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District heating in cities as a part of low-carbon energy system

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ABSTRACT

In this paper, district heating (DH) scenarios that are sustainable in terms of CO_2 emissions and costs are formed and analysed. Three different cases i.e. the Helsinki region, Warsaw and Kaunas, are modelled, and the plans and goal of the cities and the companies supplying DH in the studied regions are reviewed. The aim of this study is to analyse how carbon neutrality could be reached in the studied DH systems by 2050. It was found that increased use of biomass and waste as well as utilization of geothermal and waste heat could be expected in the studied regions in the future. In addition, increasing energy efficiency and lowering heat losses in the DH network is important especially in Warsaw. Carbon capture and storage technologies could also play an important role in reducing emissions in the future but this would increase the heat production costs significantly.

KEYWORDS

District heat, energy poverty, CO_2 emissions, district heating scenarios, cities, carbon neutrality

INTRODUCTION

This paper presents initial modelling results of the EU Horizon 2020 project REEEM about the role of district heating (DH) systems in selected European cities to support the energy transition. Reducing CO_2 emissions in the energy sector is essential for climate change mitigation and renewable energy sources (RES) are likely to play an increasingly important role in the future European energy systems. The aim of this paper is to compare different district heating scenarios and to identify scenarios that are sustainable both in terms of CO_2 emissions and energy poverty. Case studies on district heating are performed in three European cities i.e. Helsinki region, Warsaw and Kaunas. District heating plays a significant role in all of the studied cities but there are notable differences between them in market structure, ownership, fuels and technologies used, as well as in the specific heat demands and

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housing stocks. In addition, different national and city-level policies affect the behavior of both energy producers and consumers. The main goal of this study is to analyse how carbon neutrality could be reached in the studied DH systems by 2050.

In this paper, the plans and goals of the studied cities and DH companies are reviewed, and possible future DH scenarios are formed based on this analysis. The studied scenarios include a heat storage and a higher share of biomass and waste in heat production. Heat production by geothermal and solar thermal technologies, and increased utilization of waste heat are also covered by the analysis. It is also assumed that carbon capture and storage (CCS) technologies are used in 2050 in order to reduce emissions from the combustion of fossil fuels. The optimal operation of each DH system i.e. running of the plants, use of storage and ensuring necessary reserves and balancing capacities are determined by minimizing the heat production costs. The studied DH scenarios are compared based on their CO_2 emissions and costs in particular.

Objectives of the cities and projects planned in the studied DH systems

The studied cities and DH companies have plans and targets concerning the sustainability of the heat production. These plans and objectives are reviewed in this section and the studied scenarios are formed based on these plans and expert opinions.

Helsinki region

The Finnish national emissions should be cut by 16% from the 2005 levels by 2020 and the share of renewable energy in the final energy consumption increased to 38% by 2020 [1] [2]. In Finland government aims to abandon coal use in energy production and to halve the use of fossil oil by 2030 [3]. In the longer term, Finland’s objective is to become a carbon-neutral society and greenhouse gas (GHG) emissions should be reduced by 80-95% by 2050 [4]. In order to reach these targets, emissions from energy production need to be cut. In this paper, the emissions from DH and accompanied electricity production are studied in the capital area of Finland.

The studied region consists of three cities i.e. Helsinki, Espoo and Vantaa, and altogether there are around 1.1 million people living in the area. Each city has own plans and strategies concerning climate and energy production. In each city, DH is supplied by different company and there is thus three DH networks and companies in the studied region. In Helsinki, DH is supplied by Helen and in 2015 the total DH consumption was 6.4 TWh. Fortum Oyj provides DH in the city of Espoo and DH consumption in 2015 was 2.1 TWh in Espoo. In Vantaa, DH consumption was around 1.7 TWh in 2015 and DH is supplied by Vantaan Energia Oy [5].

The climate strategy for the Helsinki Metropolitan area to 2030 set carbon neutrality as a target by 2050. There is also an intermediate goal to reduce emissions by 20% by 2020 [6]. The city of Helsinki has announced in a strategy programme that the carbon dioxide emissions in Helsinki are reduced by 30% (compared to 1990 levels) by 2020 [7]. Helen, owned by the city of Helsinki, has an intermediate target to reduce carbon dioxide emissions by 20% and to increase the share of renewable energy to 20% by 2020. The company has also set a target to reach carbon neutrality by 2050. In order to reach these target, Helen plans e.g., to invest in the production of renewable energy, utilize new technology to reduce emissions and to improve energy efficiency [8]. The city of Espoo plans to reach carbon neutrality by 2050 and to reduce resident-specific emissions by 60% by 2030 compared to 1990 [9]. The city of Vantaa aims at reducing its emissions by 20% by 2020 compared to 1990 levels [10]. Various projects are planned by the DH companies in the three cities and main projects are listed below.

Plans of Fortum Oyj in Espoo [11] [12]:

- Utilization of excess heat from a hospital. This would cover heat demand for around 50 single-family houses (i.e. approximately 1000 MWh).
- Use of geothermal heat in Otaniemi. Heat output around 40 MW.

Plans of Vantaan Energia Oy in Vantaa [13]:

- Modernization of Martinlaakso 1 CHP plant (earlier fired by oil and gas) so that it would use bio fuels in 2019.

Plans of Helen Ltd in Helsinki [14] [15] [16]:

- Helen has decided to close Hanasaari coal CHP plant by 2024.
- New pellet-fired heating plant will be built. Heat output of the plant is 92 MW.
- Pellet systems will be used in Hanasaari and Salmisaari CHP plants. Approximately 5-7% of coal can be replaced by wood pellets.

Warsaw

As an EU Member State, Poland has targets concerning GHG emissions and the share of RES. By 2020, the increase of national GHG emissions should be limited to 15% compared to 2005 levels and the share of RES increased to 15% in the final energy consumption [2] [1]. In addition, directives such as the Directive on Industrial Emissions [17] further affect plants by setting requirements concerning e.g., SO_2 and NOx emissions and there is thus a need for modernization of some plants. Poland also participate in the EU ETS which affects energy production costs through CO_2 prices.

At national level, the main legislative framework is specified in the Energy Law Act and in it e.g., the support system mechanisms and rules for electricity and gas systems are established. In order to promote the utilization of RES, a system of green certificates has been introduced in 2005 and electricity suppliers are obliged to have a certain share of RES in their total volumes of electricity sales. In addition, electricity generated from RES is exempt from the excise tax [18] [19] [20]. The Energy Policy of Poland until 2030 aims especially to improve energy efficiency and enhance the security of fuel and energy supplies. It is also mentioned that security of fuel and energy supplies should be enhanced and the electricity generation structure diversified by introducing nuclear energy. There are also goals to develop competitive fuel and energy markets and to reduce the environmental impact of the power industry. Objective of doubling the amount of energy produced in the CHPs is also set [21].

It should, however, be noted that there are large deposits of coal in Poland while gas and crude oil are mainly imported [21]. As energy security is considered as an important objective in Poland [20], this is likely to affect also the fuels used for energy production in the future. It is estimated that coal will be an important energy source also in the future decades in Poland [22] [23].

In Poland, the share of coal in the energy mix for heat production was over 70% in 2011 [24]. In addition, the plants are rather old and inefficient, and the heat losses of the heating network are around 12% in Poland [22] [25]. There is thus a need to diversify the energy mix and to increase energy efficiency in the Polish DH. This paper focuses on the DH system of Warsaw which is one of the largest in the EU. Around 80% of the buildings in Warsaw are heated with DH and in 2010, the total delivered DH was approximately 10 TWh [20] [26]. The city of Warsaw plans to achieve a biomass share of 15% of combusted fuels by 2020 and CHP plants like Zeran and Siekierki are being fitted with measures which allow them to use bio fuels. In addition, there are plans to extend the waste incineration plant ZUSOK and build another similar plant. In 2020, the share of renewable energy from solid waste would reach 8% [27]. Projects planned in the Warsaw DH system are listed below [27] [28].

- Building a new waste-to-energy facility. Electricity output of the plant is 50 MW and heat output 25 MW.
- Upgrading Zeran CHP plant. Coal-fired boilers will be retired and new unit uses natural gas. This increases the electricity output and the installed capacity of the unit is around 450 $MW_{electricity}$.
- Building a new Pruszkow CHP plant. Plant will be fired by gas, electricity output is 16 MW and heat output 15 MW.
- CHP plants Zeran and Siekierki are being fitted with measures which will allow them to use bio fuels.

Kaunas

Over several years Lithuania has made a noticeable progress towards decarbonisation of the energy sector and wider use of renewable energy sources. The share of renewable energy in gross final energy consumption was 25.8 percent in 2015, while the directive 2009/28/EC of the European Parliament and of the Council required reaching 23 percent in 2020. One of the most important grounds for this result was technology change in district heating sector where biomass was started to be used as the main fuel instead of natural gas and HFO. Total capacity of biomass plants in district heating sector increased from 518 MW in 2010 to 1589 MW in 2015 [29]. According to the data from Lithuanian District Heat Suppliers' Association, in 1997 biomass' share in the total primary fuel in district heating sector was only 1.2 percent. In 2016 the share of biomass and municipal waste reached 64.1 percent. Moreover, there are expectations to increase this number to 80 percent in 2020 [30].

Currently, there are no strict legislative requirements which affect capacity stock in district heating sector. Good case in this point is National renewable energy development programme for 2017-2023 which requires the share of heat produced from RES to be more than 40 percent in 2017 and more than 45 percent in 2023 [31], while actual value in 2015 was 46.17 percent [32]. The new National Energy strategy is still under preparation stage at Ministry of Energy of Lithuania ant it should set new aims for the development of Lithuanian energy sector. Nevertheless, common goals related with climate change, decarbonisation and development of renewable energies are broadly understood and taken into account when new decisions at DH sector are considered.

Kaunas DH system with annual heat consumption of about 1 TWh is second largest in Lithuania. Similarly to other parts of Lithuania, there was a significant shift towards biomass use in district heat production and now biomass is the main fuel. Kaunas district heating system is operated by AB "Kauno energija", which produces heat in its heat plants or purchases from independent heat producers. The situation in Kaunas district heating system is especially remarkable due to high penetration of independent heat producers. In 2016, 9 independent heat producers were producing district heat for Kaunas city integrated DH network and two in Kaunas region [33]. DH system operator purchased 59 percent of heat in 2016, the remaining part was produced in the facilities that belongs to AB "Kauno energija"

[34]. The important role of independent heat producers and drawbacks of existing regulatory system cause discussions about the role of regulation in DH sector itself and possibilities to orient overall system towards competition under free market conditions.

Currently only new waste to energy CHP (24 MWe and 70 MWth) could be treated as planned project in Kaunas DH system, but there are also some initiatives of earlier stage (e.g., gas fired CHP).

Data and assumptions

EnergyPRO software and MESSAGE modelling package are used in the simulations presented in this paper. EnergyPRO is an input/output model that solves the optimal DH operation strategy by minimizing the total variable costs so that the hourly heat demand is met. In contrast, MESSAGE deals not only with DH operation, but also with investment [35] and provides optimal operation and development solutions for entire time period analysed. Both approaches are not limited to district heat production. In EnergyPRO, revenues from electricity sales are taken into consideration in the variable costs, MESSAGE allows for modelling separate energy products which can be used either for fulfilling demands or for selling in the market which is not covered by the model.

For the cases of Helsinki region and Warsaw, it is assumed that the total annual heat demand is at current level and the profile of the demand is determined based on outdoor temperature. The reference temperature i.e. when heating is needed is 17^{o}C. It is assumed that energy used for hot water generation is constant and approximately 20% of the annual heating demand [36] [24]. In Kaunas case district heating demand projections have been prepared taking into account energy efficiency improvements such as buildings' renovation, demographic developments and other factors.

Current production units and their properties in the DH systems of Helsinki region, Warsaw and Kaunas are described in Tables A1-A3 in the appendix. Since the modelled Helsinki region consists of three DH systems, it is assumed that transmission capacity between Espoo and Helsinki is 80 MW, and between Vantaa and Helsinki 130 MW [37]. The assumed technical properties of the plants are described in

Table 1 and the cost assumptions concerning the operation of the plants are presented in Table 2.

Table 1. Technical assumptions concerning heat production units in Helsinki region and Warsaw [38]

	HOBs	**CHP plants**	**Heat pumps**
Allowed load, of full capacity	0 – 100 %	40 – 100 %	0 – 100 %
Minimum operation hours	No minimum operation hours	168 hours (one week)	No minimum operation hours
Starting up period	1 hour	4 hours	0 hours
Shutting down period	1 hour	4 hours	0 hours
Heat rejection (auxiliary DH	Not possible/needed	Can be used when electricity price is	Not possible/needed

cooler)	high

Table 2. Cost assumptions concerning production [38]

	HOBs	CHP plants	Heat pumps
Start-up costs	0 €	2,500 €	0 €
Variable operation and maintenance costs	5 €/MWh$_{heat}$	4 €/MWh$_{electricity}$	5 €/MWh$_{heat}$
Fuel price in Helsinki region	Fuel market price + taxes	Fuel market price + taxes (90% of the fuel used for heat production is subject to taxes)	Electricity spot price + distribution cost + electricity tax
Fuel price in Warsaw	Fuel market price + taxes	Fuel market price + taxes	

Assumed fuel and electricity prices are presented in Table 3 and fuel taxes are summarized in Table 4. In Kaunas case, linear price changes are assumed for fuels and electricity from current price levels to the prices assumed in Table 3 for 2050. Thus, price convergence is achieved during study period. Fuels used in heat production in heat only boilers (HOBs) are subject to a tax in Finland. In CHP plants 90% of the amount of produced heat conducted into the network is subject to the tax and electricity production in CHP units is not taxed [38]. The assumed investment costs and O&M costs for CCS are summarized in Table 5. Annuities of investments presented in Table 5 are calculated using an interest rate of 5% and a lifetime of 40 years. It is assumed that with CCS technologies, 90% of emissions can be captured.

Table 3. Cost assumptions concerning fuel and electricity prices[1]

	2050	Reference
Carbon price	90 €/tCO_2eq	[41]
Coal, import price	29 $/boe (16.3 €/MWh)	[41]
Oil, import price	130 $/boe (73.1 €/MWh)	[41]
Natural gas, import price	79 $/boe (44.4 €/MWh)	[41]
Waste in CHP plant (Finland)	-45 €/t$_{waste}$ (i.e. gate fee)	[42]
Biomass price	27.5 €/MWh	[43] [44] [45] [46]
Wood chips	40 €/MWh	
Wood pellets	46 €/MWh	
Average electricity price in Finland	56 €/MWh	[47]
Average electricity price in Poland	64 €/MWh	[47]
Average electricity price in Lithuania[2]	60 €/MWh	Assumed average between Finland and Poland

[1] Assumed that 1 boe=1.63 MWh, 1 MWh=3.6 GJ [39], 1 USD=0.917 € [40]
[2] Daily, weekly and seasonal variation of electricity prices was not taken into account in this study.

Table 4. Fuel taxes used in the model (VAT is excluded) [48] [49] [50]

Country	Fuel	Price
Finland	Natural gas tax, HOB	18.6 €/MWh
	Natural gas tax, CHP	12.9 €/MWh
	Light fuel oil tax, HOB	22.9 €/MWh
	Light fuel oil tax, CHP	15.1 €/MWh
	Heavy fuel oil tax, HOB	23.7 €/MWh
	Heavy fuel oil tax, CHP	15.5 €/MWh
	Coal tax, HOB	27 €/MWh
	Coal tax, CHP	17.1 €/MWh
	Bio oil tax	48 €/MWh
	Electricity distribution cost	21 €/MWh
	Electricity tax	22.5 €/MWh
Poland	Light fuel oil tax	5.4 €/MWh
	Natural gas tax	1.1 €/MWh
	Coal tax	1.1 €/MWh

Table 5. Assumptions concerning investment costs and variable O&M costs of CCS [51] [52]

Investment cost	
Geothermal District Heating	1.8 M€/MW
Rebuilding coal power plants to biomass	0.18 M€/MW (wood pellets) 0.42 M€/MW (wood chips, straw) 0.52 M€/MW (wood chips, dried)
Modernization of existing plant in Warsaw	0.06 M€/MW[3]
Carbon capture (NGCC-CCS)	1.3 M€/MW
Carbon capture (coal-CCS)	2.5 M€/MW
Waste-to-Energy CHP Plant in Warsaw	8.5 M€/MW_{th}
Waste-to-Energy CHP Plant in Kaunas	6.25 M€/MW_e
Heat storage investment cost	30 €/m^3*Volume(m^3)
Heat pump	0.53 M€/MW
O&M costs	
Variable O&M cost (NGCC-CCS)	0.9 €/MWh
Variable O&M cost (coal-CCS)	4.5 €/MWh
Fixed O&M cost (NGCC-CCS)	38,000 €/MW/year
Fixed O&M cost (coal-CCS)	65,000 €/MW/year

Results

Studied scenarios

The studied scenarios for Helsinki region and Warsaw are formed based on expert opinions and the earlier described plans and goals of the cities and DH companies. In the reference

[3] In this study, it is assumed in the Warsaw 2030 scenario that existing plants will be modernized. The costs of modernization depend on the modifications that will be done in a specific plant and it is therefore difficult to estimate these costs. It has been for example estimated that the modernization of Siekierki CHP plant could cost around 120 M€ i.e. approximately 0.06 M€/$MW_{heat\ output}$ [53]. We have used this as a rough estimate of the modernization costs in Poland.

scenario, it is assumed that the currently planned projects (described earlier in Section *Objectives of the cities and projects planned in the studied DH systems*) are implemented. Scenarios 2030 and 2050 present the possible situation in those years. The assumptions of the studied scenarios are presented in Table 6.

Table 6. Studied scenarios for Warsaw and Helsinki region, and their assumptions

Region	Scenario	Assumptions
Helsinki region	Reference scenario	Planned projects are implemented
	2030	Projects assumed in the reference scenario Coal and oil replaced by natural gas (50%) and wood chips (50%) in CHP plants Coal and oil replaced by wood pellets in HOBs
	2050	Projects assumed in the reference and 2030 scenarios Utilization of waste heat will be increased to 20% of heat demand Geothermal energy in Helsinki, heat output 40 MW Heat storage included in the system, capacity of the storage is 1% of the annual heat demand [52] CCS in gas-fired plants
Warsaw	Reference scenario	Planned projects are implemented
	2030	Projects assumed in the reference scenario Network losses are cut to half Plants are modernized: efficiency increased from 75% to 85% in existing plants. Efficiency in the new Pruszkow CHP plant is 92% Increase in biomass use: 50% of Zeran's capacity (i.e. 15% of total heat capacity in Warsaw) use biomass
	2050	Projects assumed in the reference and 2030 scenarios Coal-fired CHP plants equipped with CCS Coal-fired HOB replaced by waste CHP Oil-fired HOB replaced by bio-HOB (50%) and natural gas HOB (50%)

For Kaunas DH system two scenarios are considered: "Business as usual" (BAU) and "Carbon free" (C-Free) scenario. Optimal investment decisions and operation scheduling is allowed in both scenarios. However, no emission limitation is used in the BAU scenario, while linear decrease of CO_2 emissions from current level up to zero in 2050 is considered in the C-Free scenario. Operation of all existing technologies is allowed during their technical life time. Rebuilding of existing technologies after end of their technical life time, extension of their capacities, as well as construction of new Waste-to-Energy CHP (70 MW_{th}), electrical (20 MW_{th}) and steam-driven absorption heat pumps (20 MW_{th}), solar collectors, heat storages are considered among new candidate heat producing technologies in both scenarios.

Annual emissions and heat production costs are summarized in Table 7. As can be seen, costs as well as the annual emissions are slightly lower in the 2030 scenarios than in the reference/BAU scenarios in all cases analysed. Yet, in 2050 scenario costs increase rather much which is due to the high investment costs of CCS technologies in particular. In the Kaunas BAU scenario, cost increase is rather modest. Yet, in the C-Free scenario costs increase quite much by 2050.

The shares of energy produced with CHP plants, HOBs and heat pumps are also presented in Table 7. There is a significant increase in the use of heat pumps in Helsinki region in 2050 which is due to increase in the utilization of waste heat and geothermal energy. Results also show that in Warsaw, the share of CHP production increases in 2030 and 2050 scenarios which is in line with the goal of increasing the CHP production. In Kaunas, the share of CHP production increases especially in the BAU scenario.

Table 7. Results from the simulations

Region	Scenario	Annual GHG emissions [$MtCO_2$-eq]	Heat production costs [€/MWh_{heat}][4]	Share of energy production in CHP plants [%]	Share of energy production in HOBs [%]	Share of energy production with heat pumps [%]
Helsinki region	Reference scenario	(1) 3.35 (2) 3.2	65	57	29	13
	2030	(1) 1.7 (2) 1.55	62	52	34	14
	2050	(1) 0.29 (2) 0.15	78	50	21	30
Warsaw	Reference scenario	(1) 3.58 (2) 3.45	56	40	60	
	2030	(1) 2.59 (2) 2.47	47	60	40	
	2050	(1) 1.15 (2) 0.28	93	69	31	
Kaunas	BAU scenario 2020	0.09	59	18	82	
	2030	0.072	67	41	49	10
	2050	0.066	66	49	30	21
	C-Free scenario 2020	0.09	59	5	95	
	2030	0.073	67	19	72	9
	2050	0	128	24	60	16

It should be noted that the emissions from waste use depend on the type of waste. In the results presented here, it is assumed that the emission factor for waste is 114 $kgCO_2$-eq/MWh (1 in Table 7) or 0 $kgCO_2$/MWh (2 in Table 7) for Helsinki region and Warsaw [10]. For Kaunas DH system it was assumed that solid recovered fuel produced from municipal waste, will include practically only materials of biologic origin and therefore is CO_2 neutral. It was also assumed that the emissions from the use of biomass, wood pellets and wood chips are zero in all studied cases.

Consumption of different fuels is illustrated in Figures 1-3. The results show that in the Helsinki region the consumption of natural gas and coal decrease in the 2030 and 2050 scenarios compared to the reference case while the consumption of wood pellet increases. It can also be seen that the electricity consumption increases in 2050 scenario due to the increased use of waste and geothermal heat. In Warsaw (Figure 2) there is a significant drop in the use of coal in 2030 and 2050 scenarios compared to the reference case. In addition, the use of light fuel oil decreases and the use of biomass increases. In the 2050 scenario, the use of waste fuel also increases due to the new waste CHP plant. In the Kaunas DH case (Figure 3) significant decrease of fuel consumption is related with heat demand decrease that is caused by the efficiency improvements of buildings. In addition, gradual decrease of natural gas consumption and increase of municipal waste utilisation is visible during the study period,

[4] Average variable cost for 1 MWh of produced heat (investment cost are included in the costs in 2030 and 2050 scenarios) in Helsinki and Warsaw cases. Marginal heat production cost in Kaunas DH case.

especially in the C-Free scenario. Reduced consumption of wood chips is conditioned by decreased heat demand and increased consumption of municipal waste.

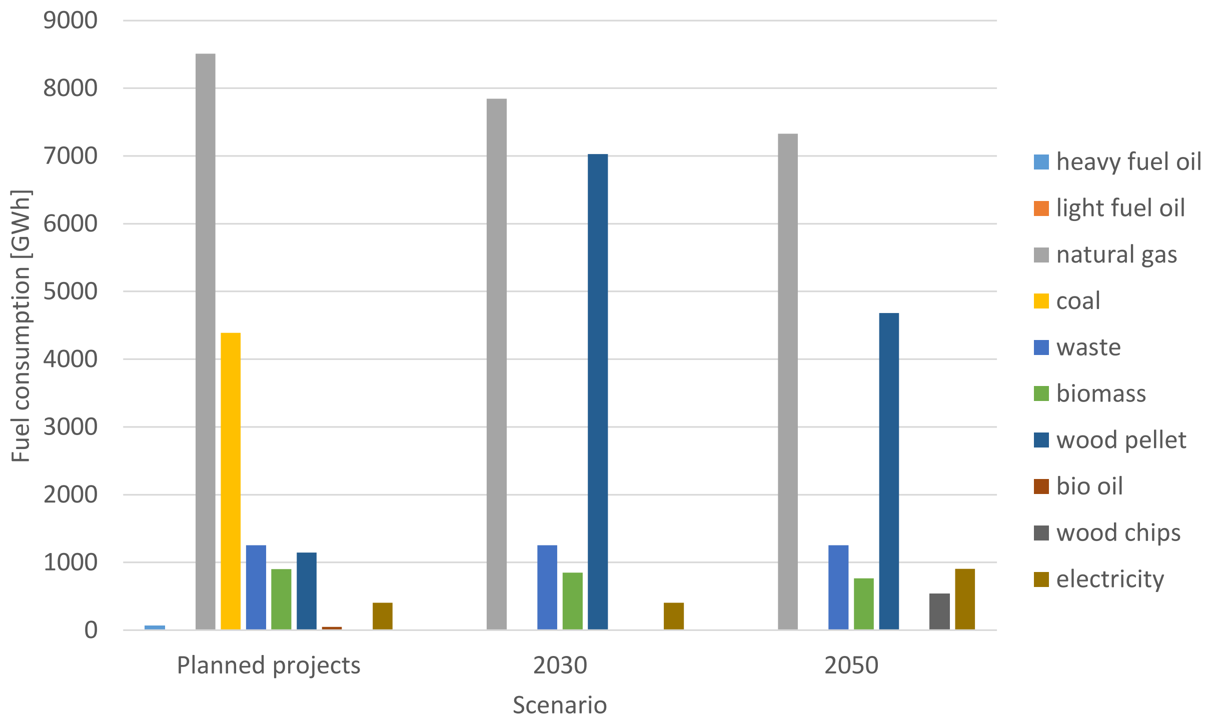

Figure 1. Fuel and electricity consumption in the DH system of Helsinki region in different scenarios

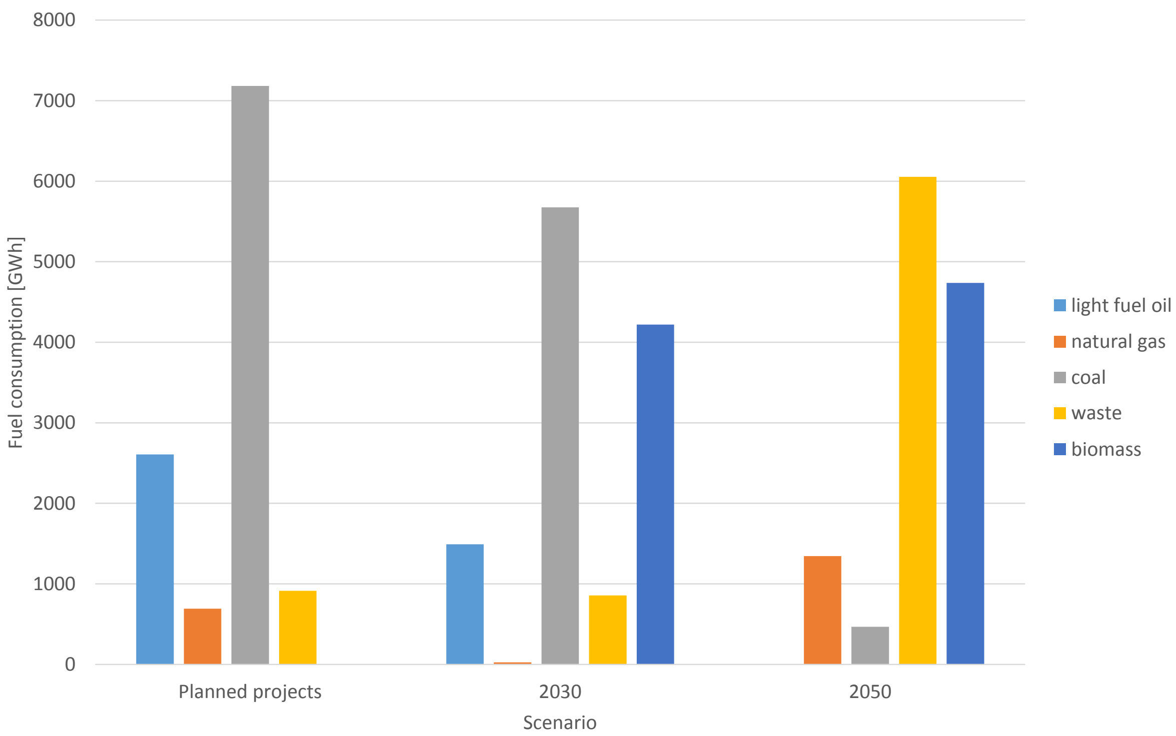

Figure 2. Fuel consumption in Warsaw DH system in different scenarios

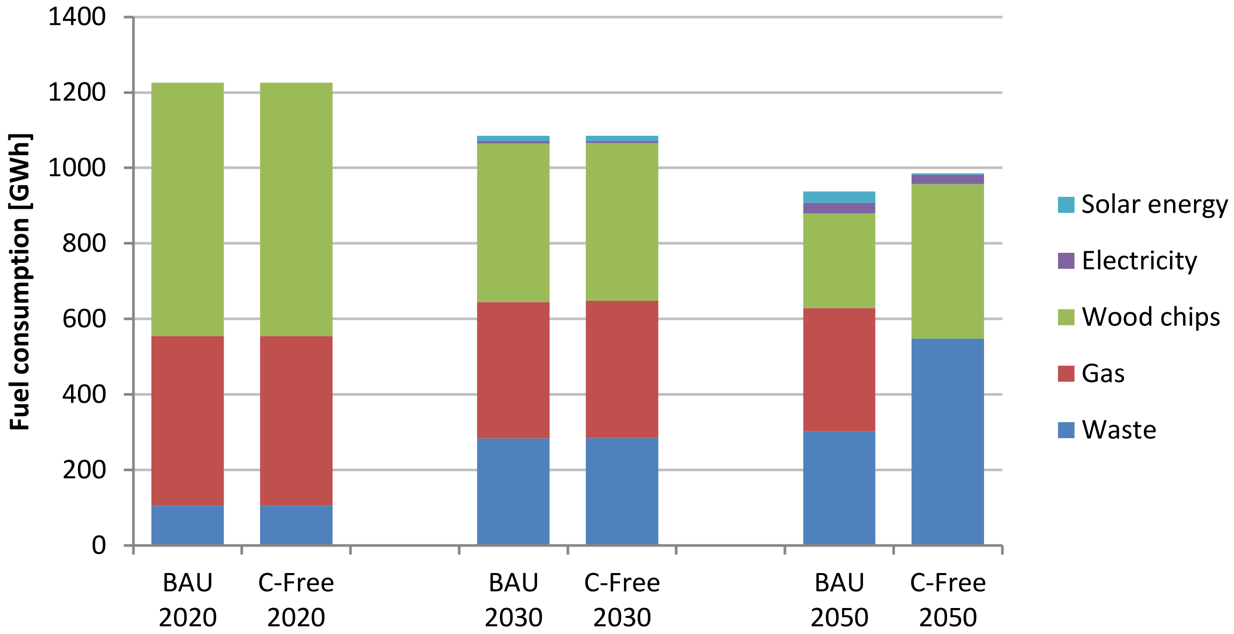

Figure 3. Fuel consumption in Kaunas DH system in different scenarios

Discussion and conclusions

In this paper, ways to reduce emissions in three European DH systems were studied. Scenarios towards this objective were formed based on literature and the goals and plans of the studied cities and the DH companies operating in these regions were reviewed.

The Helsinki region has three DH networks and in each network, DH is supplied by a different company. In Finland, it is aimed that by 2030 coal use will be abandoned in energy production and the use of fossil oil will be cut in half [3], and the use these fuels should therefore be replaced even before 2050. This analysis showed that especially increased use of wood fuels and waste heat as well as utilization of geothermal heat could be expected in the studied region in the future. In addition, the use of thermal storage and CCS technologies could be used in order to reach carbon neutrality by 2050.

It was found that in Warsaw and Kaunas, increased energy efficiency and use of biomass and waste are considered important in the future development of the DH system. Currently DH in Warsaw is mainly produced with coal and the emissions are therefore high. It should, however, be noted that energy security is considered important which may hinder the replacement of coal with other fuels such as natural gas. The results of Warsaw DH system in particular showed that even if significant emission reductions can be achieved with CCS technologies, this will increase the average heat production costs quite much with the assumptions used in this study. Therefore other possibilities to reduce emissions should be considered and planned. On the other hand, for example in the Helsinki region, the cost increase was lower probably due to the more diversified use of different technologies.

Future research could consider more scenarios and elements that could be used in order lower emissions and costs. For example use of solar heat and different kinds of heat storages could be studied in more detail. In addition, demand-side flexibility and changes in heat demand as well as open district heating system could be analysed. Sensitivity analysis for fuel and CO_2 prices and investment costs should also be performed. Since variation in electricity prices can affect the operation of the DH system and heat production costs, the effects of various electricity price scenarios could be studied further. Different policy scenarios concerning e.g., subsidy for electricity and heat production with renewable energy could be tested. It should also be noted that consumers may switch from district heating to another heating source especially if there are cheaper heating options available. These changes further affect the demand of DH and they could thus be considered in future research.

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Appendix

Table A.1. Current production units and their properties in Helsinki region [5]

Plant	**Heat output (MW)**	**Electricity output (MW)**	**Fuel heat input (MW)**	**Main fuel**
Espoo, Owner: Fortum Oyj				
Kivenlahti	40	-	45	Wood pellet
Suomenoja 7	17	-	18	Natural gas
Tapiola	160	-	180	Natural gas
Suomenoja 3	80	-	89	Coal
Vermo1	80	-	90	Natural gas
Vermo2 (bio oil)	35	-	41	Bio oil
Vermo2 (gas)	45	-	49	Natural gas
Kaupunginkallio	80	-	88	Light fuel oil
Otaniemi	120	-	129	Natural gas
Juvanmalmi	15	-	17.6	Natural gas
Kalajärvi	5	-	5.9	Light fuel oil
Masala	5	-	5.9	Natural gas
Kirkkonummi	31	-	36	Natural gas
Suomenoja 1 (CHP)	160	80	265	Coal
Suomenoja 2 (CHP)	214	234	498	Natural gas
Suomenoja 6 (CHP)	110	45	167	Natural gas
Suomenoja (heat pump)	45	-	15	Electricity
Helsinki, Owner: Helen Ltd				
Plant	Heat output (MW)	Electricity output (MW)	Fuel heat input (MW)	Main fuel
Alppila	164	-	180	Light fuel oil
Munkkisaari	235	-	247.5	Heavy fuel oil
Ruskeasuo	280	-	300	Heavy fuel oil
Lassila	334	-	363	Natural gas
Patola	240	-	258	Natural gas

Salmisaari 1	120	-	132	Heavy fuel oil
Salmisaari 2	180	-	185	Coal
Salmisaari 3	7.7	-	12	Heavy fuel oil
Jakomäki	56	-	62	Heavy fuel oil
Myllypuro	240	-	266	Natural gas
Vuosaari	120	-	129	Natural gas
Hanasaari 1	56	-	66	Heavy fuel oil
Hanasaari 2	282	-	299.4	Heavy fuel oil
Salmisaari B (CHP)	300	160	506	Coal, wood pellet (7%)
Hanasaari B (CHP)	420	226	726	Coal, wood pellet (7%)
Vuosaari A (CHP)	160	160	356	Natural gas
Vuosaari B (CHP)	420	470	974	Natural gas
Katri Vala (heat pump)	90	-	30	Electricity
	Vantaa, Owner: Vantaan Energia Oy			
Plant	Heat output (MW)	Electricity output (MW)	Fuel heat input (MW)	Main fuel
Koivukylä	145	-	160	Natural gas
Hakunila	80	-	88	Natural gas
Maarinkunnas	200	-	215	Natural gas
Lentokenttä	92	-	108	Heavy fuel oil
Varisto	92	-	100	Natural gas
Jussla	10	-	11.8	Light fuel oil
Martinlaakso 2 (CHP)	135	80	230	Heavy fuel oil
Martinlaakso 4 (CHP)	120	60	196	Natural gas
Jätevoimala	140	76.4	240	Waste
Martinlaakso Gt	75	58	148	Natural gas

Table A.2. Current heat production units and their properties in Warsaw [54] [55] [55]

Plant	**Heat output (MW)**	**Electricity output (MW)**	**Main fuel**	**Started to operate**	**Owner**
EC Zeran	1580	386	Coal	1954	PGNiG Termika S.A.
EC Siekierki	2078	620	Coal	1961	PGNiG Termika S.A.
EC Pruszków	186	9.1	Low-carbon coal	1914	PGNiG Termika S.A.
Heat Power Station Kaweczyn	465	-	Coal	1983	PGNiG Termika S.A.
Heat Power Station Wola	465	-	Light fuel oil	1973	PGNiG Termika S.A.

CHP Energetyka Ursus	110	6	Coal	Energetyka Ursus Sp. z o.o.

Table A.3. Current heat production units and their properties in Kaunas [56] [57]

Plant	**Heat output (MW)**	**Electri-city output (MW)**	**Efficiency, share**	**Main fuel**
Independent heat producers				
Boilers				
'Danpower Baltic' JSC/"GECO Kaunas" JSC	20		1.03	Wood chips
"Lorizon Energy"JSC	13.3		1.03	Wood chips
"Aldec General" JSC	20		1.03	Wood chips
'Danpower Baltic' JSC/"Oneks invest"JSC	48.5		1.03	Wood chips
"Ekopartneris" JSC	17.5		1.03	Wood chips
Water heating boilers of Kaunas CHP	673		0.9	Gas
Prie-heaters	255		0.9	Gas
CHP				
"Danpower Baltic Kaunas" JSC (CHP)	20	5	0.172*/0.858**	Wood chips
"Foksita" JSC	33	5	0.172*/0.858**	Wood chips
Turbines of Kaunas CHP	279	170	0.211*/0.685** 0.284*/0.524**	Gas
"Kauno energija" JSC				
Boilers				
"Petrasiunu katiline"	19.2		1.03	Wood chips
"Petrasiunu elektrine" Biomass boilers	30		1.03	Wood chips
"Petrasiunu elektrine" PTVM-100	207		0.9	Gas
"Petrasiunu elektrine" BKZ 75-39	57.8		0.92	Gas
"Silko katiline"	21		1.03	Wood chips
"Silko katiline"	23.5		0.93	Gas
"Inkaro katiline"	20		1.03	Wood chips
"Pergales katiline"	40.25		0.92	Gas
"Juozapaviciaus katiline"	10.8		0.9	Gas
Independent heat producers. Total				
Biomass boilers	119.3		1.03	Wood chips
Gas boilers	928		0.9	Gas
Biomass CHP	53	10	0.172*/0.858**	Wood chips

Gas CHP	279	170	0.211*/0.685** 0.284*/0.524**	Gas
"Kauno energija" JSC. Total				
Biomass boilers	90.2		1.03	Wood chips
Gas boilers	339.35		0.9	Gas

*Electrical efficiency in combined electricity and heat production regime.

**Thermal efficiency in combined electricity and heat production regime.