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The risks of electrified district heating in Finland's cold climate

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ABSTRACT

Decarbonizing fossil fuel-dependent district heating systems is essential for achieving carbon neutrality, particularly in cold climates. In Finland, district heating operators are concentrating on electrifying these systems. However, the 2022 energy crisis in Europe has highlighted concerns about heat production costs and the security of heat supply with this approach. This study examines the economic feasibility and risks associated with electrified district heating systems and the early decommissioning of thermal power plants in the interconnected district heating systems of Helsinki, Espoo, and Vantaa. The case study is simulated and optimized to find the least-cost solution while meeting heat demand for various 2025 scenarios, assuming high energy market prices as in 2022 and more normal circumstances. Simulation results indicate that shutting down fossil fuel-based combined heat and power plants in Helsinki and Espoo would create a shortfall in base-load heat production, increasing dependency on heat imported from Vantaa. Both cities are expected to employ more cost-competitive biomass boilers to mitigate the reduction in coal-based heat production, which would decrease operational costs but also reduce revenue from electricity sales due to reduced combined heat and power capacity. Consequently, Vantaa is likely to benefit from its substantial storage and waste and biomass combined heat and power capacity, enabling efficient heat production at reduced costs. Across both scenarios, the analysis demonstrates a significant decrease in emissions and less reliance on imported fuels, highlighting the potential benefits of electrified district heating systems even amidst high electricity market prices.

1. Introduction

The 21st century has witnessed an escalating climate crisis, driven by human-induced global warming. This has catalyzed international response, exemplified by significant agreements like the Paris Agreement [1]. These global commitments highlight the need for radical changes in our economies and societies to reduce carbon emissions rapidly. The heating sector is particularly relevant in this context, especially in cold climates [2]. Buildings in the European Union (EU) are responsible for 40 % of final energy consumption and 36 % of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition [3]. District heating (DH) is considered an efficient alternative to individual heating systems combusting fossil fuels in Europe. Large centralized production units and distribution networks enable the utilization of a variety of different heat sources. DH provides a significant share of the heat delivered in buildings in various European countries, such as Denmark (around 65 %), Finland (50 %), Sweden (more than 45 %), as well as in Russia (around 40 %) and China (more than 15 %) [4]. In Finland, heating demand for buildings accounted for 27 % of final energy consumption in 2022, and DH contributed to 45 % of the market share in residential, commercial, and public buildings [2].

DH systems in Finland face challenges due to their reliance on fossil fuels such as coal, natural gas, and the domestic high-emission fuel peat [5]. Finland's energy and climate goals aim to eliminate coal in energy by 2029 and cut peat consumption by half by 2030 [6,7]. Furthermore, the European Union Emission Trading System (EU ETS) has increased the costs of fossil fuel energy production to reduce emissions [8]. Imported fossil fuel prices, especially for natural gas, have increased, influenced by market imbalances and geopolitical tensions like the Russia-Ukraine war, moving from roughly 50 €/MWh in 2019 to over 200 €/MWh in 2022 [2]. To address these challenges and achieve the set targets, a strong reduction in fossil fuel use in DH is essential. However, it is equally important that the alternatives are not only low-carbon but also cost-effective and reliable, given the rising issue of energy poverty in Europe [9]. Sector-coupling is a promising technique for increasing flexibility while also unlocking the significant emission reduction potential of the heating sector, as renewable electricity can be used to power the sector [10]. The electricity generation matrix in Finland

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Nomenclature

Abbreviations

CHP	combined heat and power
DH	District heat
EU ETS	European Union emission trading system
HP	Heat pump
HOB	Heat-only boiler

Symbols

t	Time step (hour)
C_OM	O&M cost (€/MWh)
C_fuel	fuel cost (€/MWh)
C_fuel, tax	fuel tax (€/MWh)
C_CO2	CO_2 cost (€/MWh)
$CHP_{i,t}$	heat produced by the *i* th CHP unit at each hour (MWh)
$C\_HP_{i,t}$	heat production cost of HP (€/MWh)
$C\_HOB_{i,t}$	heat production cost of HOB (€/MWh)
C_elec_t	electricity consumption cost (€/MWh)
C_elec, tax	electricity tax (€/MWh)
$C\_elec, distribution$	electricity distribution cost (€/MWh)
$C\_CHP_{i,t}$	heat production cost of CHP (€/MWh)
DA_t	day-ahead market hourly prices (€/MWh)
$E\_CHP_{i,t}$	electricity produced by a CHP unit (MWh)
$HP_{i,t}$	heat produced by the *i* th HP at each hour (MWh)
$HOB_{i,t}$	heat produced by the *i* th HOB at each hour
Q_{SH}	annual space heating demand (MWh/a)
$Q_{j,t}$	hourly heat demand of j th DH system (MWh)
Q_{DHW}	Annual domestic hot water demand (MWh/a)
$S_{ch\arg e,t}$	The amount of heat added to the TES (MWh)
$S_{disch\arg e,t}$	the amount of heat taken from the TES (MWh)
S_t	The amount of heat stored in the TES (MWh)
T_t^o	hourly outdoor temperature (°C)
$T_{j,k,t}$	The amount of heat transmitted from DHN_j to DHN_k at hour *t* (MWh)
$\eta_{HOB,i}$	Efficiency of HOB (%)
$\eta_{CHP,i}$	CHP fuel to heat efficiency (%)

makes this integration particularly attractive. Finland has successfully incorporated a wide range of renewable and low-emission energy sources into its electricity system, including wind and nuclear [11]. As a result, Finland has the third smallest specific CO_2 emission from electricity generation in the EU in 2022 [12]. This low-carbon electricity production offers a significant opportunity for the decarbonization of DH systems via sector-coupling and power-to-heat technologies. Javanshir et al. [13] investigated the electrification and decarbonization of a middle-sized Finnish DH system through coupling the electricity and heating sectors using large-scale heat pumps (HPs), electric boilers, and wind power. Under a bilateral agreement between the wind power producer and DH operator, wind power was provided at a fixed price for the consumption of electrified units within the DH system. The optimal scenario phased out carbon-intensive peat while maintaining cost-effective heat prices. Arabzadeh et al. [14] investigated deep decarbonization strategies using Helsinki as a case study. They found that achieving a carbon-neutral energy system by 2050 is possible, but it requires coupling with external energy systems, especially when integrating significant variable renewable energy sources like wind power. Jokinen et al. [15] explored the integration of electricity and DH to reduce CO_2 emissions, emphasizing the link between building and energy sectors. Using a mixed-integer linear programming model in a Finnish context, the study showed that incorporating wind power and retrofitting buildings to a lower environmental impact significantly reduced costs and emissions. Javanshir et al. [16] evaluated the role of power-to-heat technologies such as HPs and electric boilers in providing ancillary balancing services to the electrical power system, and subsequently, an alternative revenue stream for DH operators. Pesola [17] investigated the operation of hybrid heating systems that combine centralized DH and decentralized HPs. Their approach focused on sector coupling, allowing electrified heating assets to offer ancillary services to the power market. Results indicated that incorporating decentralized assets can enhance the efficiency of the primary side of a DH network, potentially reducing operating costs by 24 %. Sorknæs [18] evaluated the growing use of renewable electricity sources and the role of DH electrification in integrating these sources. Results highlighted the flexibility of DH systems due to their varied energy conversion methods and affordable storage options. The study compared energy scenarios in Austria and Denmark, showcasing differing approaches to renewable energy. The results emphasized the increasing importance of devices like HPs in integrating renewable energy.

In autumn 2021, Russia's restriction of natural gas flows to Central Europe and subsequent geopolitical events, including the conflict with Ukraine, led to sharp increases in natural gas and electricity prices, impacting the EU's energy market stability and reliance on liquefied natural gas [19]. This situation resulted in a notable increase in Finland's electricity spot prices. Fig. 1 compares the average monthly electricity spot prices in Finland from 2019 to 2022 [20]. The recent European energy crisis has raised concerns about heat production costs and the security of heat supply for end-users.

The environmental and economic benefits of power-to-heat technologies and the electrification of DH systems are well-documented in the previous studies. However, the assessment of risks and economic implications of this strategy, particularly during periods of extreme market prices like those experienced in 2022 in the EU, remains understudied. This gap highlights the need for studies to understand and mitigate potential challenges in implementing these systems under fluctuating energy market conditions. This research addresses these research gaps by assessing the feasibility and risks of a highly renewable, electrified DH network in the Helsinki metropolitan area, including the interconnected DH networks of Helsinki, Espoo, and Vantaa, delivering 11.1 TWh of heat to nearly 1.1 million end-users in 2022. The study considers scenarios for 2025, factoring in both the exceptionally high energy market prices experienced in 2022 and in a more typical situation, as in 2021. The risks and consequences of electrification and the simultaneous decommissioning of large thermal plants with a focus on heat production cost and potential income loss from electricity sales are evaluated. The results identify essential DH production technologies under varying fuel and electricity price scenarios.

The novelty of this research lies in the evaluation of the shift from traditional fossil fuel-based combined heat and power (CHP) systems towards electrification within the context of fluctuating energy market conditions and the recent energy crisis. Distinguished by its simulation of the interconnected DH systems across Helsinki, Espoo, and Vantaa, this study assesses the viability and challenges of electrified DH networks under variable energy pricing scenarios, such as the recent European energy crisis of 2022. This study provides insight on the synergistic effects and operational dynamics of a regional energy transition. The analysis contributes essential knowledge on the role of biomass and waste-to-energy plants in maintaining energy security and affordability. It also highlights the transformative potential of large-scale HPs and electric boilers in making DH systems competitive and sustainable amidst energy market volatilities. This research evaluates the transition from conventional to electrified DH systems not only from economic and environmental perspectives but also of broader sustainability and the security of supply. This study's implications extend

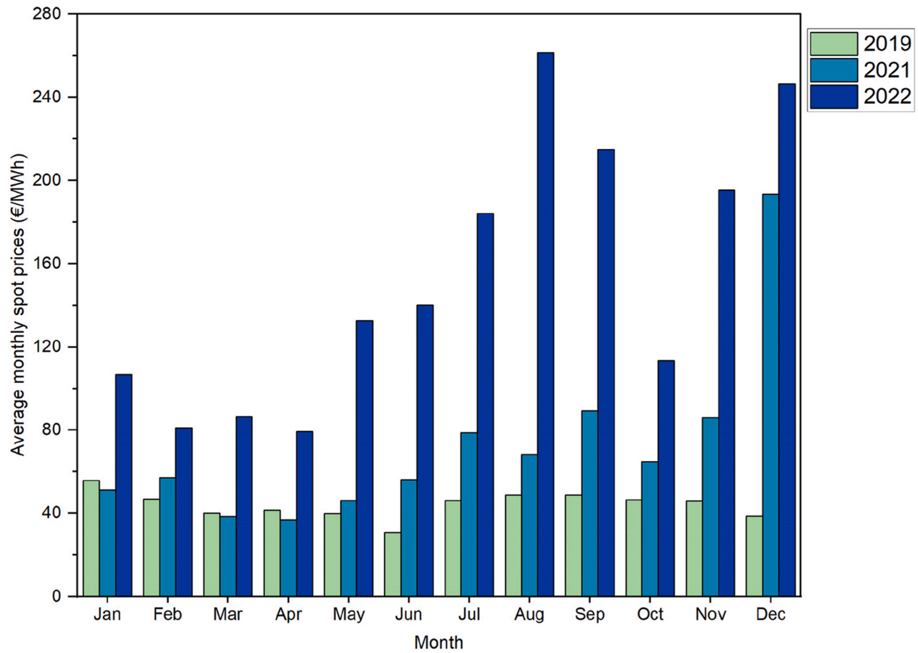

Fig. 1. The comparison of average monthly electricity spot prices in 2019, 2021, and 2022 in Finland [20].

beyond the Finnish context, offering insights for countries and regions with cold climates and significant heating demands, such as other Nordic countries, and Eastern Europe. As these regions explore strategies for decarbonizing their energy systems, the electrification of DH presents a viable pathway towards achieving carbon neutrality if there is low-carbon electricity available.

The remainder of this study is structured as follows: Section 2 describes the methodology and configuration of the case study. Sections 3 and 4 present the results and discussion, respectively, while section 5 concludes the study.

2. Material and methods

This study utilizes techno-economic analysis to examine the transition to electrified district heating systems in the Helsinki metropolitan area, serving as a case study for broader applicability in similar climatic and infrastructural contexts. This approach combines the use of the EnergyPRO software, recognized for its comprehensive modeling capabilities of diverse energy production units and optimization for the cost-effective heating solution, to model energy systems with an in-depth analysis of different energy market scenarios [21]. The choice of this software is based on its proven reliability in previous studies and its capability to handle the complexities of interconnected DH systems [22]. Input parameters, such as historical electricity and fuel prices, weather data, and CO_2 emission allowance prices, are selected based on their relevance and impact on DH system operations. Hourly heat demand is calculated based on heating degree days (Eq. (7)) for each city [23]. The DH business in Finland is a natural monopoly, meaning that there is no competitive market for heat, but heat prices are regulated. Thus, the revenue from heat sales is not included in the analysis [24]. The Helsinki metropolitan area is chosen due to its significant reliance on DH and its ambitious targets for carbon neutrality. This region's DH system, characterized by a mix of fossil-based and renewable heating sources, provides a relevant and challenging context for assessing the feasibility and implications of system-wide electrification. Different future scenarios are selected to reflect different energy market conditions to assess the resilience and economic viability of electrified DH under varying circumstances.

The objective function is expressed in Eq. (1), where $HP_{i,t}$, $HOB_{i,t}$, and $CHP_{i,t}$ represent heat produced by the i th HP, heat-only boiler (HOB), and CHP units, respectively at each hour (t) [23]. $C\_HP_{i,t}$, $C\_HOB_{i,t}$, and $C\_CHP_{i,t}$ denote the variable heat production cost of HP, HOB, and CHP units at each timestep, respectively, which were calculated using Eqs. (2)–(4) [23]. $E\_CHP_{i,t}$ is the electricity produced by a CHP unit and DA_t is the day-ahead market hourly price. Heat production cost of a HP is determined by the sum of the electricity consumption cost (C_elec_t), electricity tax (C_elec, tax), electricity distribution cost ($C\_elec, distribution$), and O&M cost (C_OM_{HP}) divided by COP. While, for a HOB the variable heat production cost consists of fuel cost (C_fuel), fuel tax (C_fuel, tax), CO_2 cost (C_CO2), and O&M cost of each HOB unit (C_OM_{HOB}) divided by the efficiency of each unit ($\eta_{HOB,i}$). $\eta_{CHP,i}$ is the fuel to heat efficiency of a CHP unit. Note that the revenue from electricity sales of a CHP unit was considered in the objective function as a negative cost. Thermal energy storage (TES) dynamics is obtained using Eq. (5), where S_t is the amount of heat stored in the TES at each hour. $S_{ch\arg e,t}$ and $S_{disch\arg e,t}$ denote the amount of charged and discharged heat to TES, respectively. The heat content in a TES should be between minimum and maximum capacities of the storage.

$$\min : \sum_{i=1}^{n}\sum_{t=1}^{8760}\left(HP_{i,t}\times C\_HP_{i,t}\right)+\left(HOB_{i,t}\times C\_HOB_{i,t}\right)+\left(CHP_{i,t}\times C\_CHP_{i,t} - E\_CHP_{i,t}\times DA_t\right) \tag{1}$$

$$C\_HP_{t,i}=\left(C\_elec_t+C\_elec,tax+C\_elec,distribution+C\_OM_{HP}\right)/COP_i \tag{2}$$

$$C\_HOB_{t,i}=\left(C\_fuel+C\_fuel,tax+C\_CO2+C\_OM_{HOB}\right)/\eta_{HOB,i} \tag{3}$$

$$C\_CHP_{t,i}=\left(C\_fuel+C\_fuel,tax+C\_CO2+C\_OM_{CHP}\right)/\eta_{CHP,i} \tag{4}$$

$$S_t=S_{t-1}+S_{ch\arg e,t}-S_{disch\arg e,t} \tag{5}$$

Heat demand balance is expressed in Eq. (6), which indicates that the heat production from different units, i.e., CHP, HP, HOB, TES charge/discharge, and heat transmission to/from other cities, should be equal to the hourly heat demand of each DH system ($Q_{j,t}$), calculated by Eq. (7). $T_{j,k,t}$ is the amount of heat transmitted from DHN_j to DHN_k at hour t.

Bidirectional heat transmission between cities should not exceed the maximum capacity at each hour. $\sum_{k\neq j} T_{k,j,t}$ sums up all the heat transmitted to DHNj from all other networks. Similarly, $\sum_{k\neq j} T_{j,k,t}$ sums up all the heat transmitted from DHNj to all other networks.

$$\sum_{j=1}^{n}\left(HP_{j,t} + CHP_{j,t} + HOB_{j,t}\right) + \sum_{k\neq j} T_{k,j,t} - \sum_{k\neq j} T_{j,k,t} + S_{disch\ arg\ e,j,t} - S_{ch\ arg\ e,j,t} = Q_{j,t} \tag{6}$$

Annual domestic hot water demand is assumed to be 30 % of total annual heat demand and is divided equally among all the hours of the year [25]. As space heating demand is linearly dependent on outdoor temperature, it is assumed that hourly space heating demand is zero if the outdoor temperature is 17 °C or higher. Assuming that space heating is switched off between May and September, heat demand consists only of the demand for domestic hot water. Eq. (7) can be used to calculate the hourly heat demand (Q_t) during the heating season, where Q_{SH} is annual space heating demand, Q_{DHW} is annual domestic hot water demand, and T_t^o is the hourly outdoor temperature [23]. Based on the temperature situation in 2019, a similar heat demand for 2025 is assumed. The DH operator in Helsinki, Helen Ltd, has published hourly heat consumption data, which was used for Helsinki's demand in 2019 [26].

$$Q_t = \frac{Q_{SH}}{\sum_t \max\left(0, 17 - T_t^o\right)} \times \max\left(0, 17 - T_t^o\right) + \frac{Q_{DHW}}{8760} \tag{7}$$

2.1. Case study

Three interconnected DH networks in the Helsinki metropolitan area, including Helsinki, Espoo, and Vantaa, are analyzed in this research. The area includes Helsinki with 630,000 inhabitants, Espoo with 300,000 inhabitants, and Vantaa with 230,000 inhabitants. The DH network in each city is owned and operated by a different company and each operator has formulated decarbonization strategies for the transition to clean DH. Heat exchanger stations facilitate bi-directional heat flow between the cities, but there is no overall joint DH optimization for the region [23]. The transmission capacities are 120 MW between Espoo and Helsinki and 130 MW between Vantaa and Helsinki. To optimize the entire system as a cohesive unit in a hypothetical case, heat transmission between cities is considered cost-free. However, when presenting city-level results, the heat transmission cost and revenue for each city are included in the calculations.

The Helsinki DH network operator, Helen, plans to end coal usage by 2025 by shutting down two coal-fired CHP units at Salmisaari and Hanasaari, replacing them with large-scale HPs, electric boilers, and TES. Table 1 summarizes all units within the Helsinki DH network from 2022 to 2025.

Fortum, the Espoo DH network operator, has also decided to discontinue the use of coal by 2025 by introducing low-carbon technologies such as heat recovery from data centers, new HPs, and biomass-fueled power plants. A 100 MW HP utilizing excess heat from the Espoo Datacenter is anticipated to be a key component of Espoo's DH decarbonization [28]. The Espoo DH network's production units are listed in Table 2.

For Vantaa, a waste-to-heat power plant provides the baseload and will be expanded under the decarbonization strategy [30] by the operator, Vantaan Energia. Coal use at the Martinlaakso plant ceased in spring 2022, and coal is a reserve fuel for winter heat supply security. The waste CHP plant in Vantaa combusts waste from the whole metropolitan region. In the simulations, the available waste was limited, but there is an increased projection for 2025 compared to 2022, which is also considered in the simulations. Vantaa is also planning the world's largest underground TES. Table 3 includes the units within the Vantaa DH network.

Table 1
Production units in the Helsinki DH network between 2022 and 2025 [5,27].

Unit	Fuel	Electrical/Thermal capacity (MW)
Existing units in 2022 network configuration		
HOB	Light fuel oil	136
HOB	Heavy fuel oil	873
HOB	Natural gas	912
HOB	Wood pellet	92
HP Katri Vala	Wastewater	155
HP Esplanadi	Wastewater	22
HP Vuosaari	Sea water	13
Vuosaari CHPs	Natural gas	630/587
Thermal storage	–	305000 m3[a]
To be decommissioned after 2022		
HOB Salmisaari	Coal	170
CHP Salmisaari	Coal	160/300
CHP Hanasaari	Coal	226/420
To be deployed after 2022		
Vuosaari HOB	Biomass	260
Salmisaari HOB	Wood pellet	150
HP Salmisaari	Ambient air	20
Electric boiler	Electricity	280

[a] Total volume of three TESs within the Helsinki DH network.

Table 2
Production units in the Espoo DH network between 2022 and 2025 [5,29].

Unit	Fuel	Electrical/Thermal capacity (MW)
Existing units in 2022 network configuration		
Suomenoja HPs	Wastewater	70
Vermo HOB	Bio-oil	35
Kivenlahti HOB	Wood pellets	90
HOB	Light fuel oil	85
HOB	Natural gas	456
TES	18000 m^3	
Suomenoja 2 CHP	Natural gas	234/214
Suomenoja 6 CHP	Natural gas	49/80
Kivenlahti HOB	Woodchips	52
To be decommissioned after 2022		
Suomenoja 1 CHP	Coal	80/160
To be deployed after 2022		
Vermo HP	Ambient air	11
Espoo Datacenter	Datacenter	100

Table 3
Production units in the Vantaa DH network between 2022 and 2025 [5,30].

Unit	Fuel	Electrical/Thermal capacity (MW)
Existing units in 2022 network configuration		
HOB	Natural gas	427
HOB	Light fuel oil	92
Martinlaakso 1 CHP	Wood chips	28/100
Jätevoimala CHP waste	Waste	76/140
Martinlaakso 2 CHP	Wood chips[a]	80/135
Martinlaakso 4 CHP	Natural gas	88/90
To be deployed after 2022		
TES	Hot water	1,000,000 m3
Martinlaakso CHP	Wood chips	20/22.5
HOB	Waste	64

[a] Coal in 2022, then changed to wood chips in 2025.

In the reference scenario, the case study is simulated with the system's current components and energy market prices of 2022. Adjustments for 2025, aligned with decarbonization pathways proposed by DH operators [23], are considered in scenario 1 and scenario 2, both using the anticipated configurations for 2025. However, while scenario 1 is modeled with the relatively moderate energy market prices (2021 electricity and fuel prices), scenario 2 incorporates the significantly elevated electricity and fuel prices from 2022. Due to the confidentiality of the fuel purchased prices by companies, the national average natural gas price published in statistics is used. Table 4 shows the main financial parameters used in the simulations. The reference scenario and scenario 2 use 2022 input data, while 2021 market prices and input are used in scenario 1. The design parameters of the HPs and other units are sourced from Refs. [13,16,31].

Table 5 illustrates the inputs and outputs used in simulating the case study DH networks.

To verify the validity of the results, the case study in 2019 is calibrated against the actual fuel consumption of each DH system for the year 2019, as gathered from the annual reports [27,30,37]. Table 6 compares the numerical results of fuel consumption for each city DH system and the actual fuel consumption in 2019.

3. Results

In this section, the results from the simulations and techno-economic analysis of the considered scenarios are presented. Figs. 2–4 illustrate the duration curves of the Helsinki DH network in different scenarios. In the reference scenario, a significant portion of Helsinki's heat demand (70 %) was produced by coal and natural gas-fired CHP plants, as shown in Fig. 2, with HPs contributing 13 % to the demand. According to the modeling results, Helsinki produced more heat than required, exporting 10 % of its output to neighboring cities. The spikes in Figs. 2–4 are justified by the profitability of CHP production during high electricity prices and the flexibility to store excess heat in TES. Although there is a lower heat demand during summertime, CHPs operate due to higher electricity prices. The higher spikes in the duration curve in the reference scenario in Fig. 2 as compared to Figs. 3 and 4 is justified by the higher CHP capacity in the entire network in 2022 than 2025.

Table 4
Financial parameters used in the simulations

Parameter		Value (€/MWh)	
		2021	2022
Fuel tax [32]			
Coal	HOB	32	32
	CHP	24	24
Natural gas	HOB	23	23
	CHP	15	15
Light fuel oil		30	30
Heavy fuel oil		27	27
Fuel cost [2]			
Coal		15[a]	42[a]
Natural gas		42[a]	126[a]
Heavy fuel oil		33[a]	50[a]
Light fuel oil		51[a]	170[a]
Bio-oil		70	70
Wood pellet		48	48
Wood chips		25[a]	25[a]
Waste		−7.95	−7.95
Electricity costs			
Electricity spot price [20]		72[b]	155[b]
distribution cost	Helsinki [23]	32.80	32.80
	Espoo [33]	31.40	31.40
Electricity tax [32]		6.9	6.9
CO_2 3price [34]		80[c]	80[c]

[a] While average monthly values of fuel prices are used in the simulation, the value in the tables refers to the yearly average value.

[b] Hourly values of spot price are ere used in the simulation, while this refers to the to the yearly average value.

[c] Yearly average values in €/ton CO_2.

Table 5
Input and output parameters used in the simulation of the case study DH networks

Inputs	Process	Outputs
Financial parameters • Fuel cost and fuel tax [2] • Emission allowance prices [34] • O&M cost of units [35] • Electricity tax and distribution costs [32] **External variables** • Hourly outdoor temperature [36] • Electricity spot prices [20] • Input/output temperatures of heat source/sink of HPs • Hourly heat demand of each city **Technical parameters** • units' heat and electricity input/output capacity • units' minimum load and efficiency • Storage capacity • minimum operation time of units • heat transmission capacity between cities • Fuel emission factors [13]	• Simulation of the case study DHN during each studied year • Objective: minimizing heat production costs based on marginal production costs and revenues of units • Markets: Day-ahead electricity market	• Optimal operation of the units in the DH system • Hourly heat production of units • Hourly fuel/electricity consumption of units • Hourly storage content • Hourly transmitted heat between cities

Figs. 3 and 4 reveal that by 2025, Helsinki would not have sufficient economic production capacity for base load, due to the shutdown of coal-fired plants. Thus, it would import more heat from Vantaa, whereas in the reference scenario base load was mostly produced with the CHP plants. Heat imports from the other cities would contribute to 22 % and 20 % of Helsinki's heat demand in scenarios 1 and 2, respectively, making the city dependent on importing heat from other cities during the entire year. In these scenarios, CHPs would cover 33 % and 21 % of the city's heat demand. This deficit can partly be covered with the wood chip and pellet-fired HOBs (biomass), which would cover 33 % and 39 % of Helsinki's heat demand in scenarios 1 and 2, while the total share of these fuels was 7 % in the reference scenario. These fuels are more economical than HPs and electric boilers during high electricity prices. Despite the large integration of new HPs and an electric boiler in 2025, there would not be any significant increase in the production of electrified units in 2025. They would contribute to 16 % and 23 % of the city's heat demand in scenarios 1 and 2.

In the Espoo DH network, the shutdown of coal-fired CHP operations in 2025 would lead to a decrease in total CHP production from 45 % of the city's heat demand in the reference scenario to 33 % and 20 % in scenarios 1 and 2, both of which rely on natural gas-based CHP units. HPs and biomass-fired HOBs serve as the base-load production, whereas natural gas-fired HOBs are reserved for peak load demands. In scenarios 1 and 2, HPs would account for 14 % and 15 % of the Espoo DH network's heat demand, respectively, a slight variation from the 14 % observed in the reference scenario. Remarkably, the data center in scenarios 1 and 2 can almost entirely compensate for the deficit left by the discontinued coal-fired CHP, producing 32 % and 29 % of the city's heat demand.

Table 6
Comparison of fuel consumption from simulations of model calibration for the year 2019 versus the real values from statistics in 2019

Fuel consumption (GWh)	Helsinki DHN		Espoo DHN		Vantaa DHN	
	Real situation	Simulation	Real situation	Simulation	Real situation	Simulation
Coal	6500	5500	2042	1800	60,	850
Natural Gas	5000	6800	729	1300	245	350
Oil	106	0	4.6	1.0	1.5	0.9
Bio	226	350	244	150	533	680
Waste	0	0	0	0	1120	1137
Electricity	133.6	95	180	55	0	0
Total	11965	12745	3200	3306	2500	2247

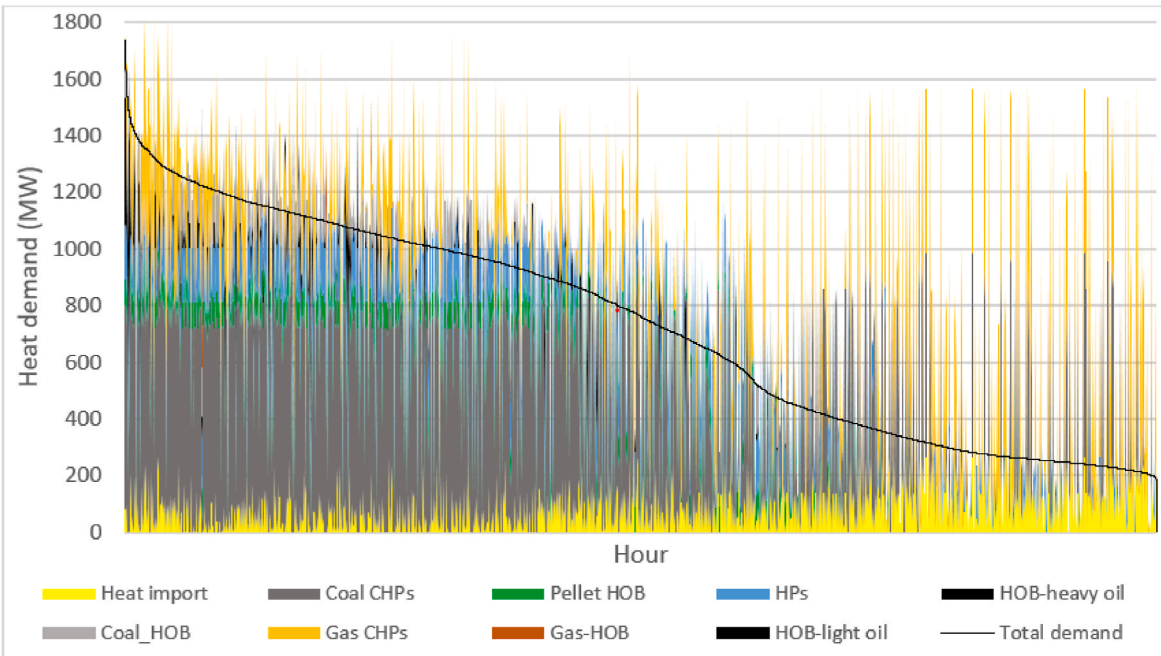

Fig. 2. Duration curve of the Helsinki DH network in the refence scenario in 2022.

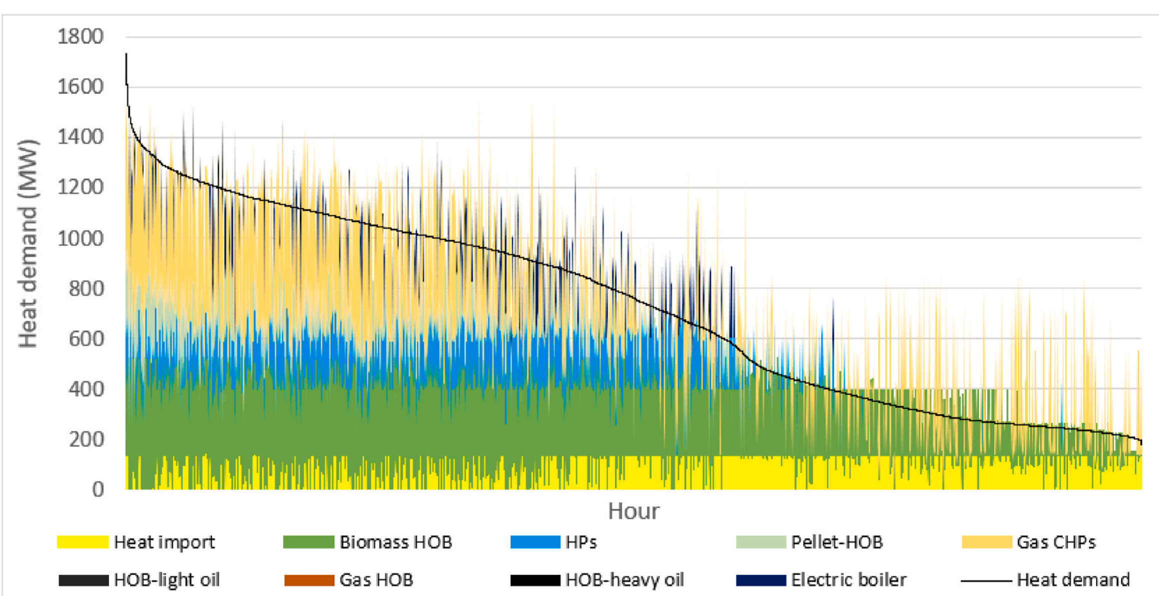

Fig. 3. Duration curve of the Helsinki DH network in scenario1 (2025 with 2021 prices).

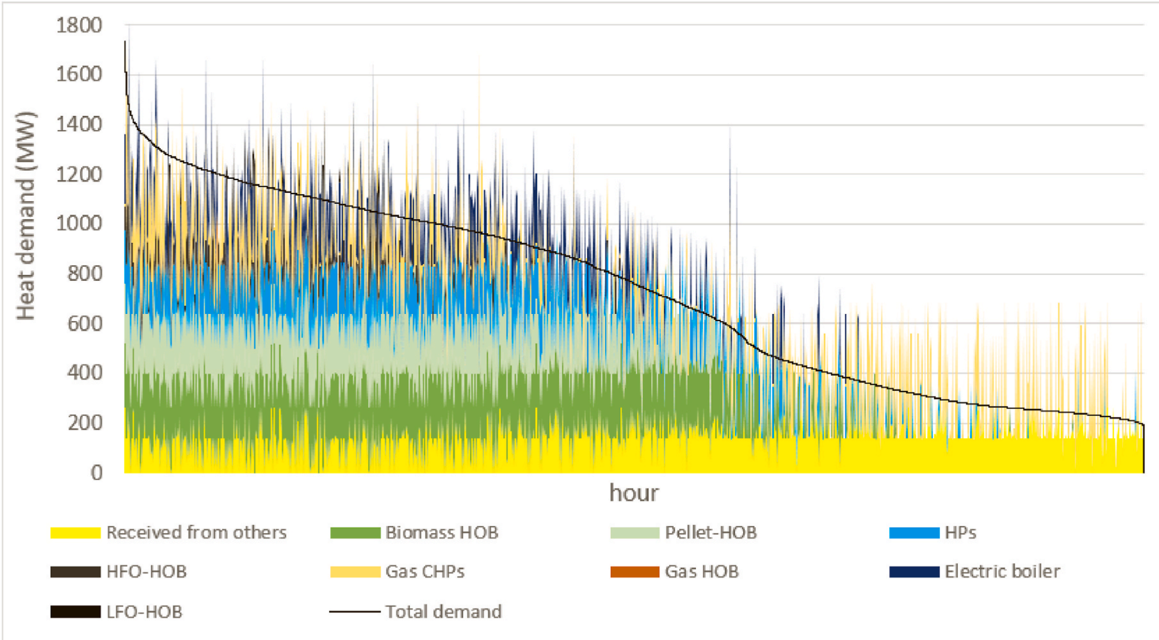

Fig. 4. Duration curve of the Helsinki DH network in scenario 2 (2025 with 2022 prices).

In the Vantaa DH network, the integration of a large-scale TES system in 2025 will allow CHP units to be more in operation during periods of elevated electricity prices compared to the 2022 setup (which lacked the TES). This would increase revenue generation and consequently reduce the heat production cost in 2025. Considering all the CHP units in Vantaa, scenarios 1 and 2 would produce 146 % and 142 % of Vantaa's heat demand, respectively, through these CHP units. In contrast, the reference scenario accounted for only 109 %. This indicates a potential for a significant portion of Vantaa's CHP production to be transmitted to Helsinki. The coal-powered CHP plant, producing 32 % of the city's heat demand in the reference scenario, is slated for discontinuation in 2025. The full-load hours of the natural gas-powered CHP plant in Vantaa increased from 1567 h in the reference scenario to 2892 and 2082 h in scenarios 1 and 2. Furthermore, in Vantaa, the integration of the new wood-fired CHP plant is projected to increase the consumption of biomass fuels in Vantaa from 1101 GWh annually to 2452 GWh and 2749 GWh in scenarios 1 and 2. The new waste incineration unit combusting commercial waste and increased fuel limit in 2025 will help

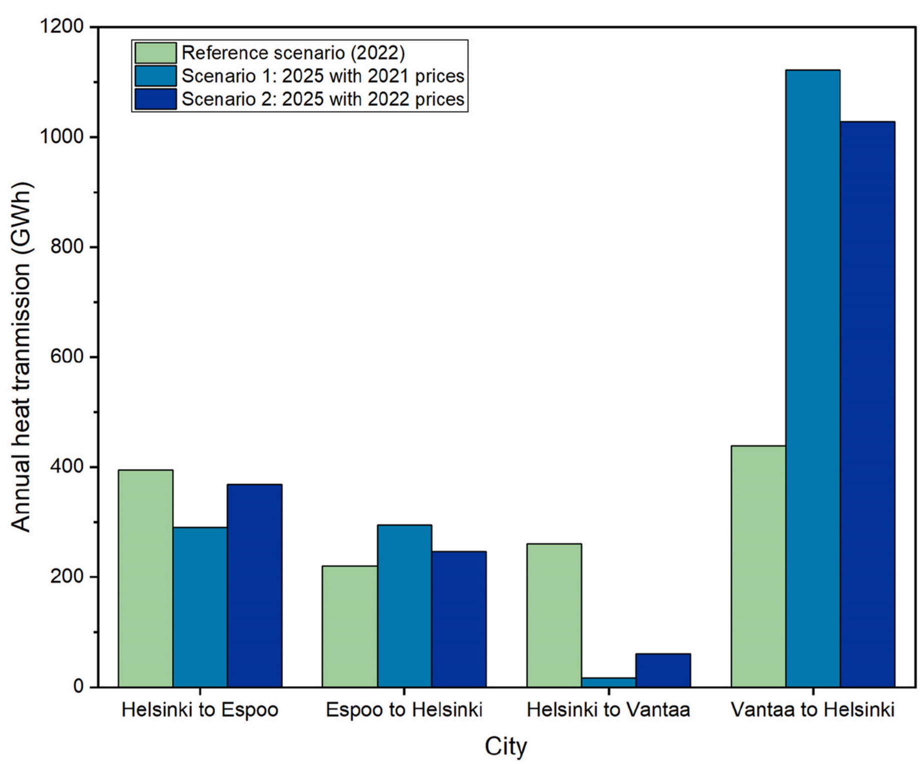

Fig. 5. Annual heat transmission between cities in different scenarios.

Vantaa produce economic and sustainable heat in the future as well.

Fig. 5 depicts the annual amount of heat transmission between cities in the simulations. While the amount of heat exchanged between Helsinki and Espoo would not change significantly, the amount of heat transmission between Vantaa and Helsinki would grow substantially. While in 2022 Helsinki covered 7 % of its annual heat demand with heat transmission from Vantaa, this number would increase to 18 % (1121 GWh) and 16 % (1027 GWh) in scenarios 1 and 2, respectively, making Vantaa the largest heat exporter. The reason for this increase is that Vantaa can produce cheap heat with its biomass-fueled CHP plants and the large regional waste incineration CHP plant in 2025 scenarios.

Table 7 presents total fuel consumption within the DH network for the case study, categorizing the results by fuel type, encompassing both imported fuels including natural gas, oil, and coal, and domestic fuels including biomass, waste, and electricity. In this analysis, electricity is classified as a domestic fuel, considering the large-scale integration of wind and nuclear power in Finland. A marked rise in natural gas consumption is observed in scenario 1 relative to other scenarios, which can be attributed to the more affordable gas prices, as mentioned in Table 4. The decision to decommission coal-fired CHP plants in Helsinki by 2025 would lead to a substantial increase in the consumption of biomass-based fuels in scenarios 1 and 2. Interestingly, even with the notably elevated electricity prices in scenario 2 relative to scenario 1, the former sees a larger electricity consumption. This results from the considerably higher prices of imported fuels in scenario 2. Notably, the system can reduce its reliance on imported fuels by augmenting the use of domestic sources, such as biomass and electricity-driven production. Abandoning coal in Helsinki and Espoo would not increase the consumption of natural gas in heat production if the natural gas price remains high.

Fig. 6 is divided into three parts: Fig. 6 (a) shows the annual variable operation cost, i.e., the sum of operational costs including fuel cost and tax, O&M cost, taxes, electricity consumption cost, and CO_2 cost of all units within the system as presented in Eqs. (2)–(4). Fig. 6(b) shows the annual revenues from selling electricity produced by CHP units in the day-ahead electricity market. Fig. 6(c) shows the annual variable heat production cost of each system in different scenarios.

Fig. 6(a) shows a notable decline in the annual variable operation cost for the Helsinki DH system in both scenarios 1 and 2. This reduction is primarily attributed to the increased utilization of cost-effective biomass fuels in scenarios 1 and 2. Other cities also witness a modest dip in operational costs, resulting from a shift towards biomass consumption as opposed to coal. Conversely, shutting down CHP capacities in both Espoo and Helsinki DH networks in 2025 leads to diminished revenue from electricity sales in scenarios 1 and 2, as shown in Fig. 6(b). Consequently, this translates to increased heat production costs in these cities for scenarios 1 and 2 compared to the reference scenario. As for Vantaa, the integration of an expansive TES coupled with economical CHP production from wood-based and waste resources in 2025 ensures that the revenue from electricity sales surpasses operational costs across all scenarios, resulting in negative variable heat production cost. Especially during high electricity prices in 2022, Vantaa benefits from CHP production from domestic fuels and selling the produced electricity with high market prices.

Table 7
Comparison of fuel consumption (GWh) by fuel type in different scenarios

Fuel type	Reference (2022)	Scenario 1 (2025 with 2021 prices)	Scenario 2 (2025 with 2022 prices)
Coal	9004	0	0
Oil	251	54	290
Natural gas (total)	4073	7157	4713
Natural gas (CHP)	4022	7153	4700
Natural gas (HOB)	46	5	12
Biomass	2495	4866	5879
Waste	1137	1865	1783
Electricity	490	707	1072
Share of imported fuels in total fuel consumption (%)	76	49	36

In scenario 1, the annual operation costs of each DH network are lower than in scenario 2. Due to the higher electricity prices in scenario 2, the annual revenue of electricity sales is higher, but the higher electricity price did not increase the operation of the CHP plants. Even though the revenues of electricity sales are higher in scenario 2, the lower fuel costs in scenario 1 would increase electricity production. In scenario 1, 4634 GWh of electricity was produced, 30 % more than in scenario 2. Especially the operation of the natural gas-fired CHP plants differs between the scenarios 1 and 2. In total, the natural gas-fired CHPs produce 51 % more electricity in scenario 1 than in scenario 2. Regardless of the higher electricity price of scenario 2, the average utilization factor of the HPs in all the three cities is higher.

Fig. 7 illustrates the annual CO_2 emissions from individual DH networks as well as the cumulative emissions from the entire network. By reducing reliance on imported fossil fuels in scenarios 1 and 2, a marked decline in total emissions (62 % and 72 % in scenarios 1 and 2) can be observed. The largest drop in emissions would be in Helsinki, where the emissions would decrease 70 % and 78 % in scenarios 1 and 2. In the reference scenario, coal-fueled units accounted for 80 % of Helsinki's annual emissions. In the Espoo reference scenario, the coal-fired CHP plant produced 70 % of Espoo's annual emissions. In scenarios 1 and 2, Espoo's emissions would decrease by 46 % and 66 %. The smallest, but still significant emission drop is seen in Vantaa, where the total emissions decrease by 41 % and 48 % compared to the reference scenario. Converting the coal-fired CHP plant to combust biomass has a great contribution to the decrease there as well. One reason for lesser emission reductions in Vantaa is the increased waste-fuel availability in scenarios 1 and 2. The emissions of the waste incineration plant would increase 64 % and 57 % in scenarios 1 and 2 compared to the reference scenario because of the higher waste CHP capacity in scenarios 1 and 2 than the reference scenario.

4. Discussion

The rapid transformation to electricity-based DH technologies and the early closure of fossil-fueled CHP plants present both opportunities and risks, as highlighted by the scenarios in this study. This section discusses different implications such as the economic and environmental impacts, the security of supply, the long-term sustainability of the electrification approach, and the limitations of this study, while proposing directions for future research. Table 8 concisely summarizes the different aspects of this transformation.

4.1. Economic and environmental impacts

From an economic perspective, shutting down 460 MW of fossil CHP electricity generation by 2025 will result in a significant loss of electricity generation and sales, and a deficit of cheap production, especially in the Helsinki DH network in the case of high electricity prices. Helsinki would lose approximately €337 million in revenue generated in the reference scenario from the electricity sales of the Salmisaari and Hanasaari coal-fired CHPs, which would be shut down by 2025. Only with the high spot market prices experienced in 2022 could the revenues from selling electricity remain roughly at the same level. However, it should be noted that in reality, most electricity is sold at fixed prices, as companies cannot take the risk of only spot price exposure. If electricity and fuel prices remain at moderate levels (scenario 1), the total average heat production costs will increase notably from the reference situation, increasing the risk of energy poverty. Due to the high electricity price, the CHP plants enable Vantaa, the only city investing in new CHP capacity, to produce heat with negative variable costs in all scenarios. This implies that the investments to CHP capacity will be beneficial if the

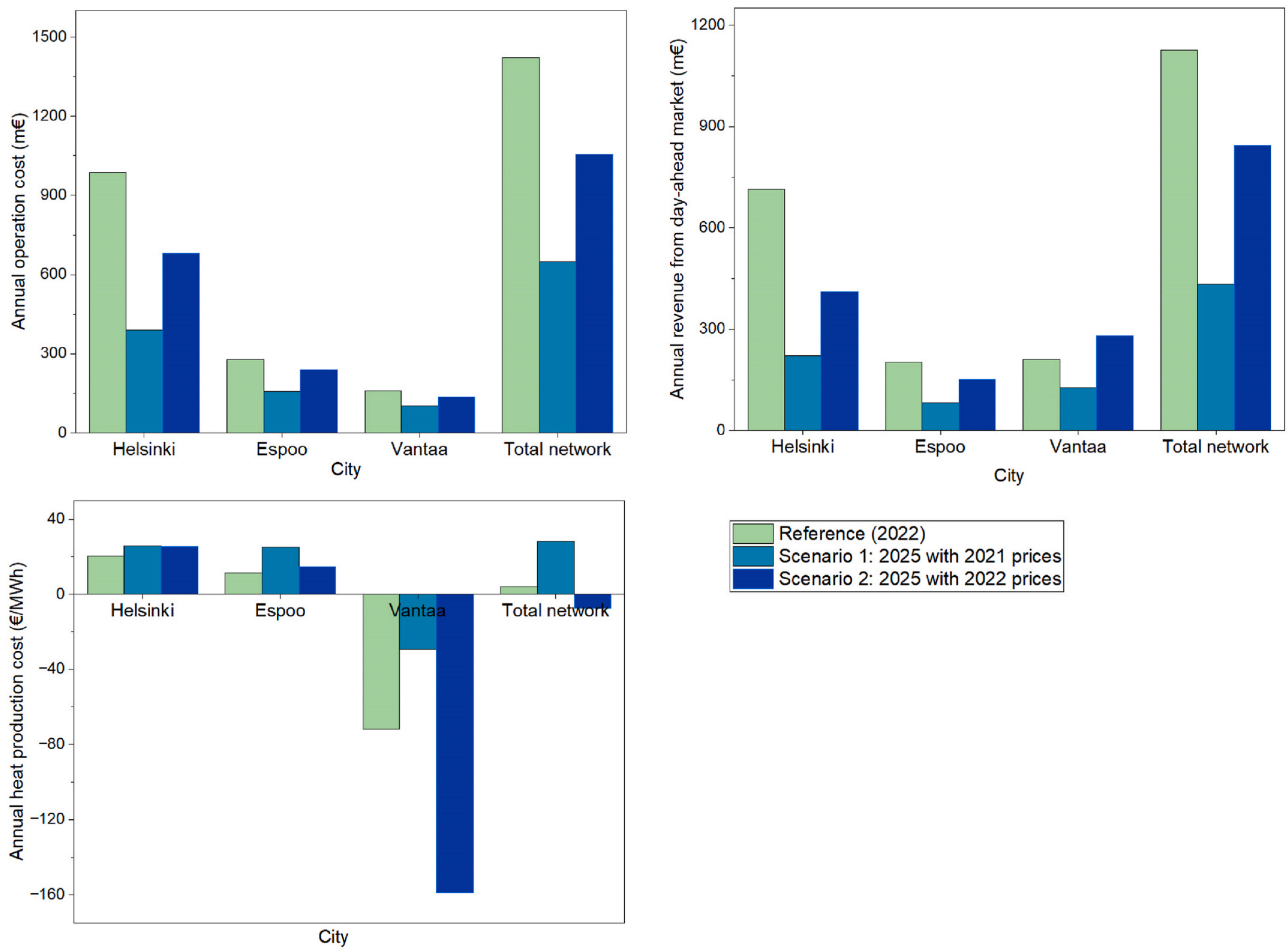

Fig. 6. (a). Annual operation cost of each city DH system and the entire network (b). Annual revenue gained from selling CHPs' produced electricity in the day-ahead market of each city DH system and the entire network (c). Average heat production cost of each city DH system and the entire network.

electricity price remains at a high level. At the same time, the large HP capacities in Helsinki and Espoo would be adversely affected from the high electricity market prices. It should be noted that in this study, only the variable operation costs were considered, without taking into account any capital or other fixed costs. Large investments always increase the customer prices of heat.

If energy prices remain at the 2022 level, closing down the coal-fired CHP plants will not result in a significant increase in natural gas consumption. However, in scenario 1, with lower energy prices, the use of natural gas, especially in CHP plants, increased by 78 % compared to the reference situation, reaching 7158 GWh. According to the official report of Helen [27], the annual natural gas consumption in the Helsinki DH network in 2021 was 2280 GWh (30 % of total fuel consumption). As official data of fuel consumption for 2022 has not yet been published by the operators, natural gas consumption is compared to 2021 statistics. Discontinuing the use of coal in heat production and the higher fuel prices would significantly increase the use of domestic fuels. In Helsinki and Espoo, HPs, electric boilers, and waste heat have a significant contribution to heat production in all scenarios. In Espoo, the share of data center waste heat in Espoo's heat production is nearly a third in scenarios 1 and 2. It is assumed that the DH operator pays an outdoor temperature-dependent buy-in price for primed waste heat, and thus electricity price does not have an impact on waste heat feasibility from the DH operator's perspective. However, the data center owner must use HPs for priming the low-temperature waste heat, and therefore high electricity prices may influence the data center owner's willingness to sell waste heat. The waste heat utilization must be beneficial for both parties to be viable.

In general, higher energy prices in scenario 2 would increase the use of power-to-heat technologies, when compared to scenario 1 price assumption of 2021. The electricity consumption in heat production increases from the reference scenario by 44 % in scenario 1 and 118 % in scenario 2. The electricity consumption increase is mainly caused by the new electric boiler in Helsinki, which contributes 3 % and 8 % of the city's heat demand in scenarios 1 and 2, respectively. Even though the electricity price is higher in scenario 2, higher fuel prices reduce the use of natural gas and thus electricity was used more for heat production in scenario 2. Due to the relatively low investment costs of electric boilers, the technology seems to be suitable against volatile energy costs in heat production. In Espoo, there are no changes in biofuel capacities between the scenarios, and the share of biofuels in heat production would decrease slightly from the reference scenario. Also, energy prices have an impact on the use of biofuels in Espoo. In scenario 1, where the prices are lower than in the reference scenario, the share drops to 21 % from one third in the reference scenario, whereas in scenario 2 the share of biofuels is still at 30 %. In Vantaa, a new wood chip-fired CHP plant will be commissioned, which would increase the biomass consumption.

In the reference scenario, coal-related emissions were a significant 77 % of the system's total emissions. Phasing out coal-fired plants and incorporating more electrified units, coupled with the elevated prices of

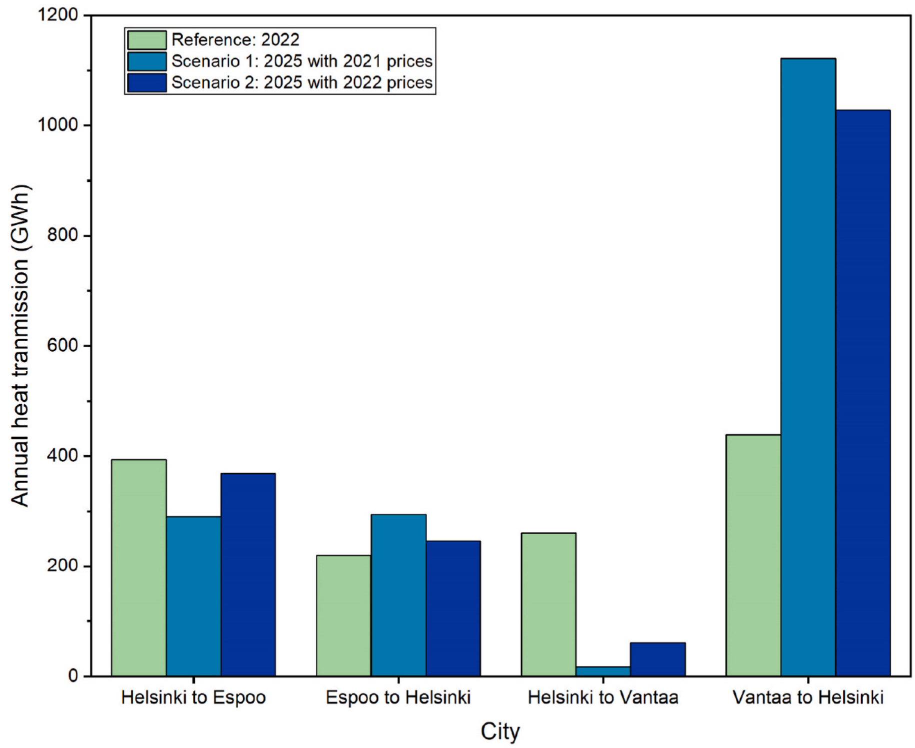

Fig. 7. Annual CO_2 emissions from each city DH network and the entire network.

Table 8
SWOT analysis of the scenarios

Strengths	Weaknesses
• More efficient system with less primary energy use in both scenarios • Significant reduction of CO_2 emissions in both scenarios	• Less income from CHP electricity generation in both scenarios • Higher customer prices of heat, especially in scenario 1 • Higher biomass consumption and risk of reduced carbon sinks in both scenarios • Strongly growing reliance on imported natural gas in scenario 1 • Environmental impacts of large-scale waste incineration and continued large, combusted waste volumes
Opportunities	**Threats**
• New technologies, e.g., large air-to water HP's and world's largest underground heat storage ensure reliable and cost-efficient operation in both scenarios	• More stringent rules of biomass use from e.g., the EU in both scenarios • Delays in the planned large data center in both scenarios • Less waste to energy material in future in both scenarios • No common agreement on heat transfer between the individual cities in both scenarios

imported fuels, would significantly reduce CO_2 emissions. However, this decline in emissions is realized through a marked surge in biomass consumption, from 2.5 TWh in the reference scenario to 4.9 and 5.9 TWh in scenarios 1 and 2, respectively. Subsection 4.2 addresses concerns about the long-term sustainability of increased biomass consumption in Finland. The integration of waste-to-energy technology within DH systems is a common approach to waste management, addressing both environmental impacts and the challenges of waste volumes. The DH operator in this study (Vantaan Energia) focuses on extending material lifecycles and optimizing energy flows, exemplified by expanding waste treatment to include non-recyclable fractions and developing new hazardous waste treatment facilities [38]. This strategic emphasis mitigates potential negative impacts through the efficient destruction of hazardous materials and significant waste volume reduction and enhances energy security. The new plants operate with advanced air pollution control systems. However, it can be argued that the growing dependence on waste combustion is against the EU long-term goals of fully circular economy and prevention of waste [39]. Thus, also a long-term strategy with significantly reduced combustible waste amounts should be developed.

4.2. Long-term sustainability and security of heat supply

The escalating reliance on biomass in Finland has raised significant concerns, notably due to the substantial reduction in the size of national forest carbon sinks [40]. Natural carbon sinks are planned to be an essential part of achieving Finland's ambitious goal of net-zero emissions in the forthcoming decade [6]. The carbon sink goal for the year is −21 million tons CO_2/year. In 2018–2021, the amount of carbon sinks in Finnish forests has collapsed from the level of about −20 million tons CO_2/year up to a net carbon source of 0.9 Mton CO_2/year [2]. This shift towards increased biomass consumption may introduce energy security challenges, as the sustainability and availability of biomass resources come under scrutiny. It underscores the necessity for a balanced approach, where environmental goals align with energy reliability and security considerations.

The integration of waste heat from data centers into DH systems introduces some risks due to the operational differences between the rapidly evolving data center industry and the long-term stability required by DH infrastructures. Data centers, subject to swift technological shifts and market demands, have shorter planning horizons compared to the decades-long lifecycle (typically 40–50 years) of DH systems. This fundamental difference requires contractual agreements and strategic risk management similar to portfolio diversification to mitigate dependencies and ensure a reliable heat supply [41]. Regarding the long-term sustainability of the electrification approach, the transition to electrified DH in Finland leverages the country's robust electricity sector, characterized by reliable low-carbon sources such as nuclear power and increasing wind power generation.

4.3. Implications for other regions, limitations, and future studies

The findings from this study on the electrification of DH systems in the Helsinki metropolitan area have implications beyond the Finnish borders, offering insights for regions globally that face similar climatic conditions and heating demands. The transition to electrified DH systems, as explored in this research, exemplifies a sustainable pathway that aligns with the goals of carbon neutrality, energy security, and the reduction of dependency on imported fossil fuels. This approach is particularly relevant for countries in Northern Europe and Eastern Europe, where the climatic conditions and energy requirements mirror those of the case study in this work. However, this requires a low-carbon electricity production, which is not yet the case in many Eastern European countries. The lessons learned from Helsinki's approach to DH system electrification—such as the integration of power-to-heat technologies like large-scale HPs and the importance of addressing electricity pricing volatility—offer a blueprint for other regions.

There are some limitations that bear implications for the findings of this work. Simplifying heat network dynamics in simulations might not fully capture real-world complexities, such as potential bottlenecks and the distribution of heating units, despite considering the network heat loss in the simulations. This highlights the need for more detailed network analyses in subsequent research. Electricity price volatility and the use of a deterministic model based on historical prices add uncertainty, especially given the difficulty in predicting future market trends. Although the study attempts to accommodate electricity price fluctuations by examining different years in different scenarios, accurately forecasting such prices, particularly in Finland's volatile market, remains a challenge. Additionally, our revenue calculations from electricity sales do not consider electricity producers' hedging practices, which could significantly affect the study's financial assessments. The impact of large-scale electrification on electricity market dynamics, especially on demand, needs further investigation. The scenario approach to fuel costs and CO_2 emission allowances does not fully address all uncertainties, particularly for long-term forecasts. Furthermore, the study models the three cities as a unified system without accounting for inter-company competition or heat transmission fees, potentially leading to an overestimate of heat transmission volumes.

5. Conclusions

This study investigates the economic viability and the potential risks associated with transitioning to electrified district heating (DH) in the Helsinki metropolitan area, Finland. The study examines the effects of electrifying DH systems and phasing out thermal power capacities by 2025 on heat production costs, electricity sales revenue, and overall energy sustainability. Two scenarios for 2025 are considered: one with more regular electricity prices as observed in 2021 (scenario 1) and the other with high prices akin to 2022 (Scenario 2), providing insight into how such transitions would perform under varying market conditions. By examining the implications of electrifying DH systems and phasing out thermal power capacities by 2025, this work provides an understanding of how such transitions impact heat production costs, electricity sales revenue, and overall energy sustainability. The move away from coal-fired combined heat and power (CHP) plants would create a deficit in affordable baseload heat production, prompting Helsinki to become a net importer of heat from neighboring cities. Heat imports would account for up to 22 % and 20 % of the city's annual heat demand, a significant increase from the 7 % observed in the reference scenario. Meanwhile, electrified heating solutions, such as heat pumps and electric boilers, are projected to cover a larger portion of Helsinki's heat demand (16 % and 23 % of annual heat demand in scenarios 1 and 2), indicating a shift toward more sustainable heat production methods. In scenarios 1 and 2, electrified heating in the entire system would increase by 14 % (174 GWh) and 49 % (593 GWh), respectively, compared to the reference situation, demonstrating that electrified DH is competitive, even under extreme conditions.

Significantly, the shortfall in fossil fuel-based CHP production would be partially compensated for by an increase in biomass consumption and the integration of large-scale waste incineration plants. Biomass consumption in Vantaa is expected to rise markedly from 1101 GWh in the reference scenario to 2452 GWh and 2749 GWh in scenarios 1 and 2, respectively. Likewise in Helsinki, the share of biomass in total fuel consumption would increase from 7 % to 33 % and 39 % in scenarios 1 and 2. The integration of a large-scale thermal energy storage in Vantaa would allow CHPs to produce more heat and store it for later use or export it to the other cities. While in the reference scenario CHP production made up 109 % of Vantaa's heat demand, this number would increase to 146 % and 147 % in scenarios 1 and 2 due to exports to Helsinki and Espoo. Hence, higher revenue from electricity sales would decrease heat production cost in Vantaa, while heat production cost in Espoo and Helsinki would increase amid lower CHP production. The forthcoming large-scale data center in Espoo is anticipated to play a significant role in heat production, fulfilling up to 32 % and 29 % of Espoo's annual heat demand.

If the natural gas price remains very high (as in 2022), abandoning coal would not increase the consumption of natural gas in heat production. In this case, biomass use would increase by 135 % in scenario 2 compared to the reference situation, with clear risks of unsustainable supply and rising prices. In the case of natural gas prices remaining at a moderate level (as in 2021), natural gas use would increase by 76 % and biomass use by 95 % in scenario 1 compared to the reference scenario. As electrified DH technologies were found to be cost-effective even with very high energy prices, electrification may thus contain far less risks than biomass in this case study. From an environmental perspective, total CO_2 emissions would decrease by a considerable 62 % and 72 % in scenarios 1 and 2. The share of imported fuels also would decrease from 76 % in the reference scenario to 48 % and 36 % in scenarios 1 and 2, indicating higher energy security and lower dependency on fuel imports under this approach.

The practical implications of this work for industry include informing the strategic planning and investment decisions of DH system operators as they navigate the transition to low-carbon heating solutions. For policymakers, this analysis provides evidence-based insights to guide the development of regulations and standards that support the decarbonization of heating systems, encourage the adoption of renewable energy sources, and facilitate sector coupling. Furthermore, this research contributes to the academic discourse on sustainable energy systems, offering the assessment of the techno-economic feasibility and environmental impacts of DH system electrification. By examining the case of the Helsinki metropolitan area, the potential of large-scale heat pumps, electric boilers, and thermal energy storage to aid in transforming urban heating systems is demonstrated. This approach not only addresses the immediate challenges posed by high energy costs and security of supply but also positions DH as a cornerstone of sustainable urban development. The lessons learned and methodologies applied here have widespread applicability, offering a scheme for similar transitions in other cold-climate regions with low-carbon electricity production that are committed to achieving a sustainable energy future. The findings of this study suggest that electrified DH systems can effectively reduce dependency on imported fossil fuels, lower carbon emissions, and enhance energy security, aligning with environmental, social, and governance (ESG) criteria, and contributing to several United Nations' sustainable development goals (SDG) [42].

It is important to note that acknowledging the limitations mentioned in the discussion section is crucial for understanding the broader applicability of the findings of this study and for guiding future research efforts. The challenges of modeling complex energy systems underscore the importance of continued innovation in simulation methodologies and the integration of more granular datasets. Future studies could enhance the robustness of our findings by incorporating dynamic network modeling, advanced forecasting methods for electricity pricing, and more nuanced considerations of market behaviors. Additionally, exploring the implications of different policy and consumer behavior scenarios could provide deeper insights into the feasibility and impacts of transitioning to electrified district heating systems. In conclusion, while this study offers valuable insights into the potential of electrified DH systems, it also highlights the need for cautious interpretation of simulation results and for further research to address the identified limitations.

CRediT authorship contribution statement

Nima Javanshir: Methodology, Software, Data curation, Writing – original draft, Writing – review & editing, Validation, Visualization. **Sanna Syri:** Methodology, Writing – original draft, Writing – review & editing. **Pauli Hiltunen:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sanna Syri reports financial support was provided by European Union. Sanna Syri reports financial support was provided by Academy of Finland. Sanna Syri reports financial support was provided by FINEST TWINS project.

Data availability

Data will be made available on request.

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