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Low-temperature waste heat enabling abandoning coal in Espoo district heating system

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Abstract

Espoo has set a goal to abandon the use of coal in its district heating system by the year 2025. The local district heating operator is producing a major share of Espoo’s heat demand with combined heat and power units, but a large share of that thermal capacity will be closed by 2025. The plan is to replace the closed down capacity with renewable fuels, heat pumps and waste heat utilisation. The goal of this paper is to simulate the impacts of these emission reductive acts on the production costs and CO2 emissions of the system. The possibility of utilising waste heat from data centres in the district heating system is evaluated. The results show that abandoning coal in the city's heating system leads to a significant reduction of CO2 emissions with a small increase of annual production costs. Waste heat enables emission reductions even further, and the increase of production costs can be prevented.

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1. Introduction

Espoo is a city of about 280 000 inhabitants in southern Finland. In the Espoo area, an energy company, Fortum, is operating the district heating (DH) network that also extends to the neighbouring cities of Kauniainen and Kirkkonummi. The network has a total production capacity of over 1200 MWth, and in 2016, the total heat demand, including the distribution losses, was about 2.4 TWh. A majority of the heat demand is produced by combined heat and power (CHP) using coal or natural gas as fuel [1]. As a part of Espoo’s climate strategy, Fortum has decided to abandon coal use in Espoo. The first big step for the decarbonising of the Espoo DH system will be closing all the coal-burning units by the year 2025. This is estimated to increase the share of carbon-neutral heat to 85% by 2026. Fortum has planned to close down the coal-fired 80 MWth heat-only boiler (HOB), and coal-fired 160 MWth steam turbine (ST) CHP plant. A natural gas-fired, combined-cycle gas turbine (CCGT) and open-cycle gas turbine (OCGT) will still be kept operational in the future [2]. The plan is to replace the closed down capacity with two new wood-chip-burning HOBs [3,4] and by adding the third heat pump (HP) unit to the existing HP plant [5]. The total length of the network is 880 km [1]. The map of the network can be seen in Ref. [6].

Fortum is also planning to utilise waste heat from the planned new 100 MW data centre (DC) in Espoo [7]. Data centres consume large amounts of power, and according to Lu et al. [8], 97% of that power can be recovered as heat. Thus, utilising waste heat would be an attractive option for both the DC company and the DH operator, but relatively low temperatures give some limitations to the reusability of the heat. In liquid-cooled DCs, heat is captured closer to the applications than in air-cooled applications, thus the recovered temperature is higher. Waste heat temperature from a liquid cooling system is typically 50 °C–60 °C and from air cooling systems 25 °C–35 °C [9]. Often, DC waste heat is not at a high enough temperature to be utilised directly in a DH system. In a modern DH system, centrally produced heat is distributed to customers by hot water circulating in a network. A DH operator controls the temperature of the supply water leaving the production plant, which varies usually between 75 °C to 120 °C according to the outdoor temperature [10]. The supply water cools down in customers’ households, and the temperature decreases more when the outdoor temperature is higher. Fortum is also planning to utilise waste heat from the planned new 100 MW data centre (DC) in Espoo [7].
upgraded to the higher temperature. Another option would be feeding the waste heat in return water, where the temperature usually does not exceed 50 °C [10].

The decarbonising process continues until 2029, when the goal is to have a 95% share of carbon-neutral heat in the network. Due to the security of supply, some natural-gas-based capacity is kept operational and compensation mechanisms will be used [2]. The scope of this study is to analyse the first big step of abandoning coal in the Espoo DH system. Using the already-published waste heat buy-in prices and the existing plans of replacing the coal-based capacity is the novelty of this paper, and it gives a realistic basis for the study. In this paper, the additional costs of upgrading waste heat to the supply temperature are considered as well. DH operator primes the waste heat to the supply temperature of 75 °C–120 °C with additional electric heat pumps. This kind of solution is applied in a DC in Mäntsälä (20 000 inhabitants), in Finland, where the local DH operator buys DC waste heat at a temperature of 35 °C–40 °C and primes the heat to the DH supply temperature with heat pumps. In addition, the heat pumps provide needed cooling for the DC [11]. Fortum's outdoor-temperature-dependent buy-in prices are used, and the operation costs of the heat pumps are added to the buy-in costs [12]. Since the published prices are meant only for heat providers with a capacity of less than 5 MWth, a sensitivity analysis is conducted to further study the value of waste heat on such a great scale. The sensitivity to used HP technology and price of CO₂ emission allowances is also tested.

According to The Finnish Energy Ltd. [13], district heating prices have increased approximately 1.5% per year during last five years, while the emissions have decreased 24% at the same time. Fossil-fuel-based production has been replaced with low emission fuels and by increased utilisation of waste heat from different sources. The main goal of this paper is to analyse the impact of the planned carbon dioxide (CO₂) emissions reduction on DH production costs in the Espoo area. Coal-based production is replaced with wood fuels and increased heat pump capacity. Also, the planned 100 MW data centre is included in the model to study the feasibility of low-temperature waste heat in a DH system.

Mathiesen et al. [14] studied a transition to a 100% renewable energy system with a high amount of fluctuating wind and solar power. According to the study, the best results are achieved when the electricity, heating and transport sectors are merged into a smart energy system. For example, electricity-consuming heat pumps can help balance a fluctuating electricity market and, rather than investing in electricity storages, storing excess electricity as heat or fuels is more beneficial. Hæst et al. [15] had similar conclusions: Heat storages can lower the production costs of DH and the importance increases as fluctuating of the electricity markets increases. Heat pumps can be beneficial in the respect to DH production costs as long as electricity prices stay at a modest level. In Ref. [16], Mathiesen et al. concluded that the importance of DH increases in 100% renewable systems, and expanding the DH instead of individual heating systems would increase fuel efficiency.

Wahlroos et al. [17] studied the impacts of waste heat on Espoo's DH network in the situations of 2015 and 2013, when all the CHP plants were still in operation. According to the study, waste heat utilisation is profitable, and it decreases the production costs, but it also decreases the profits of electricity production as the waste heat replaces CHP production. Wahlroos assumed the waste heat was to be fed directly on the supply side. The quality of DC waste heat is too low for current Finnish supply temperatures, so it would need priming near the heat source with additional heat pumps or electric boilers. If the heat is fed in return water, the network's existing HOBs and CHP plants would take care of raising the temperature to the desired level. The waste heat feed in return water would raise the return water temperature, which would decrease the network efficiency due to increased heat losses and decreased CHP, flue gas condenser and heat pump efficiency [18]. In other words, waste heat feed on the return side is less valuable than the feed on the supply side [12].

In this paper, the studied measures for decarbonising of the DH system are limited to the increased use of renewable fuels and waste heat sources (sewage water and DC waste heat). The 4th-generation district heating (4GDH) network could bring many other possibilities for decreasing CO₂ emissions in the heating sector. The low temperature district heating (LTDH) network plays an important role in this development [19]. Volkova et al. [20] identified six goals to achieve in the transition towards 4GDH system. Lower distribution temperatures, increasing renewable non-fuel heat sources and lowering the heat losses in the network have the highest potential, but these measures also have the biggest barriers. In large DH systems, the transition to 4GDH requires a long period of time, thus the further consideration was left outside of this study. During the transition time towards 4GDH, a more realistic option for lowering the DH network operation temperatures would be implementing low-temperature energy cascades parallel to the existing DH network. Energy cascades could be introduced to nearby business or renovated areas, and the low-temperature sub-network could utilise, for example, return flow of the existing high-temperature network. Low-temperature networks would also ease the utilisation of waste heat sources and heat pumps in the area [21]. Lower operating temperatures of a DH network would also allow lower quality heat sources to be utilised in the network [22].

According to Connolly et al. [23] heat demand can be decreased significantly by improving energy efficiency of the buildings in European countries, but the costs would be relatively high. While it is possible to decrease the space heating demand, consumption of hot water is likely to increase by the year 2050. Helin et al. [24] studied policies of apartment building energy renovations in Finland. While the majority of the building stock is old, it is possible to achieve approximately 10% savings in annual DH consumption and 2% reduction of the peak demand with a modest level of energy-efficiency renovations by the year 2050. Taking into account these findings, it is reasonable to assume that the development of the building stock does not have a significant impact on the heat demand in this paper's time scale (2016–2025).

2. Systems and assessment methodology

Fig. 1 represents a flow chart of the research. The motivation of the paper was to study feasibility of large-scale DC waste heat utilisation and Espoo’s other decided measures for decarbonising its DH system. The main goal of the study was to analyse the impact of decarbonising and waste heat utilisation on production costs and carbon emissions. For modelling the DH system, commercial software EnergyPRO was used [25]. All data were collected from public sources.

The paper seeks answers to the following questions:

- What is the impact of the studied decarbonisation technologies and waste heat utilisation on DH production costs?
- Can the city's goal of 85% carbon-neutral heat production be reached? How large of an emission reduction can be reached with the studied measures?
- Is data-centre waste heat a feasible solution for replacing fossil-based production?
- How would buy-in costs of waste heat, CO₂ allowance price or a used data-centre cooling system affect the results?
2.1. The model

The district heating network is modelled using EnergyPRO software from EMD International A/S [25]. In the model, electricity prices, energy demands, outdoor temperature and district heating supply temperature are defined as a time series for each time step. EnergyPRO optimises the running order of production units according to their marginal production costs, taking into account possible restrictions of the production units [26]. In this paper, the used time step is 1 h, and the optimisation period is one year.

The Espoo DH network is modelled in a total of four different scenarios: Scenarios before the transition to coal-free system with and without waste heat from DC and after the transition also with and without waste heat. The DH network consists of different CHP plants, HOBs, HPs and one 800 MWh heat storage. The optimisation goal is to minimise the total district heating production costs. Revenues of produced electricity are subtracted from the total district heat production costs. Revenues from sold electricity are calculated €/MWh of produced electricity, and HPs pay for electricity as €/MWh of consumed electricity.

The scenarios are labelled as “A” for the current DH system before the actions to abandon coal and “B” after abandoning coal. A1 and B1 are the scenarios without waste heat utilisation and A2 and B2 with waste heat utilisation. Objective functions minimising the production costs in each scenario are presented in Equations (1) and (2). In the equations, \( Q_{CHP} \) is the hourly fuel consumption of a CHP plant and \( P_{CHP} \) is the electricity production. \( Q_{HOB} \) is the fuel consumption of a HOB. \( P_{WWHP} \) and \( P_{DCHP} \) are the electricity consumption of the waste water heat pump (WWHP) and data centre heat pump (DCHP). \( c_{fuel} \) and \( c_{CO2} \) are the fuel costs, the operation and maintenance costs and the costs from CO2 allowances of a CHP plant or HOB, respectively. \( p_i \) is the hourly spot market price and \( c_{D} \) is the costs from electricity distribution and electricity tax. \( c_{O&M} \) is the operating costs of the HPs. \( c_{WH} \) is the hourly buy-in price of waste heat and \( c_{start} \) is the starting costs of a CHP plant.

\[
\text{Min.} \sum_{ij} \left[ Q_{CHP} \left( c_{fuel} + c_{O&M} + c_{CO2} \right) - P_{CHP} p_i \right] + \sum_{j} n_{start} c_{start} \tag{1}
\]

\[
\text{Min.} \sum_{ij} \left[ Q_{HOB} \left( c_{fuel} + c_{O&M} + c_{CO2} \right) - P_{HOB} p_i \right] + \sum_{j} n_{start} c_{start} \tag{2}
\]

Equation (1) minimises the annual costs of the scenarios A1 and B1. In A1, all the CHP plants are operational, \( j \in \{1, 2, 3\} \), and there are total of 13 HOBs, \( k \in \{1, \ldots, 13\} \). In the scenario B1, the coal consuming CHP plant and HOB are removed, and two new HOBs are added, thus \( j \in \{2, 3\} \) and \( k \in \{2, \ldots, 15\} \). The scenarios A2 and B2. The production units are the same as in A1 and B1, but the DCHP is added to the models. In A2, \( j \in \{1, 2, 3\} \) and \( k \in \{1, \ldots, 13\} \). In B2, \( j \in \{2, 3\} \) and \( k \in \{2, \ldots, 15\} \).

2.2. Heat demand, electricity price and outdoor temperature

The operator of the Helsinki DH network, Helen, has published hourly data of heat consumption in 2016 [27]. The data from 2016 was chosen to be used in this study, because it was publicly available. The small differences in total heat consumption between years from 2016 to 2019 are more likely to be caused by the different outdoor temperatures [1]. [28–30] The consumption profile of the Helsinki DH network is scaled down to match Espoo’s 2410 GWh [1] district heat consumption in the given year. For outdoor temperature and electricity price, hourly publicly available data for the year 2016 is used, so that the time series corresponds to the data of the heat demand. Data for outdoor temperature are from the Kaisaniemi observation station close to Espoo in Helsinki [31]. The hourly profile of the electricity spot market price [32] is scaled to estimate the electricity price in 2025.

2.3. Supply and return water temperatures

The supply water temperature is set in each time step according to the outdoor temperature of 2016 and a district heating network control curve [10]. According to the curve, the supply temperature is set to its maximum of 120 °C when the outdoor temperature lowers below –30 °C. The supply temperature gets its minimum
value of 75 °C when the outdoor temperature is +5 °C or more. Between −30 °C and +5 °C, the supply temperature decreases linearly as the outdoor temperature rises. With the 2016 weather data, the control curve leads to a maximum supply temperature of 112 °C. The DH water is assumed to return from the customers in a constant temperature of 50 °C.

2.4. Data centre waste heat and heat pumps

According to Wahlroos et al. [17], DC waste heat provides a more or less constant heat source throughout the year, every hour of the day. In this paper, it is assumed that the heat pumps priming the DC waste heat can provide a constant 100 MW load, and any excess waste heat can be rejected. Fortum has defined buy-in prices as a function of the outdoor temperature (Table 1) [12]. Hourly outdoor temperatures are rounded up to define the hourly buy-in price.

Because it is assumed that the DH operator runs the heat pumps and is responsible for upgrading the quality of waste heat, and all the costs of operating the HPs are added to the DH production costs, buy-in prices of the return side are used. Waste heat is utilised only if it is beneficial according to the total production costs. In the model, the amount of purchased waste heat is counted by subtracting the hourly amount of consumed electricity from the produced heat in the DCHP. Here, it is assumed that heat pumps use the DC’s hot 35 °C cooling air and 50 °C cooling liquid as a heat source and heat up 50 °C DH return water to the desired supply temperature. Heat recovery from the cooling liquid circulation counts for 60% of the total waste heat recovery, and 40% of the heat is recovered from the cooling air. According to Davies et al. [9], COP of a two-stage HP in a similar system can be 5.5.

EnergyPRO simulates the impact of HP’s operating temperatures by calculating Lorentz COP for each time step with the given temperatures. Lorentz COP is multiplied by the heat pump’s efficiency, which is defined in the design conditions. In Table 2, assumed characteristics of the wastewater heat pump (WWHP) and data centre heat pump (DCHP) are represented. A more detailed presentation of the calculation method can be found in Ref. [26]. In the model, the heat source’s hot temperature is assumed to be weighted averages of 60% of liquid stream in the temperature of 50 °C and 40% of air in the temperature of 35 °C. In the HP, the temperatures decrease by 10 °C.

In this paper, it is assumed that the heat pumps, both WWHP and DCHP, can achieve the supply temperature independently. In reality, the efficiency of HPs decreases significantly when the supply temperature increases and, for the highest supply temperatures, other production units are needed. For example, in Helsinki, HPs are able to produce heat at a temperature of 90 °C, and for higher temperatures, a HOB is needed for priming the heat [34]. In Mänttä, the local DH operator is utilising the waste heat of a DC. 3 MW of waste heat is upgraded to a temperature of 85–87 °C, which is enough for summertime demand, and during the peak demand hours, heat is primed to a higher supply temperature [34]. Nevertheless, the assumed supply temperature exceeds 90 °C only 6.6% of the time, and the highest supply temperatures are used during the hours when there are already other units running as well, so the error should not be significant.

2.5. Production units

A total of four different scenarios are implemented. Scenarios are labelled as “A” for the current DH system before the actions to abandon coal and “B” after abandoning coal. A1 and B1 are the scenarios without waste heat utilisation and A2 and B2 with waste heat utilisation. In each scenario, the 2016 heat demand and outdoor temperatures are used.

The price of CO₂ allowances is assumed to be 27.50 €/tCO₂, which is roughly an average between the 2019 price level [35] and the estimated 2030 price in Ref. [15]. The average electricity price is interpolated between year 2016 and the estimation of 2030 in Ref. [15], and the hourly profile of 2016 is scaled up. Fuel prices are averaged out between 2020 and 2030 values of [15]. Taxes and electricity distribution costs are collected from Ref. [15].

Economic assumptions are presented in Table 3. Emission factors of the fossil fuels are collected from Ref. [36]. Electricity consumption is assumed to cause CO₂ emissions of 91 kg/MWh, which was the average of Finnish electricity consumption in 2019 [37]. CO₂ allowances are paid from fossil fuel combustion. In Table 4, a production unit is marked with A if it is included in the scenarios before the transition and B after the transition to a coal-free system.

In the sensitivity analysis, the time series of the waste heat buy-in price is multiplied by factors from 0.00 to 1.20, and the average DH production costs, waste heat utilisation factor and total annual waste heat buy-in costs are compared. The buy-in costs are revenue for the DC operator and thus important when considering the feasibility of waste heat recovery from the DC operator’s perspective. Also, the high utilisation factor of the waste heat recovery system can help to cover the high investment costs and benefit both parties.

2.6. Sensitivity analysis

In a sensitivity analysis, the time series of the waste heat buy-in price is multiplied by factors from 0.00 to 1.20, and the average DH production costs, waste heat utilisation factor and total annual waste heat buy-in costs are compared. The buy-in costs are revenue for the DC operator and thus important when considering the feasibility of waste heat recovery from the DC operator’s perspective. Also, the high utilisation factor of the waste heat recovery system can help to cover the high investment costs and benefit both parties.

In the sensitivity analysis, HP characteristics of different waste heat recovery systems are compared as well. Chilled water, air, hybrid liquid/air and all-liquid cooling systems are compared. In Table 6, the HP characteristics are shown. Because the chilled water temperatures are close to the operating temperatures of the WWHP, the same design parameters are used. For air, liquid/air and all-liquid cooling systems, the characteristics are collected from Ref. [9]. The liquid/air characteristics are the same as presented in Table 2.

The price of the competing fossil energy source can be expected to have an impact on the feasibility and utilisation of DC waste heat, thus the sensitivity to CO₂ allowance price is tested as well. The average production costs, DCHP utilisation factor and total CO₂ emissions were calculated after changing the CO₂ allowance price to 35.00 €/tCO₂.

| Table 1 | Buy-in prices for a feed in supply side as a function of outdoor temperature [12]. |
|----------------|-----------------------------------------------|
| Temperature (°C) | -20  | -16  | -12  | -10  | -8   | -4   | -2   | 0    | 2    |
| Buy-in (€/MWh)  | 35   | 35   | 35   | 35   | 35   | 32   | 32   | 28   | 21   |
|                 | 21   | 18   | 14   | 10   | 10   | 10   | 8    |      |      |
### 3. Results

Average production costs of each scenario are calculated by dividing the total yearly cost by the total amount of produced heat. In Table 7, the average production costs and total CO₂ emissions are represented. Abandoning coal leads to a small increase in the average production costs in scenario B1; but with waste heat utilisation in scenario B2, the average production costs can be lowered below the level of A1. The emissions of CHP production are allocated to heat and electricity production according to the units’ power-to-heat ratio, and only the emissions of heat production are considered in the values of Table 7.

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#### Table 2

Design characteristics of WWHP and DCHP. Data of WWHP are based on [33] and DCHP on [9]. The table represents the designed DH supply and return temperatures, COP, thermal and electric capacities, heat source temperatures and the calculated HP efficiency.

|                     | WWHP | DCHP |
|---------------------|------|------|
| Electricity (MWₜₜ)  |      |      |
| COP                 | 3.7  | 5.5  |
| DH return (°C)      | 50   | 50   |
| DH supply (°C)      | 65   | 70   |
| Source hot (°C)     | 14   | 44   |
| Source cold (°C)    | 7    | 34   |
| Capacity (MWₜₜ)     | 47   | 100  |
| HP Efficiency       | 52.6%| 34.6%|

* The value in brackets is the heat pump capacity after adding the new HP in scenarios B1 and B2. In the model, all the WWHPs are modelled as one unit.

#### Table 3

Assumed fuel and electricity prices.

|                     | Price         | Tax HOB | Tax CHP | CO₂ emissions |
|---------------------|---------------|---------|---------|---------------|
| Electricity spot-price | Average: 61.09 €/MWh | —       | —       | 0.091 t/MWhₜₜ |
| Electricity distribution | 43.50 €/MWh | —       | —       | —             |
| Coal                | 27.50 €/CO₂  | 27.00 €/MWh | 17.10 €/MWh | 0.334 t/MWhₜₜ |
| Natural gas         | 27.80 €/MWh  | 17.60 €/MWh | 12.90 €/MWh | 0.349 t/MWhₜₜ |
| Oil                 | 52.75 €/MWh  | 22.90 €/MWh | 12.90 €/MWh | 0.336 t/MWhₜₜ |
| Bio oil             | 67.00 €/MWh  | —       | —       | —             |
| Wood pellets        | 34.00 €/MWh  | —       | —       | —             |
| Wood chips          | 28.00 €/MWh  | —       | —       | —             |

* CHP plants sell electricity at an hourly spot market price. Electricity consuming units buy electricity at the spot price, and distribution costs and electricity tax are added to the costs.

#### Table 4

Production units.

| Scenarios | Type          | Fuel      | MWₜₜ | MWₜₜ | MWₜₜ | Min. load |
|-----------|---------------|-----------|------|------|------|-----------|
| A         | Suomenoja 1 CHP [38] | ST: Coal  | 265  | 160  | 80   | 40%       |
| A, B      | Suomenoja 2 CHP [38] | CCGT: NG  | 498  | 214  | 234  | 40%       |
| A         | Suomenoja 6 CHP [38] | OCGT: NG  | 132  | 73   | 45   | 40%       |
| A         | Suomenoja 3 [1]  | HOB: Coal | 78   | 70   | 0    | 20%       |
| A, B      | Kvenlahi [3]    | HOB: Pellet | 90 | 80   | 0    | 20%       |
| A, B      | Suomenoja 7 [38] | HOB: NG   | 18   | 17   | 0    | 20%       |
| A, B      | Tapiola [1]     | HOB: NG   | 180  | 160  | 0    | 20%       |
| A, B      | Vermo NG [39]   | HOB: NG   | 90   | 80   | 0    | 20%       |
| A, B      | Kaupunginkallio [1] | HOB: LFO | 90   | 80   | 0    | 20%       |
| A, B      | Otaniem [1]     | HOB: NG   | 129  | 120  | 0    | 20%       |
| A, B      | Juvanmalmi [1]  | HOB: NG   | 17   | 15   | 0    | 20%       |
| A, B      | Kalajarvi [1]    | HOB: LFO  | 6    | 5    | 0    | 20%       |
| A, B      | Masala [1]      | HOB: NG   | 6    | 5    | 0    | 20%       |
| A, B      | Kirkkonoumu [1] | HOB: NG   | 36   | 31   | 0    | 20%       |
| A, B      | Vermo Bio-oil [39] | HOB: Bio-oil | 98 | 90   | 0    | 20%       |
| A, B      | Suomenoja HP* [33] | HP: El.  | 15   | 47   | 0    | 0%        |
| B         | Kvenlahi 4 [3]  | HOB: Chips | 49  | 44   | 0    | 20%       |
| B         | Suomenoja HP New* | HP: El. | 7.5  | 23.5 | 0    | 0%        |
| B         | Ammassuo [4]    | HOB: Chips | 99  | 89   | 0    | 20%       |

* COP of a heat pump is calculated on every time step.

#### Table 5

Operation costs and characteristics of the production units.

| Type | Min. operation time | Min. non-operation time | O&M cost | Starting cost |
|------|---------------------|-------------------------|----------|---------------|
| ST   | 24 h                | 24 h                    | 4.50 €/MWhₜₜ | 2500 €/start  |
| CCCT | 24 h                | 24 h                    | 4.50 €/MWhₜₜ | 2500 €/start  |
| OCCT | 4 h                 | 4 h                     | 4.50 €/MWhₜₜ | 0 €/start     |
| HOB  | 4 h                 | 4 h                     | 2.00 €/MWhₜₜ | 0 €/start     |
| WWHP | 0 h                 | 0 h                     | 3.00 €/MWhₜₜ | 0 €/start     |
| DCHP | 0 h                 | 0 h                     | 3.00 €/MWhₜₜ | 0 €/start     |
Waste heat utilisation costs and operation hours are presented in Table 8. The utilisation factors of waste heat are 63.8% and 64.6%. The breaks in utilisation hit on the periods of high electricity prices. Higher electricity prices raise the costs of data centre heat pumps, but at the same time, the profitability of CHP production increases; thus the breaks are covered mostly by increased CHP production. Figs. 2 and 3 show DCHP production in comparison to the electricity price and CHP heat production. During the summertime, when the heat demand is low, the charging and discharging of heat storage is enough to cover some of the breaks in DCHP production. When comparing A2 to A1, the waste heat decreased production costs 4.4%. Adding waste heat in B2 decreased the production costs from B1 by a similar percentage.

Table 9 represents fuel consumptions in each scenario, and Table 10 shows the shares of heat production by a production unit and energy source. In scenario A1, 47.1% of the heat is produced from coal, and introducing waste heat utilisation into the system in A2 decreases the share of coal-based production to 36.3%. Abandoning coal increases natural gas consumption 24.9% in B1 from A1. In B2, natural gas consumption is 12.5% higher than in A2. The share of fossil fuels in production decreases to 20.1% in B2 from A1’s value of 69.3%. When A1 and B1 are compared, abandoning coal increases natural gas consumption in both CHP and HOB units. The largest relative increase is seen in natural-gas-fired HOBs. This increases the production costs during winter. Annually, natural-gas-fired HOBs represent 5.4% of the total production costs in A1 and 12.3% in B1. The share of WWHP production also increases, but this can be partly explained by the increased capacity.

During the summertime, marginal costs of heat production is lower in B1 than in A1. This is due to the increased HP capacity and the new wood chip combusting units. The wood-chip-burning units, with a total capacity of 133 MW, produce 57.3% of the heat demand during the period from May to September. In comparison, a coal-burning, back-pressure steam turbine, with a thermal capacity of 160 MW, produces 47.5% of the heat demand in the same period in scenario A1. In Fig. 4, the monthly average marginal cost and monthly average production cost are presented. The hourly marginal cost is defined as the production cost of the most expensive production unit that is running on each hour. If the CHP units are rejecting heat, the marginal cost is zero. During hours, when there is no heat production, but all the demand is met by discharging the heat storage, the marginal cost is defined as the marginal cost of the last hour, when the heat was produced.

In the sensitivity analysis, it can be seen that the utilisation factor of the DCHP increases as the buy-in price decreases. In Fig. 5, the changes in the DCHP utilisation factor and total buy-in costs can be seen as the buy-in price time series is multiplied with factors from 0.00 to 1.20. For evaluating the feasibility of waste heat selling from the DC operator’s perspective, the point where the revenue of a DC operator reaches its maximum can be defined. In B2, the maximum total buy-in costs are paid when the prices of Table 1 are multiplied by 0.97. This would lead to a 0.1% higher revenue for the DC operator, and the utilisation factor would be 66.5%, 3.0% higher than in the original case. The average DH production costs would be 33.27 €/MWh, 0.2% lower than with the original pricing. In scenario A2, higher revenue for the DC operator can be achieved. By multiplying the buy-in price time series with a factor of 1.10, the total buy-in costs increase 1.2% from the original A2, but a higher price would also mean higher DH production costs and a lower utilisation factor of DCHP. The utilisation factor would decrease 6.6% and average DH production costs increase 0.8%.

The sensitivity of the results of the DCHP characteristics was also tested by changing the input parameters of the DCHP (Table 6). In Table 11, the results of this analysis are shown. The chosen HP and cooling technology have a significant impact on the feasibility of waste heat in the DH system and total operation costs of DCHP. In A2, the differences are slightly smaller in the average DH and DCHP production costs. It can also be seen that with chilled water- and air-cooling systems, the utilisation factors of waste heat are higher in A2 than in B2. The annual COPs of the DCHP are higher in scenario A2, especially with the chilled water-cooling system. The reason for this is that higher production costs of DCHP decrease summertime production more in B2 than in A2; and in the summer, the DCHP can operate with a higher COP due to a lower supply temperature. In B2, changing DCHP parameters from liquid/air cooling system to a chilled-water system decreases summertime production (April–September) by 90.0% and wintertime production by 37.6%. In A2, the decrease is 53.1% in the summer and 33.9% in the winter.

The model was initially run with CO2 of 27.50 €/tCO2, which would mean only a modest increase from the current price level, when coal-based production is abandoned. In Table 12, results with a higher allowance price of 35.00 €/tCO2 are shown and compared to the initial values of Tables 7 and 8.

### 4. Discussion

#### 4.1. Impact on the production costs

According to the results of this study, the planned changes in...
Espoo’s DH production mix would cause a relatively small increase of the production costs if waste heat is not utilised. The largest difference in production costs is seen during the winter, when the use of CHP is more extensive. During the summer, the new wood-chip-fired boilers and increased sewage water heat pump capacity provide a good alternative for the closed-down capacity. With DC waste heat utilisation in scenario B2, the productions costs can be lowered below the reference level. In this study, only the variable costs of heat production were considered, but the high investment costs of the renewable technologies and O&M costs of the network etc., which were not considered, may have an impact on the customer prices of DH as well.

4.2. Decarbonisation target and emission reduction

The district heating operator in the Espoo area has a goal to have 85% of its DH production carbon neutral by 2026. Carbon-neutral heat will be produced by heat pumps and renewable fuels [2]. In 2018, the total amount of consumed fuels for DH and CHP electricity production was 3423 GWh, of which coal consumption was 54% and natural gas consumption 27%. Electricity consumption of the HPs was 100.5 GWh [29]. These numbers correspond well to the results of the model in the reference scenario (Table 9), even though the model resulted in a slightly smaller amount of CHP production. In 2019, consumption of coal increased, and natural gas decreased from 2018; thus, the difference to the model is larger as well [30]. When comparing the results of the model to historical data, it must be noted that, in this study, the assumptions of fuel and electricity prices represent the situation in 2025, not any past year, which may cause some of the differences. With the studied carbon-neutral technologies and DC waste heat utilisation, the share of production from fossil fuels can be lowered from the reference scenario’s 69.3% to 20.1%. This is close to the city’s goal of an 85% share of carbon-neutral heat, when considering that some of the planned carbon-neutral technologies (e.g., Otaniemi 40 MW geothermal plant) were excluded from the model [2].

Kokkonen [40] studied decarbonising the Espoo DH system with large HP capacities and DC waste heat utilisation. The results are not straightforward comparable, as different assumptions were used. The results of the study showed that more extensive utilisation of heat pumps would lead to lower production costs. The share of HP production in the total DH production was 55%—69%, and the share of natural gas-combusting units was 15%—9%.

Table 9
Consumed fuels and electricity production and consumption.

| Fuel                  | A1 (Reference) | A2   | B1   | B2   |
|-----------------------|----------------|------|------|------|
| Coal (GWh)            | 1 806.9        | 1 415.5 | 0.00 | 0.00 |
| Natural gas (GWh)     | 1 078.2        | 870.5 | 1 346.9 | 979.5 |
| Oil (GWh)             | 0.00           | 0.00  | 0.00  | 0.00  |
| Wood pellet (GWh)     | 468.6          | 324.8 | 370.3 | 273.8 |
| Wood chips (GWh)      | 0.00           | 0.00  | 1 022.7 | 796.5 |
| Bio oil (GWh)         | 0.00           | 0.00  | 0.00  | 0.00  |
| Total                 | 3 353.7        | 2 610.9 | 2 739.9 | 2 049.8 |
| Electricity Consumption (GWh) | 97.8         | 199.9 | 137.0 | 242.4 |
| Electricity production (GWh) | 938.7       | 772.2 | 509.0 | 400.6 |

Table 10
Production percentages of the total heat demand by production unit and by energy source.

|                         | A1 (Reference) | A2   | B1   | B2   |
|-------------------------|----------------|------|------|------|
| Suomenoja 1 CHP         | 41.6%          | 33.8%| –    | –    |
| Suomenoja 2 CHP         | 13.6%          | 11.5%| 16.0%| 12.0%|
| Suomenoja 6 CHP         | 5.5%           | 4.4% | 6.1% | 4.3% |
| HOB coal                | 5.5%           | 2.5% | –    | –    |
| HOB NG                  | 3.2%           | 1.7% | 7.4% | 3.0% |
| HOB Pellets             | 17.3%          | 12.0%| 13.7%| 10.1%|
| HOB Chips               | –              | –    | 38.1%| 29.7%|
| WWHP                    | 13.4%          | 11.0%| 18.7%| 16.6%|
| DCHP                    | –              | 23.3%| –    | 21.5%|

Fig. 2. Hourly waste heat utilisation and CHP heat production in scenario A2. On the right axis is the electricity spot price.

Fig. 3. Hourly waste heat utilisation and CHP heat production in scenario B2. On the right axis is the electricity spot price.
Kokkonen had assumed a larger total capacity of heat pumps, thus these results can be considered to be in line with the results of this study. In the scenario of lower HP capacity, the total annual CO₂ emissions were 0.13 Mt CO₂, which corresponds to this study’s results in scenario B2, even though Kokkonen had assumed a lower emission factor for electricity consumption.

4.3. Feasibility of waste heat

The utilisation factor of waste heat is relatively high, approximately 64%–65%, in both of the production mixes of this study. High electricity price is an important factor that limits the utilisation of waste heat as it increases the costs of heat pumps. In Figs. 2 and 3, it can be seen that the breaks in waste heat utilisation usually happen when the electricity price is high. As a higher electricity price increases the revenue of electricity sales, CHP production also usually increases during these breaks. In the values of Table 10, it can be seen that introducing DC waste heat into the system has a lower impact on the CHP production than HOBs. This is especially seen between scenarios A1 and A2, where the cheaper coal-based CHP plant is still available. This supports the conclusions of Wahlroos et al. [41]. According to Wahlroos, utilising waste heat, together with CHP production, brings flexibility to the system, as CHP is used during the hours of high electricity price and waste heat is utilised when the electricity price is low.

Table 11
Results with different HP parameters.

| DC cooling | DCHP production cost (€/MWh) | DCHP utilisation factor | DCHP annual COP |
|------------|-------------------------------|------------------------|-----------------|
| Scenario   | A2                            | B2                     | A2             | B2             | A2   | B2   |
| Chilled water | 33.50                        | 34.25                   | 41.17          | 44.02          | 34.7%| 21.7%| 3.3  | 3.3  |
| Air        | 33.32                        | 34.09                   | 39.34          | 40.28          | 42.0%| 32.1%| 3.7  | 3.6  |
| Liquid/Air | 32.66                        | 33.34                   | 35.32          | 35.32          | 63.9%| 64.6%| 4.7  | 4.7  |
| Liquid     | 32.38                        | 33.05                   | 34.05          | 34.02          | 69.4%| 71.7%| 5.1  | 5.1  |

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Table 12
Results of scenarios A2 and B2 with emission allowance price of 35.00 €/tonCO₂ and comparison to the initial results. Differences are shown as increase/decrease (%) compared to the initial results.

|                  | Average production costs (Difference %) | DCHP Utilisation factor (Difference %) | Emissions (Difference %) |
|------------------|----------------------------------------|--------------------------------------|--------------------------|
| A2               | 34.77 €/MWh (6.4%)                     | 73.2% (14.7%)                        | 389.3 kt (−10.2%)        |
| B2               | 34.00 €/MWh (2.0%)                     | 67.8% (5.0%)                         | 114.6 kt (−10.8%)        |
The results’ sensitivity on electricity price was not studied in this paper, but it is obvious that the assumption of the average spot market price causes some level of uncertainty to the results. In a 2016 report [42], Finnish electricity market price was estimated to raise to approximately 50 €/MWh, and in Ref. [43], the market price was estimated to reach a level of 55–65 €/MWh by 2035. Khorasani et al. [44] estimated the average Finnish spot market price to be significantly lower, approximately 30 €/MWh, in 2030. Also, the Finnish government is considering the possibility to lower electricity tax for large-scale heat pumps producing district heating, which would decrease electricity costs significantly [45]. The average electricity price assumption in this study can be considered to be rather high, and lower electricity costs would increase the profitability of the heat pumps and waste heat utilisation.

The utilisation factor of DC waste heat can be increased by lowering the buy-in pricing from the prices in Table 1. In scenario B2, the used pricing is close to optimal from the perspective of the DC operator’s income. In A2, a 10% higher price would lead to maximum income for the DC operator, but this would also decrease the utilisation factor of waste heat. However, a higher utilisation factor could also possibly benefit the DC operator, as the heat pumps operated by the DH company can produce cooling for the DC simultaneously. For estimating the optimal pricing method, a more precise economic analysis of the DC cooling system should be made. Pärssinen et al. [46] conducted an investment analysis from a DC operator’s point-of-view with an assumption that the DC owner invests in the required heat recovery equipment. According to the study, the size of a DC affects the profitability of waste heat recovery and sales. In larger DCs, it is more profitable to invest on heat recovery than in smaller ones. For a DC operator, there may also be other reasons than just economic profit, for example public image, to invest in heat recovery.

The price of competing production methods also has a significant impact on the feasibility of waste heat. If the CO2 allowance price is increased, the utilisation factor of waste heat increases in both scenarios, A2 and B2. Also, the average production costs increase and the total annual emissions decrease. The price of emissions allowances has an impact only on the costs of fossil fuel-based production, and for that reason, the impact is higher in scenario A2, where a larger share of heat is produced by fossil fuels. With the initial assumption of 27.50 €/tCO2 of emission price, the average production costs in A2 was 2.0% lower than in B2; but after increasing the emission price, the average costs of A2 increase over the level of B2 as seen in the results of Table 12. Also, the waste heat utilisation factor increases more in A2, if the costs of fossil fuel units are increased. A higher emission price would also decrease the total emissions of production by approximately 10% in both of the scenarios A2 and B2.

Wahlroos et al. [41] listed barriers for waste heat utilisation in DCs. In addition to low quality of waste heat, for example, high investment costs, location of a DC, different business models and information security may cause that it is not feasible to utilise DC waste heat. Because of the high investment costs of a DH network, the DC should be located close to the heat consumption centres. Different business models in DH and DC industry may cause, that the DC and DH operators have different expectations for the rate of return of their investments. A DH operator has usually a natural monopoly inside the operating area; and thus, the business is often less risky. Therefore, it is likely that a DC operator expects a shorter payback time for their investments. Due to the high information security standards, DC operators often limit the access to their data. The lack of transparency between the parties makes the commercialisation of waste heat utilisation more difficult.

The potential of the heat pumps is constrained by the low quality of waste heat. The conversion of lower temperature waste heat into heat has COP in the lower end of the survey's scale. The model simulates the effect of the heat pump temperature on COP and it is assumed that the HPs can produce the supply temperature individually. Also, slight analysis of the used technology was left outside of the scope of this paper. Also, frequent start-ups may cause mechanical wear in large-scale HPs, and during start-up, the COP is lower [48]. These kinds of technical limitations were not considered in the model.

In this paper, the impact of different DC cooling systems was studied by changing the input parameters of DCHP in the model. The chosen cooling technology has a significant impact on the feasibility and costs of waste heat. Poorer COP of DCHP decreased the utilisation factor of DCHP. However, lower COP had a greater impact on the utilisation factor and production costs in B2 than in A2. Especially during the summer, higher production costs limited waste heat utilisation more in B2. A reason for this is that the new wood-chip-burning HOBs and increased WWHP capacity can decrease the marginal costs of base-load production during the summer. Introducing new heat sources to a system with lower marginal costs would be economically more difficult.

Because of the higher waste heat temperature, a liquid DC cooling system seems to be the most feasible technology for waste heat utilisation. A liquid cooling system can be a single-phase or a two-phase system. Single-phase cooling systems are based on the sensible heat of the coolant, and two-phase systems use the latent heat. Higher latent heat increases the cooling capacity of a two-phase system and decreases the needed mass flow of the coolant [49]. However, because the temperature of different components in a DC vary greatly, direct liquid cooling is usually used only for cooling the hottest components, while the cooler parts are cooled down by air. In such a system, using a two-stage HP with low and high temperature evaporators can improve the COP when compared to a single stage HP [9]. Also, liquid cooling and hybrid liquid/air cooling systems consume significantly less power than air cooling systems [49]. Air cooling has been the most common cooling system in DCs, but the power density has increased in newer DCs, which sets higher requirements for the performance of the cooling systems. Thus, liquid cooling systems have become more common in modern DCs [50]. In air-cooled DCs, the waste heat can be recovered from warmed up return air or from chilled water circulation. Waste heat recovery from chilled water...
circulation may allow a higher share of heat to be captured, but the temperature is lower than the warm cooling air [9].

5. Conclusions

This study analysed the implications of abandoning coal in the Espoo DH system and the possibilities of data centre waste heat providing a cost-effective external heat source to the system. Currently, the largest share of Espoo’s annual heat demand is produced by a coal-fired CHP plant. The conclusions of this study and the answers to the research questions presented in chapter 2 can be formulated as follows:

- Closing down the coal-fired CHP plant would increase the use of natural gas, especially during the winter, and this would lead to higher production costs. Utilising data centre waste heat proved to be a feasible solution for lowering the production costs and reducing carbon dioxide emissions. With DC waste heat utilisation, production costs can be lowered below the reference level, and emissions can be decreased to one-fourth of the reference level.

- With the help of waste heat utilisation, the city’s goal to have 85% of heat production from carbon-neutral sources seems achievable. In the scenarios of this study, the share of carbon-neutral production increased to 79.8%. With the utilisation of data centre waste heat, the average production cost was decreased from 34.89 €/MWh to 33.34 €/MWh, and annual CO₂ emissions decreased further from 168.1 ktCO₂ to 128.5 ktCO₂, compared to the reference of 545.5 ktCO₂. In this study, some of the planned carbon-neutral technologies were excluded from the model. For example, a 40 MW geothermal plant is estimated to produce 10% of Espoo’s annual heat demand in the future.

- The majority of the costs of waste heat comes from the electricity purchases and waste heat buy-in costs, thus these assumptions cause uncertainty to the results. Also, the costs of competing production technologies, the CO₂ allowance price and the used data centre heat-pump technology have a significant impact on the feasibility of data centre waste heat utilisation. Changing the CO₂ allowance price from 27.50 €/tonCO₂ to 35.00 €/tonCO₂ increased the average production cost by 2.0%, the DCHP use by 5.0%, and decreased the CO₂ emissions further by 10.8% in the case where the coal-fired CHP unit had been abandoned and data centre waste heat was utilised.

- Comparison between alternative heat pump technologies implied that a liquid cooling system in a DC is the recommendable technology due to the highest waste heat temperature. A liquid cooling system captures the heat closer to the server racks, which allows the heat to be recovered in higher temperatures. A higher waste heat temperature would improve the COP of the heat pumps.

Declaration of competing interest

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

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Abbreviations

- DH District heating
- CHP Combined heat and power
- HOB Heat-only boiler
- OCGT Open-cycle gas turbine
- ST Steam turbine
- CC GT Combine cycle gas turbine
- HP Heat pump
- DC Data centre
- CO₂ Carbon dioxide
- 4CDH 4th generation district heating
- LTLDH Low-temperature district heating
- COP Coefficient of performance
- WWHP Wastewater heat pump
- DCHP Data centre heat pump
- NG Natural gas
- LFO Light fuel oil

Subscripts

- th Thermal capacity
- el Thermal capacity

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