HOW TO MAXIMIZE THE SUSTAINABILITY IMPACT OF DATA CENTER WASTE HEAT UTILIZATION IN DISTRICT HEATING?

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ABSTRACT

The future requires sustainable and economically feasible solutions in the energy field to reduce CO_2 emissions and reach critical climate targets. Data center waste heat utilization in district heating could be one of these solutions, as it reduces emissions in the heating sector while increasing the energy efficiency of data centers. The profitability of this solution is dependent on multiple aspects, with national and EU-level regulation of data center waste heat utilization being one of them. In this paper, the tax regulation of data center waste heat in district heating in Finland is examined. Furthermore, changes that lead to more sustainable outcomes are proposed.

This paper quantifies the benefits of reduced electricity taxation that has recently been implemented in Finland. Two cases with data center waste heat utilization are inspected, one being in Espoo (310 000 inhabitants) and another in Seinäjoki (66 000 inhabitants). In Espoo, a large data center is expected to be vital in abandoning coal and achieving 95% decarbonization in district heating. In Seinäjoki, data center waste heat would replace the use of local carbon-intensive peat in district heating. The energy system modelling of the district heating networks is done with energyPRO software. In this study, we examine different scenarios regarding waste heat utilization and profitability with and without governmental taxation benefits.

Currently, the Finnish tax incentives for waste heat utilization seem sufficient if district heating is fossil-fuel intensive and CO_2 emission prices are high. However, if the district heating network already has low CO_2 emissions, the district heating operator may prefer a cheaper option than low-temperature waste heat. Therefore, the data center operators would not receive the lower tax class as the share of waste heat utilization is too low. The holistic analysis presented benefits both district heating and data center operators in recognizing the opportunities for data center waste heat utilization. In particular, the challenges and lack of regulative support are stated, and ways to achieve more sustainable solutions by increasing waste heat usage are proposed.

1 INTRODUCTION

The ICT sector produces 3−5% of the global greenhouse gas emissions and the share is rapidly increasing (Ministry of Transport and Communications, 2021). Globally 63% of the heating demand in buildings is covered by fossil fuels (The International Energy Agency (IEA), 2023). Therefore, both sectors are highly emitting and require a decline in associated carbon dioxide emissions to meet the EU's 2030 target of reducing 55% of the GHG emissions in comparison to the emission levels in 1990 (European Commission, 2023). This requires the ICT sector to increase the use of waste heat and increase the efficiency and sustainability of data centers (DCs). The emission from the building sectors must decrease by 60% compared to the 2015 level (European Environment Agency, 2023). The solution to reduce CO_2 emissions of DCs and heating would be to reuse the waste heat from DC in heating. In Finland, this could be done efficiently as the waste heat can be supplied to DH networks. This is also incentivized in Finnish law as DCs will get a tax reduction if enough waste heat is reused (Finnish Tax Administration, 2023a).

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The waste heat reuse in district heating (DH) in Nordic conditions has been examined (Wahlroos et al., 2018). The study discovered that it is difficult for the DC operator to gain profit from the waste heat selling due to the low quality of waste heat and high investment costs. In addition, the study states that the ERE value is a significant figure to analyze when DCs are aiming for net-zero targets. The reduction of the gap between waste heat production and waste heat reuse has been studied (Huang et al., 2020). The study finds that there are not enough global controls considering DC's operation, waste heat production and reuse. The study states that the development of global energy metrics is a significant part of improving the performance of DCs. The integration of combined cooling, heat, and power based DC with a DH and district cooling systems has been investigated (Keskin & Soykan, 2022). The study found that the integration reduces the cooling cost by 40.3% and provides flexibility to both parties.

In this study, two DH networks that are planning to purchase waste heat from DCs are modeled. One of the two DCs will be located in Espoo, which is a city in southern Finland with a population of 310 000. The DC is expected to be crucial in abandoning coal and achieving 95% decarbonization in district heating. The other will be located in Seinäjoki in western Finland which has a population of 66 000. The DC is expected to replace peat usage in the DH. The planned DCs will be 100 MW in Espoo and 21 MW in Seinäjoki. It is estimated that the waste heat from a DC could cover a third of the heat demand in both DH networks. The aim of the study is to examine if the Finnish tax reduction law with ERE requirements incentivizes to increase waste heat reuse. The study also investigates whether there is a conflict with the profitability of waste heat between DC and DH companies. Furthermore, the study recommends how the reuse of waste heat can be increased. The motivation for the study is to provide analysis for both DH and DC operators regarding opportunities in the utilization of waste heat in DH networks. Furthermore, in this research, the waste heat usage is studied in an ideal situation in Finland where the waste heat can be supplied to the DH network and there is already law support for the reuse. Thus, the study is an example situation how the regulatory environment could be changed to incentivize the reuse of waste heat in other countries besides Finland.

2 METHODS

The DH networks of Espoo and Seinäjoki are modeled with energyPRO software. The modeling software minimizes Net Production Cost (NPC) with the time step of one hour so that the heat demand is met in every hour and the optimization period is one month at a time for a year. Equation (1) shows the optimization calculation for minimizing the NPC that is applied for both cities.

$$\begin{aligned} Min.\ NPC = Min. &\sum_{i,j} \left[F_{i,j}^{CHP}\left(c_j^{fuel} + c_j^{O\&M} + c_j^{CO2} + c_j^{T} + c_j^{FI}\right) - P_{i,j}^{CHP} p_i\right] \\ &+ \sum_{i,k} F_{i,k}^{HOB}\left(c_k^{fuel} + c_k^{O\&M} + c_k^{CO2} + c_k^{T} + c_k^{FO}\right) \\ &+ \sum_{i,m}\left[E_{i,m}^{HP}\left(p_{i,m} + c_m^{D} + c_m^{T\_E} + c_m^{FO}\right) + \theta_{i,m}^{HP} c_{HP}^{O\&M}\right] \\ &+ \sum_{i}\left[E_i^{EB}\left(p_i + c^{D} + c^{T\_E}\right) + \theta_i^{EB} c_{EB}^{O\&M} + \theta_i^{WH} c_i^{WH}\right] \end{aligned} \tag{1}$$

The NPC calculation includes summing up the operation cost of every unit and the revenue from combined heat and power (CHP) units. The calculation is done for every hour of the year, thus $i \in \{1, \dots, 8760\}$. j, k and m are the number of units of CHP, heat only boiler (HOB) and heat pump (HP) correspondingly. In Espoo $j \in \{1,2\}, k \in \{1 \dots, 4\}$ and $m \in \{1,2\}$. $j \in \{1\}$ and $k \in \{1 \dots, 5\}$ in Seinäjoki. There are no HPs in the DH network of Seinäjoki. Both DH networks have one electric boiler (EB) and one purchased waste heat supply. The unit costs included in the calculation are fuel (c^{fuel}), O&M ($c^{O\&M}$), carbon allowance (c^{CO2}), tax (c^{T}), electricity tax (c^{T_E}) and transmission costs that include a fee for output (c^{FO}) for CHPs and fee for input (c^{FI}) and transmission fee (c^{D}) for HPs and EBs. For CHP plants and HOBs, the fuel consumption (F) is multiplied by the unit costs. The cost of

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HPs and EB is calculated by multiplying the electricity consumption of HPs (E^{HP}) and EB (E^{EB}) by the unit costs. For the CHP units, the produced electricity (P) is multiplied by the electricity spot price (p) to calculate the revenue of the electricity sold. The O&M cost for HPs and EBs is calculated by multiplying the produced heat (θ) by the unit cost of O&M. The cost of purchasing waste heat is calculated with the amount of purchased waste heat (θ_i^{WH}) multiplied by the cost of waste heat (c^{WH}). In addition, both DH networks include heat storage that is included in the optimization.

The COP of DC HP (COP^{WH}) for both cities is calculated using the Lorenz COP (COP_{lorenz}) seen in Equation (2) (EMD International A/S, 2019). The Lorenz COP for every hour is multiplied by the efficiency (μ) in design conditions that gives the actual COP for every hour. The Lorenz COP is calculated using the mean temperature of the delivered hot water ($T_{HighMean}$) and the heat source ($T_{LowMean}$), which are calculated using the supply temperature of DH ($T_{HighOutlet}$), the return temperature of DH ($T_{HighInlet}$), the temperature of waste heat source ($T_{LowOutlet}$) and the temperature of cooled down heat source ($T_{LowInlet}$).

$$COP^{WH} = \mu \cdot COP_{lorenz},\ where\ COP_{lorenz} = \frac{T_{HighMean}}{\left(T_{HighMean} - T_{LowMean}\right)}$$
$$T_{HighMean} = \frac{T_{HighOutlet} - T_{HighInlet}}{\ln\left(\frac{T_{HighOutlet} + 273.15}{T_{HighInlet} + 273.15}\right)},\ T_{LowMean} = \frac{T_{LowOutlet} - T_{LowInlet}}{\ln\left(\frac{T_{LowOutlet} + 273.15}{T_{LowInlet} + 273.15}\right)} \quad (2)$$

The calculation of the profit on cooling the DCs is seen in Equation (3) and is done separately for both cities. The hourly electricity consumption HP (E^{WH}) is calculated by dividing the recovered waste (θ^{WH}) heat, which the model provides, by the COP of HP (COP^{WH}). The amount cooled by HP (θ^{HP_C}) is calculated by deducting the electricity consumption from the recovered heat. The amount that is cooled by the cooling tower (CT) is calculated by reducing the cooling done by HP from the total cooling (θ^{TC}) that is 21 MW in Seinäjoki and 100 MW in Espoo, which is then divided by the COP of CT (COP_i^{CT}) to get the electricity consumption of CT (E^{CT}). The costs are calculated by multiplying the spot price and transmission cost with the electricity consumption of HP and CT. The revenue from waste heat is calculated by multiplying the waste heat amount with the buy-in price for each hour. Lastly, the profit is calculated by reducing the cost from the revenue.

$$Profit = \sum_i Revenue - Cost$$
$$= \sum_i \left[\theta_i^{WH} c_i^{WH} - E_i^{WH}\left(p_{i,m} + c_m^D + c_m^{T_E} + c_m^{FO}\right) + E_i^{CT}\left(p_{i,m} + c_m^D + c_m^{T_E} + c_m^{FO}\right)\right] \quad (3)$$
$$where\ E_i^{WH} = \frac{\theta_i^{WH}}{COP_i^{WH}},\ \theta_i^{HP\_C} = E_i^{WH} - \theta_i^{WH}, \mathrm{E}_i^{CT} = \frac{\theta^{TC} - \theta_i^{HP\_C}}{COP_i^{CT}}$$

2.1 ERE value

ERE value analysis is the focus of this study and the calculation for it can be seen in Equation (4). In the calculation, the reused waste heat is reduced from the total energy use of DC and then divided by the IT energy usage. The total energy consumption of DC is the sum of the total cooling and IT servers' electricity consumption and other sources such as the electricity use of storage drivers and the network (Shehabi et al., 2016). The IT servers' electricity consumption is related to the capacity of the DC, thus Espoo's has an hourly electricity consumption of 100 MWh and Seinäjoki has 21 MWh. It is assumed that all the electricity used in DC is converted to heat (Wahlroos et al., 2018), which means that Espoo requires hourly cooling of 100 MW and Seinäjoki 21 MW. Electricity consumption of total cooling is the sum of the electricity usage of HP and CT. The modeling provides the electricity consumption of HP, and the rest of the cooling is assumed to be done by CT. The rest of the DC electricity consumption

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is calculated by its share of the IT electricity consumption, which is expected to be 33% (Shehabi et al., 2016). Lastly, the modeling provides the waste heat utilization in DH.

$$ERE = \frac{TotalEnergy - Reuse\ Waste\ heat}{IT\ Energy} \tag{4}$$

The ERE value requirement to achieve tax class II depends on the size of the DC and it is defined by two different requirements (Finnish Tax Administration, 2023a). When the DC capacity is between 0.5—5 MW, the required ERE is 0.90. A DC capacity between 5 and 10 MW requires an ERE of 1.00 and for capacity that exceeds 10 MW there are no requirements. This means that ERE for the 100 MW DC in Espoo can be a maximum of 1.0 and for 21 MW DC in Seinäjoki it can be at most 0.98 to be allowed for tax class II.

2.2 Data

The model uses various environmental data that include hourly outdoor temperatures of Espoo and Seinäjoki from 2023 (Finnish Meteorological Institute, 2024a). The outside temperatures are used to calculate the DH supply temperature and the hourly heat demand. The supply temperature is calculated with the Equation (5) (Finnish Energy (ET), 2006), where t_u is the design temperature of the area, which is -26°C in Espoo and -29°C in Seinäjoki (Jylhä et al., 2011). t_x is the hourly outdoor temperature of Espoo and Seinäjoki. Additionally, the maximum temperature of the supply is 115°C, and the minimum temperature of the supply is 70°C when the outside temperature is over 8°C.

$$115\ ℃ + (t_u - t_x) \times \frac{45\ ℃}{(8\ ℃ - \ t_u)} \tag{5}$$

The hourly heat demand (Q) for the year 2023 and for both cities is calculated using heating degree hours (HDH) seen in Equation (6) (Ju et al.,2023). The heat demand for 2023 is unknown, thus the heat demand for 2019 is used for the calculation (Finnish Meteorological Institute, 2024a). The heating degree hours (HDH) for 2019 are calculated by adding together the HDHs of each hour (HDH_i) as seen in Equation (6) (Finnish Meteorological Institute, 2024b). HDH_i is calculated by using the average hourly outside temperatures of 24 hours (T^0), where $i \in \{1, \ldots ,8760\}$. In addition, HDH_i is zero for temperatures over 10°C. It is assumed that 70% of the heat demand comes from space heating (SH) demand and the rest is domestic hot water (DHW) demand. The SH and DHW demands for the year 2019 are calculated by multiplying the total heat demand by 0.7 and 0.3, correspondingly. As the hourly outside temperatures of 2023 are known for both cities, the HDHs are calculated for Espoo and Seinäjoki. SH demands for the year 2023 were calculated by dividing the SH demand of 2019 by the HDH of 2019 and multiplying the results by the HDH of 2023. The DHW is assumed to be the same in 2023 as in 2019 because it is not dependent on weather conditions. Therefore, hourly DHW demand is calculated by dividing the yearly DHW demand by 8760. The hourly SH demand is calculated by dividing the yearly SH demand (Q_{SH}) with the yearly HDH of 2023, which is then multiplied by the HDH_i of 2023. The hourly heat demand of 2023 is then calculated by summing up the SH and DHW (Q^{DHW}) demand for each hour.

$$Q_i = \frac{Q_{SH}}{\sum_i HDH_i} HDH_i + \ Q_i^{DHW},\ HDH = \sum_i HDH_i = \sum_i max\{0{,}17℃ - \ T_i^0\} * 1\ h \tag{6}$$

CO_2 emissions factors for emitting fuels from the year 2023 are also included in the model. The CO_2 factor for electricity is the average of the consumed electricity in Finland in 2023 (Fingrid, n.d.) and fuels' CO_2 factors are from the Statistics Finland (Statistics Finland, 2024). The CO_2 factor for electricity is 36 $kgCO_2/MWh$, 387.36 $kgCO_2/MWh$ for peat, 248.04 $kgCO_2/MWh$ for light fuel oil (LFO) and 199.87 $kgCO_2/MWh$ for natural gas (NG).

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Table 1: The economic values of the models.

		Price
Taxes (€/MWh)	Peat (CHP)	5.70
	NG	23.35
	NG (CHP)	15.72
	LFO	27.58
	Electricity I	22.53
	Electricity II	0.63
Fuel costs (€/MWh)	Peat	15.37
	LFO	86.48
	NG	67.95
	Wood pellets	78.49
	Wood chips	30.10
Electricity costs (€/MWh)	Spot price (avg.)	56.47
	Transmission fee, winter weekday	2.55, 8.96
	Fee for output	0.92
	Fee for input	0.61
CO_2 price (avg.) (€/tonCO_2)		83.60

All the economic values are based on the year 2023 and are seen in Table 1. Taxes are gathered from the Finnish Tax Administration for oil (Finnish Tax Administration, 2023b) and other fuels (Finnish Tax Administration, 2022). The fuel costs are from Statistics Finland (Statistics Finland, n.d.). The tax class I is 22.53 €/MWh which is significantly higher than tax class II, which is 0.63 €/MWh. The electricity cost includes the hourly spot-market price from Nord Pool (Nord Pool, 2024). The transmission fee for electricity is generally 2.55€/MWh but it is 8.96 €/MWh during winter weekdays from December to February from 7 am to 9 pm (Fingrid, 2023). The CHP units selling the electricity are assumed to sell it in the spot market and gain the spot market price for profit. In addition, for the carbon dioxide emitting fuels the average EU ETS CO_2 price of 2023 is included in the economic analysis (The Finnish Energy Authority, 2023). O&M costs are 2.00 €/MWh$_{fuel}$ for HOBs, 4.50 €/MWh$_{el}$ for CHP, 0.50 €/MWh$_{heat}$ for an EB, and 3.00 €/MWh$_{heat}$ for the HP in DH networks (Danish Energy Agency and Energinet, 2016). In the DC cooling examination, CT and DC do not include O&M as they are assumed to cancel each other. The buy-in prices for the purchased waste heat are determined based on the buy-in prices of Fortum, which is the DH company in Espoo, as seen in Table 2 (Fortum, 2024). The prices are connected to specific outside temperatures that are used to determine the hourly buy-in price in Espoo and Seinäjoki.

Table 2: The outside temperature limit for the corresponding buying-in prices for DH supply.

Temperature (°C)	-8	-7	-4	-3	-2	-1	4	6	7	16	16.1
Buy-in (€/MWh)	50	47.5	45	42.5	40	35	30	22	20	17.5	13

Both DCs are assumed to have a liquid cooling system where COP is 6.3, DH return is 45 °C, DH supply is 70 °C, source temperature is 50 °C and cooled down source is 40 °C in design conditions. This means that the efficiency of HP in design conditions is 23.6% (Davies et al., 2016). The capacity of HPs is based on the size of the DCs, therefore in Espoo the HP's capacity is 100 MW and in Seinäjoki it is 21 MW. The COP of HP for every hour is calculated by Equation (2). The CT is expected to have a COP of cooling of 17.5 (Murphy & Fung, 2019). The electricity consumption in design conditions is calculated by dividing the cooling requirement (100 MW or 21 MW) by the COP. The actual amount of cooling done by CT is the cooling by HP reduced from the required cooling. Detailed information on the other units is seen in Appendix A, where Table A1 and Table A2 include information on Seinäjoki and Espoo, respectively. The efficiency of the units is calculated by dividing the energy output by the sum of fuel inputs. The CHP plant is assumed to have yearly maintenance in July from 1.7 to 15.7. All the production units can operate at partial load. The CHP plant and the EB are allowed to store heat in

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thermal storage as they are located in the same area. In Espoo, the CHP plants and the HP utilizing warm sewage water are located in the same power plant with thermal storage.

3 SCENARIO DEVELOPMENT

This study focuses on four different scenarios that differ in tax classes and optimization of HP operation. Tax class I is significantly higher than tax class II, and tax class II can only be applied to DCs that reuse enough waste heat. The cooling of DC can be done with HPs or CT but only with HP, the waste heat temperature of the waste heat can increase and be supplied to the DH network. The unit cost of HP is higher than CT as the CT has a higher COP. However, the waste heat produced by HP and sold to the DH company brings profit for DC. Scenarios 1 and 2 are modeled with the HP optimization, which means profit from selling the heat must cover the difference between the unit costs of HP and CT, making the HP more profitable to run than the CT. Scenario 1 has tax class I and scenario 2 have tax class II. Scenarios 3 and 4 have the corresponding tax classes I and II, however, they do not include the optimization of which unit is more profitable to run and HP is used always when it is profitable for DH companies to purchase the waste heat. The scenarios are seen in Table 3.

Table 3. The different scenarios apply to Espoo and Seinäjoki.

Scenario	
S_1	Tax class I with optimization of HP use
S_2	Tax class II with optimization of HP use
S_3	Tax class I
S_4	Tax class II

4 THE RESULTS

4.1 District heating production

The units producing heat differ between Espoo and Seinäjoki. In Espoo, most of the heat demand is covered with the purchased heat (31%) in the scenarios without optimization. Suomenoja HP produces 22% of the heat production and Vermo HP covers 3% in the same scenarios. HOB using chips produces 10% of the heat and HOB using wood pellets produces 8%. CHP plants using NG cover together 11% of the heat demand and HOB using NG covers only 1 %. The rest of the heat demand is covered with EB (15%). In Espoo, DC waste heat is purchased mainly during winter and spring as seen in Figure 1. The rest of the heat demand during the summer is produced with HPs that run evenly throughout the year. The HOB using chips also runs evenly in winter. The units using NG produce heat in short periods outside wintertime. EB and HOB using pellets run also in winter and more often than NG units.

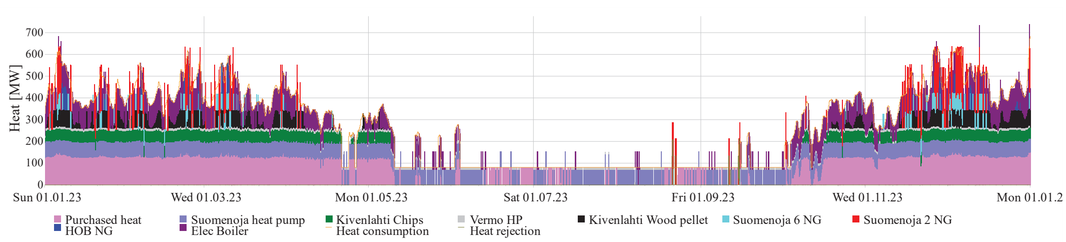

Figure 1: Yearly heat production in Espoo in scenarios without optimization of HP use.

In Seinäjoki, heat is mostly produced with the new HOB using biomass as it covers 51% of the yearly heat demand in the scenarios without optimization. The EB and the purchased heat from DC both cover 19% of the heat demand in the same scenarios. The share of CHP heat production is only 5% and the rest of the heat demand is covered with HOB_biomass_Kap. The waste heat from DC is purchased rather evenly throughout the year including summer as seen in Figure 2. The EB also covers some of the heat demand in summer, but it operates the most in autumn. The HOB biomass boilers produce heat from autumn to spring and CHP plants run during short time spans at the same time period.

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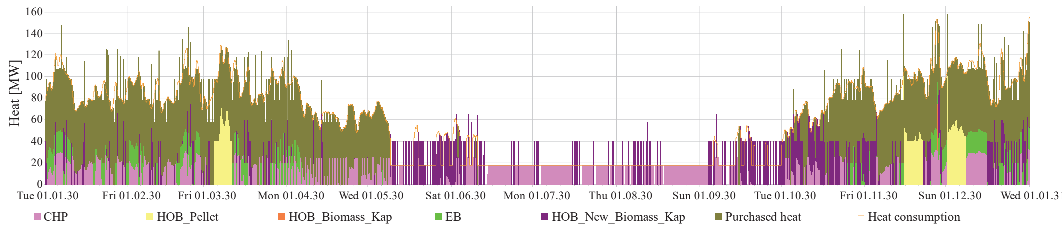

Figure 2: Yearly heat production in Seinäjoki in scenarios without optimization of HP use.

The operation expenses for Espoo and Seinäjoki are shown in Table 4. The yearly heat production expenses do not differ much between the scenarios in one city, but the expenses are lower in Seinäjoki than in Espoo. The costs are lower in Seinäjoki due to the high share of low-cost HOB biomass. In winter, Seinäjoki runs the efficient HOB, thus keeping the heat costs low. In Espoo, the DH company utilizes expensive CHP units using NG and an HOB using wood pellets during winter. Therefore, the heat production costs are twice as expensive in Espoo than in Seinäjoki in winter. However, Espoo can use cheap HPs in summer and maintain the price of heat slightly lower than Seinäjoki.

Table 4: The operation expenses in Espoo and Seinäjoki in different scenarios.

	Espoo				**Seinäjoki**			
(€/MWh)	**S_1**	**S_2**	**S_3**	**S_4**	**S_1**	**S 2**	**S_3**	**S_4**
DH OpEx year (avg.)	40.04	39.62	39.27	39.27	26.38	26.21	26.13	26.13
DH OpEx July (avg.)	10.84	10.82	10.82	10.82	12.14	12.05	12.05	12.05
DH OpEx December (avg.)	77.03	75.72	74.63	74.63	37.14	36.66	36.59	36.59

The waste heat is purchased in Espoo during winter when the cost of heat production is high, which is presented in Figure 3. It shows that the heat production costs are higher in Seinäjoki in June and July than in Espoo. Seinäjoki also has a higher waste heat utilization factor from June to September than Espoo. However, Espoo has a higher utilization factor of waste heat than Seinäjoki at other times.

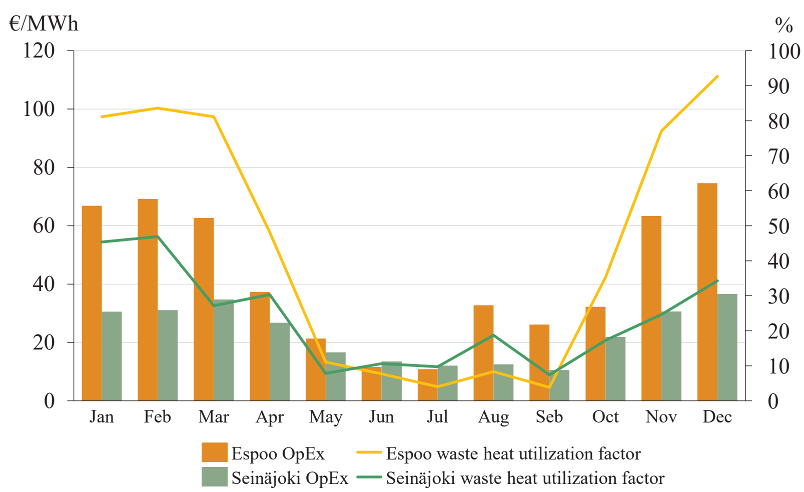

Figure 3: The monthly utilization factor and the operation expenses in Espoo and Seinäjoki during one year in scenarios without optimization of HP use.

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4.2 Economic results

The economic results are seen in Table 5. ERE value is in all scenarios lower than required. The highest ERE value in Espoo is 0.74 with tax class I when the limit is 1.00. For Seinäjoki, the limit is closer as the highest ERE is 0.96 in tax class I when the limit is 0.98. Therefore, in all the modeled situations the DC sells enough waste heat to achieve the tax reduction. In the same table, it is seen that the share of recovered waste heat is considerably higher in Espoo than in Seinäjoki. Over 60% of the time, HP is used for cooling in DC in Espoo and the same number is only 40% in Seinäjoki. Table 5 also shows the economic values of the DH cooling in different scenarios. Due to the significantly higher capacity of DC in Espoo than in Seinäjoki, the revenue from waste heat selling is considerably higher in Espoo. The highest revenue is achieved with tax class I without optimization (S_4) in both cities. However, the cooling costs are higher in these scenarios than in the same tax classes with optimization. Therefore, the most profitable scenario is tax class II with optimization (S_2) in both. The lowest profitability occurs with tax class I without optimization (S_3) in both cities.

Table 5: Data of the DC cooling in Espoo and Seinäjoki in four different scenarios.

	Espoo				**Seinäjoki**			
	S_1	**S_2**	**S_3**	**S_4**	**S_1**	**S 2**	**S_3**	**S_4**
ERE	0.74	0.72	0.69	0.69	0.97	0.95	0.94	0.94
Share of recovered waste heat	0.61	0.64	0.66	0.66	0.40	0.41	0.43	0.43
DC cooling cost (M€/year)	15.20	12.30	17.01	13.18	2.27	1.83	2.50	1.93
DC cooling revenue (M€/year)	21.34	22.13	22.79	22.79	2.57	2.67	2.73	2.73
DC cooling profit (M€/year)	6.14	9.83	5.78	9.61	0.29	0.84	0.23	0.80

5 DISCUSSION

5.1 The profitability of waste heat

The share of recovered waste heat only slightly differs between the scenarios in the same city, but the share is significantly higher in Espoo than in Seinäjoki. The reason for the difference is the lower average DH production costs in Seinäjoki than in Espoo. The DH production costs are approximately 40 €/MWh in Espoo while the costs are around 26 €/MWh in Seinäjoki. In addition, the COP of HP in DC is higher in Espoo than in Seinäjoki due to the lower outside temperatures. Therefore, buying-in prices for purchasing waste heat are more competitive in Espoo than in Seinäjoki. The results show that all the scenarios have positive cooling profit, thus the revenue from sold waste heat covers the cooling costs and even generates profit. This means that using HPs is profitable in every scenario. However, the profit difference between scenarios 1 and 2 is significant due to the tax reduction in tax class II which further incentivizes DC companies to produce high-temperature waste heat. The difference between the scenarios with or without optimization is not significant as there are only a few hours that have waste heat production in scenarios without optimization when waste heat is not produced with optimization.

The profits from the waste heat selling are quite low in comparison to the HP investment cost of. Seinäjoki has an HP of 21 MW which would approximately have an investment cost of 14 M€ when assuming that the investment cost of HP is 0.67 M€/MW (Danish Energy Agency and Energinet, 2016). Therefore, the yearly profit would only cover 6% of the investment cost and the payback period of HP would be 17 years without considering a discount factor. The payback period for HP in Espoo is 7 years even with the investment cost of 67 M€ as the yearly profit covers 15% of the investment cost. The investment can be seen as profitable if the payback period is lower than the lifetime of the investment (Wahlroos et al., 2018). The lifetime of HP can be expected to be even 25 years, therefore the investment is profitable. However, this means that DC and DH companies should have an agreement for waste heat selling and buying at least for 7 years in Espoo and 17 years in Seinäjoki. The long-term commitment to low profits can be challenging for DC companies due to the volatile nature of the DC industry. DCs often only commit to a contract for 1 to 5 years and expect a high rate of return (Wahlroos et al., 2017). On the side of DH companies, the volatile nature of the DC industry is also a problem as they cannot rely on a high share of the heat demand to be supplied by the DC if the DC only agrees to short-term

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contracts. In a similar study, a discounted payback period of 12 years was calculated for a heat reuse system for a 1 MW DC that includes, in addition to the HP, all the related costs such as connection cost to the DH network and engineering costs (Oró et al., 2019). In another study, a payback period of 5 years was achieved (Wahlroos et al., 2018). This means that the payback period of Espoo aligns with the other studies, but the period in Seinäjoki is quite long. The long payback period of Seinäjoki is partly due to the use of the buy-in price of Espoo in modeling. Seinäjoki would probably have lower buying-in prices for DH supply as heat production costs are lower in Seinäjoki than in Espoo.

The results show that ERE values do not significantly differ from each other even with the different tax classes. Therefore, tax class does not have a crucial effect on the amount of waste heat reuse. ERE value in Espoo is considerably lower than required. However, in Seinäjoki the ERE value is quite close to the required ERE and the small margin can be challenging. For example, in situations where the used values differ from the modeled situation, such as having higher electricity prices, it would not be profitable for the DC company to sell the waste heat, therefore the targeted ERE may be unreachable. However, this only applies to scenarios with the optimization as in those scenarios it is calculated if the production of waste heat is profitable compared to buy-in prices. As mentioned, the required ERE value is more challenging to achieve in Seinäjoki due to the lower heat production costs than in Espoo.

5.2 Utilization of waste heat

Especially in Seinäjoki, the DH company does not often purchase the waste heat from DC even though for the DC company it would be profitable to sell it. There are even more periods when the DH company purchases only some of the waste heat, thus DC is running the HP at a partial load. Examination of the most profitable scenarios, tax class II with optimization, reveals that in Seinäjoki there are 3 345 hours in a year when it would be profitable for the DC company to sell waste heat, but the DH company does not buy. The equivalent number in Espoo is 2 366 hours. The utilization factor is lower in Seinäjoki as the production costs for waste heat are higher in Espoo than in Seinäjoki. Analysis of the waste heat purchasing in Seinäjoki shows that waste heat is not purchased in winter months when the temperature is low, and the price of electricity is high as then CHP production is competitive due to electricity selling. In addition, DC's HP runs only partly as the HOBs using cheap biomass keep the price of the heat low. During summer, EB heat production has lower costs when the spot market price is low, thus replacing waste heat purchasing in some periods. During summer in Espoo, the DH network's HPs are more competitive with low electricity prices than the waste heat purchased from the DC. However, in winter the waste heat is highly competitive as the heat is produced with expensive pellets, and units using NG have to be used for peak demand. Therefore, DC's HP runs mainly at full capacity during winter. Furthermore, in Seinäjoki the HP runs at the maximum capacity 16% of the time when the HP is running in scenario 2. In Espoo, the share is much higher as it is 57%. In Seinäjoki, waste heat is utilized often at partial load meaning that it is often the marginal production method. The reason for the lower share in Seinäjoki is the previously mentioned lower production cost in Seinäjoki. Due to the low share, purchased waste heat is more sensitive to changes in prices and production capacity.

5.3 Incentivizing waste heat utilization

The results showed that low ERE is more challenging to achieve when the heat production costs of the DH network are already low. Increasing the temperature of waste heat is costly and producing high-temperature waste heat is uncompetitive in networks that have heat units with low emissions and costs. Therefore, the share of reused waste heat stays low even though the heat is produced in a steady stream. Correspondingly, the waste heat from DC is competitive in situations when the DH network includes more emitting fuels and expensive heat production. Then, the purchased waste heat can operate as a base heat in the DC network. To increase the use of waste heat, DH companies should be incentivized to purchase more waste heat as most of the time the DH is not buying the heat or purchasing it only partially even though the DC is willing to sell it. This combination is challenging for the DC company since to cover the investment cost of HP it requires enough profit from selling the heat in the long term. To increase the waste heat usage in both cities, the buy-in prices should align with the heat production costs, thus lowering the ERE value. In Espoo, the buy-in prices should be lower during summer as now the DH network does not utilize waste heat in summer. In Seinäjoki, the waste heat is only partly utilized

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during winter, thus the buying prices should be lower then. This would also incentivize, especially in Seinäjoki, to run the HP for more hours with full capacity, thus lowering the ERE value. The results also show that in both cities DC waste heat can provide a steady waste heat stream and provide base heat for the DH network. Waste heat also replaces biomass usage in both cities, which is beneficial for maintaining the natural carbon sinks of Finnish forests.

6 CONCLUSIONS AND RECOMMENDATIONS

The tax reduction in tax class II does not directly increase the use of waste heat when the DH work already contains low-cost and emitting heat units. However, the tax reduction leads to higher profit from heat selling that may incentivize DC company to invest in HP and produce waste heat. To increase the utilization of waste heat from DC, thus the sustainability of DC, the buy-in prices of waste heat should align with the heat production cost of the DH network. All the scenarios generate quite low profit thus the payback period of HP is at least 7 years in Espoo and 17 years in Seinäjoki. The lifetime of the HP is 20 years therefore the payback period is shorter than the lifetime and makes the investment profitable. However, the change in values such as higher electricity prices could lead to unprofitable investment.

Therefore, the Finnish law requirement of ERE value for the lower tax class does not especially increase the waste heat reuse. However, the profitability of running HPs in cooling and selling the waste heat increases significantly with a lower tax class, thus incentivizing investment in HP. Without the tax reduction, the high investment cost with low profits could be a barrier to utilizing waste heat. To increase the DC waste heat usage, DC companies should have agreements to produce waste heat and DH company to purchase it. This could lead to an outcome where the DC company produces low-emission waste heat at cheaper prices to the DH network and the DC company would increase their sustainability and profit. This would require a long-term pricing agreement so that the agreement would be beneficial for both parties. Furthermore, the buy-in prices of waste heat should be competitive compared to the cost of other heat-producing units to incentivize the DC company to produce and sell the waste heat. With the real-life prices used in this study, the waste heat of the DCs is only partly utilized even though the DC would be willing to sell it.

NOMENCLATURE

F	Hourly fuel consumption	(MWh)
c^{fuel}	Fuel cost	(€/MWh)
$c^{O\&M}$	O&M cost	(€/MWh)
c^{CO2}	Carbon allowance cost	(€/MWh)
c^{T}	Tax of CHP	(€/MWh)
P	Electricity production	(MWh)
p	Spot market price	(€/MWh)
E	Electricity consumption	(MWh)
c^{D}	Costs from electricity distribution	(€/MWh)
c^{T_EL}	Electricity tax	(€/MWh)
θ	Heat production	(€/MWh)
Q	Heat demand	(MWh)
T^{0}	Average outside temperature	°C
t	Temperature	°C

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APPENDICES

Appendix A

Table A1: The energy conversion units in Seinäjoki.

Unit	Fuel / Electricity	Input (MW)	Heat output (MW)	Electricity output (MW)
HOB_pellet	Pellet	148.5	120	0
HOB_LFO_Puh	LFO	55.7	45	0
HOB_LFO_Kap	LFO	79.2	64	0
HOB_biomass_Kap	Wood chips	24.8	20	0
HOB_new_biomass_Kap	Wood chips	49.5	58	0
CHP	Peat + Wood chips	108.7 + 34.3	100	30
EB	Electricity	40.4	40	0

Table A2: The energy conversion units in Espoo.

Unit	Fuel / Electricity	Input (MW)	Heat output (MW)	Electricity output (MW)
Kivenlahti Wood pellet	Pellet	90	80	0
HOB LFO	LFO	94.4	85	0
Kivenlahti chips	Wood chips	49	52	0
HOB NG	Natural gas	495.6	446	0
Suomenoja 2	Natural gas	498	214	234
Suomenoja 6	Natural gas	132	75	45
EB	Electricity	101	100	0
Vermo HP	Electricity	4.2*	11	0
Suomenoja HP	Electricity	22.5*	70.5	0

***Vermo HP uses ambient air as a heat source and Suomenoja HP uses warm sewage water as a heat source. The energyPRO software calculates the COP of the HPs every hour.

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