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Decarbonization strategies of Helsinki metropolitan area district heat companies

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ABSTRACT

District heating is of great significance for the Nordic countries due to the high heat demand. The Finnish government has set a national target of carbon neutrality in 2035. This implies a huge challenge and rapid system change. The Helsinki metropolitan area consists of Helsinki, Espoo and Vantaa, and in each city a different district heating company operates, and the technologies planned for decarbonization are different. This research aims to analyze these strategies with respect to carbon dioxide emissions and production costs, assuming different future European Union emissions carbon trading prices. The software EnergyPRO is used to provide least-cost optimal district heating operation solutions. From 2010 to 2030, carbon dioxide emissions from the Helsinki metropolitan area district heating will decrease by about 4.2 million tonnes. However, the average heat production costs are expected to increase considerably by almost threefold; while heat trade between the cities will reinforce the feasibility and decreases the system operation costs and total emissions. Helsinki will import heat, especially from Vantaa waste incineration plants. Higher carbon dioxide prices would reduce the total emissions, increase the total district heating operation costs, and lower the heat imported to Helsinki. As all the cities plan biomass as an alternative to fossil fuels, a higher biomass price would limit its consumption but increase natural gas usage the carbon dioxide emissions. In the future, combined heat and power plants will be used significantly less, leading to lost income on electricity sales and profoundly changing the business of the district heating companies.

1. Introduction

The Paris Agreement announced the aim to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels [1], addressing the importance of mitigating climate change. Carbon dioxide (CO_2) as one of the greenhouse gas (GHG) emissions, is the primary cause of global warming and associated environmental issues. Recently, the International Energy Agency has laid out the pathways to achieve net-zero emissions by 2050 [2]. The European Union (EU) set a target for the year 2030 to reduce GHG emissions by 40% from 1990 the level [3]. The Finnish government has also declared a goal to achieve carbon-neutrality by 2035 [4]. In addition, in 2019, a law on banning the use of coal for energy purposes from May 2029 onwards was implemented [5].

Heating plays a significant role in decarbonization as over a half of the total final energy is consumed in this sector globally, while over 80% of heat is produced by fossil-fuel powered equipment and traditional electric heating technologies [6], making it an important sector to decarbonize. A clean and efficient district heating (DH) system is a decisive pathway to mitigate climate change and air pollution, and is a mature solution for heating including domestic hot water and space heating [7]. District heating connects end-users and heat generators through a pipe network with high efficiency, which is a flexible, economical system and can provide reliable heating and cooling services relying on diversified energy resources and various energy conversion units [8].

The Nordic countries have a high heating demand due to the climate conditions, making DH systems essential [9]. In Finland, DH production amounted to 38.1 TWh in 2019, and 35% of this was generated from fossil fuels [10]. DH in Finland accounted for 10% of total emissions and 12% of the total energy consumption [11]. At the same time, 44% of

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Abbreviations:

DH	District heating
CHP	Combined heat and power
HOB	Heat-only boiler
OCGT	Open-cycle gas turbine
ST	Steam turbine
CCGT	Combine cycle gas turbine
HP	Heat pump
EU-ETS	European Emission Trading System
DC	Data center
GHG	Greenhouse gas
CO_2	Carbon dioxide
COP	Coefficient of performance
NG	Natural gas
HFO	Heavy fuel oil
LFO	Light fuel oil

GHG emissions in Helsinki city are from the heating sector [12]. The DH systems of Helsinki metropolitan area are quite dependent on fossil fuels: in 2015, 89% of DH supply was based on coal and natural gas [45].

The Helsinki metropolitan area consists of three cities: Helsinki, Espoo and Vantaa, while the DH system in each city is owned and operated by different companies: two city-owned companies Helen Ltd in Helsinki city and Vantaan Energia in Vantaa, and internationally stock-listed company Fortum in Espoo. Each city and DH company in the Helsinki metropolitan area has formulated decarbonization strategies for the transition to clean DH. Heat trading is possible between the cities, but this region does not have an overall joint DH optimization.

The purpose of this research is to examine the district heating companies' decarbonization strategies concerning the DH system in the Helsinki metropolitan area and explore its impact on climate change (i.e. CO_2 emissions) and operational performance. This research evaluates the DH systems using the energyPRO software program, focusing on low-carbon technology implementation and decommissioning of coal-fired power plants. The analysis is done from 2010 to 2030 in five-year intervals.

This paper is developed in five sections. Following this introduction, Section 2 provides a literature review about the existing DH system decarbonization and elucidates the paper's contribution. Section 3 describes the methods and data used to simulate the DH decarbonization strategies. The results of simulation from 2010 to 2030 are presented in Section 4, together with different scenarios such as carbon prices (pricing of the emissions), the choice of energy sources, and trade of heat between cities. Finally, in Section 5, concluding remarks are provided.

2. Literature review

The DH system size and placement are heavily influenced by the national energy policy [8]. From the Kyoto Protocol in 1997, only 15 involved European countries had their own target on to reduce the emission [13], while developing countries were included in the Copenhagen process in 2009 [14]. National policies have stressed ever more importance on mitigating climate change and reducing GHG emissions. At the EU level, the European Emission Trading System (EU-ETS) established a ceiling on the total CO_2 emissions in 2005, making it the world's first emissions trading system [15]. CO_2 prices rising have a considerable impact on the DH system production costs [16]. They also influence the usages of waste heat streams, such as those from data centers (DCs) in DH [17]. Büchele et al. [18] showed that integrated policy packages instead of a single policy measure may have a stronger effect on DH system emission reduction and renewable energy penetration. This shows that those policies are needed to enhance the flexibility of DH systems and realize its' potential.

Viewing the possible development of DH systems, 4th generation DH system are integrated with diverse heat sources, unlike the 3rd generation of DH that was designed for the use of fossil fuels [19]. However, the 4th generation concept is not often as suitable for the existing building stock, since it includes the ability to use low-temperature DH for space heating and domestic hot water [20]. Because the existing infrastructure is designed for high temperature, the transition to low-temperature networks in large scale systems can be expected to take several decades [21]. The focus on decarbonizing DH systems is to couple renewables and gain heat from heat recovery or waste heat instead of the dependence on fossil fuels [18,22]. Paiho and Saastamoinen [23] interviewed 29 stakeholders about the opportunities and challenges that may arise in the DH system development and recommended the use of waste heat and renewable energy in the decarbonization objective. Mäki et al. [24] constructed a model in the Apros simulation software, finding that integrating different shares of solar and thermal storage in the Finnish DH system could achieve zero-emissions in the summer for domestic hot water and reduce the use of biomass.

Heat pumps (HPs), as a low-carbon technology, could provide a viable option for DH system decarbonization. HP systems hold potential especially in small DH systems and could help DH to be fossil-free, but this is less the case for medium and large size DH systems due to the profitability of combined heat and power plants (CHPs) [25]. Ommen et al. [26] also pointed out the advantage of integrating HPs in DH networks is to eliminate the production restrictions by co-produced power in CHPs. Apart from HPs, waste heat recovery from DCs and other industrial sources could be utilized. This could not only minimize the heat production cost and emissions from DH system [17], but also reduce the operational hours of CHPs for the whole year as well as heat only boilers (HOBs) [27]. Together with district heating, seasonal thermal storage could provide the backup and could reduce the electricity demand of HPs in larger communities [28]. Hast et al. [29] found that thermal storage and carbon capture technology could play a significant role in achieving carbon neutrality and reducing coal consumption by comparing the DH systems in Helsinki, Warsaw and Kaunas.

Bühler et al. [30] analyzed Danish DH systems and found that industrial waste heat could fulfill 5.1% of the country's DH demand. Sandvall et al. [31] examined that integrated excess waste heat in DH could increase the system competitiveness especially in the case of Nice and Madrid, while at the same time, limiting the CO_2 emissions in the DH systems could lower the system cost. Askeland et al. [32] established a model using the software EnergyPLAN to simulate DH as a heating supply method instead of individual heating, it shows such this sort of shift could strengthen the flexibility of the Norwegian energy system, especially avoiding the lack of hydropower reserves during the winter months. Scharf et al. [33] studied the effect of decarbonization strategies on natural gas (NG) consumption in the German energy system, which indicated that at a specific level of GHG reduction, natural gas consumption remained constant in the energy system.

The existing literature mainly focuses on single city DH in the Helsinki metropolitan area [7,29,34] regardless of heat transmission interconnections with neighboring cities, lacking an optimal operation method in the overall DH system. Furthermore, current DH models concentrate primarily on the short-term (usually one year) system operation [34] or future possibilities of DH operation [18], which may lack a comparison between historical fluctuations and future scenarios. The research questions in this study are as follows:

- How much are the present decarbonization strategies able to reduce CO_2 emissions in the Helsinki metropolitan area from 2010 to 2030?
- How will the decarbonization strategies of DH companies in the Helsinki metropolitan area together with increasing carbon prices affect DH production costs?

- What will the impact of heat trading be between the cities in the Helsinki metropolitan area under the decarbonization strategies?

The novelty of this study is that we combined three cities DH in the Helsinki metropolitan area to analyze how a fossil fuel dependent large DH system can be transformed towards carbon neutrality in a relatively short time without excessive costs and without compromising reliability. The study simulates different scenarios considering the impact of energy prices, fuel taxes, CO_2 prices, and inter-city heat trade. Additionally, the impacts of possibly higher biomass, natural gas and electricity prices are assessed.

3. Material and methods

In this study, we use the EnergyPRO model [35] to analyze the decarbonization strategies of the DH companies in the Helsinki metropolitan area. The existing DH system in this area and potential alternative technologies from the city-level decarbonization goals until 2030 were modeled in five-year intervals by EnergyPRO.

3.1. Modeling methods

EnergyPRO is an input/output software program that optimizes the DH system operation [36]. The flow of the DH model starts from fuel input, which provides energy for DH technologies to generate heat and electricity, the electricity output can be converted to heat using HPs. Extra heat could be retained in heat storage systems for future system usage or it could become excess heat if the heat storage is full, see Fig. 1.

The mechanism of the energyPRO software is to provide a least-cost solution while ensuring the heat demand can be met by the heat supply every hour [35]. The software is used by several research institutions and utilities for modelling and analyzing energy projects with combined supply of electricity and thermal energy [35]. EnergyPRO shows the operation strategy for several power plants using merit order regulation to obtain the lowest-cost solution [17,19].

The objective function shows in Equation (1):

$$Min\Sigma_{i=1}^{n}\sum_{j=1}^{m} f_i\left(x_{ij}\right) \tag{1}$$

Where.

x_{ij} = hourly heat produced by energy conversion units via CHPs, HOBs, HPs (MW), each unit i produces heat at hour j.

$f_i(x_{ij})$ = the hourly heat production costs(€) including fuel costs, fuel taxes, O&M costs and CO_2 costs with energy conversion units, to be specific from Equation (2) to Equation (4):

$$f_i\left(x_{ij}\right)HOB = \frac{x_{ij}}{\eta}\left(P_{fuel} + P_{tax} + P_{o\&M} + P_{CO_2}\right) \tag{2}$$

$$f_i\left(x_{ij}\right)CHP = \frac{x_{ij} + q_{ij}}{\eta}\left(P_{fuel} + P_{o\&M} + P_{CO_2}\right) + 0.9 * x_{ij} * P_{tax} - q_{i,j}P_{el,j} \tag{3}$$

$$f_i\left(x_{ij}\right)HP = \frac{P_{el,j} + P_{el\ tax} + P_{distribution+}P_{o\&M}}{COP} \tag{4}$$

For HOBs, the hourly fuel consumption equals the heat production divided by the efficiency (η). Fuel costs (P_{fuel}, €/MWh), fuel taxes (P_{tax}, €/MWh), operation and maintenances costs ($P_{o\&M}$, €/MWh) and the CO_2 allowances (P_{CO_2}, €/MWh) contribute to the total costs of HOBs. It should be noted that CHPs can generate both heat (x_{ij}, MW) and electricity (q_{ij}, MW) simultaneously. Additionally, the hourly fuel consumption for CHPs equals the thermal and electricity outputs divided by the power plant efficiency (η). Unlike HOBs, only 90% of the total fuel for heat production of CHPs will be taxed, and fuels for CHPs have 100% energy content tax reduction before 2020, according to the Finnish Energy Taxation Directive. After 2020, the reduction of energy content tax 7.63 €/MWh [37]. In addition, CHP could gain profits from sold electricity, so $P_{el,j}$ is the hourly electricity price of the spot market. For HPs, the electricity spot price ($P_{el,j}$, €/MWh), electricity tax (P_{eltax}, €/MWh), electricity distribution costs ($P_{distribution}$, €/MWh) and operation and maintenances costs ($P_{o\&M}$, €/MWh) account for the total HP operation costs.

The software minimizes the yearly net operation costs (see Equations (1)–(4)). The heat demand must be met on every time step, which is 1 h in this study. The running order of the production units are calculated for every hour according to the net production costs, but some technical limitations, such as the limitations in fuel usage (see Appendix A), as well as starting and shut down times (see Appendix B) are assumed, and these have an impact on the running order as well. Instead of calculating the running order chronologically hour by hour, the software ensures the optimal operation strategy by committing the production units to the most favorable periods at first [38].

EnergyPRO can be utilized for simulating realistic DH systems from ranging from small to large scale [25,39]. The performance of the system can be reflected from technical and economic indicators. It also can be applied to analyze factors that influence the system sensitivity and predict future situations [40]. EnergyPRO optimizes the operating order of production units, taking all production unit constraints into consideration [36].

In this study, three DH systems are combined into a global DH with transmission allowed in both directions (Helsinki-Espoo and Helsinki-Vantaa). The DH system model was based on current system components, while the future DH changes were based on decarbonization pathways from the DH operating companies.

3.2. Description of DH system in the case study area

We provide data descriptions and assumptions considered in the study. This also includes the scenarios and calibration/validation of the model. The amount of CO_2 emitted by the entire DH system throughout the years is also evaluated together with policy instruments such as carbon prices and fuel taxes.

Helsinki, Espoo and Vantaa DH with the existing heat transmission connections between cities form the overall Helsinki metropolitan area DH system. The DH system in the city of Helsinki has been operated by Helen Oy since 1957 and 93% of the population were connected to DH in 2019. Fortum, Espoo Oy started to sell DH in 1967 in the city of Espoo and their DH connection rate is 77%. Vantaan Energia started in 1969 in the city of Vantaa, and currently 90% of the population uses DH [41].

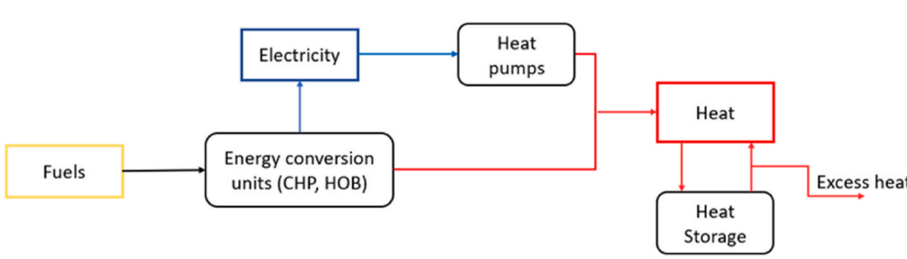

Fig. 1. Schematic diagram of the DH model by EnergyPRO.

CHPs have provided basic heat production for the DH network in the Helsinki metropolitan area, along with smaller capacity of HOBs and HPs to ensure the stability of DH system.

In the city of Helsinki, Helen owns coal-fueled CHPs located at Hanasaari and Salmisaari, and two NG-powered CHP units at Vuosaari. New biomass HOBs will be implemented for the Helsinki DH system, along with the expanded capacity of the HPs and heat storage. Helen is planning to curb the coal usage well before 2029, and the Hanasaari coal-fired power plant will be decommissioned gradually by 2024 [42]. Fortum in Espoo will abandon coal in 2025. To achieve this, low-carbon technologies such as the world's deepest a geothermal power plant in Otaniemi, heat recovery from DCs, new HP as well as biomass-fueled power plants will be introduced [43]. For Vantaa, a waste to heat power plant serves the baseload and will be expanded under the decarbonization strategy to phase out the use of coal in 2022 [35]. The waste used for the process is collected from the whole metropolitan region [36]. Vantaa is also planning the world's largest underground thermal storage system with the capacity of 90 GWh and a volume of 1 million m^3. The list of power plants in these cities is shown in Appendix A. Fig. 2 shows an overview of the strategies.

The base load of the overall DH system in the Helsinki metropolitan area is produced by CHPs and HPs, and peak load is produced by HOBs fueled by biomass, NG, coal, and oil.

Several heat exchanger stations allow heat transmission in both directions between the cities (see Table 1). The transmission capacity between Espoo and Helsinki is 80 MW, in 2018 it increased to 120 MW, and 130 MW between Vantaa and Helsinki [46]. The realized heat transmission from Vantaa to Helsinki has increased moderately, while Espoo had imported heat mostly from Helsinki in 2015. Vantaa only purchased 0.3 GWh heat from Helsinki in 2015.

Table 1
Heat transmission within the Helsinki DH system [41,44,45].

Buyer	Purchased from	Realized transmitted heat (GWh)	Heat transmission capacity (MW)
		2010/2015/2020	2010/2015/2020
Helen Oy (Helsinki)	Vantaan Energia Oy (Vantaa)	16.7/36.9/43	130
Fortum Espoo Oy (Espoo)	Helen Oy (Helsinki)	14.3/39.3/28.3	80/80/120
Vantaan Energia Oy (Vantaa)	Helen Oy (Helsinki)	3.1/0.3/5,3	130

3.3. Data descriptions and assumptions

Under the model operating approach, input parameters generally involve technological, environmental, and financial aspects. Technical factors include the plants' capacity, efficiency, startup time, etc., while the financial data consists of all the costs during the plant's operation. Emission factors for fuels are used to calculate the total emissions from the fuel consumption, see Fig. 3.

3.3.1. Heat demand and outdoor temperature

It is assumed that 40% of annual heat demand is used for heating up domestic hot water, and the annual domestic hot water demand is divided evenly to every hour of the year. Space heating demand is dependent on outdoor temperature, so that hourly space heating demand is assumed to be zero, if outdoor temperature is 17 °C or more. From May to September the space heating is assumed to be turned off, thus the heat demand consists only the domestic hot water demand. During the heating season, the hourly heat demand can be calculated

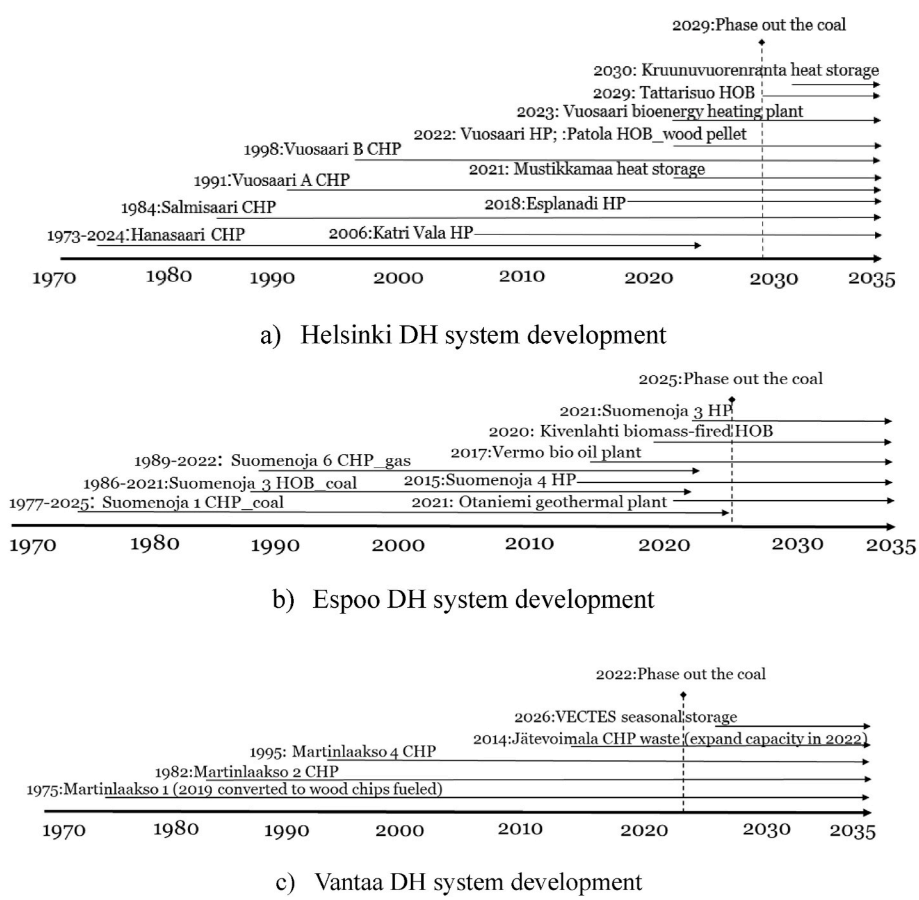

Fig. 2. Historic and planned development of the three case cities' DH systems [41,44,45].

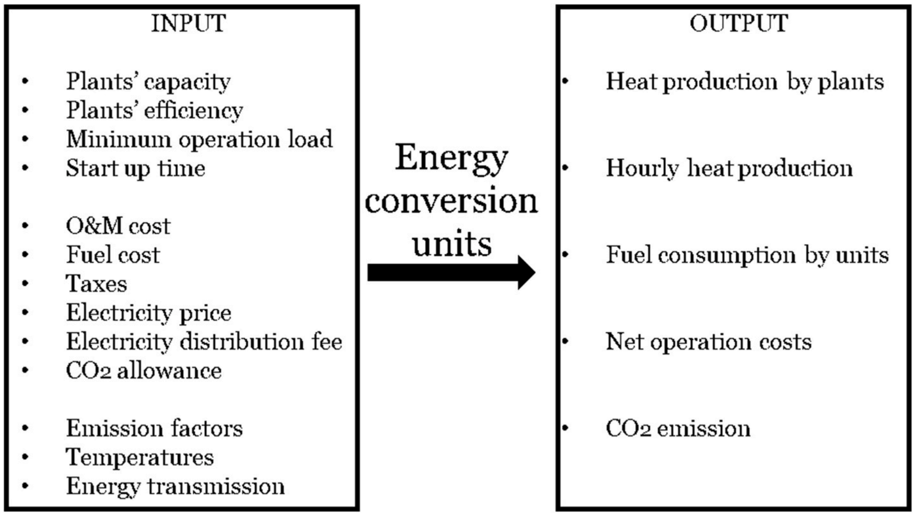

Fig. 3. Input and output parameters used in the model.

with Equation (5), where Q_{SH} is annual space heating demand, Q_{DHW} is the annual domestic hot water demand, and T_i^0 is the hourly outdoor temperature. The air temperature data is obtained from different meteorological observation points in Helsinki, Espoo and Vantaa [47]. The 2025 and 2030 heat demand will be assumed based on the 2020 temperature data.

$$\varphi_i = \frac{Q_{SH}}{\sum_i max\{0,\ 17^\circ C - T_i^0\}} * max\{0,\ 17^\circ C - T_i^0\} + \frac{Q_{DHW}}{8760\ h} \tag{5}$$

Annual heat demands are gained from Finnish Energy Ltd statistics [41,44,45]. The DH operator in Helsinki, Helen Ltd, has published hourly heat consumption data, which is used for Helsinki's demand in 2015 and 2020 [48,49].

3.3.2. Financial data

Table 2 shows the fuel taxes, fuel costs, CO_2 prices for CHPs and HPs, and electricity price for HPs used in the simulations.

Taxes. According to the Energy Taxation Directive [37], from 2011 to 2020, CHPs had fewer fuel taxes than HOBs since fuel for CHPs heat production is excluded from energy content taxes, and the taxable fuel volume in CHP is 90% of heat production. After 2020, instead of the total energy content tax, the reduced taxes for CHPs will be 7.63 €/MWh [37]. Bioenergy is exempted from fuel taxes. For the future simulation years 2025 and 2030, 2020 taxes are assumed.

Fuel prices. National data from Statistic Finland is used [50]. Vantaan Energia will receive a gate fee for managing wastes [7]. For the future years, interpolation is applied based on the generally rising trend [51] of coal and natural gas. Waste and bio-oil prices are assumed to be the same in the future years [29]. Estimations of the price for HFO (heavy fuel oil) and LFO(light fuel oil) are based on the price spreading trend [16].

Electricity price. The Nord Pool day-ahead market in Finland shows a declining trend from 2010 to 2020 [52]. Hourly electricity prices are used as time-series data to increase the accuracy of the simulation. Since the earliest hourly historic data that could be obtained was in 2013, the hourly data for 2010 simulation was scaled based on the year 2013 situation. In addition, with more nuclear power and wind power in Finland's electricity market [16], this research assumes the same electricity price for 2025 and 2030 models as for 2020.

Electricity related costs. Electricity taxes have increased gradually since 2010, which is contradictory to the electricity price trend. The Finnish Government has reduced electricity taxes on HPs in district heating systems. As a result, for the years 2025 and 2030, the electricity tax for HP will remain constant at 6.9 €/MWh [37]. Apart from that, the electricity distribution fee includes costs during electricity distribution and is involved in the HP operation costs. The city of Helsinki and Espoo have different responsible companies which distribute electricity,

Table 2
Financial parameters and assumed projections of future financial data.

Financial parameters			2010	2015	2020	2025	2030
Taxes [37] (€/MWh)	Coal	HOB	7.12	22.16	29.17		
		CHP		15.35	21.54		
	Natural gas	HOB	2.10	15.36	20.65		
		CHP		8.71	13.02		
	Light fuel oil		6.26	22.90	27.53		
	Heavy fuel oil		5.94	23.70	24.52		
Fuel costs [50,51,59,60] (€/MWh)	Coal		9.94	8.58	8.38	9.16	9.94
	Natural gas		25.10	23.24	23.20	27.31	31.43
	Heavy fuel oil		50.50	35.00	54.00	54.50	55.00
	Light fuel oil		77.50	84.20	76.20	76.99	77.74
	Bio-oil		–	62.00	67.00		
	Wood pellet		–	–	46.77	48.12	49.52
	Forest chips		–	–	22.24	22.88	23.53
	Waste		−7.95				
Electricity costs [37,52–54] (€/MWh)	Electricity spot price (averaged)		56.85	29.66	28.02		
	Electricity distribution cost	Helsinki	21.00	28.10	32.80		
		Espoo		26.10	31.40		
	Electricity tax		16.90	22.40	22.53	6.90	
CO_2 price [61] (€/tonCO_2)			14.41	7.69	24.8	40	

generally, Caruna Espoo Oy (for Espoo) distributed electricity at a lower price than Helen Oy (for Helsinki) [53,54].

Operating and maintenance (O&M) cost. For CHP, the O&M costs are assumed as 4 €/MWh electricity production. Both HPs and HOBs O&M costs are considered as 5 €/MWh heat production in the simulation [29].

Investment costs. When calculated for the total system operation costs, the annualized investment cost is expressed in Equation (6) [55].

$$AIC = \frac{r(1+r)^n}{(1+r)^n - 1} * IC \tag{6}$$

Where, AIC = The annualized investment cost (€/year).

r = The interest rate, which this research considered as 5% [29].

n = The lifetime of power plants, which this research considered 40 years for HOBs, CHPs, heat storage, and 35 years for HPs [56].

IC = The investment costs (M€). The amount of investment information was collected from news or companies' websites, and includes assumptions based on existing power plant investment and capacity, see Appendix CTable B 1-Table B 3 for further information.

Since St1 Oy owns the Otaniemi geothermal power plant in Espoo, Fortum only pays for the purchased heat price from it, and the same situation exists for Espoo DC waste heat [57,58]. Hence, there is no investment cost considered for those two technologies.

CO_2 emission and allowances. The emission factor of electricity in Finland [62] is used to calculate the CO_2 emissions from HPs, while for future year simulations, the 2020 electricity emission factor is assumed. Under the EU emission trading system (EU-ETS), CO_2 prices fluctuated over time (see Table 3). They fell to the lowest price point in 2013, when it was less than 5 €/ton_{CO2}, but rose above 50 €/ton_{CO2} in 2020 [61]. In this research, the daily CO_2 price averaged in a year will be used, which is 14.41 €/ton_{CO2} in 2010, 7.69 €/ton_{CO2} CO_2 in 2015, and 24.80 €/ton_{CO2} in 2020. In 2025 and 2030, the CO_2 price is assumed to be 40 €/ton_{CO2} in both years, since the price of CO_2 has already reached over 44 €/ton_{CO2} recently.

3.3.3. Technical data

HPs performance. This research applied the HPs performance as the input hot water from 50 °C and out at 65 °C, while it applied cold water cooled from 14 °C down to 7 °C for the DH system in Helsinki metropolitan area. The coefficient of performance for HPs in Helsinki is considered to be constant at 2.58 [64], while in Espoo this is considered to be 2.54, calculated from the heating capacity divided by the electricity capacity [64].

CHPs and HOBs performance. Different energy conversion units have different efficiencies when they combusted the fuel to generate energy (see Appendix B). Generally, the efficiency ranged from 80% to 90%, which is calculated from the total energy output divided by the fuel input. All types of CHPs are considered to have the same minimum load at 40% of the full workload [29]. Both combined-cycle gas turbine power plants (CCGT) and open-cycle gas turbine power plants (OCGT) are gas-fueled. CHP_ OCGT has a lower ramp-up time (0.5 h) than CHP_CCGT (4 h), and a lower shut down time (1 h for OCGT while 2 h for CCGT). All the technical data will be kept the same for different year simulations.

Table 3
CO_2 emissions factors and CO_2 allowance [61–63].

Fuel	Emission factor of fuels (kg CO2/MWh)	Emission factor of electricity (kg CO2/MWh) 2010/2015/2020&2025&2030	CO_2 allowance (€/MWh) 2010/2015/2020/2025&2030
Coal	300		4.3/2.3/7.4/12
Heavy fuel oil	220		3.2/1.7/5.5/8.8
Light fuel oil	201.9		2.9/1.6/5/8.1
Natural gas	153.9		2.2/1.2/3.8/6.2
Bio-oil	200		2.9/1.5/5.0/8.0
Municipal waste/mixed waste	111.1		1.6/0.9/2.8/4.4
Electricity		244/104/74	

3.4. Sensitivity analysis and scenario development

In the sensitivity analysis, the effect of different CO_2 prices on the 2030 DH system in the Helsinki metropolitan area is analyzed (see Table 4). The scenarios set the CO_2 price at 40 €/t CO_2 (2030_C40) as a reference scenario, the CO_2 price raised to 60 €/tCO_2 (2030_C60), 80 €/tCO_2 (2030_C80), 100 €/tCO_2 (2030_C100) so that different scenarios are developed, lower emission price than reference scenario at 30 €/tCO_2 (2030_C30) will also be conducted. Additionally, without the heat trading between 3 cities in 2030 with a different carbon price, the 2030_C30_notrade, 2030_C40_notrade, 2030_C60_notrade, 2030_C80_notrade and 2030_C100_notrade will be compared with heat transmission allowed scenarios.

In the sensitivity analysis, a 30% higher biomass price under the 100 €/tCO_2 price (2030_C100_bio), 30% higher fossil fuel price (2030_C100_ff) are also compared. In addition, since the Finnish average electricity price was record high in 2021, we also set a 2030_C100_ele scenario with annual average price of about 56 €/MWh, about the same as in 2010. To evaluate the its impacts on future DH operation costs and fuel consumption.

3.5. Calibration and model validation

Fuel prices especially NG may differ for the cities since the city-level NG consumptions varied massively in 2010 and 2015 (Helsinki consumed over 7000 GWh in 2015, while Espoo and Vantaa only consumed 438 GWh and 310 GWh separately) [44,45]. Due to the confidentiality of the fuel purchased prices in companies which is not made publicly available, this research adjusted the NG price in different cities based on the national NG price to make the model valid compared to the real situation.

2010 and 2015 NG calibrated prices are shown in Table 5. At the same time, the model limited the coal usage for Helsinki to 2 coal-fired CHPs for a total amount of 400 GWh. If the COP of the HPs for both years raised to 2.7, the result would be close to reality (see Appendix D). The following results comparison will be based on this calibration.

4. Results

Fig. 4 shows a comparative result from 2010 to 2030 and is based on

Table 4
Scenarios relating to different CO_2 price and heat trade scenarios for the simulations. Other parameters excluding the carbon price are fixed. The carbon price will increase from 30 to 100 €/tonne CO_2 in the 2030 scenarios, with and without inter-city heat trading.

Scenarios	Carbon price €/tCO_2	Heat transmission between cities
2030_C40 (ref.)	40	✓
2030_C40_notrade		–
2030_C30	30	✓
2030_C30_notrade		-
2030_C60	60	✓
2030_C60_notrade		-
2030_C80	80	✓
2030_C80_notrade		-
2030_C100	100	✓
2030_C100_notrade		-
2030_C100_bio		✓
2030_C100_ff		✓
2030_C100_ele		✓

Table 5
Natural gas (NG) price for calibrated model in 2010 and 2015 [50].

€/MWh	2010	2015
Helsinki	24.2	20.9
Espoo	24.2	26.3
Vantaa	25.5	26.3

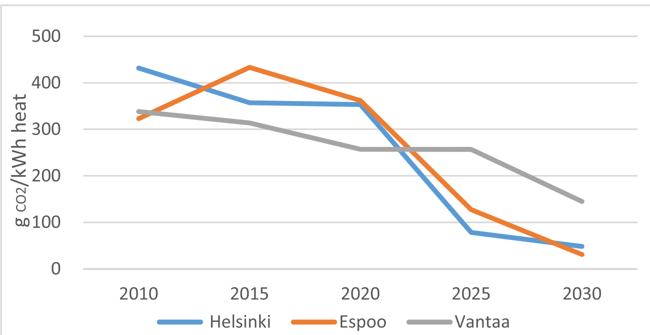

Fig. 4. City-level CO_2 emission intensity reductions when producing 1 kWh heat during 2010–2030.

the 2030 situation for different CO_2 prices and heat transmissions (Fig. 5). We also present the DH system operation costs (Fig. 6), the amount of transmitted heat (Fig. 8) as well as the percentage of heat productions by different types of units (Fig. 9).

The CO_2 emission intensity (= the CO_2 emissions when the DH generates 1 MWh heat) in the three cities decreases over the years. There will be a sharp reduction from 2020 to 2025 in both Helsinki and Espoo. In 2030, Espoo will have the least CO_2 emission intensity at 36.2 gCO_2/kWh heat, which decreased from 323 gCO_2/kWh in 2010. Helsinki DH will emit 53.8 gCO_2/kWh while Vantaa will emit 144.8 gCO_2/kWh in 2030. With the introduction of the waste incineration power plants in Vantaa, it would emit the most heat generation of the three cities after 2025. The increase in natural gas prices caused greater coal consumption in heat production, thus reflecting a moderate increase of emission in Espoo in 2015. The overall DH system emission reduction rate in 2030 will be approximately 85.8% compared with the 2010 level. Both Helsinki and Espoo DH will reduce their total emission by about 91% from 2010, for Vantaa about 61.5% reduction will take place.

Fig. 5 reflects that higher CO_2 prices will lower the total emission of the overall DH system. It also shows the effectiveness of EU-ETS. Generally, when the CO_2 price reached 100 €/tCO_2, the total DH system would emit 244 kt CO_2 (35.4%) less compared with the 30 €/tCO_2

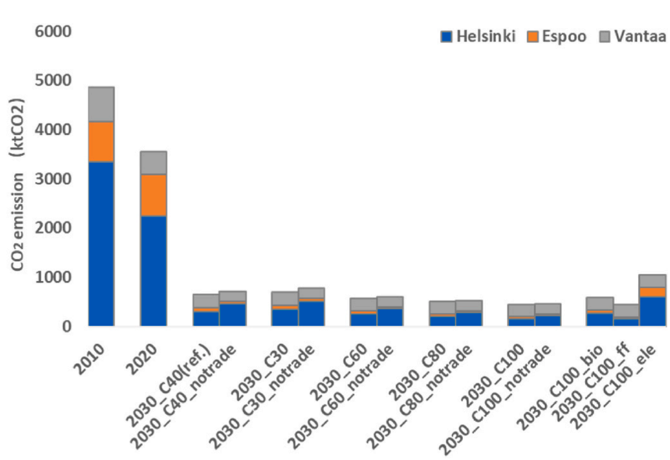

Fig. 5. DH system emissions under different CO_2 prices and heat trade scenarios.

(2030_C30) scenario. Similarly, the heat transmission between the cities in Helsinki metropolitan area will always cause overall CO_2 emission decrease, especially when the CO_2 prices are lower. At the city level, only Helsinki's DH system will emit more emissions without heat transmission, contrarily, the Espoo and Vantaa DH systems will emit less. For example, Vantaa DH emission would be reduced by about 17% when the CO_2 price at 100 €/tCO_2 and without heat transmissions (2030_C100_notrade) compared with the 2030_C100 scenario. In Espoo, a no heat trade scenario and higher emission price contributes to 27% lower emission from DH than with a CO_2 price at 40 €/tCO_2.

A sensitivity analysis with a 30% higher biomass fuel price (both wood chips and wood pellets)was conducted for the scenario with 100 €/tCO_2 price (2030_C100_bio). With higher CO_2 emission prices, it is very likely that the biomass fuel demand will increase. In this case, the overall system emission would increase by about 143 $ktCO_2$. 2030_C100_ff scenario shows the same reduction trend, and the overall system emission is even less (440.66 $ktCO_2$). With higher biomass fuel price, wood chips consumption would decrease by 5% and wood pellets by 6% in the Helsinki metropolitan area DH system. Additionally, with higher fossil fuel price, about 3.8% less natural gas would be used. The use of HPs would also increase by 3% to meet the heat demand. However, if the electricity price remains higherin 2030 (2030_C100_ele), NG will be the main fuel for DH production (34% of the total fuel consumption), since it would not be profitable to use HPs. CO_2 emission in 2030_C100_ele scenario would be considerably higher, 1045.8 $ktCO_2$.

The total DH system operation costs associated with expenditures during the generation process of energy conversion units, decreased from 634.2 M€ in 2010 to 389.6 M€ in 2030. Similarly, the revenue from electricity sales underwent a dramatic drop from 515.7 M€ in 2010 to only 91.6 M€ in 2030. Fig. 6 also indicates that higher CO_2 prices will contribute to higher system operation costs and lower revenue from electricity sales. Without heat transmission there would be an increase in the total operation costs. To be specific, at a 100 €/tCO_2 price, the total DH operation costs will be 8.3 M€ higher than the reference scenario (2030_C40), and about 2% higher than the 2030_C30 scenario. Additionally, the 2030_C100_notrade scenario will increase the total operation costs by out 6.4% compared to the 2030_C100. In the 2030_C100_bio scenario both the system operation expenditure (463.7 M€) and revenue from electricity (77.7 M€) will increase, so as the 2030_C100_ele scenario, where operation expenditure will be 561.1 M€ and revenue from electricity will be 313.8 M€. On the contrary, with higher fossil fuel price at 100 €/tCO_2 (2030_C100_ff), only 72 M€ will be received from the electricity market. With the CO_2 price decreasing to 30 €/tCO_2, without heat trade(2030_C30_notrade) the DH system may incur 6.6% more expenses than for the 2030_C30.

The Helsinki city DH system is the largest city system, and it operates with the highest total costs, followed by Espoo and Vantaa (see Fig. 7). In 2015 all three cities' DH system had lower operation costs due to the low heat demand and carbon price that year. The net operation expenditures (including annualized investment costs but excluding electricity sales) will increase about 178.9 M€ for the Helsinki DH, 65 M€ for the Espoo DH and 40.5 M€ for the Vantaa DH from 2010 to 2030. Annualized investment costs of all three cities will rise with the implementation of low-carbon technologies. Espoo has the smallest investment cost, since the geothermal power plant is owned and constructed by another company, St1 Ltd. The revenue from electricity will decline for all cities. Helsinki has the largest reduction, as the income from electricity will drop by about 309.5 M€, while in Vantaa the income from electricity sales will decrease only by about 19.7 M€.

The average heat production cost (€/MWh) represents the expenses when the DH system produces one MWh of heat. This is calculated as the total cost of heat generation including the annualized investment cost (but extracting electricity revenue from the total production costs) divided by the total heat output (see Fig. 7). The average heat production costs grew steadily before 2020, and they will be almost four times higher in 2030 compared to 2010 in all three cities. When Vantaa

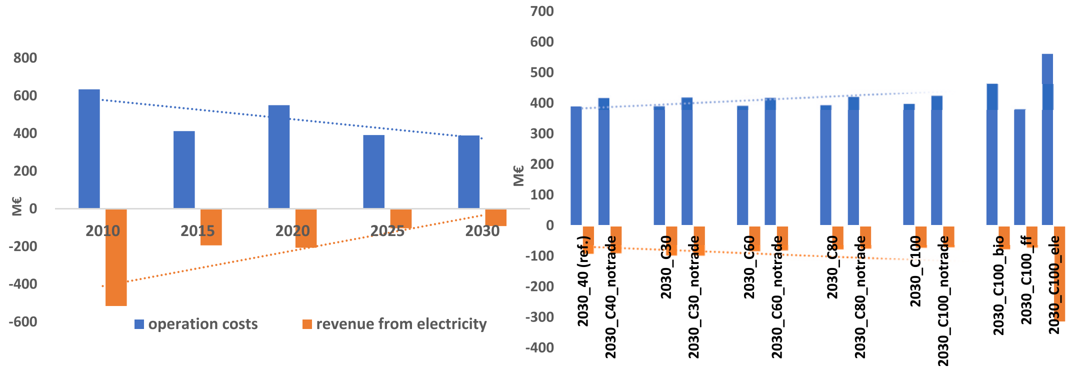

Fig. 6. DH system total operation costs with revenue from electricity in M€ (drawn as negative costs). Left: 2010–2030 scenarios; Right: under different carbon price scenarios in 2030.

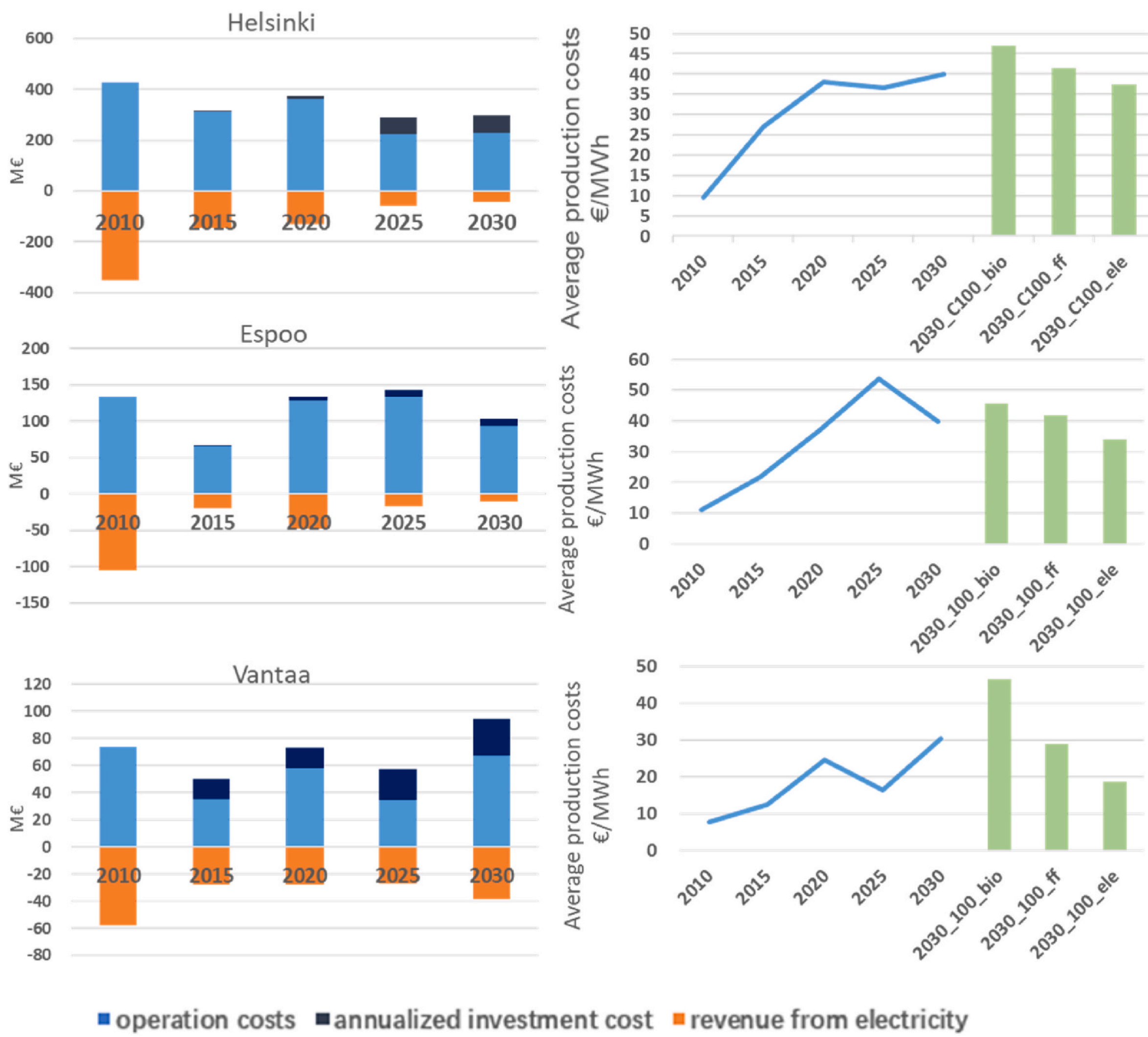

Fig. 7. Operation costs with annualized investment cost and revenue from electricity sales in the 3 individual cities during 2010–2030 (for 2025 and 2030 scenario 40 €/tCO_2 were assumed, for the 2030_C100_bio assumed 100 €/tCO_2 and 30% higher biomass price were assumed).

expands the waste incineration power plant, it will also increase its average heat production costs to 30.44 €/MWh in 2030, while it could decrease in Espoo to 38.87 €/MWh with the heat transmission. Additionally, with higher biomass prices, average heat production costs will increase in all three cities. For Vantaa, this would be about 53% more than in the 2030_C40 scenario, followed by Helsinki (18%) and Espoo (15%). On the contrary, with higher electricity prices(2030_C100_ele), average heat production costs in Helsinki, Espoo and Vantaa will reduce by 2.4€/MWh, 5.8€/MWh and 11.9€/MWh separately compared with the 2030_C40 scenario. When the fossil fuel prices increase, the heat production costs in Helsinki and Espoo will increase to around 42€/MWh, while for Vantaa it will decrease to 29 €/MWh.

As the heat transmission is allowed in both directions for Helsinki-Vantaa and Helsinki-Espoo, imported heat from Helsinki will increase during the year but decrease from Espoo and Vantaa (see Fig. 8). Helsinki is the largest heat producer in the study area, with around 881.8 GWh heat exported to the neighboring cities in 2010. The situation changes by 2030, as the total imported heat into Helsinki rises from 306.7 GWh in 2010 to 1522 GWh in 2030. On the contrary, Vantaa will export the most heat in 2030 at about 1053.7 GWh to Helsinki. For Espoo, the commissioning of the geothermal power plant and heat recovery from DCs will allow Espoo to export heat to Helsinki instead of importing it.

Different CO_2 emission prices will impact the realized heat transmissions between cities. Higher CO_2 prices would raise the amount of exported heat from Espoo to Helsinki (about 30 GWh more heat at 100 €/tCO_2), and would lower the heat transferred from Vantaa to Helsinki conversely (about 45 GWh less heat at 100 €/tCO_2), compared to the reference scenario.

Before 2020, coal and NG-based CHPs dominated the total heat

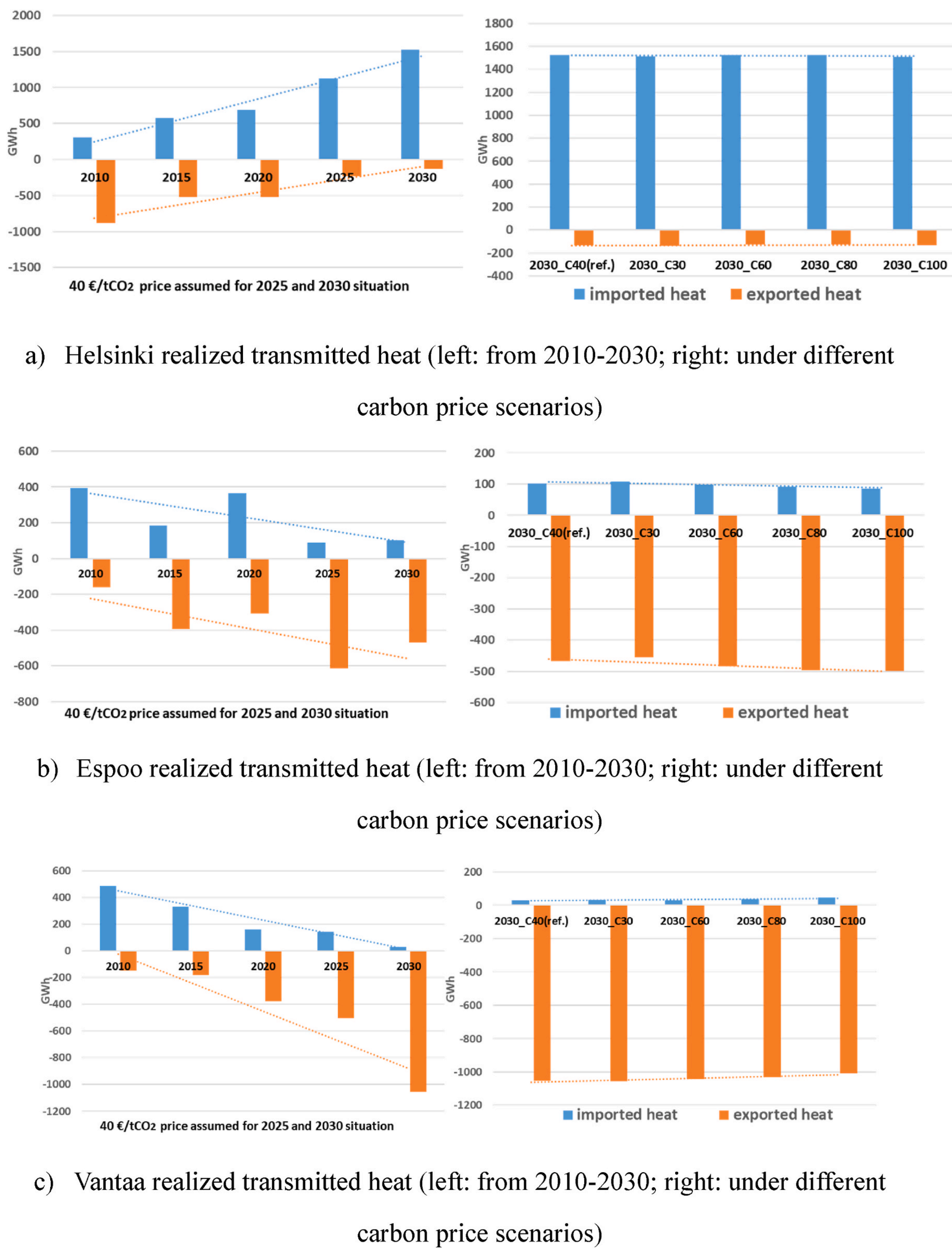

Fig. 8. Imported and exported heat from the three cities in the Helsinki metropolitan area.

production: 77.6% of heat was produced by CHPs for the Helsinki DH in 2010, followed by Vantaa (71%) and Espoo (67%), as it shown in Fig. 9. The commissioning of the waste incineration power plant in Vantaa expands the amount of heat produced by CHPs in the Vantaa DH system to 2468 GWh, which is 85.2% of total DH heat production in 2030. Oppositely, HPs and heat recovery will become the main sources (45%) of heat production instead of CHPs (5%) in the 2030 Espoo DH system. Due to the biomass-fueled HOBs as well as imported heat, CHPs will only account for about 12% of heat production for Helsinki. In addition, more heat will be generated by HPs, increasing from 0.06% of the total DH in 2010 to 14% in 2030.

An increasing CO_2 emission price from 40 €/tCO_2 to 100 €/tCO_2 has a significant impact on natural gas usage in DH systems. It decreases the NG-based power plant heat production in Helsinki by about 54%, by 57.6% in Espoo and by 43% in Vantaa, compared to the reference scenario (see Appendix E). Instead, biomass power plants will produce more heat to ensure a sufficient heat supply, Heat production by biomass-fueled HOBs in Espoo would increase by 12% and in Helsinki by about 5%.

The share of fossil fuels utilized in the DH systems of the Helsinki metropolitan area are estimated to be reduced from over 80% before 2020 to about 21% in the 2030 reference scenario (see Appendix F). Simultaneously, the biomass share in 2030 (58.4%) will be five times higher than in 2010 with more biomass-based HOBs implemented. However, biomass is also a limited resource with a considerable risk of increasing prices and uncertain supply in the future.

In 2030, the geothermal power plant and DC waste heat in Espoo will operate almost the whole year to provide the baseload in the Helsinki metropolitan area, followed by waste combustion CHP (83.8% of the annual operating time) and biomass fueled CHP (80% of the annual operating time) in Vantaa. The HOBs fueled by gas will be used for peak load.

5. Discussion

The study provides insights into the decarbonization strategies of the Helsinki metropolitan area. In the following, the emissions reduction potential and the role of carbon prices are discussed. Heat production costs are also included along with the feasibility of heat trade between the cities. Finally, the impact of carbon price and biomass feedstock price is elucidated.

5.1. Emissions reduction

Low-carbon technologies, such as HPs and the geothermal power plant in Espoo would reduce emissions of combusting fuels. DC waste utilization in Espoo is considered here as zero-emission, since the DC is operated by another operator [57] and the CO_2 emissions from electricity are small in Finland already today. Apart from that, Vantaa uses waste as an alternative to fossil fuels and can avoid emissions as well as benefitting. Capacity expansion of heat storages will also reduce emissions [7], these can store heat when more heat is produced than the demand, and then release the heat during the peak hours. However, this research did not consider the heat loss from heat storages or the rather small operation costs of storages.

Higher CO_2 prices will reduce the total CO_2 emissions from the overall system according to the results (see Fig. 5). Geothermal, HPs, waste, biomass, and other zero-emission technologies are becoming baseload energy conversion units.

5.2. Heat production costs

The heat production cost in the Helsinki metropolitan area DH system would increase along with the decarbonization goals before 2020, but the costs will drop in the future. Since fossil fuels coal and NG were cheaper even with fuel taxes compared with biomass, making fossil fuel was still profitable in heat generation. In addition, fuel taxes on CHPs were lower than on HOBs, along with the fact that only 90% of the total heat was taxed, making it beneficial to use for the DH system (see section 3.3.2).

Hast et, al [7]. found that heat storage could benefit the system in terms of lower average heat production costs. This study also shows that with the expansion of heat storage, both the average production costs and total operation costs could decrease after 2020. The slight increase in the average production costs in the future may relate to the investment costs [7]. Implementation of new low-carbon technologies, such as heat recovery and the geothermal power plant in Espoo would operate regardless of O&M and investment costs since Fortum only spends on purchasing the heat. The expansion of the waste incineration power plant brings significant investment costs, which increases Vantaa's DH operation expenditures and average production cost. Revenue from electricity will decrease along with the phasing out of the CHPs, and DH companies will lose income from electricity sales. On a national level,

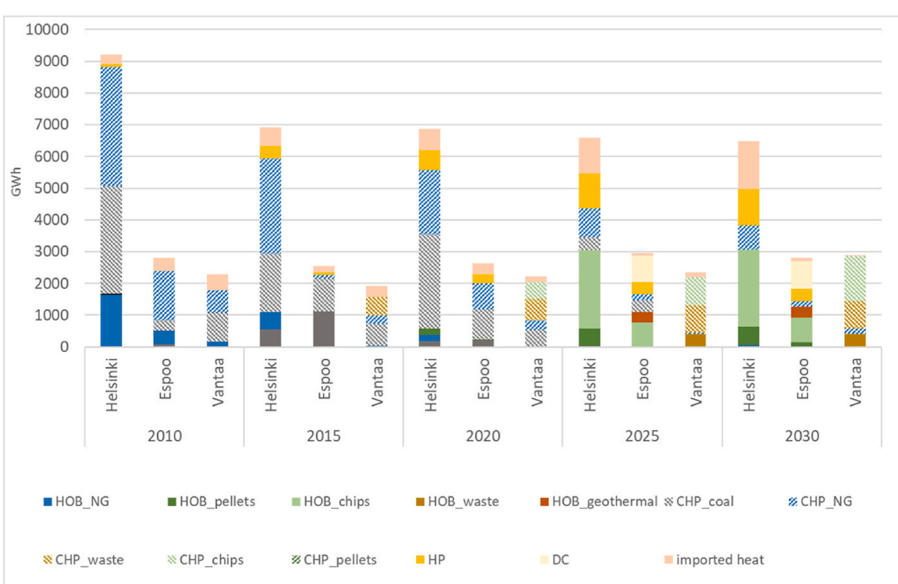

Fig. 9. Heat production by different types of units and energy sources from 2010 to 2030 (for the 2025 and 2030 scenarios 40 €/tCO_2 was assumed).

more wind and nuclear power and imported electricity will replace the missing electricity production [16].

Without heat trade between cities, Espoo and Vantaa would reduce the working load of their power plants, thus increasing the DH system's total costs. Tax for HPs will drop in the future from category I (22.53 €/MWh) to category II (only 6.9 €/MWh) for DH [37], thus also increasing the share of HPs in heat-production as well as decreasing in the system operation costs. This study indicates that a tax reduction is a needed policy measure to support the low-carbon transition of DH systems. However, with the higher electricity prices, it will cause the HPs lose the profit in producing the heat, but more revenue will be received from CHPs in electricity generation.

This analysis was conducted with 5% interest rate applied for the economic calculations, aiming to represent the viewpoint of the DH companies, A lower interest rate would make the annualized investments somewhat smaller.

5.3. The feasibility of heat transmission

In 2010, Helsinki generated and exported the most heat of the three cities, with Hanasaari and Salmisaari coal-fired CHPs operating almost the whole year, and exports taking place particularly in the summer. However, CHPs would not be dominant in the DH system with the decommissioning of the Hanasaari CHP in Helsinki and Suomenoja CHP in Espoo. The commissioning of the Vantaa waste combustion power plant expansion and the geothermal power plant in Espoo will change the trade pattern. Helsinki will import more heat from its neighboring cities.

Heat trade between the cities is beneficial, it reduces the production costs and emissions at the same time in all the scenarios. As a profitable energy conversion method, waste-combusted CHP would operate for 83.5% of the whole year in 2030. This will enable Vantaa to export more heat to Helsinki. However, this simulation fixes the amount of waste used for combusted due to the limitation of resources. The same situation exists for Espoo, where both geothermal power plant and waste heat recovery will run almost all the year with low operation costs, producing enough heat to transfer excess heat to Helsinki. More imported heat from Vantaa and Espoo into Helsinki will accelerate its DH decarbonization as well as ensure it meets the local heat demand.

5.4. Impact of the carbon price

Carbon prices will influence heat production costs. Khosravi et al. [16] assumed the CO_2 price to be 30 €/tCO_2 in 2030 and this may influence DH production costs considerably. All fossil fuel-based power plants in 2030 will have to pay for CO_2 allowances, thus a higher CO_2 price increases the costs of power plants which combust fossil fuels. Hiltunen and Syri [17] pointed out that increasing the CO_2 allowance price would raise average production costs and reduce emissions of the Espoo DH system. NG as a fossil fuel is sensitive to CO_2 prices. The total emissions will decrease with less NG consumption with high CO_2 prices. Even though the waste emission factor is lower than that for NG, waste fueled CHP would use NG as a backup until the CO_2 price reaches 80 €/tCO_2, according to the scenario runs of this paper. An increasing carbon emission cost would probably be transferred to the waste producers as higher gate fees. Biomass accessibility has not been considered in the simulation, yet biomass use shows a huge increase along with CO_2 price increase. High CO_2 prices make it less profitable for Espoo and Vantaa to export heat, so Helsinki could produce the heat by using local biomass instead of importing heat from elsewhere.

5.5. Impact of the fuel prices

A 30% higher biomass price makes it a less economic fuel at the analyzed 100 €/tCO_2 price. In this case the DH system would operate at a high operation cost and emit higher emissions with more NG usage. Furthermore, 30% higher of fossil fuel price at 100 €/tCO_2 price (2030_C100_ff) still makes biomass profitable. Since using NG as fuels should pay taxes and CO_2 allowance costs, while biomass only pays for the fuel costs, and with the existing limitation on waste fuel, NG could be the most suitable alternative for the DH operators to ensure sufficient heat production. Specifically, if electricity prices increase in the future, NG consumption will increase sharply for CHPs to generate heat and electricity, and also CO_2 emissions remain at higher level. When the biomass consumption decreases, HPs and NG will increase their share.

6. Conclusion

This study examined the decarbonization strategies of district companies in the Helsinki metropolitan area, and the effects of carbon prices and heat trade between the three cities in the area.

Under the city-level DH system decarbonization goals, DH in the Helsinki metropolitan area shows a sharp decrease in emissions. Over 80% reductions in CO_2 emission will be realized by 2030 compared to 2010. The Helsinki DH system is the largest of the three cities. The decarbonization strategies of Espoo and Vantaa include very innovative elements: at Otaniemi, the world's deepest geothermal heat plant will start operation, and Vantaa is planning the world' largest underground heat storage.

The average heat production costs of the DH system will increase with the use of low-carbon technologies. The geothermal power plant and heat recovery from DCs in Espoo, as well as the waste incineration power plants in Vantaa are profitable for DH heat production, even with investment costs and high CO_2 prices. High CO_2 prices and no heat trade between the cities would increase the total DH operation costs.

Heat transmission increases the feasibility of the overall decarbonized DH system in the Helsinki metropolitan area, and it decreases CO_2 emissions as well as production costs. Helsinki especially benefits from importing heat from Espoo and Vantaa, thus limiting the system emissions and cost increase.

A higher CO_2 price has a considerable impact on DH system emissions and system production costs. The total emissions from the whole DH system would decrease by 35% if the CO_2 price rises from 30 €/tCO_2 to 100 €/tCO_2, and simultaneously the total DH operation costs would increase by 2%.

Waste to energy technology in Vantaa should be regarded as a medium-term solution only, with material accessibility limitations and the aim for a more complete circular economy. Total waste consumption will remain constant with different CO_2 prices. A sensitivity analysis of a 30% higher biomass price in the 100 €/tonne CO_2 price scenario indicated that if a high biomass price materializes, then natural gas may remain in a substantial role, slowing down the development to full decarbonization.

These decarbonization strategies also imply that the business of DH companies is facing a profound change. Until today, efficient production in CHP plants with significant income from electricity sales has been a key asset of the DH companies in Finland. These strategies and the scenario analysis presented in this paper imply that the companies will to a large extent lose this income. Instead, heat recovery from DC, the geothermal power plant and other available sources would provide the baseload of heat demand. Biomass-based power plants will play an important role in the future DH, and HPs will increase their share in the overall heat production. A high future electricity market price would slow down this transition.

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Credit author statement

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Declaration of competing interest

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

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Appendix A. Power plant list

Table A.1
Summary of heat generation units in Helsinki DH network in 2019 [41].

Unit type	Unit	Starting year	Heat output (MW)	Power output (MW)	Main fuel
HOB	Alppila	1964	136	–	light fuel oil
	Munkkisaari	1969	235	–	heavy fuel oil
	Ruskeasuo	1972	248	–	heavy fuel oil
	Lassila	1977	324	–	natural gas
	Patola	1982	228	–	natural gas
	Salmisaari	1986	190	–	coal
	Salmisaari	1977	8	–	heavy fuel oil
	Jakomäki	1968	44	–	heavy fuel oil
	Myllypuro	1978	240	–	natural gas
	Vuosaari	1989	120	–	natural gas
	Hanasaari	1977	56	–	heavy fuel oil
	Hanasaari	2009	282	–	heavy fuel oil
	Salmisaari	2018	92	–	wood pellets
HP	Katri Vala	2006	105	–	-
	Esplanadi	2018	22	–	-
CHP	Salmisaari B	1984	300	160	coal
	Hanasaari B	1973	429	218	coal
	Vuosaari A	1991	158	160	natural gas
	Vuosaari B	1998	429	470	natural gas

Table A.2
Summary of heat production units in Espoo DH network in 2019 [41].

Unit type	Unit	heat output (MW)	Power output (MW)	Main fuel
HOB	Kivenlahti	40	–	wood pellet
	Suomenoja 7	17	–	natural gas
	Tapiola	160	–	natural gas
	Suomenoja 3	80	–	coal
	Vermo1	80	–	natural gas
	Vermo2(bio oil)	35	–	bio oil
	Vermo2(gas)	45	–	natural gas
	Kaupunginkallio	80	–	light fuel oil
	Otaniemi	120	–	natural gas
	Juvanmalmi	15	–	natural gas
	Kalajärvi	5	–	light fuel oil
	Masala	5	–	natural gas
	Kirkkonummi	31	–	natural gas
HP	Suomenoja 4	40	–	-
CHP	Suomenoja 1	162	75	coal
	Suomenoja 2	213	234	natural gas
	Suomenoja 6	80	49	natural gas

Table A.3
Summary of heat production units in Vantaa DH network in 2019 [29,41].

Unit type	Unit	Starting year	Heat output (MW)	Power output (MW)	Main fuel
HOB	Koivukylä	1972	75	–	natural gas
	Hakunila	1972	80	–	natural gas
	Maarinkunnas	2002	180	–	natural gas

(*continued on next page*)

Table A.3 (*continued*)

Unit type	Unit	Starting year	Heat output (MW)	Power output (MW)	Main fuel
	Lentokenttä	2008	92	–	light fuel oil
	Varisto	2014	92	–	natural gas
CHP	Martinlaakso 2	1982	135	80	heavy fuel oil
	Martinlaakso 4 (Combined cycle)	1995	120	60	natural gas
	Martinlaakso 1 (bio)	2019	110	30.8	wood chips
	Jätevoimala	2014	147	76	waste

Appendix B. Energy technology data

Table B.1
Fuel conversion efficiency for different types of power plant [7].

City	units	total fuel input (MW)	total energy output (MW)	energy conversion efficiency
Helsinki	HOB_coal	185	180	97.30%
	HOB_natural gas	1016	934	91.93%
	HOB_heavy fuel oil	1118.9	1036.7	92.65%
	HOB_light fuel oil	180	164	91.11%
Espoo	HOB_coal	89	80	89.89%
	HOB_natural gas	525.2	473	90.06%
	HOB_light fuel oil	93.9	85	90.52%
	HOB_pellet	45	40	88.89%
	HOB_bio oil	41	35	85.37%
Vantaa	HOB_natural gas	563	517	91.83%
	HOB_light fuel oil	119.8	102	85.14%

Table B.2
Energy production units operation parameters in DH system [34,56,65].

Unit	Min. Load	Min. Operation Time	Starting up period	Shutting down period
CHP-ST	40%	24 h	8 h	8h
CHP-CCGT	40%	4 h	4 h	2h
CHP-OCGT	40%	4 h	0.5 h	1h
HOB	–	–	0 h	0h

Note: CHP-ST refers to the combined heating power plant with a steam turbine, generally fueled by coal and other solid fuels (in this research including waste, wood chips).
Gas-fueled CHP including CCGT and OCGT (Suomenoja 6, Martinlaakso GT).
Since HOBs are not modeled individually, it hasn't considered starting up period and shutting down period in the model.

Appendix C. Investment cost data

Table C.1
Helsinki low carbon technologies invested in DH system

		Investment cost(M€)	Lifetime	Annualized investment cost(M€)
Katri Vala HP	stage1	120.00	35	8.51
Esplanadi HP		10.00	35	0.71
Salmisaari wood pellet		20.00	40	1.42
Katri Vala HP	stage2	20.00	35	1.42
Katri Vala HP	stage3	66.67	35	4.73
Mustikkamaa		15.00	40	0.98
Patola HOB_wood pellet		26.09	40	1.85
Vuosaari HP		15.00	35	1.06
Vuosaari HOB_wood chips		650.00	40	46.12
Tattarisuo HOB_ wood chips		190.00	40	13.48
Kruunuvuorenranta		17.31	40	1.13

There is no accurate commission year of the Tattarisuo and Patola HOBs_biomass in Helsinki DH, it will be involved in the 2025 model. Investment cost of wood chips fired HOB is assumed as 0.5 M€/MW fuel input [56].

Table C.2
Espoo low carbon technologies invested in DH system

		Investment cost(M€)	Lifetime	Annualized investment cost(M€)
Suomenoja HP	stage 1	14.40	35	0.88
Bio oil HOB		30.00	40	1.75
Heat storage		1.04	40	0.06

(continued on next page)

Table C.2 (*continued*)

		Investment cost(M€)	Lifetime	Annualized investment cost(M€)
HOB_wood pellets		40.00	40	2.33
Suomenoja HP	stage 2	8.00	35	0.49
HOB_wood chips		74.00	40	4.31

Different stage of HP in both Helsinki and Vantaa are estimated according to the first stage investment and capacity.

Table C 3
Vantaa low carbon technologies invested in DH system

	burn waste tonne/year	Investment cost(M€)	Lifetime	Annualized investment cost(M€)
CHP_waste	374000	258.06	40	15.04
HOB_waste	200000	138.00	40	8.04
VECTES		75.00	40	4.37

Investment cost of waste incineration power plants are assumed by 690 €/ton waste consumption [56].

Appendix D. Model validation results

Table D.1
Table D Model validation results 2015

GWh	Helsinki		Espoo		Vantaa		Total 3 areas	
	Real situation	Model result	Real situation	Model result	Real situation	Model result	Real situation	Model result
Coal	4232	3704	2064	2971	1183	1181	7479	7856
Natural gas	7541	7476	438	222	310	486	8289	8183
Fuel oil	181	0	90	0	42	0	313	0
Bio	34	0	0	0	0	0	34	0
Waste	0	0	0	0	1017	1017	1017	1017
others	0	0	6	0	0	0	6	0
Heat pumps	422	397	227	102	0	0	649	499
Total	12409	11577	2826	3295	2552	2683	17787	17555

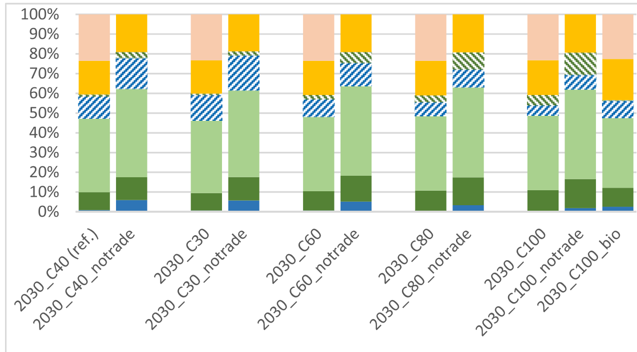
Comparison of real situation and model result about fuel consumption in DH in 2015 in Helsinki metropolitan area(GWh).

Table D.2
Model validation results 2010

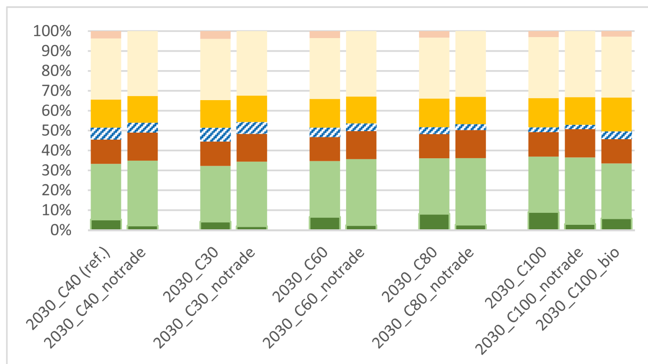
	Helsinki		Espoo		Vantaa		Total 3 areas	
	Real situation	Model result	Real situation	Model result	Real situation	Model result	Real situation	Model result
Coal	5281	5798	948	597	1272	1557	7501	7953
Natural gas	9253	10397	3878	4091	2142	1468	15273	15955
Fuel oil	369	39	52	1	110	0	530	40
Bio	0	0	21	0	7	0	28	0
Waste	165	0	0	0	0	0	165	0
others	15067	16234	4900	4689	3531	3025	23498	23948
Heat pumps	5281	5798	948	597	1272	1557	7501	7953
Total	9253	10397	3878	4091	2142	1468	15273	15955

Comparison of real situation and model result about fuel consumption in DH in 2010 in Helsinki metropolitan area(GWh).

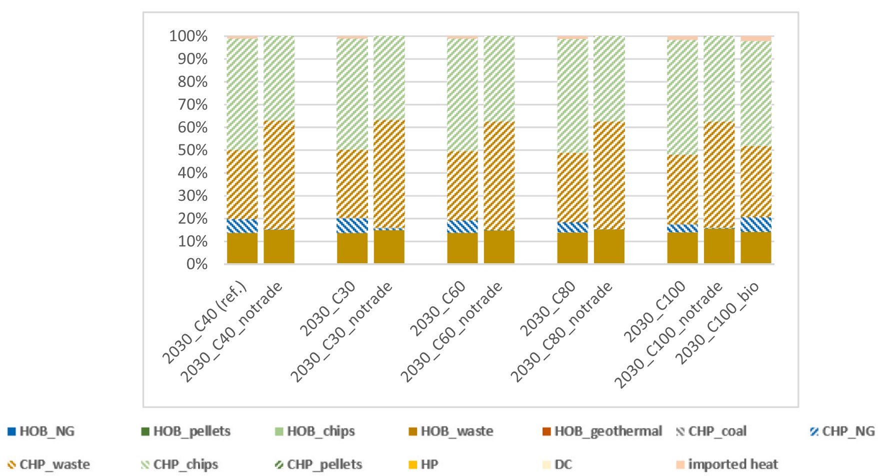
Appendix E. Production percentage in city-level DH system



a) Helsinki



b) Espoo



c) Vantaa

Fig. E.1. a), b) and c). Production percentage of total heat production by different types of units and energy sources under different scenarios.

Appendix F. Fuel consumption in 2010 and 2030

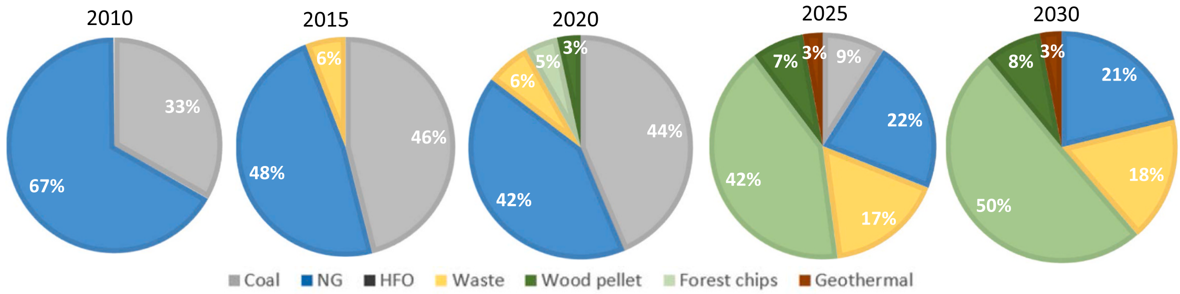


Fig. F.1. Percentage of fuel consumption from 2010 to 2030.

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