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Sustainable heating alternatives for 1960's and 1970's renovated apartment buildings

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A R T I C L E I N F O

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A B S T R A C T

The Finnish Government target of carbon neutrality by 2035 is challenging for the district heat (DH) systems of Finnish cities, as nearly 50% of the DH fuels are still fossil or peat. The DH price in Finnish cities is rising intensively. To avoid energy poverty, it is imperative to develop low-carbon DH solutions affordable for all customers. The feasibility of various low-carbon scenarios supplying a DH network is investigated with three different energy renovation levels. Biomass combustion technologies (combined heat and power (CHP) and heat only boiler (HOB)) and waste heat recovery technologies (Heat Pump and Electric Boiler) are analyzed. The economic and sensitivity analyses of the DH network are carried out from utility and end-user viewpoints. The operation cost and break-even price of heat are calculated in different renovation levels. Biomass HOB has the lowest operation cost at all renovation levels followed by waste heat-heat pump. Waste heat-heat pump + electric boiler has the lowest total cost, 53–58 €/MWh, at all renovation levels. Waste heat recovery scenarios were found sensitive to changes in electricity price. Waste heat-heat pump has the lowest overall emissions, whereas biomass combustion causes high emissions of biogenic CO_2, NO_x and particulate matter.

1. Introduction

According to the Sixth Assessment Report (AR6) by the International Panel on Climate Change (IPCC), finalized on August 6, 2021, human activities are considered as the main reason for the increased occurrence of extreme outcomes of climate change such as heavy precipitation, drought and tropical cyclones. Therefore, to curb global warming to an acceptable level, it is imperative to make strong and rapid reductions in the emission of CO_2, CH_4 and other greenhouse gases (AR6 Climate Change 2021, 2021). In the European Union (EU), the policy known as the European Green Deal, was published on December 2019 by the EU Commission. The European Green Deal is planning to achieve climate neutrality in the EU by 2050, i.e., net zero emission of greenhouse gases. Reaching this target requires about 55% reduction in the emissions of these gases by 2030 compared with 1990 levels. To achieve this goal in the energy sector, it is essential to develop decarbonization in power and heat generation units and to improve energy efficiency in buildings (A European Green Deal, 2019). For this reason, a legislative framework has been established by the EU that includes the Energy Performance of Buildings Directive (2010)/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU. In the EPBD, there are a variety of policies and methods which help national EU governments to improve energy performance of buildings and boost the existing building stock. Therefore, the EU countries must apply efficient measures of renovation to decarbonize the national building stocks by 2050 (Energy performance of buildings directive, 2022).

In Finland, the Finnish long-term renovation strategy 2050 was prepared to reduce the energy consumption and emissions of the existing building stock by 90% and it was submitted to the EU in 2020. To achieve this goal, the strategy focuses on energy efficiency and space utilization efficiency, as well as on low-carbon heating solutions such as low-carbon DH networks (Implementation of the EPBD Finland, 2022).

However, while the share of renewable and other clean sources of energy in supplying DH networks of Finnish cities has increased in recent years, fossil fuels and peat are still used to support nearly 50% of DH networks (Statistics Finland - Production of electricity and heat 2019, 2019). Finland's official target is carbon neutrality by the year 2035 (Government's climate policy, 2035). The large shares of nuclear, hydropower, biomass and wind generation make the Finnish electricity very low-carbon and consequently, electrification of DH networks would be desirable from a CO_2 reduction viewpoint.

One of the main challenges facing the decarbonization in heating systems is the rising heating cost. In Finland DH is a competitive

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Abbreviation

AR6	Sixth Assessment Report	HOB	Heat Only Boiler
BECCS	Bioenergy with Carbon Capture and Storage	HR	Heat Recovery
BEP	Break-Even Price	IPCC	International Panel on Climate Change
CCS	Carbon Capture and Storage	LCC	Life Cycle Cost
CHP	Combined Heat and Power	LTR	Low Temperature Radiators
$CO_{2\text{-eq}}$	carbon dioxide equivalent	MSW	Municipal Solid Waste
DH	District Heating	NO_x	Nitrogen Oxide
EER	Energy Efficiency Retrofit	NPV	Net Present Value
EP	Energy Poverty	nZEB	nearly Zero Energy Buildings
EPBD	Energy Performance of Buildings Directive	O&M	Operation and Maintenance
EPOV	Energy Poverty Observatory	PV	Solar Electric Systems
ETS	Emissions Trading System	ST	Solar Thermal
EU	European Union	TRY	Test Reference Year
		UEH	Urban Excess Heat
		U-value	Thermal insulation factor

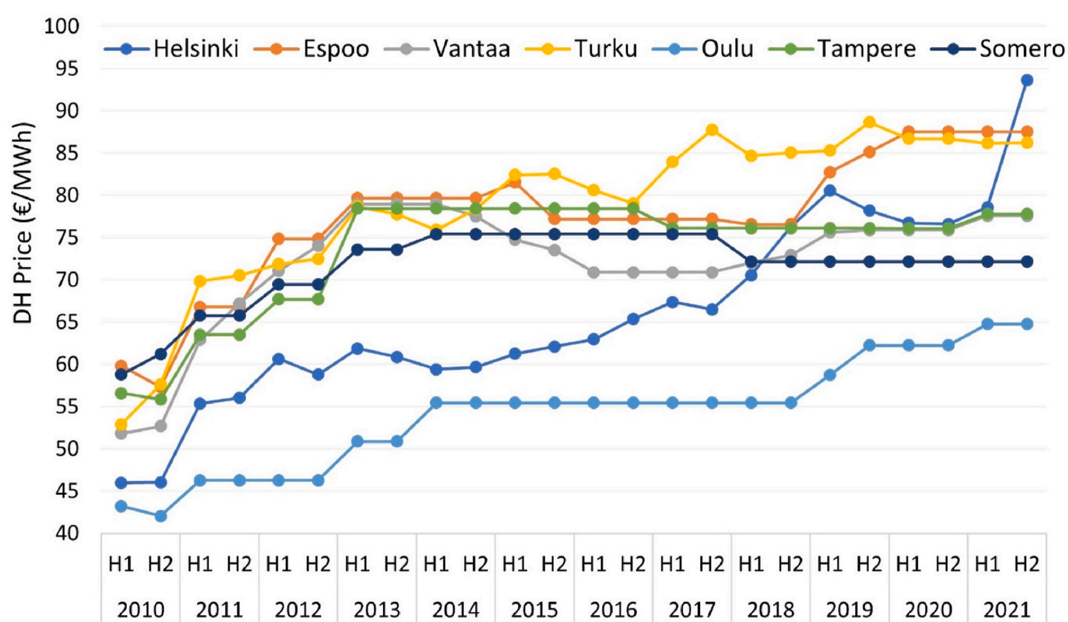

Fig. 1. The DH price in six largest cities and a small community with biomass-HOB (Somero) in Finland during 2010–2021 (District heat price statistics, 2022), H1 and H2 represent the first and second half year, respectively.

business, where the price in each city is impacted by the technologies used and their capital costs, the prices of fuels and the EU carbon dioxide Emissions Trading System (ETS) (District heating price to surge – price hikes of 70 per cent possible by 2020, 2020). DH price in Finnish cities has a strongly increasing trend since 2010. Fig. 1 illustrates the DH price for six largest cities in Finland during the period of 2010–2021. In addition, an example of a small community (Somero) is shown (District heat price statistics, 2022).

In Oulu, which has the lowest DH price in this category, local fuels peat and wood make up more than 90% of the fuels supplying the power plants (Finland, 2018). At the moment, the DH price in most cities in Finland is rising intensively. DH companies are announcing large price increases, for example a raise of 30% compared to previous Autumn was announced by the Helsinki DH company Helen Ltd in September 2021. As the main reason behind these changes, the EU ETS carbon price has risen from 6 euros in 2016 to over 80 euros in 2022 (Carbon Price Viewer, 2022). In contrast, the graph for Somero as a small community with biomass HOB shows the least fluctuations during the period and even a decline in the price in 2018.

Energy Poverty (EP) can be defined as a situation in which households can't afford the cost of energy required in daily life, or in a strict definition, a state in which the households are obliged to spend an unreasonably high share of their income to meet their basic needs to energy (Energy Poverty in Europe, 2022). While there are several reasons behind EP, ranging from low income and financial problems to poor energy efficiency in houses, the rising heating cost plays a significant role in this issue. According to the Energy Poverty Observatory (EPOV) in 2018, about 7.7% of the Finnish population was unable to pay their utility bills due to financial problems and 1.7% of the population couldn't keep their houses adequately warm (Member State Report of the EU Energy Poverty Observatory (EPOV) in Finland," 2020, 2020). Although these figures are relatively low in comparison with most European countries (Castaño-Rosa, 2022), there is a vulnerability due to recent rising price in DH systems. Therefore, it is important to take the heating cost into account when decarbonizing the DH networks.

2. Literature review and contribution of this paper

In this chapter, relevant recent studies are reviewed in three subsections of low-carbon DH networks based on heat pumps and waste

Table 1
Summary of literature review.

Reference	Country	Year	Measures/Technologies decarbonizing DH systems	Summary of results
Lund et al. (2016)	Denmark	2016	Large scale heat pumps	The optimal capacity for heat pumps in Danish DH network is in the range between 2 and 4 GW of thermal power.
Khosravi et al. (2021)	Finland	2020	Recovering waste heat from a data center and LuxTurrim5G smart poles by Heat pump and Heat Only Boiler (HOB)	Heat pump is more cost-effective to recover waste heat from data center with LCOE of 31.92 €/MWh (if it is powered by PV system) and LCOE of 35.16 €/MWh (if it is powered by electricity market).
Hiltunen and Syri (2020)	Finland	2020	Recovering waste heat from a data center by Heat pump	The electricity price has a significant impact on the feasibility of waste heat utilization.
Sandvall et al. (2021)	Sweden	2020	Urban Excess Heat (UEH) sources	Utilization of UEH in DH system is more profitable compared to a DH system with a boiler.
Moser and Lassacher (2020)	Austria	2020	Industrial waste heat	About 7% of the heat supplied by national district heating networks in Austria is provided by industrial waste heat.
Hammar and Levihn (2020)	Sweden	2020	Biomass fired CHP plant	Combusting biomass has a higher potential to mitigate climate change compared to Municipal Solid Waste (MSW), also utilizing carbon capture and storage (CCS) improves this potential.
Balaman and Selim (2016)	-	2016	Biomass based renewable energy supply chain	Developed a new decision model that can be used effectively to design sustainable biomass-based energy supply chain with DH systems in various regions.
Karschin and Geldermann (2015)	Germany	2015	Bioenergy production and distribution	Developed a model to assess the economic and environmental effects by different input parameters in bioenergy villages in various regions.
Paredes-Sánchez et al. (2018)	Metropolitan Area of Vigo (MAV)	2018	Wood waste from wood processing industries	The production and use of wood waste in the MAV, helped to develop a total of eight DH systems and to improve the economic balance of this region.
Hirvonen et al. (2019a)	Finland	2018	Optimizing different renovation measures to reduce the annual carbon dioxide emissions and LCC	Proposed four different levels of renovation measures for different age groups of apartment buildings.
Monzón-Chavarrías et al. (2021)	Portugal, Spain	2020	Renovating residential buildings based on nZEB requirements	The proposed renovations may decrease the carbon dioxide emissions by 80–96% in Portugal and 71–94% in Spain.
Liu et al. (2018)	China	2018	Efficient renovation measures in buildings	Proposed a framework that helps policy makers to have a cost-effective analysis of Energy Efficiency Retrofit (EER) to reduce the energy used in buildings.
Hirvonen et al. (2021)	Finland	2021	Efficient renovation measures in buildings	The proposed energy retrofit measures can make a decline of 25–63% in district heating demand, and a reduction of 50–75% in CO2 emissions by 2050.

heat recovery, low-carbon DH networks based on biomass fuels, and efficient renovation measures to decarbonize buildings. Table 1 summarizes these studies considering the year and location of study. Then the contribution of the current study is presented at the end of this section.

2.1. Low-carbon DH networks based on heat pumps and waste heat recovery

In recent years, heat pumps have been investigated from different views to develop low-carbon DH networks. Their availability in different scales as well as their high potential to recover waste heat from different sources with a wide range of temperature make heat pumps a popular technology in developing low-carbon DH networks. Rasmus Lund et al. investigated the feasibility of large-scale heat pumps in district heating systems in Denmark. They concluded that the optimal capacity of heat pump in Danish DH network would be in the range between 2 and 4 GW of thermal power, and a total potential benefit of 100 M€/year in the year 2025 (Lund et al., 2016). A. Khosravi et al. investigated the feasibility of heat pumps and HOB to retrieve waste heat from a data center and LuxTurrim5G smart poles. They compared different scenarios providing electricity for heat pump as well as different fuels for HOB and concluded heat pumps as a cost-effective way to retrieve waste heat from data centers (Khosravi et al., 2021). Pauli Hiltunen et al. evaluated the feasibility and possibility of using waste heat from a data center to decarbonize DH systems. They used heat pump to improve the temperature of waste heat and concluded that the electricity price has a significant impact on the feasibility of waste heat utilization (Hiltunen and Syri, 2020). Akram Sandvall et al. evaluated the impact of four different Urban Excess Heat (UEH) sources on DH system in different cities in Sweden. They concluded that the use of UEH in DH system not only improves the competitiveness of DH against individual heating systems, but also makes it more profitable compared to a DH system with a boiler (Sandvall et al., 2021). Simon Moser et al. reviewed the existing implementations of external use of industrial waste heat in Austria and concluded that DH networks have the highest implementations (42 of 45 implementations). According to their study, about 7% of the heat supplied by national district heating networks in Austria is provided by industrial waste heat (Moser and Lassacher, 2020).

2.2. Low-carbon DH networks based on biomass fuels

The potential of biomass fuels to develop low-carbon DH systems has been investigated in many studies. Torun Hammar et al. investigated the potential of a new CHP plant to mitigate climate change in Stockholm, Sweden. In their study, the dynamic effects on a fourth generation DH system were assessed. They carried out different scenarios including forest residues combustion, Municipal Solid Waste (MSW) combustion, waste wood combustion, hard coal combustion, and wood chips combustion with carbon capture and storage (BECCS). As a result, they found that combusting wood chips has a higher potential to mitigate climate change compared with hard coal and MSW, also utilizing carbon capture and storage (CCS) improves this potential (Hammar and Levihn, 2020). Balaman et al. developed a new decision model for a sustainable design of biomass based renewable energy supply chain integrated with DH systems with thermal energy storages. They presented this model with the aim of minimizing the costs while maximizing the level of meeting heat demand. They concluded that the presented model and algorithm can be used effectively to design sustainable biomass-based energy supply chain with DH systems in various regions (Balaman and Selim, 2016). Ingo Karschin et al. presented a linear mathematical model to optimize bioenergy production and distribution system by considering different factors of DH systems in bioenergy villages such as biomass availability, number of heat customers and heat loss. They used

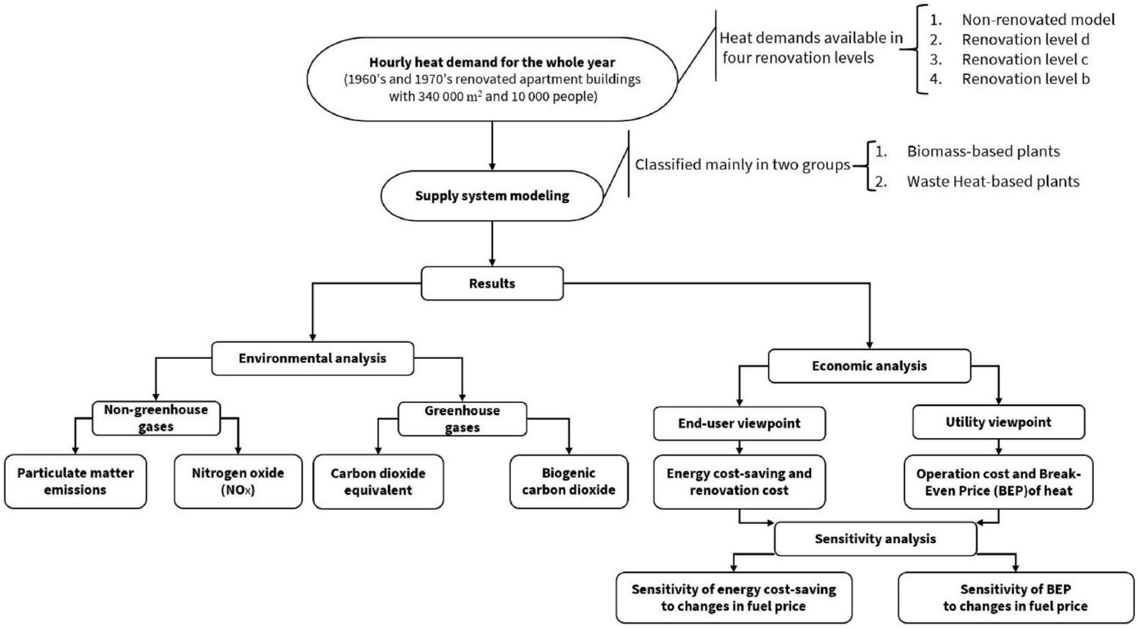

Fig. 2. The schematic diagram of analyzing process and the goals of the current study.

a small village in Lower saxony in Germany as the case study and proposed the use of the model to assess the economic and environmental effects by different input parameters in bioenergy villages in various regions (Karschin and Geldermann, 2015). Paredes-Sanchez et al. studied bioenergy from wood processing industry in the Metropolitan Area of Vigo (MAV). The purpose of their study was to improve the existing methods and develop new methods to evaluate wood waste in terms of quantity, energy and cost, while considering techno-economic and environmental analyses. The production and use of wood waste in the MAV helped to develop a total of eight DH systems and to improve the economic balance of this area (Paredes-Sánchez et al., 2018).

2.3. Efficient renovation measures to decarbonize buildings

Energy efficiency of buildings plays an important role in decarbonizing DH systems. Janne Hirvonen et al. classified Finnish apartment buildings in four different age groups. Each group of these apartment buildings was optimized for different renovation measures with the aim of reduction in annual carbon dioxide emissions and Life Cycle Cost (LCC). As a result, they proposed four different levels of renovation measures for each group of apartment buildings (Hirvonen et al., 2019a). Marta Monz'on-Chavarrías et al. assessed nearly Zero Energy Buildings (nZEB) requirements to renovate the residential buildings with the construction year between 1961 and 1980 in Portugal and Spain. They concluded that this renovation would decrease the carbon dioxide emissions about 80–96% in Portugal and 71–94% in Spain (Monzón-Chavarrías et al., 2021). Yuming Liu et al. proposed a framework based on the LCC of buildings in northern regions of China. This framework would help policy makers to have a cost-effective analysis of Energy Efficiency Retrofit (EER) to reduce the energy used in buildings (Liu et al., 2018). Janne Hirvonen et al. investigated the potential of four energy retrofit measures in Finnish building stock. They concluded that the proposed energy retrofit measures can make a decline of 25–63% in district heating demand, and a reduction of 50–75% in CO_2 emissions by 2050 (Hirvonen et al., 2021). These studies highlight the importance of building energy efficiency measures in meeting ambitious decarbonization targets.

2.4. Contribution of this paper

Based on the literature review above, there are strengths and weaknesses in each solution of decarbonizing DH systems. However, in the existing literature, there is no study comparing these solutions in a DH network. This paper aims to develop a low-carbon and sustainable DH network located in Southern Finland by comparing and analyzing the mentioned solutions. The alternatives supplying DH network are investigated in six different scenarios:

- Biomass-CHP (100% sizing of peak demand) (Fig. 3a)
- Biomass-HOB (100% sizing of peak demand) (Fig. 3a)
- Biomass-CHP (50% sizing of peak demand) + Biomass-HOB (50% sizing of peak demand) (Fig. 3a)
- Electric Boiler (100% sizing of peak demand) (Fig. 3b)
- Waste Heat-Heat Pump (100% sizing of peak demand) (Fig. 4a)
- Waste Heat-Heat Pump (50% sizing of peak demand) + Electric Boiler (50% sizing of peak demand) (Fig. 4b)

At the same time, the apartment buildings located in the DH network are investigated at three different energy renovation levels and the reference level. In other words, the performance of each scenario supplying DH network is investigated in four different heat demand scenarios based on four different energy renovation levels.

The economic analysis of the DH network is carried out from two points of view: utility viewpoint and end-user viewpoint. At the utility viewpoint, the operation cost and break-even price (BEP) of heat are calculated and compared for different scenarios supplying DH network with different building renovation levels. At the end-user viewpoint, the non-renovated level of buildings is considered as the reference case to calculate energy cost-saving. The energy cost-saving is compared to renovation cost by different renovation levels to find the best level from the end-user viewpoint. In environmental analysis, the emissions of greenhouse gases and non-greenhouse gases, i.e., Nitrogen Oxide (NO_x), and particulate matter, by each scenario and renovation level are calculated and compared. Moreover, the sensitivity of each scenario to changes in fuel price is investigated in a sensitivity analysis by considering the BEP of heat and cost-saving as target variables. The fuel for biomass combustion scenarios is wood chips, but in waste heat recovery scenarios both electricity and waste heat are considered as input "fuel".

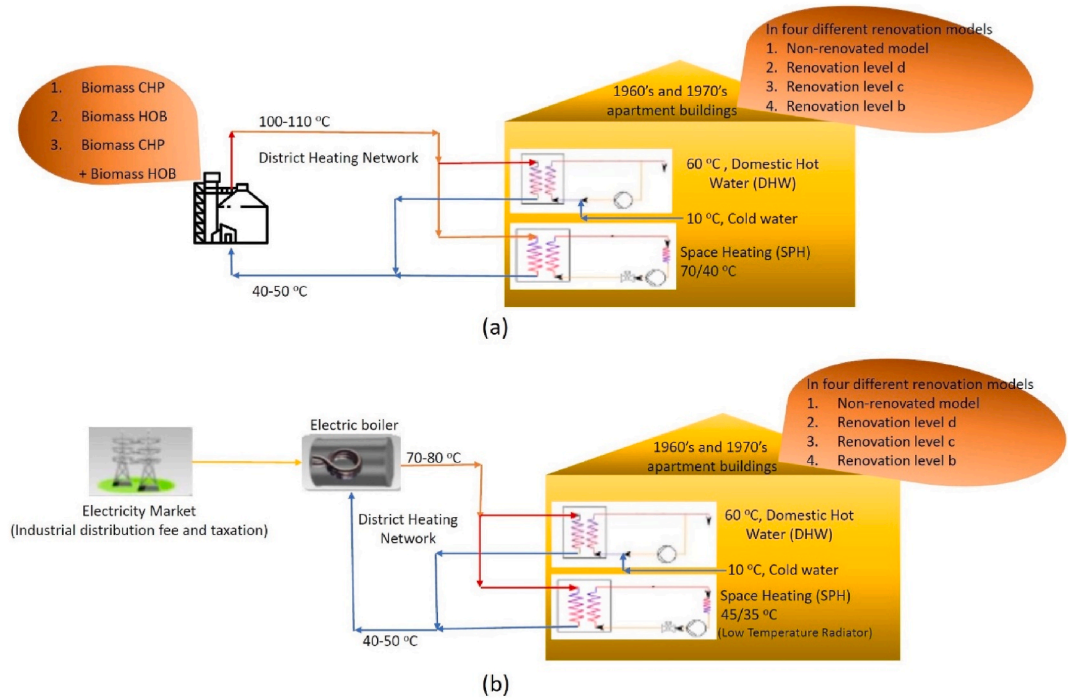

Fig. 3. The schematic diagram for a) biomass-based scenarios and b) the scenario of Electric boiler.

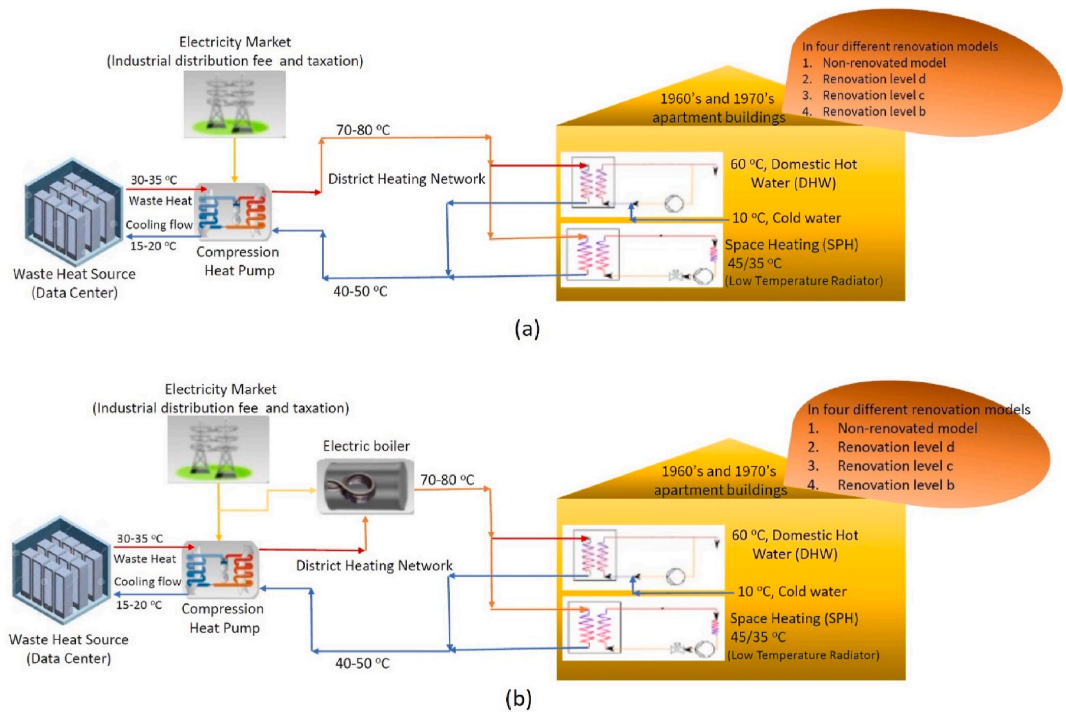

Fig. 4. The schematic diagram for a) the scenarios of Waste Heat-Heat Pump and b) Waste Heat-Heat Pump + Electric boiler.

Sensitivity analysis reveals the most sensitive scenarios to changes in fuel price. Fig. 2 describes the process of calculations.

Briefly, the main contributions of this paper are stated as below:

- A comprehensive comparison between biomass combustion technologies and waste heat recovery technologies (in different scenarios) as two significant solutions to develop low-carbon DH networks.
- Evaluation of each scenario supplying DH system in three different energy renovation levels as the third necessary solution in developing low-carbon DH systems.
- Considering both utility and end-user viewpoints in economic analysis, to find the most profitable solution in each case.
- Investigating a novel scenario where the supply system is composed of an electric boiler (with low capital cost and high operation cost) and a heat pump (with high capital cost and low operation cost).

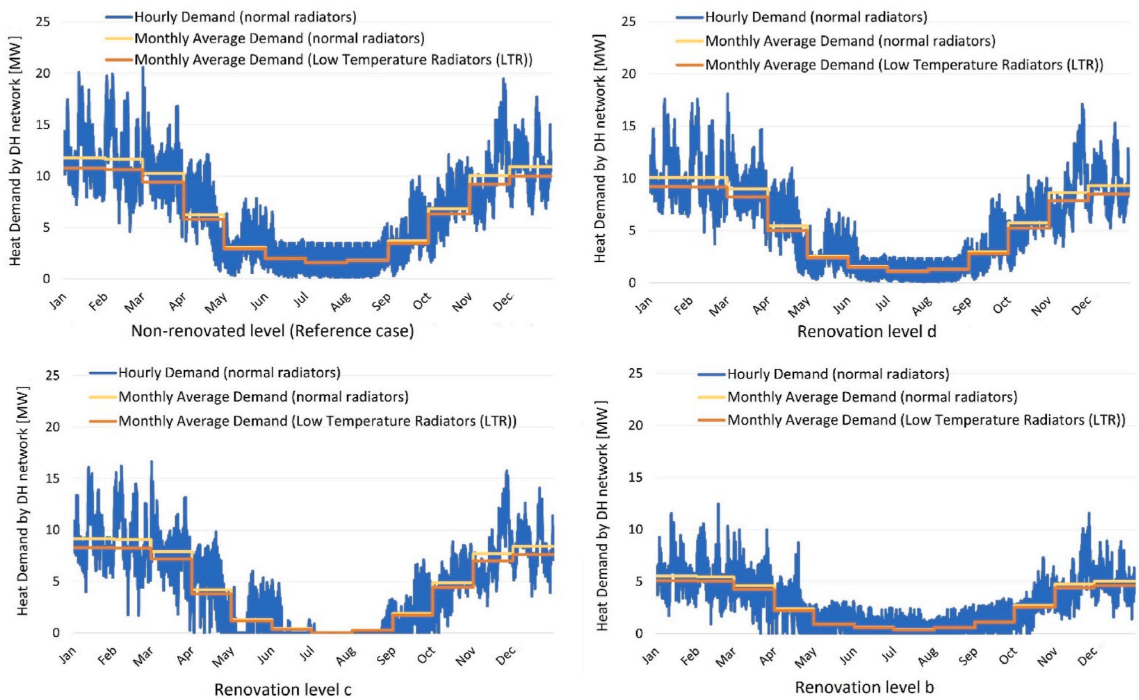

Fig. 5. Hourly and monthly average heat demand by DH network in different energy renovation levels (Hirvonen et al., 2019a).

3. Materials and methods

This section includes five subsections as following: Description of buildings and the renovation measures, Modeling the scenario supplying DH network, Economic analysis, Sensitivity analysis, and Environmental analysis.

3.1. Description of buildings and the renovation measures

The evaluated DH network in this paper focuses on one of the most common building types in Finland with the construction year before 1976. This represents a large part of the apartment building stock in Finnish cities. Our hypothetical case area located in southern Finland with an area of 340 000 m^2 and a population of 10 000. Suburb regions of this size were commonly and rapidly constructed in growing Finnish cities from the late 1960's to the early 1970's, when Finland experienced a boom in former rural population moving to cities due to reduced labour need in agriculture and forestry.

In this paper, we evaluate the potential of three different cost-effective renovation measure sets for the mentioned building by considering a variety of technologies supplying the DH network. We notate the renovation levels according to the original scenarios developed in (Hirvonen et al., 2019a) i.e., b, c, d. Table 1 compares the mentioned renovation levels with the reference case (non-renovated level).

The thermal insulation factor (U-value) for different parts of the building shows how heat demand can be reduced at different renovation levels. In addition to this, at all renovation levels, the auxiliary equipment i.e., solar thermal (ST), and solar electric systems (PV) are used to support the main heating system. Furthermore, in the reference case, there is no heat recovery (HR) in the building, but in the renovated models, HR from wastewater is possible through two different options i.e., passive HR (30% efficiency) and active HR (70% efficiency). Renovation level b has the highest initial investment and the highest ability to reduce energy consumption. While renovation level c is a moderate solution, the renovation level d has the lowest initial investment and the lowest ability in reducing energy consumption compared to the other cases. More detailed information about these renovation measures is available in (Hirvonen et al., 2019a).

The scenarios supplying DH network in this paper are classified as high-temperature scenarios, i.e., biomass combustion scenarios, and low-temperature scenarios, i.e., waste heat recovery scenarios. In high-temperature scenarios, the radiator used in the buildings is a normal radiator with the temperature range of 70/40 °C (Fig. 3a), but in low-temperature scenarios the considered radiators in the buildings are Low Temperature Radiators (LTR) with temperature range of 45/35 °C (Figs. 3b and 4a and b). LTR is about 10% more efficient compared to normal radiators, making a small difference in the heat demands between high-temperature and low-temperature scenarios.

Fig. 5 shows the hourly and monthly average heat demand for each renovation level by high-temperature and low-temperature scenarios. The use of thermal insulation in different parts of the buildings, mainly in the roofs and windows, as well as the use of supporting systems and sewage HR reduce the heat demand significantly. At the renovation level c, the heat demand during August is almost zero, which is due to the use of active HR and solar energy in this renovation level. A detailed description of the hourly energy demand calculation can be found in (Hirvonen et al., 2019a). In brief, they are the result of IDA-ICE model simulations of building energy performance in the conditions of Southern Finland. In addition, multi-objective optimization was performed with MOBO software, utilizing the NSGA-II genetic algorithm and parallel computation. Thus, the multi-objective optimization ensured that the most cost-efficient combinations of energy renovation measures were chosen in the scenarios b, c and d, representing renovations of varying ambition.

Since the heat demands shown in Fig. 5 are for a Test Reference Year (TRY) (Hirvonen et al., 2019a) all data used in the DH modeling including biomass price, electricity price, the initial investment for used technologies and their Operation and Maintenance (O&M) cost is the average of values in the years 2015–2020.

3.2. Modeling the scenario supplying DH network

This subsection is continued in two parts of modeling description for biomass combustion scenarios and modeling description for waste heat recovery scenarios.

Table 2
The main features in different renovation levels compared to the non-renovated model (Hirvonen et al., 2019a).

Parameters		Non-renovated model	d*	c*	b*
Heat Demand (GWh)	Radiator (70/40 °C)	58.1	49.2	40	24.7
	LTR (45/35 °C)	53.7	45.3	36.3	23
Investment Cost (€/m^2)	Radiator (70/40 °C)	0	122	156	339
	LTR (45/35 °C)	37	159	193	376
U-values (W/m^{2}K)	Walls	0.81	0.81	0.81	0.36
	Roof	0.47	0.1	0.08	0.08
	Doors	2.2	2.2	2.2	2.2
	Windows	1.7	0.8	0.7	0.8
Supporting Systems	ST (m^2)	0	5	55	55
	PV (kW$_p$)	0	35	30	30
Ventilation		No HR	No HR	No HR	HR + DBV
Sewage HR		No HR	Passive HR	Active HR	Passive HR

*b: (Average cost solution), c: (Cost-neutral solution), and d: (Least cost solution).

3.2.1. *Biomass combustion scenarios*

The biomass combustion scenarios are modelled with the help of energyPRO software of EMD International A/S, Aalborg, Denmark. EnergyPRO can provide a comprehensive analysis of different electricity and thermal energy producing systems from technical and economic views. More information about energyPRO software is available in (energyPRO, 2022).

To select the most suitable fuel for combustion-based scenarios, the feasibility of different bioenergy fuels was evaluated. Biogas has a considerable potential to decarbonize DH networks, but its high price compared to existing fossil fuels like natural gas has reduced its chance in this competition (Natural gas price reduced, 2016). Thus, solid biomass fuels, i.e., wood pellets, wood chips, and cereal straw were considered. Due to the high baling and transporting cost, cereal straw is not a suitable case for Southern Finland, although it can be regarded as a possible biomass fuel in Southeast Finland (Laitila et al., 2016). Moreover, the price of wood pellets in Finland is by far higher than wood chips (Biomass price, 2022). Therefore, wood chips are the most feasible and cost-effective solid biomass fuel in Southern Finland.

The biomass combustion technologies are investigated in three different scenarios as below (Fig. 3a):

- o Biomass-CHP (100% sizing of peak demand)
- o Biomass-HOB (100% sizing of peak demand)
- o Biomass-CHP (50% sizing of peak demand) + Biomass-HOB (50% sizing of peak demand)

The technical and economic data used for the biomass-CHP (reported in Table 5) is according to the data of a real biomass plant located in Järvenpää, Finland (Bioenergy plant connects järvenpää and, 2022). In all biomass combustion scenarios, the considered price for wood chip is the average of its price in Finland in the years 2015–2020, which equals

Table 4
The electricity distribution fee and taxation for industrial users by the Caruna company in Southern Finland (Electricity distribution rates, 2022).

Parameter		Value (€/MWh)
Electricity distribution fee	Daily transmission, winter	11.12
	Other time transmission	7.27
Electricity taxation		7.03

Table 5
The technical and economic data used in modeling different technologies to supply the DH network ("Bioenergy plant connects järvenpää and, 2022), (Technology catalogue for the production of electricity and district heating, 2022), (Flyktman et al., 2595).

Technical and Economic data	Biomass CHP (based on Järvenpää power plant)	Biomass HOB	Electric Boiler	Heat Pump
Total efficiency/COP	87%	92%	98.50%	5
Thermal efficiency	57.60%	-	-	-
Electrical efficiency	29.40%	-	-	-
Variable O&M [€/MWh input]	1.4	2.65	0.85	1.7
Fixed O&M [€/MW output/y]	30 000 [€/MW-el]	14 000 [€/MW input]	1085	2000
Initial Investment [M€/MW input]	1.079	0.7	>10 [MW] 0.07 <10 [MW] 0.15	0.67
Technical lifetime [years]	25	25	20	25

to 21 €/MWh (Statistical databases, 2022).

3.2.2. *Waste heat recovery scenarios*

While there are several options of waste heat available, the waste heat source investigated in this paper is a data center. In Espoo, there is a 100 MW data center planned to be connected to the DH network (Hiltunen and Syri, 2020). Since low-grade waste heat from a data center has an average temperature about 35 °C (Wahlroos et al., 2017) auxiliary technologies are needed to raise its temperature for supplying the DH network. In this paper, the potential of a compression heat pump and an electric boiler in raising waste heat temperature are investigated as following scenarios:

- o Waste Heat-Heat Pump (100% sizing of peak demand) (Fig. 4a)
- o Waste Heat-Heat Pump (50% sizing of peak demand) + Electric Boiler (50% sizing of peak demand) (Fig. 4b)

In the modeling of waste heat recovery scenarios, the heat buy-in price list by Fortum company in Espoo (Open district heating purchase prices, 2022) was used as the reference for waste heat price (Table 3). It should be noted that waste heat price in the scenario of waste heat-heat pump (Fig. 4a) is according to prices for the supply side in Table 3, because in this scenario the waste heat is feeding the supply side of the DH network. However, in the scenario of waste heat-heat pump +

Table 3
The waste heat price according to heat buy-in price by Fortum company for Espoo (Open district heating purchase prices, 2022).

Outdoor Temperature (°C)	≤ −8	(-7.9, −7)	(-6.9, −4)	(-3.9, −3)	(-2.9, −2)	(-1.9, −1)	(-0.9, 4)	(4.1, 6)	(6.1, 7)	(7.1, 16)	16.1 ≤
Supply Side (€/MWh)	50	47.5	45	42.5	40	35	30	25	22.5	20	15
Return Side (€/MWh)	35	33.5	32	28	28	21	21	18	14	10	8

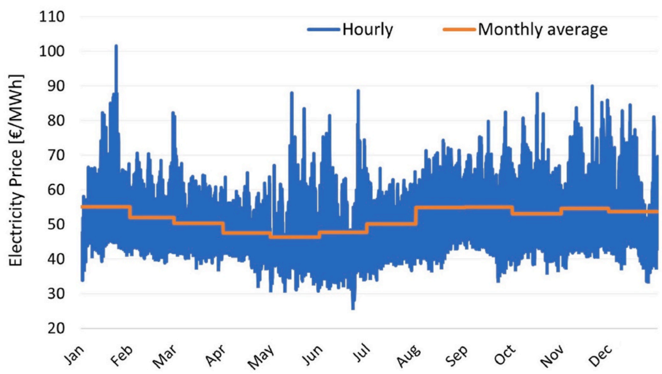

Fig. 6. The electricity price, including spot price, distribution fee and taxation for Industrial users during a TRY in Finland (Market data, 2022), (Electricity distribution rates, 2022).

electric boiler (Fig. 4b), the waste heat price is according to return side price, since in this case the waste heat is feeding the return side of the DH network.

The electricity price consists of three parts: the hourly Nord Pool spot price, distribution cost, and electricity tax. The hourly Nord Pool spot price in TRY was estimated by the average of the hourly spot prices in the years 2015–2020 (Market data, 2022). Moreover, the considered distribution cost and electricity tax in TRY (Table 4) are the average costs listed by the regional distribution company Caruna during 2015–2020 (Electricity distribution rates, 2022). Fig. 6 shows the hourly electricity price for industrial users during a TRY in Finland.

3.3. Economic analysis

This paper aims to find low-carbon DH solutions which are affordable for customers. As an indicator, the Break-even Price (BEP) of heat produced by each scenario is evaluated. Also heating cost, savings and profitability of the energy efficiency investments are evaluated as explained in the following.

3.3.1. Break-even price (BEP) of heat (utility viewpoint)

In BEP analysis, in addition to operation cost, the initial investment which has a significant impact on the feasibility of each scenario is involved, too. To see the thermal capacity and the initial investment by each scenario and renovation level please refer to the appendix, Table.A2 and Table.A3, respectively.

The operation cost is composed of fuel cost (i.e., wood chips or waste heat + electricity), variable O&M cost, and fixed O&M cost.

$$\text{Operation Cost} = C_{\text{fuel}} + C_{\text{variable O\&M}} + C_{\text{Fixed O\&M}} \tag{1}$$

While the only income in each scenario is from selling heat to the DH network, in biomass CHP, the revenue from exporting generated electricity to the grid is considered as well. This electricity is sold to the grid according to the hourly Nord Pool spot price in TRY which is the average spot price in the years 2015–2020. Therefore, the net income is calculated as below:

$$\text{Net Income} = R_{\text{heat sale}} + R_{\text{electricity sale}} - \text{Operation Cost} \tag{2}$$

The Net Present Value (NPV) for each scenario in each renovation measure is as below:

$$\text{NPV}_n = \sum_{t=1}^{t=n} \frac{\text{Net Income}}{(1+r)^t} - \text{Initial investment} \tag{3}$$

In which n is the number of years, r is the interest rate of energy with the value of 0.02 (Hirvonen et al., 2019b) and the initial investment for each scenario has been reported in Table 5.

Finally, the BEP of heat produced by each scenario after n years is calculated. In this research, 20 years ($n = 20$) was considered as the required time to cover the initial investment by net income. It should be noted that the residual value after the lifetime of each technology was assumed zero.

3.3.2. Heating cost, saving, and profitability during life cycle (end-user viewpoint)

In this section, we want to find how each renovation level brings energy cost-saving to customers. For this reason, the heating cost during the life cycle is calculated based on BEP as below:

$$\text{Cost of heating}_{25} = \sum_{t=1}^{t=25} \frac{\text{Break even price of heat}}{(1+r)^t} \tag{4}$$

In which r is the interest rate of energy with the value of 0.02 (Hirvonen et al., 2019b). Then, in each scenario supplying DH network, to calculate energy cost-saving by each renovation level, the non-renovated model of buildings is considered as the reference case. In other words, saving for each renovation level is defined as heating cost by non-renovated model minus heating cost by that renovation level.

However, energy cost-saving is not the only parameter in finding the most profitable renovation level since different levels of renovation have different costs. To decide about the most profitable renovation level in each scenario, we consider both the energy cost-saving and the renovation cost. The costs of buildings renovation (Table 2) are according to (Hirvonen et al., 2019a).

3.4. Sensitivity analysis

To show the sensitivity of different scenarios supplying DH network to input variables and to find the least sensitive scenario in each renovation level, a sensitivity analysis is carried out. In this analysis, wood chip price, electricity price as input to electric technologies and waste heat price are investigated as input variables. The target variables are the BEP of heat and cost-saving by each scenario and renovation level. In all cases, the changes in target variables are calculated by changing input variables from −10% to 10%. The sensitivity analysis is presented for the renovation level b (the highest level of renovation).

3.5. Environmental analysis

The average emission factors by waste heat recovery scenarios were calculated by considering the emission factor of different fuels, i.e., coal, oil, natural gas, peat, and wood biomass and their share in annual electricity generation in Finland (Fuel classification 2021, 2021)–(Purchase of electricity by energy, 2022), to see the average emission factors please refer to Table.A1 in Appendix.

The greenhouse gases emissions by each scenario supplying DH network are assessed as $CO_{2\text{-eq}}$ which includes carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). However, CO_2 from combustion of biomass fuels (biogenic CO_2) increases the concentration of CO_2 in the atmosphere only when the utilization exceeds the annual natural carbon sink (Fossil vs biogenic CO2 emissions, 2022).

Moreover, the emission rate of NO_x and particulate matter as non-greenhouse but harmful emissions are calculated and compared for each scenario supplying DH network (Häsänen et al., 1986)- (Karvosenoja et al. Johansson).

4. Results and discussion

In this section the results of economic, sensitivity, and environmental analysis are presented in three subsections, respectively.

Table 6
The operation cost (€/MWh) by different scenarios supplying the DH network in different renovation levels.

The Supply system	Non-renovated (€/MWh)	d (€/MWh)	c (€/MWh)	b (€/MWh)
Biomass CHP	44.8	45	45.8	47.1
Biomass HOB	30.8	31	31.7	38.6
Biomass CHP + Biomass HOB	43.5	43.9	44.4	46.4
Electric Boiler	55.1	55.1	55.1	55.7
Waste Heat-Heat Pump	40.9	41.2	42.5	42.2
Waste Heat-Heat Pump + Electric Boiler	43.7	43.8	44.4	44.6

Table 7
The break-even price of heat (€/MWh) by different scenarios supplying DH network in different renovation levels.

The Supply system	Non-renovated (€/MWh)	d (€/MWh)	c (€/MWh)	b (€/MWh)
Biomass CHP	68.4	70.4	77.2	88.6
Biomass HOB	46.7	47.5	50.4	61.2
Biomass CHP + Biomass HOB	55.3	57.2	61.8	73.3
Electric Boiler	56.7	56.8	57	58
Waste Heat-Heat Pump	55.9	56.8	60.4	63.6
Waste Heat-Heat Pump + Electric Boiler	52.9	53.4	55.3	57.7

4.1. Economic analysis

4.1.1. Break-even price of heat (utility viewpoint)

Table 6 compares the operation cost by each scenario and renovation level. In all renovation levels, the operation cost by biomass HOB is by far lower than other plants supplying DH network. In contrast, the highest figure in each renovation level is for the scenario of electric boiler. In each scenario, the non-renovated level of the DH network has a lower operation cost per unit (€/MWh) compared to the renovation levels b-d, which is due to the higher heat demand and its direct influence on the required capacity, fuel cost and O&M cost.

Table 7 shows the BEP of heat by each scenario and renovation level. According to Eqs. (2) and (3), the BEP of heat is directly influenced by operation cost and initial investment. Higher operation cost leads to a higher BEP, thus in each scenario the BEP of heat for the non-renovated level is by far lower than that for renovation levels b-d (comparing Tables 6 and 7). In a similar argument, higher initial investment leads to a higher BEP. While the initial investment for biomass HOB is by far higher than that for waste heat recovery scenarios, its lower operation cost makes it competitive with waste heat recovery scenarios.

4.1.2. Cost saving during life cycle (end-user viewpoint)

Fig. 7 compares the heating costs and savings by each scenario and renovation level. Savings calculated as the difference between the heating cost at the non-renovated level and at the renovation levels b-d. In each scenario supplying DH network, renovation level b has the highest saving, since it has the lowest heat demand compared to the non-renovated level.

Biomass CHP is the most expensive scenario at each renovation level, but it brings the highest savings to end-users. Obviously, scenarios with a lower heating cost and higher cost-saving are more desirable for end-users. As shown in Fig. 7, the scenario of waste heat-heat pump + electric boiler performs best for this purpose.

Fig. 8 compares the energy cost-saving with the renovating cost in each scenario. Although renovation level b brings the highest saving, it is the most expensive renovation measure. Therefore, in each scenario supplying DH network, the most profitable renovation level is the renovation level c.

However, the ratio of energy cost-saving to renovating cost is generally low in Fig. 8 (Hirvonen et al., 2019a). Some parts of renovation are compulsory and should be implemented by the passage of time regardless of whether the end-users want energy cost-saving or not.

4.2. Sensitivity analysis

4.2.1. Break-even price of heat (utility viewpoint)

Fig. 9 shows the sensitivity of the BEP of heat by different scenarios to changes in fuel price. Among the biomass combustion scenarios, biomass CHP has the lowest sensitivity to wood chip price. In contrast, the electricity price has a significant effect on the BEP of the electric boiler. The scenario of waste heat-heat pump has the lowest sensitivity to electricity price, which is due to the lower electricity consumption in this scenario.

4.2.2. Cost saving during life cycle (end-user viewpoint)

The sensitivity of cost-saving by different scenarios to changes in fuel price is illustrated in Fig. 10. The energy cost-saving has the least sensitivity to changes in fuel price in the scenario of biomass HOB, while the maximum occurs with the electric boiler. Overall, the cost-saving by

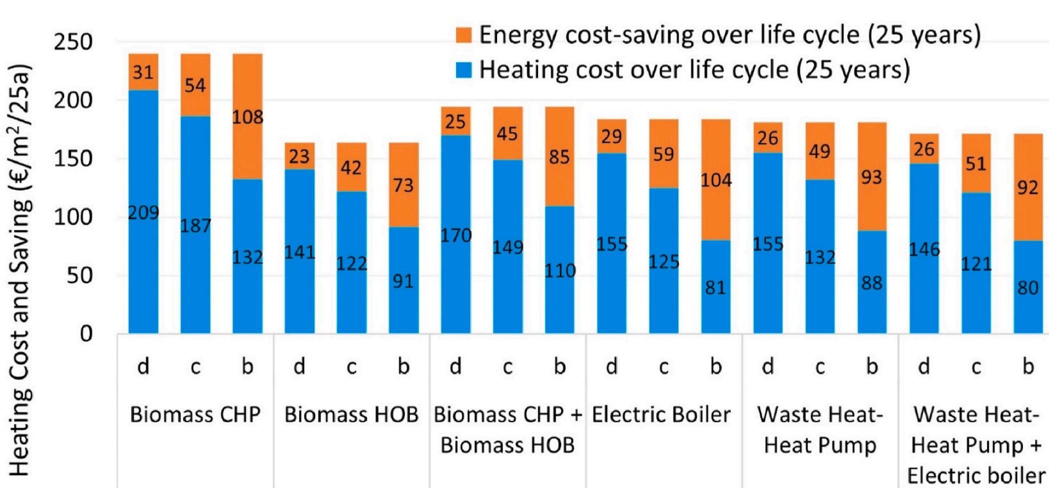

Fig. 7. Heating cost and energy cost-saving over the life cycle (25 years) for different scenarios supplying DH network at different energy renovation levels. In each scenario, the non-renovated level of buildings has been considered as the reference case to calculate cost-savings.

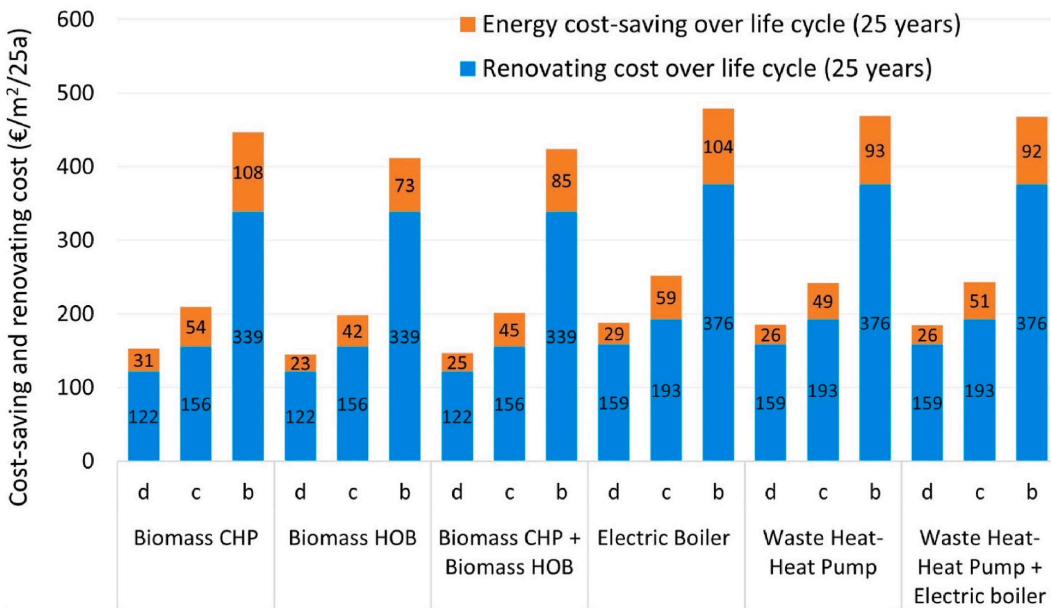

Fig. 8. Comparing buildings renovation cost (Hirvonen et al., 2019a) and energy cost-saving over life cycle to find the most profitable renovation level in each scenario supplying DH network.

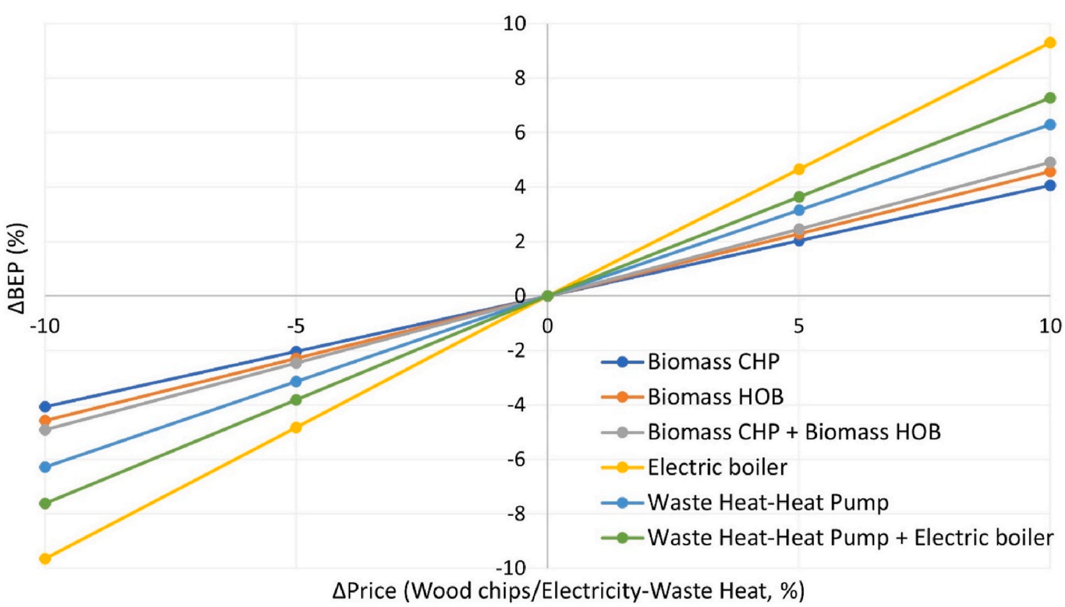

Fig. 9. The effects of changes in the fuel price (wood chips/electricity-waste heat) on the BEP by different scenarios supplying DH network in renovation level b.

biomass combustion scenarios is less sensitive to changes in fuel price compared to that in the waste heat recovery scenarios.

4.3. Environmental analysis

The results of environmental analysis are shown in Fig. 11 and Fig. 12. In Fig. 11, the biogenic CO_2 emissions from biomass combustion technologies are by far higher than for waste heat recovery technologies. Biogenic CO_2 emission from biomass combustion has been absorbed by biomass during its growth, but excessive use of biomass fuels leads to imbalance in this carbon cycle (biogenic carbon dioxide, 2022). If biogenic CO_2 emissions are not considered, the scenarios with electric boilers produce the highest CO_2 equivalent emissions.

Fig. 12 shows the emission rate of NO_x and particulate matter by different scenarios supplying DH network in each renovation level. Biomass combustion is an important source of NO_x and particulate matter emissions. In waste heat recovery scenarios, waste heat-heat pump has the lowest emissions due to lowest electricity consumption by this scenario. Among different renovation levels, renovation level b has the lowest emissions since it has the lowest heat demand (highest level of renovation).

Overall, Figs. 11 and 12 reveal that the use of biomass fuels in DH networks should be limited since their excessive use leads to a significant increase in greenhouse and non-greenhouse gases emissions.

5. Conclusion and future directions

This study evaluated the possibilities of energy efficiency renovations and electric technologies utilizing waste heat streams to supply both affordable and environmentally sustainable heating to typical

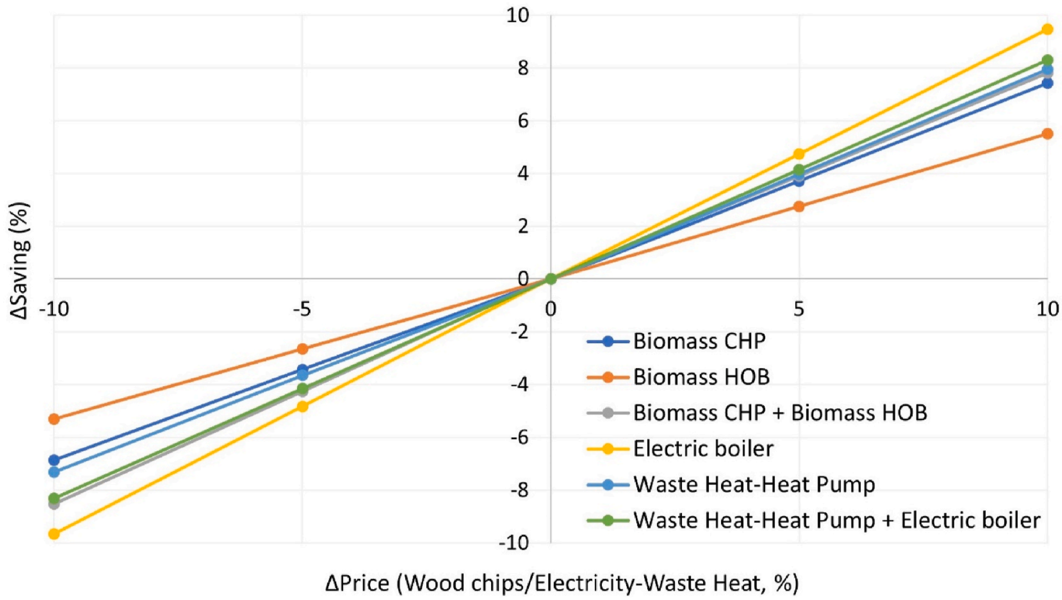

Fig. 10. The effects of changes in the fuel price (wood chips/electricity-waste heat) on cost saving by different scenarios supplying DH network at the renovation level b.

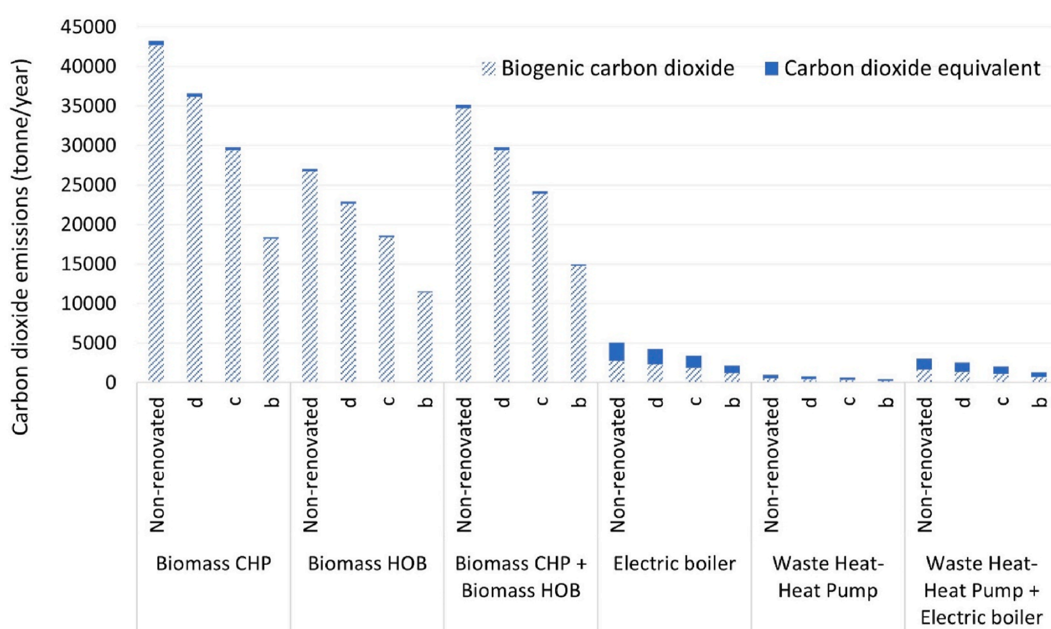

Fig. 11. The annual emissions (carbon dioxide equivalent) by each scenario and renovation level (Fuel classification 2021, 2021; Tsupari et al., 2005; "Purchase of electricity by energy, 2022). According to the official statistical convention, carbon dioxide emissions from biomass combustion are counted as zero in national emission inventories.

aging suburbs in Finland. Although combusting biomass fuels is considered carbon-neutral, their excessive use leads to an imbalance in the carbon cycle and a higher concentration of CO_2 in the atmosphere. In other words, forests as one of the main sources of biomass fuels are an important carbon sink in the environment absorbing huge amounts of CO_2 from the atmosphere, therefore increasing forest cutting means reducing an important carbon sink.

As a possible alternative to biomass combustion plants, waste heat recovery can play a significant role in developing low-carbon DH networks. However, the feasibility of waste heat sources and the affordability of recovering technologies are the main issues facing these scenarios. Furthermore, applying a cost-efficient energy renovation method plays a considerable role in reaching a low-carbon DH network. However, the cost of retrofit is an important factor that should be considered in evaluating different renovation measures.

The current study evaluated the performance of different solutions to develop a low-carbon DH network. Scenarios supplying DH network were evaluated in two main groups of biomass combustion scenarios and waste heat recovery scenarios. At the utility viewpoint, the results show that biomass combustion scenarios have a lower operation cost but a higher BEP of heat compared to waste heat recovery scenarios. Biomass HOB has the lowest operation cost at each renovation level. However, the lowest BEP depends on the level of renovation. In renovation level b (the most ambitious level considered) the scenario of waste heat-heat pump + electric boiler has the lowest BEP.

At the end-user viewpoint, energy cost-savings are not sufficient to

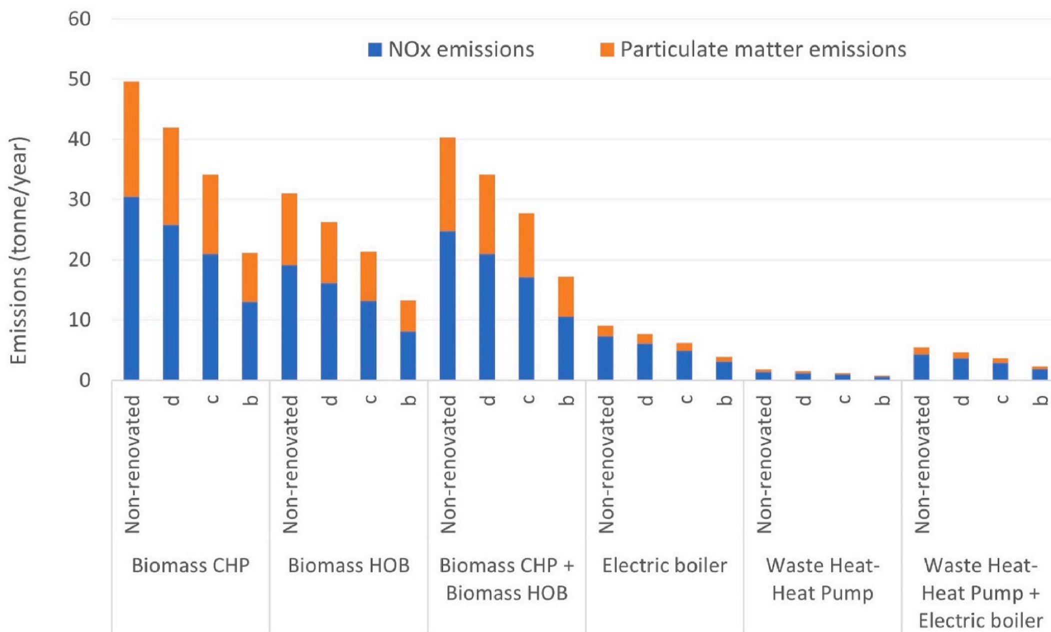

Fig. 12. The annual nitrogen oxide (NO_x) and particulate matter emissions by each scenario supplying DH network in each renovation level.

recover the cost of renovations. The renovation level b has the highest energy cost-saving in each scenario, but it is also the most expensive renovation level. Considering both indexes of energy cost-saving and renovation cost, the renovation level c is the moderate level in all scenarios supplying DH network, and thus it could be recommended as the alternative bringing the best mutual benefit.

Sensitivity analysis was carried out to find the sensitivity of BEP of heat and energy cost-saving by each scenario to changes in fuel price. In each studied case, biomass combustion scenarios are less sensitive to changes in fuel price compared to waste heat recovery scenarios. The sensitivity of electric boiler (with 100% of peak demand) to changes in electricity price was by far higher than other scenarios. Thus, this alternative poses risks in terms of affordability.

Environmental analysis showed that biomass combustion scenarios are a significant source of both greenhouse and local air pollutant gases, as indicated in this study by NO_x and particulate matter emissions. Therefore, the use of biomass fuels in DH networks should be limited. In waste heat recovery scenarios, the waste heat-heat pump has the lowest emissions.

In conclusion, while biomass HOB is the cheapest scenario in higher heat demands (the renovation level d), considering the renovation levels c and b as the most effective renovation levels, and noting the results of environmental analysis, the scenario of waste heat-heat pump + electric boiler can be considered as the most recommendable scenario supplying DH network by this study. In lower renovation levels (d and non-renovated level) the recommendable scenario could be both biomass HOB and waste heat-heat pump. In these levels of renovations, while biomass HOB is by far cheaper, the emissions by waste heat-heat pump are significantly lower. Practical implications of these results are that cities should carefully consider the possibilities of utilizing waste heat streams instead of the conventional low-carbon technologies based on biomass. In connection with this, emphasis should be placed on energy renovation measures that allow the utilization of lower temperature DH. This study implies also that economic incentives are needed for housing owners to realize energy efficiency renovations. Similar results have been published concerning refurbishing of apartment housing stock in Estonia, where renovations are recommended (Kuusk and Kurnitski, 2019). Further, also large heat pumps and utilization of low temperature sources were found economic for Tallinn, Estonia (Pieper et al., 2019). Also, the results of (Lund et al., 2016) are similar to our findings, showing a 2–4 GW economic potential of large HPs for Denmark.

There are also several limitations regarding the results of this study and further research needs. As the recommendable technologies, waste heat and partially electric boiler, depend on affordable electricity, the recent price hikes of electricity on the European markets due to the Ukrainan war may result in these electricity-consuming technologies becoming less economically attractive at least over the short term. The capacities of available waste heat sources may also become a limiting factor. Especially data centers are so far available only in a limited number of cities in Finland.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2022.100087.

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