Wahlroos, Mikko; Pärssinen, Matti; Manner, Jukka; Syri, Sanna

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Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks

Mikko Wahlroos [a, *, 1], Matti Pärssinen [b, **, 1], Jukka Manner [b], Sanna Syri [a]

[a] Department of Mechanical Engineering, Aalto University, School of Engineering, P.O. Box 14100, FIN-00076, Aalto, Finland
[b] Department of Communications and Networking, Aalto University, School of Electrical Engineering, P.O. Box 13000, FIN-00076, Aalto, Finland

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ABSTRACT

Data centers seek solutions to increase energy efficiency and lower costs by novel methods. Waste heat utilization is considered to be one of the major trends in the near future, especially in the Nordic countries, where heat demand is high. In this paper, waste heat utilization was analyzed from the perspectives of both the data center and district heating network operators. Timing of the data center waste heat production was considered based on an existing data center load profile. For the district heating network operator, the system level effects of increased waste heat utilization were quantified by simulating district heating production in the city of Espoo, Finland, with actual plant and heat demand data for 2013 and 2015. Results showed that with high shares of waste heat in the district heating system, i.e. 20–60 MW, the system level operational cost savings were 0.6–7.3% in the case study. Utilizing waste heat decreased utilization hours of both combined heat and power plants and heat-only boilers. The analysis showed that pricing of the procured waste heat affects the utilization level of waste heat, but operational hours of waste heat utilization were over 95% in all scenarios.

1. Introduction

The energy efficiency of data centers (DC) is becoming increasingly more important as the number of DCs is rapidly growing. It is estimated that DCs already accounted for 1.1–1.5% of the world's total electricity consumption in 2010 [1]. DCs require vast amounts of cooling energy. The electricity consumed in a DC almost completely converts to heat. However, most of the heat is not utilized, even though different solutions already exist. Global warming creates an increasing amount of cooling demand at the same time as power density/floor space in DC is increasing and a demand for processing power is rising faster than processing technology is advancing [2]. With rapid increase in the capacity and size of DCs, there is a continuous increase in the energy consumption and related CO_2 emissions [2].

The cold climate in Nordic countries is extremely suitable for DCs, by providing the much-needed 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 3.3% in 2015 [3] in Finland and 8% in 2014 in Sweden [4]). DH with highly efficient combined heat and power (CHP) is exceptionally common in Finland and Sweden. Current solutions and DC projects in the Nordic countries for utilizing waste heat have been studied for example in Wahlroos et al. [5].

In the current DH network supply, temperatures are typically around 75–120 °C, depending on the outside temperature [6]. 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. To comply with the EU regulations, for example, Finland is aiming at near zero energy buildings (nZEB) in the new building stock by the year 2020. The very low energy demand of the new buildings is particularly suitable for low-temperature heat supply and enabling the move to 4th generation DH systems [6]. Therefore, there may be even more potential utilizing the waste heat from DCs in the future. If the

* Corresponding author.
** Corresponding author.
E-mail addresses: mikko.wahlroos@aalto.fi (M. Wahlroos), matti.a.parssinen@aalto.fi (M. Pärssinen), jukka.manner@aalto.fi (J. Manner), sanna.syri@aalto.fi (S. Syri).

[1] Mikko Wahlroos and Matti Pärssinen have equally contributed to the manuscript.

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Nomenclature

CHP	Combined Heat and Power
COP	Coefficient of Performance
CPU	Central Processing Unit
CRAC	Computer Room Air Conditioner
CUE	Carbon Usage Effectiveness
DC	Data Center
DCE	Data Center Efficiency
DH	District Heating
DHW	Domestic Hot Water
EOC	Environmentally Opportunistic Computing
EPC	Energy Proportionality Coefficient
ERE	Energy Reuse Effectiveness
ESX	VMware Elastic Sky X server
FVER	Fixed to Variable Energy Ratio
HOB	Heat Only Boilers
HVAC	Heating Ventilation Air Conditioner
IT	Information Technology
LTDH	Low Temperature District Heating
nZEB	near Zero Energy Building
PDE	Power Density Efficiency
PUE	Power Usage Effectiveness
RCI	Rack Cooling Index
REF	Renewable Energy Factor
RTI	Return Temperature Index
SHI and RHI	Supply and Return Heat Indexes
sPUE	System Power Usage Effectiveness
TCI	Thermal Correlation Index
TE	Thermodynamic Efficiency
WUE	Water Usage Effectiveness

supply temperature of the DH network can be decreased to as low as 50 °C, lower quality heat would be easier to feed into the system. Typically, waste heat from DC is low quality (<85 °C), and thus it cannot be utilized in current networks to its full extent.

It has been suggested that excess waste heat from thermal power plants could satisfy the whole heat demand for buildings in Europe [7]. For the waste heat utilization to be realized, the business case has to be mutually attractive; i.e., there has to be economic potential for both the heat provider and the DH operator. Even though there have been many studies on DC waste heat utilization, many of the projects have not been realized, as the real economic incentive has been lacking from either party.

The overall aim of this paper was to improve the sustainability of a DC and investigate when waste heat is available, if it can be trusted as a reliable source of heat, and how it impacts DH production as a whole. Secondly, how DC waste heat utilization affects other heat production units in a DH network was studied.

The sub targets of the research were 1) form a waste heat supply profile of a sample DC, 2) conduct simulation to the Espoo DH network with actual plants, operating costs, and different waste heat levels, and 3) investigate waste heat utilization and pricing impact on heat production in a DH network.

2. Related work

2.1. Green data center

According to Deng et al. [8], to become a green DC, two main influencing factors need addressing: renewable energy usage and energy efficiency. Goiri et al. [9] have studied the implementation of solar panels with DCs and the scheduling of power demand with variable renewable generation to minimize the use of electrical grid to supply power. Oro et al. [10] have 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. To have a green image, DC operators have different strategies for procuring renewable electricity. An operator can produce their own electricity on-site or off-site by solar or wind power. In addition, or as an alternative, they can purchase electricity certified as green energy (green certificates, a guarantee of origin, power purchase agreements, etc.).

According to Bertoldi [11], making DCs more energy efficient requires a concerted effort to optimize power distribution, cooling infrastructure, information technology (IT) equipment, and IT output. Pedram et al. [12] have suggested that the economics of operating a DC is comprised by four main factors that contribute to the Total Cost of Ownership (TCO) of a DC. The factors are resiliency, downtime, financial considerations, and vertical scalability.

Weller-McCormack [13] has suggested that ICT sustainability is not a high priority for most ICT departments. The single most important reason ICT managers and leaders do not prioritize sustainability or feel they have a compelling reason to do so, is the lack of visibility regarding actual power consumption [13]. Only one in seven include the cost of ICT power consumption in their ICT budgets. The report indicated that the lowest awareness index score comes from the energy efficiency metrics.

Pakbaznia et al. [14] have explained that there are two main systems for DC air conditioning: the Heating Ventilation Air Conditioner (HVAC) and Computer Room Air Conditioner (CRAC). In computing, and especially in enterprise DCs, HVAC systems control the temperature, humidity, air flow, and air filtering. HVAC must be planned for and operated along with other DC components, such as computing hardware, cabling, data storage, fire protection, physical security systems, and power. Cooling is performed by the CRAC unit. Hot air transfers its heat to a cold substance, typically cold water or air, while passing through a pipe in the CRAC unit. When cold enough, the air enters a room via CRAC fans. The heated substance is directed to a chiller for cooling.

Energy-efficiency targets have recently increased for the modern new DC sites. It is also a part of the image of a company which DC operators want to emphasize. The energy consumption profile of DCs differs significantly from that of a conventional office or a commercial building; the electricity consumption of IT systems is remarkably high. According to a large Finnish DC operator, Telia(formerly Sonera) [15], the operation of their new DC generates 200 GWh of heat annually. Hence, the possibilities to provide the waste heat to a DH grid should be examined in order to reach the energy-efficiency targets.

Lu et al. [16] have calculated DC energy efficiency and the potential for waste heat capturing based on real production data. Results have shown that, in fact, waste heat could be captured from 97% of the total power consumed. Lu et al. have concluded that waste heat of a 1 MW DC (operating at half of its nominal load) could fulfill the heat demand for an over 30,000 m^2 non-domestic building annually.

Marcinichen et al. [17] have suggested that utilizing DC waste heat in a nearby power plant could increase the energy efficiency of the power plant by up to 2.2% as well as cut CO_2 emissions; while Ebrahimi et al. [18] have proposed that retrofitting absorption cooling machines to utilize waste heat could have payback in less than a half year in a 10 MW DC. Kupiainen [19] has calculated that DC utilizing free cooling in combination with a heat pump, rather than a refrigeration machine, would result in a lifetime savings of 280,000€ in 20 years compared to the reference case. According to Stenberg [20], investing in a heat pump in DC, which produces cooling energy and where 75 °C waste heat is sold to a DH network, could have a payback time of less than two years. Sorvari [21] has suggested that hot-water cooled servers could satisfy almost the whole heat demand for 60,000 m^2 of rental cottages and spa in Northern Finland.

2.2. Energy efficiency and waste heat reuse metrics

The Green Grid has specified 4 characteristics of efficient DC metrics: 1) intuitive metric name, 2) scalability to techno-economical changes, 3) scientific accuracy, and 4) the granularity to provide data-driven decisions [22]. Lajevardi et al. [23] have suggested that measuring the performance of an energy efficiency metric is the first step in energy efficiency improvement. It allows tracking the improvements, changes, comparisons between technologies, and benchmarking against average industry performance. According to Nada et al. [2], the assessment of metrics - against intended goals and values of their effectiveness in terms of reporting, targets, education, analysis, and decision support – is needed.

A vast number of energy efficiency metrics that measure energy consumption exists, aimed at reducing the total consumption of electricity in the DC. In the following paragraphs, there are examples of such metrics. The key energy efficiency metrics in the domain of heating, ventilation, and air conditioning (HVAC) in a DC include Thermal Correlation Index (TCI) [24], Rack Cooling Index (RCI) [23], Return Temperature Index (RTI) [23], Supply and Return Heat Indexes (SHI) and (RHI) [23], Power Density Efficiency (PDE) [23], and Thermodynamic Efficiency (TE) [25]. Generic data center energy efficiency metrics include, for example, Power Usage Effectiveness (PUE) [23], Data Center Efficiency (DCE) [23], System Power Usage Effectiveness (sPUE) [2], and Fixed-to-Variable Energy Ratio (FVER) [2].

Metrics for utilization of renewables and decreasing CO_2 emissions include Water Usage Effectiveness (WUE) [26], Carbon Usage Effectiveness (CUE) [26] and Renewable Energy Factor Ref [26]. Energy Proportionality Coefficient (EPC) is an important system-level, energy efficiency metric.

The most widely adopted energy efficiency benchmark metric is PUE. PUE is defined as the ratio of total power used by a building site, divided by the amount of power used by the IT equipment [23]. PUE is overly simplified and does not provide the technical base for proper engineering analysis [22]. For example, Fiandrino et al. [27] have suggested that existing, widely adopted energy efficiency metrics do not distinguish DC communication systems from the computing servers, as both are IT equipment.

All of the aforementioned metrics give a statistical window to energy efficiency and the use of renewables aiming to support objective decision making. Nonetheless, they do not address the benefit of waste heat capturing and reuse. According to Zimmermann et al. [28], Energy Reuse Effectiveness (ERE) has been designed to measure the benefits achieved by introducing waste heat reuse from a DC. Energy reuse has a direct impact on the energy efficiency of a DC. ERE is a variant of PUE and can be calculated from the equation:

$$ERE = \frac{P_{DataCenter} + P_{Cooling} - P_{Reuse}}{P_{IT}}. \tag{1}$$

In Equation (1), $P_{DataCenter}$ and $P_{Cooling}$ together denote the total power consumption of a DC. The P_{Reuse} denotes the power supplied to a secondary application, for example DH. P_{IT} denotes the power usage of IT equipment. ERE was the primary energy efficiency metric for the purposes of this paper. Adaptation of ERE in the industry is based on implemented waste heat recovery solutions. As PUE is still the de facto benchmark metric, the implication is that a majority of DCs do not reuse waste heat.

3. Potential for data center energy reuse and requirements

3.1. Data center load profiles

Waste heat generation was simulated based on the load profile of a DC in Espoo. Data for the profile was measured from actual DC production systems. The selected DC represents a typical service provider profile with multiple customers utilizing a shared infrastructure and services. No direct free cooling is used. Figs. 1–5 describe five aspects of a DC load, which together form the DC load profile. The data was taken from the same one-week period from three different management systems.

Fig. 1 shows the load-balanced server backup traffic, measured from the router link. Backup traffic was sequential and at its peak from 9 p.m. to 7 a.m. Fig. 2 presents the service traffic in/out of the DC. Measures were taken from the Internet routers' ports. In Fig. 2, the Bits/s In (in green) actually means the traffic leaving the DC, and the Bits/s Out (in blue) means traffic coming into the DC. Service traffic was highest during 7 a.m.–10 p.m. Weekends show lower service traffic compared to the business days. From Fig. 1 data combined with Fig. 2 data, it can be concluded that the combination of service traffic and backup traffic form a uniform traffic profile, equally spread across each hour of the day.

Fig. 3 illustrates the power usages of 4 VMware Elastic Sky X (ESX) servers. The role of these servers is to host the virtual servers of customers. The power consumption is stable. Fig. 4 illustrates volatility on each of the server central processing unit (CPU) utilization percentage. The minimum and maximum were in the 20% range. The conclusion from Fig. 3 together with Fig. 4 data was that power consumption and payload processing were also uniformly spread across each hour of the day.

The combined results of all Figs. 1–4, imply that the DC is operating every hour of the day with similar load profile and power consumption. Altogether, this suggests that the DC as a whole is a stable source of waste heat each hour of the day. This implication is supported by Fiandrino et al. [27], which suggests that neither computing servers nor network switches are energy-proportional. Many servers consume up to 66% of their peak power consumption when idle. For network switches, this ratio can reach 85%.

In a DC, load balancing is achieved with virtualization and

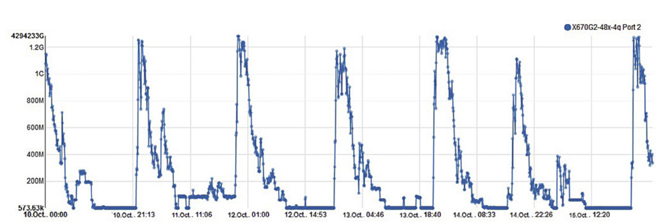

Fig. 1. Load balanced backup traffic. Y-axis represents traffic in bits per second (bps) from DC and x-axis time in weekdays.

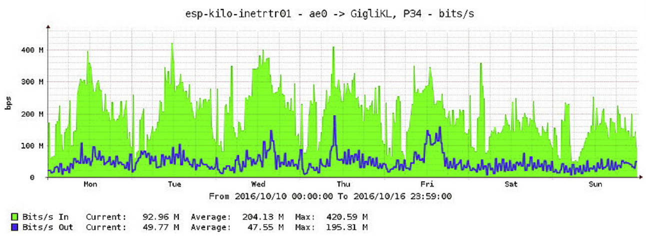

Fig. 2. Service traffic. Y-axis represents traffic in bits per second (bps) from DC and x-axis time in weekdays.

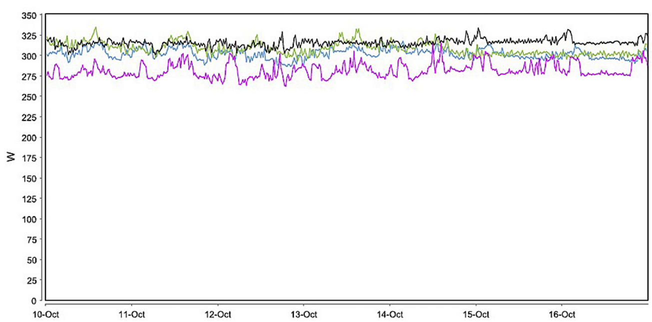

Fig. 3. Shared ESX server power consumption. Y-axis represents power usage (W) and x-axis time (day-month). Colors represent four different ESX servers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

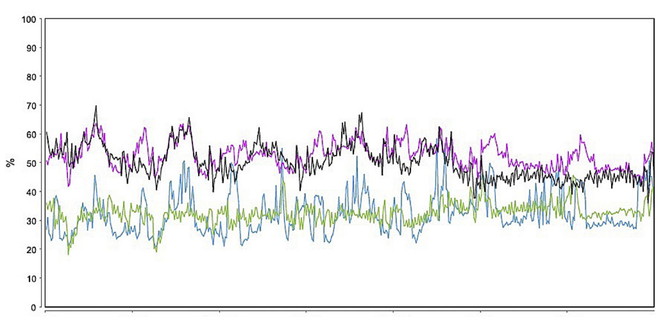

Fig. 4. Shared ESX server CPU usage. Y-axis represents CPU usage (%) and x-axis time (day-month). Colors represent four different server CPUs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

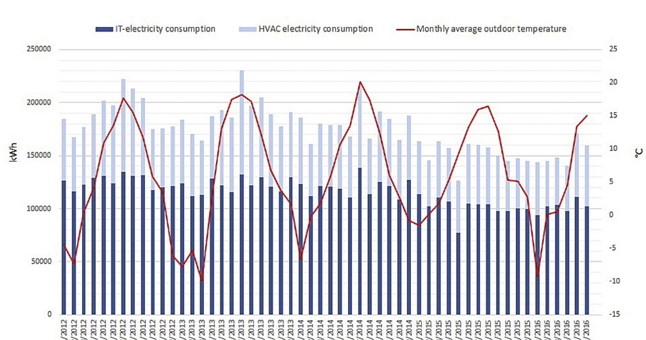

Fig. 5. Monthly electricity consumption of actual DC and average monthly outside temperatures in Espoo [29]. Left y-axis represents power consumption (kWh), right y-axis represents monthly average outdoor temperature (°C) and x-axis time in months.

network-level load balancing. In addition, multiple customers with several different services and user groups ensure that each hour of the day, ESXs and networking equipment operate at a stable power consumption level. During night-time the backup traffic creates load to compensate for the otherwise lower service usage. The conclusion is that DCs can be considered a steady waste heat source. It is possible to use Fig. 5 as an assumption for simulation of waste heat production of a DC. Fig. 5 provides evidence that IT electricity consumption correlates strongly with HVAC electricity consumption. Based on the insight from a sample DC operator, part of the fluctuation in IT electricity consumption is caused by renewing the equipment and increasing or decreasing physical capacity. The fluctuation in the overall electricity consumption is positively correlated with average monthly outside air temperature. Positive correlation is higher when the average monthly outside air temperature is above 10 °C. Below that point, the electricity consumption is varying more as a function of facility and IT-equipment electricity consumption and can be considered to be almost constant. In all situations, the IT-electricity consumption can be reused.

3.2. Statistical analysis

Fig. 5 was plotted into scattered charts in order to evaluate the distribution of observed data. The data was normally distributed. Two-tailed Pearson correlation significance test was selected based on the distribution and wide usability of *t*-test.

For IT- and HVAC energy consumption, $t_1 = 7.91897$, and for total energy consumption and outside temperature, $t_2 = 2.82625$. The $p < 0.05$ was considered significant. Both t-values result with 52° of freedom $p < 0.00001$. The Pearson correlation coefficient was significantly positive.

Fig. 6 and Fig. 7 gave evidence that there is a temperature range where energy consumption is close to constant. Fig. 6 shows the moving average ($n = 4$) of total electricity consumption. Regular regression analysis with linear least squares resulted in data fitting line $y = 1000.9x + 168994$. The conclusion was that the total energy consumption increases as the outside temperature increases. The moving average is fluctuating at a low range until the temperature reaches 17 °C. Fig. 7 illustrates that the outside average temperatures above 10 °C have the strongest positive correlation with electricity consumption.

3.3. Requirements for data center waste heat utilization in DH network

Considering waste heat reuse in DH networks, the main

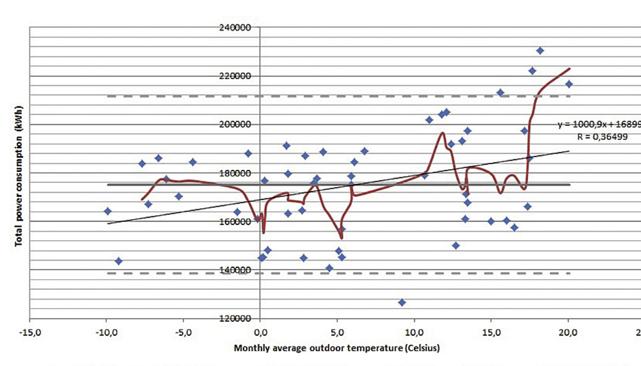

Fig. 6. Moving average of observations with subset of four. Y-axis represents total power consumption (kWh) and x-axis monthly average outdoor temperature (°C).

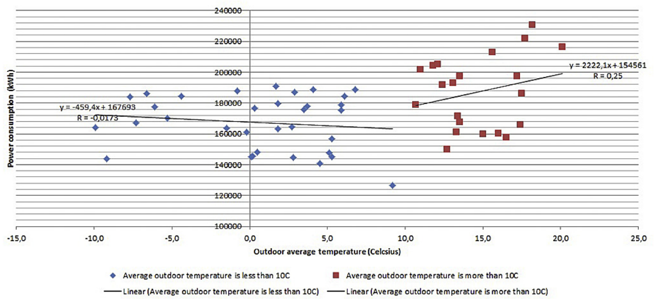

Fig. 7. Observations near 10 °C outdoor average temperature. Y-axis represents total power consumption (kWh) and x-axis monthly average outdoor temperature (°C).

deciding factors are the location of the DC, price of waste heat, and quality of waste heat. In this paper, the quality of heat referred to both the temperature of waste heat and timing of waste heat availability. DH demand is highest in the wintertime, while in summertime, DH is required mainly on heating domestic hot water (DHW). Therefore, it is important to analyze whether waste heat is available when it is truly needed.

Almost all of the waste heat can be recovered as has been suggested, for example, in Refs. [16] and [17]. As it was analyzed in previous sections, it was estimated that waste heat would be available on a rather constant load. However, DCs are operating on a totally different timescale compared to, for example, new heat production plant investments. DCs are typically committed to contracts and clients on a 1- to 5-year time scale, but heat production unit investments typically have technical lifetimes of 15–40 years. This may lead to problems in contracts as DCs may not be able to commit themselves to long-term contracts on supplying waste heat. De facto, DCs are rarely operating on full nominal capacity, and therefore nominal capacity is not an appropriate metric to analyze waste heat availability.

The temperature of captured waste heat depends on the location where it is captured and on cooling technology. In air-cooled DCs, waste heat can generally be captured between 25 °C and 35 °C. In liquid cooling solutions, waste heat can be captured closer to processors, where operating temperatures are higher and thus the captured waste heat is of a higher temperature, e.g. 50–60 °C. The best locations for capturing waste heat have been discussed in Refs. [18] and [30].

Waste heat from DCs is typically low temperature, but heat pumps can be used to increase the temperature. If heat pumps are integrated to DCs, they can, in addition, produce cooling energy for the server room. However, it is still rare that heat pumps are used as the only source for cooling energy. If heat pumps are used as the primary method to supply cooling energy, it is necessary that waste heat can be fed, for example, to the DH system.

Connecting DC waste heat to DH has been discussed in Refs. [5], [30]. Waste heat is typically recovered from hot aisles to the ventilation system. Through the ventilation system, low-grade waste heat, e.g. 35 °C, can be directed to the heat exchanger or heat pump. Stream temperatures are fitted depending on the desired temperature for the DH network. In order to conduct heat transfer, heat pumps are connected to both the supply (e.g. 75 °C) and the return side of the DH network (e.g. 40 °C). Cooled waste heat (e.g. 20–25 °C) can then be directed back to the cooling system of the DC.

The coefficient of performance (COP) of the heat pumps in DCs typically range between 3.0 and 6.3 [30] and the COP decreases when the desired temperature is increased. One important question in using a heat pump is who will make the investment. Heat pumps are heavy investments and increase the electricity consumption; therefore, if the investment is made by a DC operator, there must be long-term prospects for being able to sell the heat. If the heat pump is not integrated into the DC, the investment is typically done by the DH operator.

Buying waste heat from external sources may have huge benefits for DH network operators. With buying waste, the DH network operator can reduce production costs by replacing more expensive peak load production. In addition, peak load production is typically produced by fossil fuels, and therefore utilizing waste heat may reduce emissions of heat production. In the best scenarios, there is even the possibility that utilizing waste heat can replace the need for investing in new heat production capacity, but in these cases, the source of waste heat must be reliable.

4. Modeling the Espoo district heating network and increased utilization of waste heat

4.1. Modeled scenarios

In the case analysis, the DH network of the city of Espoo in Southern Finland was simulated. Simulations were conducted using EnergyPRO software by EMD International A/S [31]. EnergyPRO was suitable for analysis, as it is possible to analyze techno-economic operation in a system with both individual CHP plants and heat-only boilers (HOB). EnergyPro also accounts for electricity sales from the spot markets; thus, it can be conveniently used to analyze a DH network with several CHP plants with different fuels.

EnergyPRO is an input/output model, taking into account e.g. heat production plant characteristics, fuel prices, electricity prices, heat demand, ambient temperature, and DH network temperatures. EnergyPRO calculates the optimal DH operation strategy by minimizing the total operational costs of heat production on the basis of existing plants in the DH system. EnergyPRO takes into account the sales from electricity generated by CHP plants which reduce the total operational costs. Simulations were carried out by using hourly resolution and simulating one year at a time. Two years with different characteristics were selected for the simulations, 2013 and 2015. The reason for two separate years was to analyze cases with different outside temperatures and electricity prices.

Currently, there is approximately 8–15 MW of waste heat in Espoo, and a minor share of it comes from DCs. The purpose of the analysis was to calculate how an increased amount of waste heat would affect the operation of other production plants, such as CHP and HOB. Waste heat capacities and load patterns were analyzed based on an existing operational DC. The DC in question was small, 0.4 MW nominal capacity, but DC capacity was scaled by either 10-fold in moderate scenarios or 25-fold in high scenarios to simulate a system with a higher share of waste heat with a similar load pattern. Waste heat was simulated in EnergyPRO either as a single aggregated heat production plant or utilized waste heat was subtracted directly from heat demand depending on the scenarios in question (discussed below).

All of the scenarios were modeled from the perspective of DH network and investments into waste heat utilization equipment were not considered. It was assumed that the temperature of waste heat from DCs was high enough to be able to feed waste heat directly to the supply side of the DH network, without priming the heat.

4.1.1. Reference scenarios

In reference scenarios, it was estimated that there was no waste heat utilized in the DH network, but DH and electricity were produced with existing plants in the Espoo DH network in 2015. In the reference scenarios, waste heat from existing DCs was excluded.

4.1.2. Marginal cost scenarios

Marginal cost scenarios considered the case where the DH network operator is buying waste heat from external sources, i.e. DCs. The question of waste heat procurement costs was considered in marginal cost scenarios, as it is highly important for profitability from the viewpoints of both the DH network operator and the DC operator. The monthly pricing structure for waste heat is presented in Table 1. The pricing structure has been proposed in Ref. [20], and it is based on the actual marginal costs of heat production and DH producer interviews in Finland. The DH network operator would buy the waste heat if the procurement costs are below the marginal production costs of other technologies in each hour. The purpose was to analyze if there are hours when waste heat will not be utilized on proposed prices.

In the marginal cost scenarios, it was assumed that there is a constant load of waste heat throughout the year. In these scenarios, DC waste heat was simulated in EnergyPRO as an aggregated production unit. The capacity of waste heat in different marginal cost scenarios are presented in Table 2.

4.1.3. 100%-utilization scenario

In 100% utilization scenarios, it was assumed that all available waste heat would be utilized regardless of the cost of waste heat. In some cases, the contracts between the operators may not allow declining on waste heat supply, and thus all waste heat will be fed to the system. In addition, a monthly fluctuating load from the DCs was estimated according to the load pattern of the DC presented in Section 3. As the DC heat would be utilized in any case, the waste heat load was subtracted directly from the DH heat demand.

The differences in the simulated scenarios are summarized in Table 2 below. The reason for different loads in different years was due to the load profile of the actual DC analyzed in Section 3. In 2015, DC lost one of its clients; therefore, the IT load slightly decreased, which affected the waste heat production.

4.2. District heating network in the city of Espoo

The network operator in Espoo is Fortum, who is operating DH networks in many different cities in Finland and Sweden. Espoo DH network also includes the networks in the municipalities of Kirkkonummi and Masala. The net production in the Espoo DH network was 2190 GWh in 2014 [32]. The current plants of Fortum in the Espoo DH network are presented in Table A.1 in Appendix A. Fortum operates various plants with different technologies, ranging from large-scale coal-fired CHP to heat pumps and biomass plants. Baseload heat production is typically coal-fired CHP plants or natural gas-fired CHP plants. Most of the capacity in Espoo is natural gas-based HOBs. Fortum also procures heat from external producers. At the end of 2015, Fortum finished building a thermal DH storage (20,000 m^2 hot water tank) which can store 800 MWh of energy. The storage was not considered in the current scenarios, as it was not effectively used during the year 2015.

In October 2016, Fortum announced that they have a letter of intent to utilize waste heat from Telia's 24 MW DC in Pitäjänmäki, Helsinki, which is under construction [33]. Pitäjänmäki is located close to the Espoo border, where Fortum already has DH transmission capacity with Helen (DH network operator in Helsinki). Fortum has already proved the concept of utilizing DC waste heat in their network. It has been estimated that 200 GWh of heat could be recovered from the DC, which would satisfy almost 10% of the DH demand in Espoo annually.

Assumed characteristics of CHP and HOB plants are presented in Table A.2. CHP plant efficiencies were calculated based on a lower heating value of the fuel. Minimum operation hours for CHP were set at 168 h, i.e. operation of CHP plants were decided on a weekly basis and plants. Plants would operate for at least 168 if turned on and would stay turned off for at least 168 consecutive hours. Regarding the DH network characteristics, constant supply and return water temperatures were assumed based on the average annual temperatures. Return water temperature was set at 49 °C, and supply water temperature was set at 87 °C. In reality, DH temperatures depend on the outside temperature, and when the temperature is colder, supply temperatures are higher. However, in the simulations, constant DH network temperatures resulted only in a small error.

Actual DH demand for 2013, and a normalized demand for 2015, were obtained from Fortum. The actual temperatures for Espoo were obtained from Fortum for 2013, and the outside temperature for 2015 was adopted from the Finnish Meteorological Institute open access-data base [29]. The hourly heat demand and temperatures for the year 2013 are presented in Fig. 8. The load in the Espoo DH network varied between 50 MW and 780 MW in 2013 (on average 253 MW).

In the largest Finnish cities, DH is typically produced with CHP plants; thus electricity production and prices are affecting the merit order of the DH production units. DH production costs are affected by plant technology, technology and prices of different fuels, which typically represent the major share of the total variable costs. Fuel costs of different fuels alongside the fuel taxes, electricity tax and distribution costs, and Elspot electricity prices in Finland are presented in Table A.3. In 2015, coal CHP was effectively cheaper than natural gas and thus coal was widely used for baseload CHP production.

Hourly Finnish system prices for electricity derived from NordPool Elspot, presented in Fig. 9, were used in the simulations. In 2013, the average day-ahead Elspot price was 41 €/MWh, while the average price was only 30 €/MWh in 2015. The difference in electricity prices will highly affect the operation of CHP plants and therefore the merit order of the heat production units.

Table 1
Pricing of waste heat in the marginal cost scenarios (adopted from Ref. [20]).

Waste heat procurement costs (€/MWh)	
January	40.2
February	40.4
March	38.6
April	27
May	19.2
June	16
July	13.8
August	14.6
September	19.2
October	24
November	32.8
December	38

4.3. Restrictions in simulations

It was assumed that DCs are capable of producing waste heat with sufficient temperature to be fed to the supply side of the DH network. Costs for DC operators for priming the heat to a certain temperature (above 75 °C) were excluded. In reality, this is not typically the case as heat pumps are far less efficient in high temperatures, typically making the investments not profitable.

The possibility for supplying waste heat to return water was not considered in the simulations. In practice, waste heat could be supplied to the return side of the DH network when the temperature is lower. However, the quality of waste heat has to be improved for the requirements of the network, and this will cause extra costs

Table 2
Differences in simulated scenarios.

	Reference	Marginal cost	100%-Utilization
Produced waste heat fed to DH network	0%	Depending on marginal production costs of the system	100%
Cost of waste heat	–	Seasonal pricing (13.8–40.4 €/MWh)	0€ (100% will be utilized regardless of the price)
Amount of waste heat	–	Constant load 2013 – Moderate: 23.4 MW 2013 – High: 58.5 MW 2015 – Moderate: 18.7 MW 2015 – High: 46.8 MW	Monthly shifting load 2013 – Moderate: 20–28 MW 2013 – High: 50–70 MW 2015 – Moderate: 15–20 MW 2015 – High: 38–50 MW

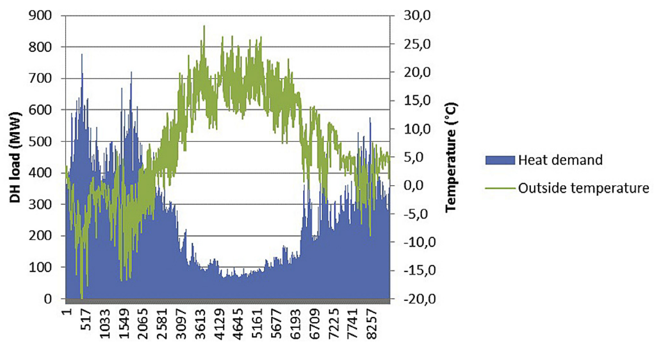

Fig. 8. Simulated hourly (x-axis) district heat load (MW) and outside temperature in Espoo in 2013.

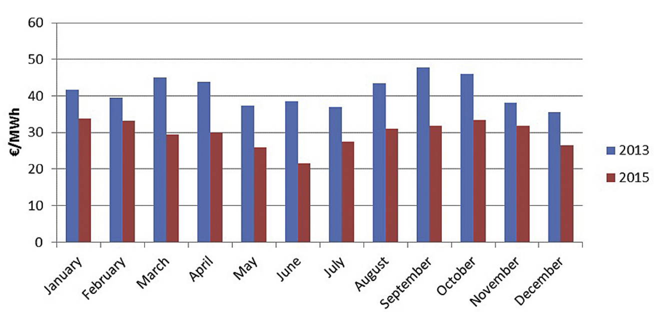

Fig. 9. Monthly average Elspot prices (€/MWh) for Finland in 2013 and 2015 [34].

for the DH network operator. It has been discussed with DH producers and suggested in Ref. [20] that the price for feeding waste heat to the return side could be half of the price compared to feeding waste heat to the supply side of the DH network.

4.4. Results of the modeling

In Fig. 10, the annual simulated electricity and heat production in the 2013 Moderate Marginal cost scenario are presented. Coal CHP (in black) was used as a baseload production, and it was used when the electricity price is high enough, which is basically almost all of the wintertime. In summertime, CHP plants were started only a few times due to the restrictions in the minimum operation hours (168 h). Natural gas-fired CHP plants (natural gas in yellow) were running approximately 30% of the time. On top of the natural gas, the heat pump production (in red) and utilized waste heat (in pink) are presented.

In Table 3 operational hours of the plants in marginal cost scenarios are presented. It is clearly visible that utilization of CHP plants decreased in all of the scenarios. The biggest impact was in 2013, when increased utilization of waste heat had the consequence of heavily decreasing coal CHP production during summertime. Simultaneously, heat pump production increased as it was no longer economical to start CHP plants. The major differences between 2013 and 2015 were in the utilization of CHP. Increasing waste heat production decreased CHP production in all of the scenarios, but CHP has far less operational hours in 2015, due to lower electricity prices. In 2015, on the other hand, heat pumps were operational during almost all hours, due to low electricity prices.

Utilized waste heat, on an hourly basis, in marginal cost scenarios is presented in Fig. 11. During most hours, the waste heat was utilized to its full capacity. During some hours, the waste heat was not utilized, and most of the time, non-utilization hours were only a few consecutive hours. In 2015, when the electricity prices were lower, waste heat was utilized during 99% of the hours while in 2013, waste heat was utilized less, i.e. 95% in moderate and high scenarios. With the current pricing system, most of the heat was utilized even if the waste heat had a high capacity. This suggests that proposed pricing structure was at least favorable for the DH network operator.

In 100%-utilization scenarios, where waste heat was subtracted directly from demand, there were some differences to marginal pricing scenarios. In the marginal cost scenarios, there were certain points where waste heat was not utilized; but in the 100%-utilization scenarios, these hours were satisfied with waste heat. The effects of utilizing 100% of the waste heat affected operations of CHP and heat pumps (only in 2013) the most by decreasing their utilization rates even further. On a few occasions in the scenarios, waste heat production satisfied the entire DH demand and produced surplus heat. Without the possibilities to store the heat, the excess waste heat could not be utilized.

One of the most important issues in utilizing waste heat is the potential savings in heat production costs. As it was discussed, waste heat utilization decreased the operation of CHP and therefore profits from electricity sales will decreased. This is more apparent in 2015, when low electricity prices resulted in less profit already in the reference scenario. In Table 4, the savings in heat production costs in different marginal cost scenarios are presented. The results showed that increased waste heat will result in savings in total production costs, e.g. 12.2% savings in the High scenario in 2013. Even if the profits from electricity decreased, the total operational costs decreased in all of the scenarios and even more when waste heat was utilized to a further extent. The results showed that utilizing waste heat affected operations of other production units, but increased utilization was profitable in any case from the systems perspective.

5. Discussion and further research

5.1. Discussion on waste heat availability and green data center

The waste heat availability in all DCs is dependent on power consumption; in the sample DC this was at least 60–80% of the

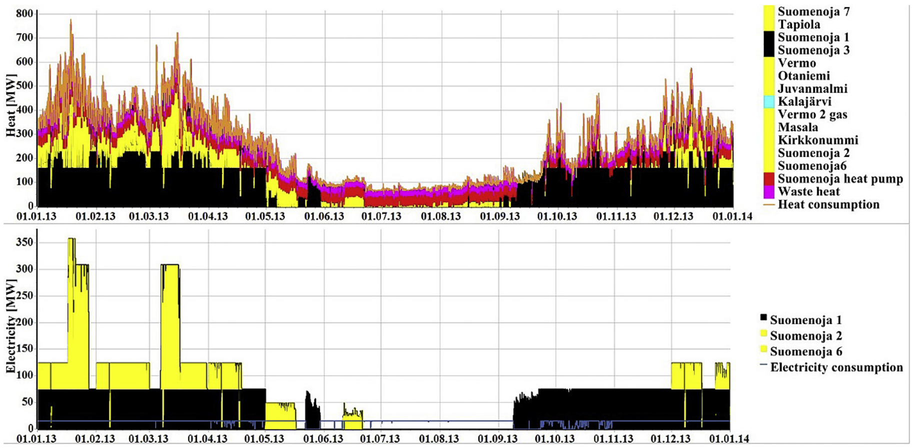

Fig. 10. Simulated heat and electricity production in Moderate Marginal cost scenario in 2013. Upper part of the figure denotes the hourly heat load of individual plants (MW) and the lower part of the figure denotes electricity load (MW) by CHP plants during the simulated year.

Table 3
Operational hours of individual plants in marginal cost scenarios (not full-load hours).

Plants		2013			2015		
		Ref	Moderate	High	Ref	Moderate	High
CHP	Suomenoja 1	82%	66%	62%	63%	61%	53%
	Suomenoja 2	9%	6%	4%	2%	2%	0%
	Suomenoja 6	39%	36%	28%	52%	43%	35%
HOB	Kivenlahti	0%	0%	0%	0%	0%	0%
	Suomenoja 7	0%	0%	0%	0%	0%	0%
	Tapiola	0%	0%	0%	4%	4%	3%
	Suomenoja 3	51%	46%	35%	65%	58%	56%
	Vermo	1%	1%	0%	3%	2%	2%
	Kaupunginkallio	0%	0%	0%	0%	0%	0%
	Otaniemi	14%	12%	9%	28%	25%	21%
	Juvanmalmi	9%	15%	12%	11%	10%	15%
	Kalajärvi	3%	4%	4%	4%	4%	4%
	Vermo 2 natural gas	22%	20%	13%	24%	31%	25%
	Masala	12%	18%	16%	15%	13%	15%
	Kirkkonummi	6%	10%	7%	8%	10%	9%
	Vermo 2 bio-oil	0%	0%	0%	0%	0%	0%
	Kivenlahti Pellets	0%	0%	0%	0%	0%	0%
Other	Suomenoja heat pump	79%	93%	92%	99%	99%	98%
	Waste heat	–	96%	95%	–	99%	99%

Table 4
Cost savings in marginal cost scenarios compared to the reference scenarios.

Marginal cost scenarios	2013		2015	
	Moderate	High	Moderate	High
Total production costs	−5.5%	−12.2%	−4.0%	−9.9%
Profits from sold electricity	−17.1%	−26.3%	−7.7%	−24.1%
Savings in total	**−0.6%**	**−6.3%**	**−3.2%**	**−7.3%**

maximum as presented in Fig. 5, regardless of the amount of service workload. By investing in a waste heat reuse system, DCs can become more energy efficient. Green DC can be obtained with outdated high energy consuming equipment by utilizing on-site or off-site renewable energy sources combined with waste heat reuse. The DC industry is highly competitive; customers may drop off, leading to lower overall capacity and the amount of waste heat may decrease. This can be verified in Fig. 6; however, the impact is small as new customers also come in during the same time period. Risk of variance in availability of waste heat can also be pooled. DH operators need many DCs to mitigate risk. An analogy can be drawn from risk mitigation through investment portfolio management. This would require DH operators to pool their contracts. Nonetheless, a DH network cannot rely solely on the waste heat from DCs.

5.2. Pricing structure of waste heat

As the case study showed, the proposed pricing structure was profitable from the DH network operator's point of view, as waste

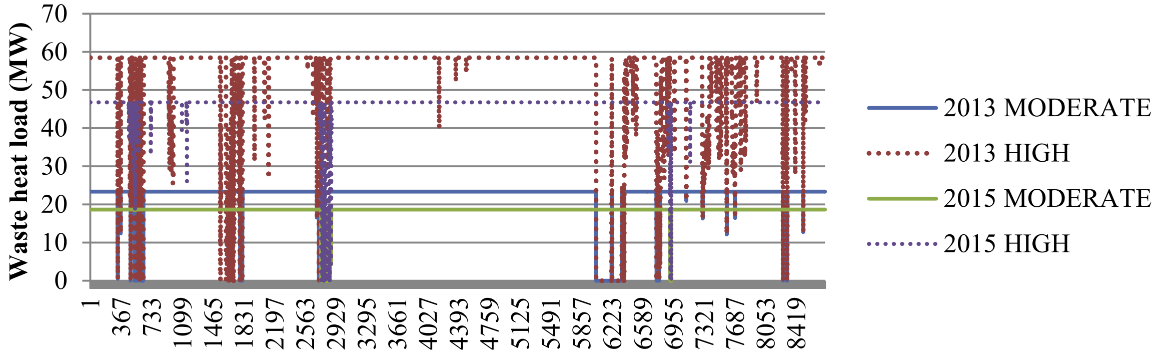

Fig. 11. Waste heat load profile in the marginal cost simulations. X-axis denotes hours of one year (8760) and y-axis denotes utilized waste heat load (MW) in different scenarios.

Table 5
Benefits and barriers of LTDH networks [37].

Benefits of LTDH	Current barriers
• Reduced losses in DH network • Higher COP values for heat pumps • Improved power-to-heat ratios in steam CHP plants • Greater utilization of low-temperature industrial waste heat • More efficient use of heat storages	• High-temperature heat demand • Short cut faults • Legionella bacteria growth at low water temperatures • Possible bottlenecks in DH network capacity due to insufficient temperature difference between supply and return

heat had a high utilization rate in all of the scenarios. It must be pointed out that these values and results did not represent the actual operation of plants or heat prices in the Espoo DH network, but they were results of simulations of the network on certain assumptions. Nevertheless, the pricing structure must be mutually beneficial so that the interest to sell and buy exists for respective parties. For a DH producer, it is most important to get the waste heat when the heat demand is at its highest; therefore, heat is typically more valuable during high heat demand periods, if there is no solution for storing the heat. However, the DC operators will produce heat constantly, and they are operating based on the processing demand. The pricing structure must be transparent and above all predictable to analyze benefits and profits in the long term. In further research, different pricing structures and their effects should be analyzed, e.g. fixed pricing and hourly pricing. Furthermore, the effects of different pricing structures should be analyzed to see how they affect investments in DCs.

5.3. Prospects for low-temperature district heating networks

Low-temperature district heating networks (LTDH) are a rather new concept, especially in Finland, where supply water temperatures have been high. LTDH have been studied and implemented, for example, in Denmark and Germany, where the heat demand is not as high as in Finland, and therefore overall temperatures in the DH networks are lower. In the LTDH supply, water temperature can be less than 50 °C and the return temperature close to 20 °C. LTDH could be well utilized in newly built housing areas with nZEBs.

LTDHs would allow smaller networks to be highly efficient where low quality heat could be utilized more efficiently. If the supply water temperatures are below 50 °C, waste heat from DCs could be directly fed to the LTDH network without the heat pump, especially from DCs with modern cooling technologies, which allow high waste heat recovery temperatures. LTDH would allow distributed heat generation and an open two-way heat network, where consumers can become prosumers of heat (both producing and consuming heat). Syri et al. [35] have studied the possibilities for open DH supply and marginal cost-based DH in Espoo, and the results show that marginal cost-based DH would increase the profitability of utilizing waste heat and the total operating costs of DH production.

The concept of environmentally opportunistic computing (EOC) has been discussed [36]. EOC servers are not located in a centralized DC, but they are integrated into apartments, office buildings etc. EOC waste heat would be captured and distributed through an inbuilt network to the nodes where the heat demand exists. EOC can be considered as a local, distributed heat network, and in that sense, they act as “DH networks”. However, the concept of EOC should be implemented with the concept of LTDH.

Table 5 presents the benefits of LTDH networks and the current barriers slowing down the development. One key issue in LTDHs is the improved prospects for heat storages. Thermal storages are highly efficient if the temperature is lower, as the heat losses decrease in lower temperatures [37].

6. Conclusions

To conclude, the combined load profile of service traffic, backup traffic, power consumption, and payload processing are equally spread across each hour of the day making DC a reliable source of heat. From the perspective of a DH network operator, utilizing waste heat in a DH network is beneficial on a system level. Waste heat utilization saved total operational costs of the simulated DH system by 0.6%–7.3%, depending on the waste heat utilization level (18.7 MW - 58.5 MW). However, the profitability was tightly linked to the pricing structure and electricity prices of the simulated years.

Utilizing waste heat improves the energy efficiency of a data center. With efficient use of waste heat, it is possible to achieve better ERE values. Waste heat is an inevitable by-product of a DC and in any case must be managed; thus making utilization an economically, environmentally and technically sustainable practice. Regardless of the current energy efficiency of a DC, utilizing waste heat improves the energy efficiency. Energy efficiency of DCs is benchmarked globally and therefore sustainable DCs have a competitive advantage. Customers and regulators are becoming aware of the ever increasing power consumption of DCs and are increasingly demanding actions to reduce power usage and CO_2 emissions.

For the DH system, utilizing waste heat decreases operational hours of other units in the DH network. During low price electricity hours, waste heat mainly replaces HOB as CHP plants are hardly used in any case. However, cheap waste heat may decrease electricity production of CHP plants, which may affect supply in electricity markets and thus increase electricity prices. Emission reductions for DH systems depends on which fuel and technology is replaced by waste heat. In the Espoo case, most of the replaced heat was fossil fuel based production, and thus waste heat utilization decreases CO_2 emissions of the DH production and improves energy efficiency on a system level. However, it must be noted that priming waste heat with heat pumps consumes electricity and therefore the overall environmental impact depends on the emission factor of the electricity in question. To further study the profitability of waste heat, it is recommended to investigate waste heat pricing structure and analyze the potential of LTDH networks to maximize the potential of the low-quality heat from DCs.

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Appendix A

Table A.1
Heat production units in DH network of Espoo in 2015 [32] [35].

Plant	Boilers	Heat output (MW)	Electricity output (MW)	Main fuel
Suomenoja 1	1	162	75	Coal
Suomenoja 2	1	213	234	Natural gas
Suomenoja 6	1	80	49	Natural gas
Suomenoja 3	1	70	–	Coal
Suomenoja 7	1	35	–	Natural gas
Kivenlahti	2	65	–	Heavy Fuel Oil
Tapiola	2	160	–	Natural gas
Vermo	2	80	–	Natural gas
Kaupunginkallio	2	80	–	Light Fuel Oil
Otaniemi	3	120	–	Natural gas
Juvanmalmi	1	15	–	Natural gas
Kalajärvi	2	5	–	Light Fuel Oil
Vermo	2	45	–	Natural gas
Masala	2	5	–	Natural gas
Kirkkonummi	4	31	–	Natural gas
Confidential external heat	–	12	–	–
Suomenoja heat pumps	–	40	–	Electricity
Vermo	1	35	–	Bio-oil
Kivenlahti pellets	1	40	–	Wood pellets

Table A.2
Characteristics and costs for CHP plants and HOB used in simulation

		CHP	HOB
Costs	Start-up cost	2500€	0€
	Variable operating and maintenance cost	4 €/MWh_{el}	5 €/MWh_{heat}
Other characteristics	Total efficiency	90%	85%
	Allowed load (of full capacity)	40-100%	0-100%
	Minimum operation hours	One week (168 h)	No minimum operational hours
	Start-up time	4 h	1 h
	Shut-down period	4 h	1 h
	Annual maintenance period	July	No annual maintenance
	Heat rejection	Possible when electricity price is high	No heat rejection needed

Table A.3
Fuel, electricity and tax prices of different fuels as of September 2015. VAT is excluded [34,38–40].

Fuel and technology	Fuel costs (€/MWh_{fuel})	Taxes (€/MWh_{fuel})	Total costs (€/MWh_{fuel})
Coal (CHP)	9	16	25
Natural gas (HOB)	28	17	45
Natural gas (CHP)	28	14	42
Light Fuel Oil (HOB)	42	19	61
Heavy Fuel Oil (HOB)	35	20	55
Wood Pellet (HOB)	47	0	47
Biodiesel (HOB)	42	48	90
Electricity spot prices 2015 (Nord Pool Elspot)		Electricity tax and distribution costs	
0-150 €/MWh_{el} (on average 30 €/MWh_{el})		39 €/MWh_{el}	

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