program administrators are: (1) technical complexity, (2) long lead times, (3) product production cycles associated with DCs, and (4) risk of a free ridership. All elements of DC operations are technically complex with a goal of ensuring reliability. Program managers must investigate whether there is sufficient and effective expertise to evaluate cooling, power delivery, and air conditioning systems [69].

There are challenges that must be solved by the change coalition. It must answer to questions such as: Who has a problem with energy efficiency and why? Who is responsible for energy efficiency and waste heat utilization? Who has the incentive to lead the change? Who are the stakeholders? How can a common vision be created where everybody wins? To be successful in leading a change, communication and public relations must be seen as strategic assets that promote the cause.

The CSFs for Step 2 are: (1) identifying key stakeholders and true leaders in a society and from organizations, (2) emotional commitment from key people, (3) team-building within a change coalition, and (4) performing an analysis of the weak areas of the change coalition, and ensuring a mix of people from different stakeholders and different backgrounds.

8.5.3. Step 3: Create a vision for change

The ideas and concepts need to be linked to a vision that society and stakeholders can grasp easily and remember. A clear vision helps everyone to understand why they need to act [21]. Advances in the underlying manufacturing process and design technologies available enable computing and storage capacities of DCs to continually increase. The increase in capacity has resulted in a steep rise in the energy consumption and power density of DCs [66]. Focused attention is needed on creating a nationwide energy efficiency and waste heat reuse strategy. It must be enforced by regulatory supervision. There are two kinds of energy consumption reductions: (1) reductions that avoid energy consumption but do not reduce power capacity requirements (temporary consumption avoidance), and (2) reduction of installed power capacity (structural consumption avoidance) [70]. Energy from IT equipment in a typical DC will either equal or exceed the heating demands of a building. A good vision is to include a DC in a building aiming for NZEB status. NZEB requires a fully integrated energy strategy, including the aggressive reuse of waste heat [28].

The CSFs for Step 3 are: (1) determining the values critical to a change, (2) a short summary, capturing the future vision, (3) a strategy to execute the vision, (4) ensuring that the change coalition can describe the vision in five minutes.

8.5.4. Step 4: Communicate the vision

Activities after the initial creation of the vision will determine the success of the change. The vision needs to be present daily in decision-making and problem-solving. A demonstration of outcomes and results is a way to convince the public about the vision. There needs to be open discussion about the sustainability of IT and energy efficiency, including waste heat recovery. The vision must be communicated so that it reaches people and business decision-makers. Consumption ultimately dictates the demand for services. The vision starts to realize itself once a demand for sustainable IT emerges instead of the lowest possible price. Joint efforts with municipalities, regulators, and companies ensure that the vision has a strong change coalition behind it [21].

The CSFs for Step 4 are: (1) public discussion about the change vision, (2) openly and honestly addressing concerns, (3) applying the vision to all aspects of operations and tying everything back to the vision, and (4) leading by example.

8.5.5. Step 5: Remove obstacles

At this step, the vision has already been communicated and a buy-in from all stakeholders has been achieved. A structure for the change needs to be put in place and possible barriers periodically evaluated. Removing obstacles empowers people to execute the vision [21]. The change coalition must solve obstacles presented in Section 5.1.

The CSFs for Step 5 are: (1) identifying or hiring change leaders whose main role is to deliver the change, (2) investigating the organizational structure, job descriptions, performance, and compensation systems to ensure they are in line with the vision, (3) recognizing and rewarding people for making the change happen, (4) identifying people who are resisting the change, and helping them understand what is needed, and (5) taking action to rapidly remove barriers (human or otherwise).

8.5.6. Step 6: Create short-term wins

Without wins, critics and negative thinkers might hurt progress, therefore short-term targets are needed. A change team may have to work hard to come up with these targets, but each "win" that is produced can further motivate stakeholders [21]. Cloud service providers typically own geographically distributed DCs. This means they can distribute workloads among geo-dispersed DCs to benefit from location diversity of different types of available renewable energy sources [46]. Cloud DCs support a wide range of IT workloads: (1) delay-sensitive non-flexible applications, such as web browsing, (2) delay-tolerant flexible applications, such as scientific computational jobs. Workload flexibility removes obstacles in integrating intermittent renewable energy [67].

A significant increase in energy efficiency is achieved through effective thermal management strategies. Thermal management reduces the OPEX of a DC [23]. Local variations in heat flows and server heat generation impact the efficiency of cooling in different places within a DC [42]. To overcome these challenges, a few key solutions have been developed: (1) Dynamic Smart Cooling (DSC), (2) heat minimization, and (3) liquid and direct free cooling. DSC is a technology used to monitor power and cooling in DCs. DSC uses a feedback-based control system in order to provide hot-spot control to DC managers [71]. It is a set of real-time control systems that can directly manipulate the distribution of cooling resources throughout a DC. DSC characteristics are: (1) a network of temperature sensors at air inlets and exhaust of equipment racks, (2) data from sensors is fed to a controller where it is evaluated, (3) the controller can independently manipulate the supply air temperature and the airflow rate of each CRAC in a DC, (4) the impact of each CRAC in a DC must be evaluated with respect to each sensor, (5) the resulting information is used to determine which CRACs to manipulate. DSC systems operate more efficiently than traditional control systems [42]. Even though an overall impact on energy efficiency is high because of the automated, dynamic nature of DSC, it is not widely adopted.

Heat minimization is an overall target for any DC, and it provides short-term wins. Excess heat damages hardware as well as decreases energy efficiency. Activities that can bring heat generation to a lower level are advisable. These include: (1) device vendors working to lower heat generation of devices, (2) an energy-proportionality and sleep modes development, and (3) increasing server inlet air temperature and variable frequency drives. Regardless of heat level, the closer a cooling solution is to a heat source, the more effective the cooling is. The more effectively cool air is delivered to a server and hot air is transferred back to a CRAC unit, the better the heat transfer is, thus resulting in higher energy efficiency. Technologies that require large investments are: air-side economization, water-side economization, evaporative cooling and a liquid cooling [72]. Most of today's DCs are equipped with servers that rely on air cooling, which has a low cooling efficiency due to undesired air recirculation. Liquid and free air cooling improve energy efficiency of a DC and are therefore becoming widely used in new DC projects. The selected cooling must be intelligently coordinated with dynamic workload allocation in order to minimize the cooling and server power of a DC [73].

The CSFs for Step 6 are: (1) identifying projects that can be implemented without help from any strong critics of the change, (2) early targets that are expensive must not be chosen as justification for the investment, (3) thoroughly analyzing potential pros and cons of targets, and (4) rewarding people who help meet targets. [21]

8.5.7. Step 7: Build on the change

Launching one new initiative using a new system is great, but launching ten initiatives means that the new system is working. The

CSFs for Step 7 are: (1) after every win, analyzing what went right and what still needs to be improved, (2) setting goals to continue building on the momentum already achieved, (3) learning Kaizen methodology, an idea of continuous improvement, (4) keeping ideas fresh by bringing in new change agents and leaders [21].

8.5.8. Step 8: Anchor the changes into the culture

Finally, to make any change lasting, it should become part of the core of an organization. The culture of a corporation often determines what gets done, so values behind the vision must show in day-to-day work. Support from leaders, including existing and new leaders, is valuable. The CSFs for Step 8 are: (1) discussion on progress of the change is needed, success stories, and repetition of other stories that are heard, (2) including change ideals and values when hiring and training new staff, (3) publicly recognizing key members of the original change coalition, and making sure everybody else remembers their contributions, (4) plans to replace key leaders of change need to be in place as they move on. This will help to ensure that their legacy is not lost or forgotten [21].

8.6. Discussion on the energy-efficiency metrics

It is informative to look at the theoretical limits of a new metric: while it is not expected to see extreme values in practice, the limits help with the understanding of the metric's development and/or definition [28].

PUE´s range is mathematically bounded from 1.0 to infinity. PUE 1.0 means 100% of the power brought to the DC goes to IT equipment and none to cooling, UPS, lighting, or other non-IT load. ERE has a range from zero to infinity. ERE does allow values less than 1.0, while PUE does not. ERE zero means that 100% of the energy brought into the DC is reused elsewhere, outside of the DC itself. ERE of 1.0 does not imply any level of efficiency in the base DC infrastructure. It could represent a very efficient infrastructure design (PUE 1.2) with a small amount of energy reuse (ERF = 0.17 and ERE = (1-0.17)*1.2) = 1.0. Conversely, it could be obtained with an inefficient infrastructure base design (PUE = 2.0) with a lot of energy reuse (ERF = 0.5 and ERE = (1-0.5)*2.0 = 1). There is not sufficient data in the field to report on the practical range of ERE from operating DCs with energy re-use. Some estimations claim that ERE from 0.6 to 1.2 and ERF from 0.2 to 0.6 may be encountered once sufficient numbers of energy reusing DCs are built; however, the exact numbers will only be learned with time [28].

ERE will be a fundamental tool as industrial and commercial buildings with DCs move towards net-zero targets. Whether the building achieves this or not in the near future will likely be primarily dependent on the size of the DC. Current on-site renewable energy sources are often somewhat higher in cost than standard electrical grid prices, and for the very large DCs this will slow the movement towards NZEB [24].

PUE allows the industry to drive towards more energy-efficient infrastructure, and a low PUE will help make the DC energy-efficient. For all but the smallest DC, the industry must go beyond efficiency and look at reuse if there is to be a change to a cost-effective NZEB. To do that, driving a low ERE will help the architect and engineers get to the NZEB with an integrated DC [28].

9. Conclusions

The Nordic countries have plenty of potential for attracting more DCs due to their suitable conditions. However, there are still a lot of barriers slowing down the efficient reuse of waste heat generated in DCs. The barriers for waste heat utilization are mainly not technical problems but rather the lack of solutions for DC operators on how to make a profit on the heat. Several DCs are already utilizing or planning to utilize their waste heat in DH networks. However the business models of how to sell waste heat to DH companies are hardly transparent.

The low availability of real energy consumption and waste heat production data from DCs is one of the main barriers for adapting waste heat to DH systems. A DC operator may lack the know-how for making the most out of the waste heat, both technically and economically. DC waste heat supply to DH networks based on real data should be analyzed in detail in order to find the most profitable business options for both parties.

The question of the business models between the DH network operator and DC operator needs to be transparent, but ultimately both parties must want to change and develop. In the end, it is essential to build on the change and bring up success stories for public discussion. In the DH sector, some companies are not motivated to improve and actively seek new energy sources to replace conventional heat generation. By raising awareness of successful waste heat utilization projects, the industry can adapt to a new ways of thinking.

Awareness of energy-related costs must reach decision-makers in the ICT field. A standard way of measuring energy efficiency and waste heat potential needs to be established. In addition, there needs to be sufficient activities from government regulation and legislative enforcement to further enable transformation towards energy efficiency and waste heat utilization.

It is advisable that DC providers choose energy efficiency as a strategic initiative and set ambitious targets, such as NZEB. The reasons for this are not only cost savings and higher profits but also the contribution to global solutions for reducing energy consumption and CO_2 emissions. ERE is a more effective metric than PUE for considering the total efficiency of a DC. There are benefits in having multiple metrics, as values of different metrics reveal where an individual DC should focus activities to increase energy efficiency most effectively. ERE and PUE values are symptoms of actions. In order to understand the causes and actions required, more detailed energy efficiency metrics, such as those suggested in this article, are required.

Acknowledgements

This work was supported by Fortum Foundation Scholarships (grant numbers 201500047, 201600076) and the STEEM project of Aalto Energy Efficiency Programme. The authors would also like to thank Ari Kurvi from Yandex for an interview.

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