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Published in:
Energy

DOI:
10.1016/j.energy.2018.03.156

Published: 01/06/2018

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Hast, A., Syri, S., Lekavičius, V., & Galinis, A. (2018). District heating in cities as a part of low-carbon energy system. *Energy*, *152*, 627-639. https://doi.org/10.1016/j.energy.2018.03.156

Energy 152 (2018) 627–639

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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

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ARTICLE INFO

Article history:
Available online 29 March 2018

Keywords:
District heat
Energy poverty
CO_2 emissions
District heating scenarios
Cities
Carbon neutrality

ABSTRACT

In this paper, district heating scenarios towards carbon neutral district heat production in 2050 were formed for Helsinki region, Warsaw and Kaunas based on the plans and goals of the studied cities and the companies supplying district heat in these regions. 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. Increased energy efficiency and carbon capture and storage technologies could also be utilized. According to the results, the annual emissions in Helsinki region could be cut by 90% by 2050 compared to the reference case and the average heat production costs increase only by 16%. In Warsaw, emissions were cut by 75% by 2050 but the heat production costs increased by 40%. In Kaunas, emissions can be cut from 0.102 to 0.087 million tonnes of carbon dioxide by 2050 with modest cost increase (29%). Yet, if the emissions are cut to zero, the marginal heat production costs increase by 55%. The cost increase thus depends strongly on the case and in order to limit the increase of heating costs and energy poverty, diversified use of different technologies should be considered.

1. Introduction

Reducing emissions in the energy sector is essential for climate change mitigation and for meeting EU's emission objectives. Study by Connolly et al. [1] suggests that district heating (DH) could play an essential role in the cost-effective decarbonization of the EU energy system and compared with alternative scenarios, DH might be a tool to achieve reductions of carbon emissions and use of primary energy at a lower cost [1]. In many countries DH is considered as an important part of reaching their environmental goals [2] and for example in Denmark, a spread of renewable sources based DH is one of the essential preconditions in reaching a goal to make Danish heating sector free of fossil fuel until 2035 [3]. Yet, the current DH systems need to be developed and the use of fossil fuels reduced while utilization of e.g. renewable energy sources and waste heat is increased. Low-temperature DH systems and use of heat storages and heat pumps could also be developed further. In addition to heating, district cooling is also likely to have an important role in the future energy systems [4]. Besides environmental aspects, it is also important to take the costs and affordability of DH into account in order to curb energy poverty since for example in EU, even 11% of population may be affected by energy poverty [5].

District heating has a potential to contribute to the operation of future low-carbon energy systems with a large share of renewable energy sources due to its flexibility to integrate different energy sources [6] and more efficient use of resources maximizing the benefits of cogeneration and the economy of scale [7]. There are different strategies in which district heating can contribute to the overall process of the transition to the low-carbon energy system. Two main directions are the decarbonization of district heating itself and the introduction of low-carbon district heating and cooling solutions in cases when decentralized options are unable to be equally attractive in terms of pollution, convenience, and efficiency. However, both of them face certain challenges related to the increasing energy efficiency, changing technical requirements, availability of resources, etc.

Decarbonization measures range from the utilization of more efficient technologies or less polluting fossil fuels such as natural gas instead of coal to the implementation of district heating systems that are fully based on renewable energy sources. If it replaces coal, natural gas cogeneration can be considered as a decarbonization measure due to lower emissions [8]. Despite the fact that the cost ranges of 100% renewable energy systems are relatively broad [9], the use of renewable energy sources is the dominant

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https://doi.org/10.1016/j.energy.2018.03.156

trend since the partial replacement of the pollutants is often considered as an intermediate step towards fully renewable and carbon-free energy system. The technologies in fully renewable energy system also might be different which affects also the development of district heating systems. For instance, the penetration of wind energy in power production might be among the reasons to expand district heating to enable effective integration of fluctuating generation [7]. Although biomass is considered as the most obvious option for traditional district heating systems, its availability limits are diverse in different studies [10]. In some cases, additional efficiency measures are needed to decrease biomass demands [11]. Studies on the DH systems of Järvenpää [12] and Stockholm [13] indicate that other technologies such as solar collectors, heat pumps and heat storages are also among the options to be integrated to the future low-carbon district heating systems in order to provide heat to the consumers and to contribute to the balancing of renewable energy production. New trends in district heating are related not only to the changes in centralized heat generation, but also to the transformation of the network itself which is required to address building automation, prosumers' involvement, and smart integration of mixed energy systems [14]. The decentralization trends in district heating could be reinforced by the utilization of excess heat from buildings which along with the development of near-zero energy buildings will increase the need for the seasonal heat storages in district heating networks [15].

Consumer-side energy efficiency measures such as refurbishment of buildings can be treated as a partial alternative (or competing measure) to district heating as it might considerably decrease heat demand in terms of both capacity and heat required [16]. Therefore, existing capacities might fail to be utilized sufficiently and the efficiency of new smaller units might be lower [17]. Moreover, the decreasing heat demand in buildings reduces the energy density. This process negatively affects the development of district heating, since high heat density along with the economy of scale is among the main preconditions to make district heating attractive heat supply option: even CHP-retrofit and utilization of recovered heat might be not feasible if the energy density is not sufficient [18]. The Danish municipality of Helsingør is also a good case in point. To optimise the cost, the share of district heating in total heat supply should increase: while in 2030 it is 32–41% which is close to baseline value (33%), it could grow to 38–44% in 2050 and the growth limits are mainly imposed by relatively low (compared to Copenhagen and some other Danish cities) heat density. In parallel, energy efficiency measures should be implemented and district heating demand in absolute numbers could decrease by 20–39% in 2030 [19].

In addition to the development of competing individual technologies, the role of district heating in a future energy system depends on local conditions and locally specific features [20]. Local conditions are greatly dependent on municipal level energy strategies [21], decisions made at the municipal level [22], other related decisions such as gate fees for waste-to-energy plants [23], and overall waste management system [24]. The national energy policies [14] are also very important in the development of DH systems. It is thus not enough to perform country-level decision-making since objectives and situation in every municipality might be different. Therefore, case studies focusing on particular DH systems need to be performed. The peculiarities of different cities are addressed in the scientific literature by analyzing cases of Turin [25], Geneva [26], Göteborg [27], Ludwigsburg-Sonnenberg [28], four Austrian cases [29], etc. Such studies provide valuable insights into the development and operation of DH system in particular cases, but they fail to serve as a basis for broader analysis. One or several cities in the same country would not allow making more general conclusions about the future role of DH since the local-level information needs to be aggregated in the bottom-up basis to obtain regional, national or international levels [20]. More general conclusions and recommendations could, however, be drawn from the comparison of the results for different cities [30]. Plans of local energy companies are also of great importance, as they will need to be proactive not only in the development of the district heating system, but also in the promotion of services it can provide [31].

This paper presents initial modelling results of the EU Horizon 2020 project REEEM about the role of district heating systems in selected European cities to support the energy transition. The aim of this paper is to compare district heating development pathways in different contexts 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 housing stocks. In addition, different national and city-level policies affect the behaviour of both energy producers and consumers. The main goal of this study is to analyze 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 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.

2. District heating in the studied cities

2.1. Helsinki region

In Finland, approximately half of the population is served by DH and in the larger cities, the market share of DH is even 90% [32]. According to analysis by Pöyry [33] DH will maintain significant role in the Finnish energy system also in the future. Yet, the market shares of heat pumps and hybrid heating systems have increased in recent years and there is thus more competition in the Finnish heating sector. Requirements to increase the energy efficiency of buildings decrease the building heating loads [34] which may further affect the profitability and market share of DH in Finland [33].

The Finnish national emissions should be cut by 16% from the 2005 levels by 2020 [35] and the share of renewable energy in the final energy consumption increased to 38% by 2020 [36]. In Finland government aims to abandon coal use in energy production and to halve the use of fossil oil by 2030 [37]. 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 [38]. 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 [39].

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 [40]. 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 [41]. 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 [42]. The city of Espoo plans to reach carbon neutrality by 2050 and to reduce resident-specific emissions by 60% by 2030 compared to 1990 [43]. The city of Vantaa aims at reducing its emissions by 20% by 2020 compared to 1990 levels [44]. Various projects are planned by the DH companies in the three cities and main projects are listed below.

Plans of Fortum Oyj in Espoo:

- Utilization of excess heat from a hospital. This would cover heat demand for around 50 single-family houses (i.e. approximately 1000 MWh) [45].
- Use of geothermal heat in Otaniemi. Heat output around 40 MW [46].

Plans of Vantaan Energia Oy in Vantaa:

- Modernization of Martinlaakso 1 CHP plant (earlier fired by oil and gas) so that it would use bio fuels in 2019 [47].

Plans of Helen Ltd in Helsinki:

- Helen has decided to close Hanasaari coal CHP plant by 2024 [48].
- New pellet-fired heating plant will be built. Heat output of the plant is 92 MW [49].
- Pellet systems will be used in Hanasaari and Salmisaari CHP plants. Approximately 5–7% of coal can be replaced by wood pellets [50].

The DH system of Espoo has been studied in the scientific literature e.g. by Syri et al. [51] who developed an hourly model for the concept of open district heating. Their analysis showed that significant cost and fuel savings could be achieved with this concept. Carbon-neutral heat production technologies for Helsinki were evaluated with multicriteria method by Kirppu et al. [52]. They found that short-term heat storages and electric boilers based on renewable power were the most preferred alternatives. The DH system of Järvenpää and Tuusula, near the region studied in this paper, was analyzed using EnergyPRO by Hast et al. [12]. They analyzed the effects of future electricity price scenarios, and searched optimal combination and dimensioning of different DH components. They found that the most profitable solution was to include both a heat storage (1% of annual DH energy) and a heat pump (20% of the peak heat demand) in the system. In the research presented in this paper, three DH systems were studied instead of one and scenarios of their possible future development were formed so that several technology options were considered.

2.2.Warsaw

As an EU Member State, Poland has targets concerning GHG emissions and the share of renewable energy sources (RES). By 2020, the increase of national GHG emissions should be limited to 15% compared to 2005 levels [35] and the share of RES increased to 15% in the final energy consumption [36]. In addition, directives such as the Directive on Industrial Emissions [53] 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 participates 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 for example the support system mechanisms and rules for electricity and gas systems are established [54]. 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 [55]. In addition, electricity generated from RES is exempt from the excise tax [56]. 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 [57].

It should, however, be noted that there are large deposits of coal in Poland while gas and crude oil are mainly imported [57]. As energy security is considered as an important objective in Poland [56], 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 [58,59].

In Poland, the share of coal in the energy mix for heat production was over 70% in 2011 [60]. In addition, the plants are rather old and inefficient, and the heat losses of the heating network are around 12% in Poland [58] [61]. 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 [56]. Around 80% of the buildings in Warsaw are heated with DH and in 2010, the total delivered DH was approximately 10 TWh [62]. 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% [63]. Projects planned in the Warsaw DH system are listed below.

- Building a new waste-to-energy facility. Electricity output of the plant is 50 MW and heat output 25 MW [64].
- 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 $MW_{electricity}$ [65].
- Building a new Pruszkow CHP plant. Plant will be fired by gas, electricity output is 16 MW and heat output 15 MW [65].
- CHP plants Zeran and Siekierki are being fitted with measures which will allow them to use bio fuels [63].

According to the authors' knowledge, there is a lack of international scientific literature concerning the operation and future development of the Warsaw DH system even though it is the largest DH system in the EU [56]. Research has been done on the effects of solar radiation and wind speed on the heat demand in Warsaw DH system by Wojdyga [66]. A study on the small solar DH systems with heat storage includes analysis of the system in Warsaw [67], and the concept of smart heating network for the Warsaw DH is studied and designed in Ref. [68]. Analysis of the possible development of Polish DH systems showed that in the future, increased combustion of municipal waste can be expected in addition to utilization of biomass as a fuel. Cogeneration and trigeneration systems will also be developed but high costs are a disadvantage of the cogeneration based solutions [61]. Due to the currently low heat prices, operational costs often exceed the income from heat and electricity sales, and cogeneration investments do not guarantee a return on investment. Support system for the development of cogeneration is thus needed [69]. In a study on the economic aspects of geothermal energy in Polish DH, it was found that even though the costs of geothermal energy are higher than those of coal, geothermal energy is still cheaper than biomass, natural gas or fuel oil [70]. Analysis of the Polish energy policy point out e.g. that there are problems related to the stability and quality of law in the energy sector [59].

2.3.Kaunas

Over several years Lithuania has made a noticeable progress towards decarbonization of the energy sector and wider use of renewable energy sources. The share of renewable energy in gross final energy consumption was 25.8% in 2015, while the directive 2009/28/EC of the European Parliament and of the Council required reaching 23% 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. The total capacity of biomass plants in district heating sector increased from 518 MW in 2010 to 1589 MW in 2015 [71]. 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%. In 2016 the share of biomass and municipal waste reached 64.1%. Moreover, there are expectations to increase this number to 80% in 2020 [72].

Currently, there are no strict legislative requirements which affect capacity stock in district heating sector. A 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% in 2017 and more than 45% in 2023 [73], while the actual value in 2015 was 46.17% [74]. The new National Energy strategy is still under preparation stage at Ministry of Energy of Lithuania and it should set new aims for the development of Lithuanian energy sector. Nevertheless, common goals related to climate change, decarbonization 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 [75]. DH system operator purchased 59% of heat in 2016, the remaining part was produced in the facilities that belong to AB "Kauno energija" [76]. 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 MW_e and 70 MW_{th}) could be treated as a planned project in Kaunas DH system, but there are also some initiatives of the earlier stage such as very flexible gas-fired CHP mainly devoted to provide auxiliary services for the electricity system.

The development of DH system in Kaunas has not been widely discussed in the international scientific literature. More research has been done in the field of the reliability of DH system and other technical peculiarities. Kaunas case has been used in the analysis of pipe break accidents [77], reliability assessment of pipeline network systems [78], and network failure probabilities [79]. Kaunas city case is also analyzed in the context of DH market liberalization [80]. The analysis of the development and operation of heat generation sources in Kaunas is valuable not only in terms of the role of DH in the future low-carbon energy system but it can also provide additional insights for the research in other fields related to DH system.

2.4.Methods

The scenarios studied in this paper are formed based on the plans and objectives of the cities and DH companies described earlier. In addition, expert opinions were taken into account when scenarios were formed. Modelling of the Helsinki region and Warsaw is done with EnergyPRO and Kaunas DH system is modelled with MESSAGE. EnergyPRO has been used in analyzing various DH cases (see e.g. Ref. [12,81–83]). In addition to DH cases, MESSAGE has been used for example in assessing GHG emission scenarios [84–86].

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 [87] and provides optimal operation and development solutions for entire time period analyzed. 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. Optimization in EnergyPRO is performed based on the priority numbers determined for each production unit at each time step and the optimization is not performed in a chronological way [88]. The solution may therefore differ from the most optimal solution and as pointed out e.g. by Hast et al. [12] it is important to check whether a more optimal solution could be found by altering the model settings. These aspects are taken into consideration in the results presented later in this paper.

3.Data and assumptions

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 °C. It is assumed that energy used for hot water generation is constant and approximately 20% of the annual heating demand [60,89]. In Kaunas case district heating demand projections have been prepared taking into account energy efficiency improvements such as buildings' renovation, demographic developments and other

Table 1
Technical assumptions concerning heat production units in Helsinki region and Warsaw [12].

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

factors.

Current production units and their properties in the DH systems of Helsinki region, Warsaw and Kaunas are described in Tables A.1-A.3 in the appendices. 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 [90]. 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.

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 the 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 [12]. 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.

4.Results

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

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 (up to 70 MW_{th}), electrical and steam-driven absorption heat pumps, solar collectors, heat storages are considered among new candidate heat producing technologies in both scenarios.

The common trend for all development scenarios is the decommissioning of old and inefficient capacities since current Kaunas district heating system can be characterized as having a big excess heat capacity, which mainly consists of old natural gas-fired boilers. Another reason to decrease installed capacity is expected decrease of energy demands due to efficiency improvements (mainly, deep renovation of buildings). The development of heat storages might be an additional factor which allows for peak

Table 2
Cost assumptions concerning production [12].

	HOBs	CHP plants	Heat pumps
Start-up costs	0 €	2500 €	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	

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

	2050	Reference
Carbon price	90 €/tCO_2eq	[93]
Coal, import price	29 $/boe (16.3 €/MWh)	[93]
Oil, import price	130 $/boe (73.1 €/MWh)	[93]
Natural gas, import price	79 $/boe (44.4 €/MWh)	[93]
Waste in CHP plant (Finland)	−45 €/t_{waste} (i.e. gate fee)	[94]
Biomass price	27.5 €/MWh	[95–98]
Wood chips	40 €/MWh	
Wood pellets	46 €/MWh	
Average electricity price in Finland	56 €/MWh	[99]
Average electricity price in Poland	64 €/MWh	[99]
Average electricity price in Lithuania[b]	60 €/MWh	Assumed average between Finland and Poland

[a] Assumed that 1 boe = 1.63 MWh, 1 MWh = 3.6 GJ [91], 1 USD = 0.917 € [92].
[b] Daily, weekly and seasonal variation of electricity prices was not taken into account in this study in Kaunas case.

Table 4
Fuel taxes used in the model (VAT is excluded).

Country	Fuel	Price
Finland	Natural gas tax, HOB	18.6 €/MWh [100]
	Natural gas tax, CHP	12.9 €/MWh [100]
	Light fuel oil tax, HOB	22.9 €/MWh [100]
	Light fuel oil tax, CHP	15.1 €/MWh [100]
	Heavy fuel oil tax, HOB	23.7 €/MWh [100]
	Heavy fuel oil tax, CHP	15.5 €/MWh [100]
	Coal tax, HOB	27 €/MWh [100]
	Coal tax, CHP	17.1 €/MWh [100]
	Bio oil tax	48 €/MWh [101]
	Electricity distribution cost	21 €/MWh [101]
	Electricity tax	22.5 €/MWh [102]
Poland	Light fuel oil tax	5.4 €/MWh [102]
	Natural gas tax	1.1 €/MWh [102]
	Coal tax	1.1 €/MWh [102]

Table 5
Assumptions concerning investment costs and variable O&M costs of CCS.

Investment cost	
Geothermal District Heating	1.8 M€/MW [103]
Rebuilding coal power plants to biomass	0.18 M€/MW (wood pellets) [103] 0.42 M€/MW (wood chips, straw) [103] 0.52 M€/MW (wood chips, dried) [103]
Modernization of existing plant in Warsaw	0.06 M€/MW[a] [103]
Carbon capture (NGCC-CCS)	1.3 M€/MW [103]
Carbon capture (coal-CCS)	2.5 M€/MW [103]
Waste-to-Energy CHP Plant in Warsaw	8.5 M€/MW_{th} [103]
Waste-to-Energy CHP Plant in Kaunas	6.25 M€/MW_e [103]
Heat storage investment cost	30 €/m^{3}*Volume (m^3) [105]
Heat pump	0.53 M€/MW [103]
O&M costs	
Variable O&M cost (NGCC-CCS)	0.9 €/MWh [103]
Variable O&M cost (coal-CCS)	4.5 €/MWh [103]
Fixed O&M cost (NGCC-CCS)	38,000 €/MW/year [103]
Fixed O&M cost (coal-CCS)	65,000 €/MW/year [103]

[a] 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€/$MW_{heat\ output}$ [104]. This has been used as a rough estimate of the modernization costs in Poland.

shaving and decreasing needs for investment in peaking capacities.

The new investments in the Kaunas DH scenarios analyzed are made mainly to replace part of existing capacities after the end of their lifetime. In both scenarios, investments are put to biomass heat only boilers, but there is also the considerable capacity of new gas-fired boilers installed. The main purpose of these boilers is peaking and reservation, but they are used only for reservation at the end of the study period in the C-Free scenario. Consequently, their capacity is lower in the C-Free scenario. The capacity of waste-to-energy CHP is lower than expected (up to 60 MW_{th} in BAU and 34 MW_{th} in the C-Free scenario) due to relatively low heat demand during summer which would result in not optimal utilization of bigger capacities. In the case of C-Free scenario, accounting of GHG emissions decreases the attractiveness of waste as an energy resource. In both scenarios, solar collectors also receive some investment, but their share in the capacity structure remains modest. The main difference between the modelled scenarios is a high penetration of steam-driven absorption heat pumps in C-Free scenario (65 MW_{th} of total installed capacity in C-Free scenario in 2050 compared to 15 MW_{th} in BAU in the same year), but it should be noted that the prospects of this technology heavily depends on the developments in the electricity markets and other additional factors.

Annual emissions and heat production costs are summarized in Table 7. As can be seen, costs as well as the annual emissions in Helsinki and Warsaw 2030 scenarios are slightly lower than in the reference scenarios. Yet, in 2050 scenario costs increase rather much which is due to the high investment costs of CCS technologies in particular. In Kaunas heat prices are growing in both analyzed scenarios, mainly due to growing fuel prices. Yet, more significant costs increase in the C-Free scenario can be seen after 2030. This additional cost increase is related to the necessity of replacing peaking gas boilers by more investment intensive free carbon technologies. CO_2 emission increase in Kaunas BAU scenario in 2030 is caused by increased utilization of municipal waste in waste-to-energy CHP, which later is compensated by reduced utilization of natural gas. In the C-Free scenario CO_2 emissions are permanently going down during entire study period.

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. In Poland, there is a goal to increase the CHP production and the results show that in the 2030 and 2050 scenarios there is a small increase in the share of CHP production from the already high share (80%) in the reference scenario. In Kaunas, the share of CHP production increases in the BAU scenario. In the C-Free scenario share of CHP increases until 2030 while later it is decreasing due to significant growth of absorption heat pumps utilizing the same fuel as biomass CHP's.

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 [44]. In Kaunas DH system case, the emission factor for waste plays an important role in the choice of technologies. C-Free scenario requires full decarbonization of district heating sector and any emission factor for waste other than zero would either prohibit the utilization of waste for fuel purpose or CCS should be introduced at the end of study period. However, this is at some extent political decision related to the waste treatment strategy: it is possible in principle that solid recovered fuel produced from municipal waste, includes only materials of biologic origin and therefore is CO_2 neutral. Despite this, a more realistic scenario is that some fossil-based materials take a part in the composition of municipal waste. Therefore, 114 $kgCO_2$-eq/MWh emission factor has been assumed in Kaunas case. It was, however, 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 Figs. 1–3. The results show that in the Helsinki region the consumption of natural gas and coal decrease significantly 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 (Fig. 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 rather much. In the 2050 scenario, the use of waste fuel also increases due to the new waste CHP plant. In the Kaunas DH case (Fig. 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 utilization is visible during the study period, especially in the C-Free scenario.

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 [105] 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%)

Table 7
Results from the simulations.

Region	Scenario	Annual GHG emissions [$MtCO_2$-eq]	Heat production costs [€/MWh_{heat}][a]	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) 2.94 (2) 2.71	50	55	31	14
	2030	(1) 0.64 (2) 0.41	39	29	57	14
	2050	(1) 0.27 (2) 0.04	58	29	39	32
Warsaw	Reference scenario	(1) 4.65 (2) 4.52	66	80	20	
	2030	(1) 2.56 (2) 2.43	42	83	17	
	2050	(1) 1.19 (2) 0.21	93	82	18	
Kaunas	BAU scenario 2020	0.102	59	18	82	
	2030	0.105	68	40	50	10
	2050	0.087	76	48	24	28
	C-Free scenario 2020	0.101	60	17	83	
	2030	0.082	77	30	50	20
	2050	0	93	7	27	66

[a] 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.

Reduced consumption of wood chips is conditioned by decreased heat demand and increased consumption of municipal waste.

In 2016, approximately 56% of the actual total fuel consumption in DH and CHP production was coal and 34% natural gas in Helsinki region. The share of waste was 5.9%, of wood pellet 1.2% and of electricity 1.2% [106]. Fig. 1 shows that in the reference scenario the shares are: coal 33%, natural gas 36%, waste 14%, wood pellet 7.7%, biomass 5.7% and electricity 2.8%. In the reference scenario, the already planned projects are implemented to the current DH system i.e. the scenario does not actually reflect the current situation but is closest to the current situation among the studied scenarios. When the results from the simulation are compared to the actual fuel consumption in 2016, it can be seen that the coal consumption decreases quite much compared to the actual current situation while the consumption of waste, wood pellet and electricity increases. This is a rational result since in the planned projects e.g. coal CHP plant is closed and pellet-fired heating plant is built. It can thus be concluded that the modelling results are rather reasonable.

In the Warsaw DH system, the actual fuel mix was coal (73%), natural gas (21.5%) and RES (5.5%) in 2014 [107]. Modelling results in Fig. 2 show that the fuel consumption in reference scenario was coal (59%), natural gas (23%), light fuel oil (12%) and waste (6%). Compared to the current situation, the consumption of coal decreases and the consumption of natural gas increases only slightly. The consumption of light fuel oil is, however, significantly higher than the actual consumption was in 2014, and it seems that in the modelling, the decrease in coal consumption is compensated by light fuel oil. As in the case of Helsinki region, the reference scenario does not actually reflect the current situation and the currently planned projects are already implemented to the current DH system.

In Kaunas, the most of the heat (79% in 2016) is already produced from biomass [108]. Thus, there is not so much room for the decarbonization, especially taking into account the need of manoeuvrable heat generation sources. The main driver for fuel balance change in 2020 (see Fig. 3) is the introduction of waste-to-energy CHP plant. The discussions on the capacity or even on the necessity of this plant in Kaunas are still going on [109]. The

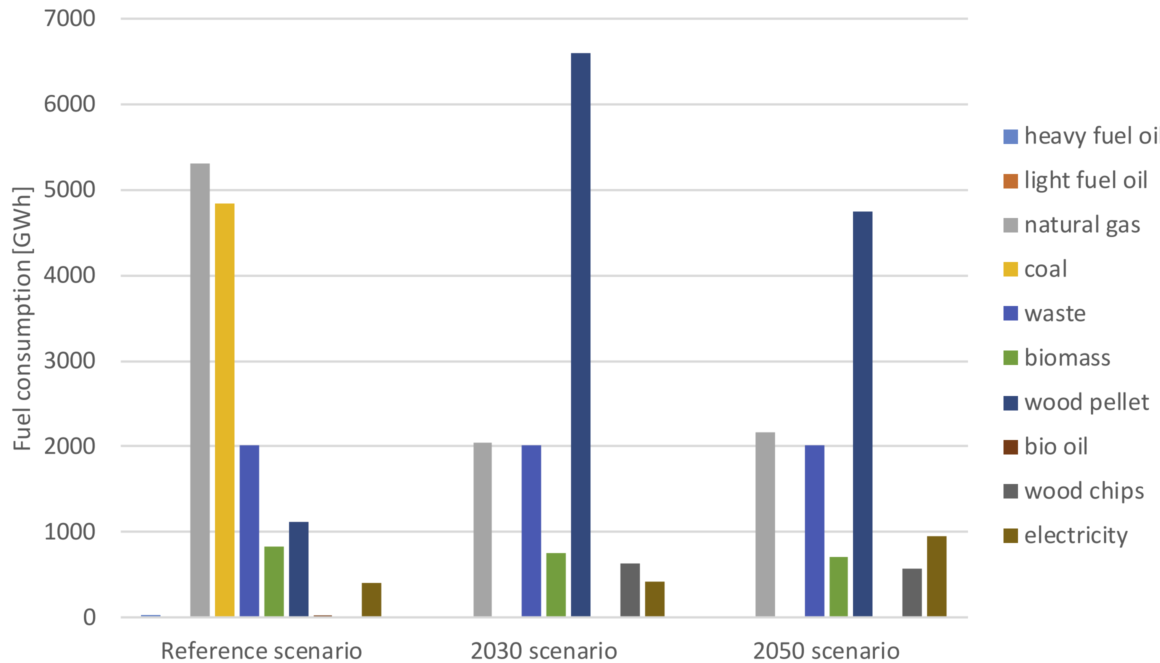

Fig. 1. Fuel and electricity consumption in the DH system of Helsinki region in different scenarios.

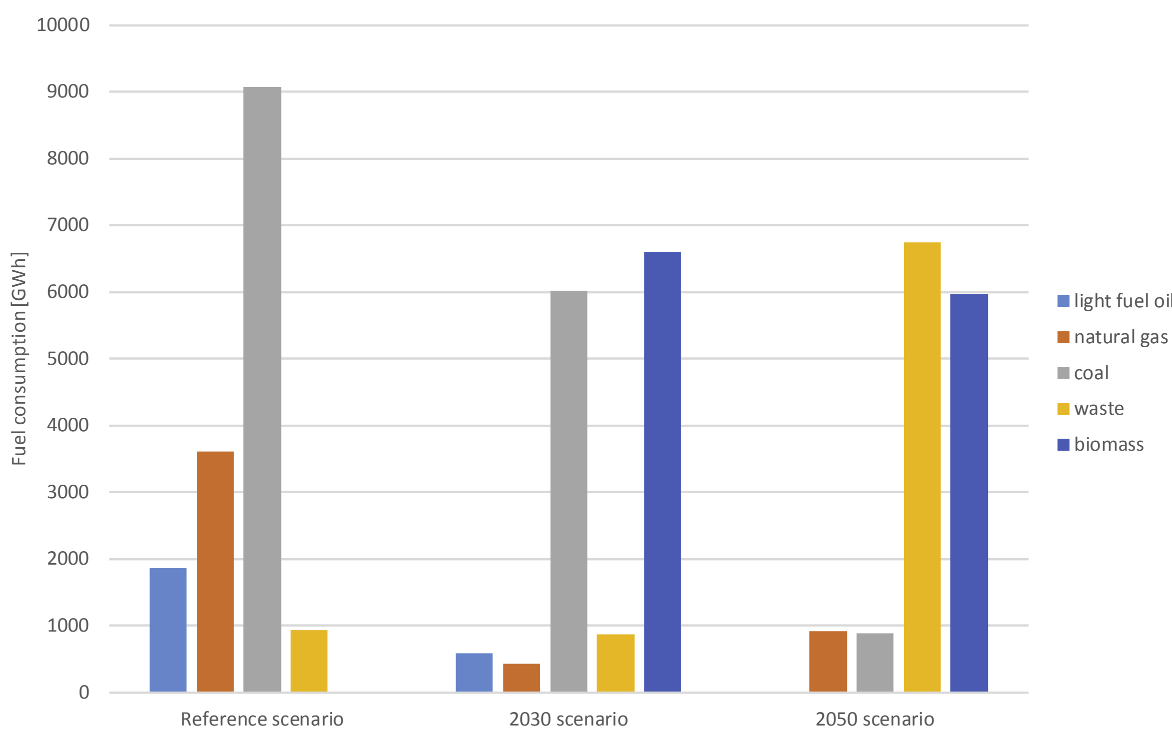

Fig. 2. Fuel consumption in Warsaw DH system in different scenarios.

modelling results show that its optimal capacity is lower than planned. Thus, the share in the total fuel balance is also not as big as expected. Also, it should be noted that the fuel in CHP plants is used to produce both heat and electricity. Therefore, its relative role is bigger than the role of the fuel that is used in heat only boilers. More considerable changes in fuel balance are expected in the development of C-Free scenario in which decarbonization leads to the avoidance of natural gas and waste replaced by biomass and electricity for heat pumps.

5.Sensitivity analysis

Sensitivity analyses for assumed fuel prices were performed for each DH system and the effects of a 15% increase and decrease in fuel prices were examined. The mentioned price increase and decrease in the Kaunas case was applied in 2050. For the interim years of the study period these changes were proportionally lower, as fuel prices for the first year of the period considered were unchanged. In Fig. 4, the changes in the average annual heat

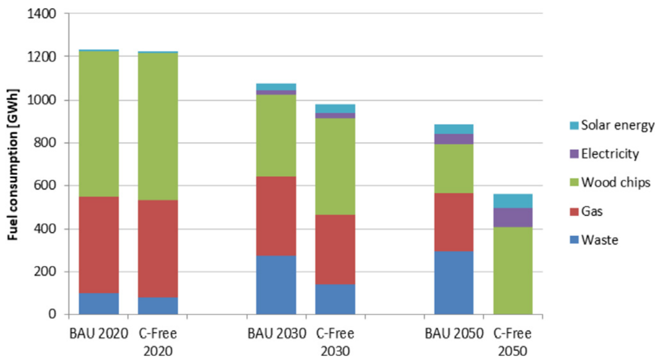

Fig. 3. Fuel consumption in Kaunas DH system in different scenarios.

production cost are presented in the Helsinki region case. As can be seen from the Figure, the prices of natural gas and coal have large effect on the cost in the reference scenario while the impact of wood pellet price is more significant in 2030 and 2050 scenarios. The changes in the average annual heat production costs in Warsaw are shown in Fig. 5 and as can be seen, in reference scenario the effect of coal price is largest. The impact of coal price, however, decreases in 2030 and 2050 scenarios and in these scenarios, the effect of electricity and biomass prices increase. The effects of higher (+15% compared to the original case) and lower (−15% compared to the original case) heat demand are also shown in Figs. 4–5. It can be seen that heat demand has rather large impact on the costs especially in the reference scenario in both regions.

The changes in the average annual heat production costs in Kaunas are shown in Fig. 6. These cost changes reflect also price related changes in the structure of heat generating technologies, as well as changes in fuel utilization. The data presented show that the changes in prices of natural gas and biomass have the greatest impact on the average annual heat production cost. In the case of the BAU scenario, rising biomass prices, as compared to natural gas price increases, have a slightly higher impact on average heat production costs. A 15% increase in biomass prices would result in a 2.6% (2 €/MWh_{heat}) increase in the average annual heat production cost in 2050. Meanwhile, the same rise in natural gas prices would generate 2.2% (1.7 €/MWh_{heat}) of the increase in average annual heat costs. However, decreasing natural gas prices, in comparison with the same change in biomass prices, lead to a lower average heat cost. In this case, the 15% decrease of natural gas price would reduce the average annual cost of heat production by 4.7% (3.6 €/MWh_{heat}) compared to only 2.1% (1.6 €/MWh_{heat}) cost reduction caused by similar price decrease of biomass price in 2050. Both, changes in the structure of heat production technologies and shift in proportions of fuel use, causes the fact that fluctuations of biomass price make the most important impact to changes of the average annual heat production cost in the Kaunas C-Free scenario. The 15% increase and decrease of biomass price would lead to correspondingly 4.9% higher and 4.2% lower average heat cost in 2050. Fluctuations of other fuel's prices have minor impact to heat cost.

6.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 [37], and the use of 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

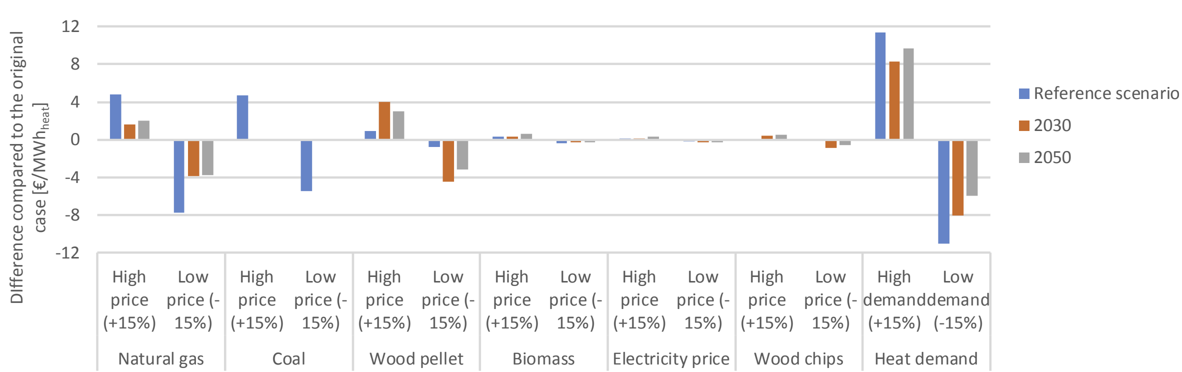

Fig. 4. Difference in the average annual heat production cost compared to the case with original fuel prices in the Helsinki region. In addition, the effects of higher and lower heat demand in heat production costs are shown.

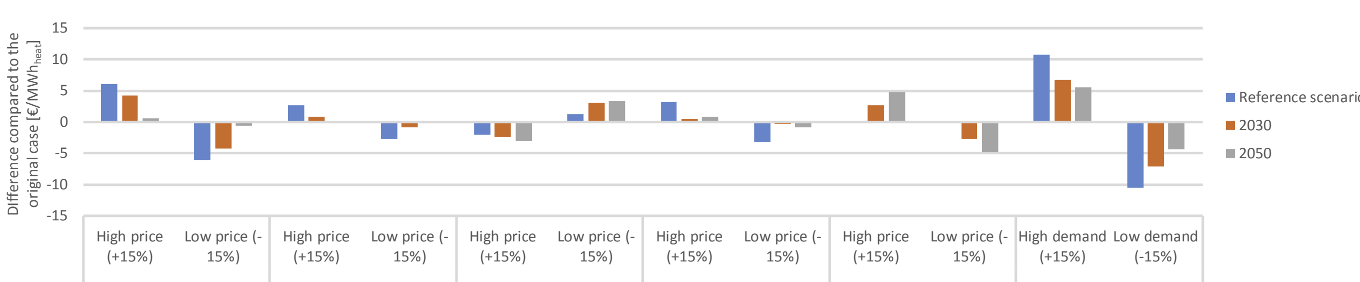

Fig. 5. Difference in the average annual heat production cost compared to the case with original fuel prices in Warsaw. In addition, the effects of higher and lower heat demand in heat production costs are shown.

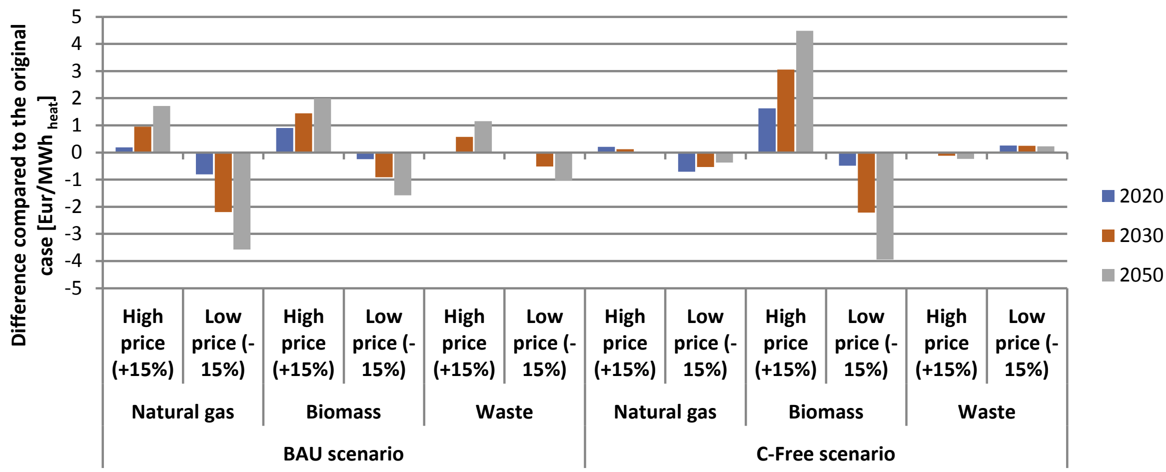

Fig. 6. Difference in the average annual heat production cost compared to the case with original fuel prices in Kaunas for both scenarios analyzed.

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 analyzed. 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 sensitivity analysis performed in this paper suggests that the level of DH demand has rather significant impact on the heat production costs. The effects of consumer heating choices and possible changes in DH demand could thus be considered in future research.

Acknowledgements

This research has received funding through REEEM project from the European Union's Horizon 2020 research and innovation programme under grant agreement 691739. The authors would also like to thank the anonymous reviewers for their comments on this paper. This publication reflects only the views of its authors, and the European Commission cannot be held responsible for its content.

Appendices

Table A.1
Current production units and their properties in Helsinki region [39].

Plant	Heat output (MW)	Electricity output (MW)	Main fuel
Espoo, Owner: Fortum Oyj			
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
Suomenoja 1 (CHP)	160	80	Coal
Suomenoja 2 (CHP)	214	234	Natural gas
Suomenoja 6 (CHP)	110	45	Natural gas
Suomenoja (heat pump)	45	–	Electricity
Helsinki, Owner: Helen Ltd			
Plant	Heat output (MW)	Electricity output (MW)	Main fuel
Alppila	164	–	Light fuel oil
Munkkisaari	235	–	Heavy fuel oil
Ruskeasuo	280	–	Heavy fuel oil

Table A.1 (*continued*)

Plant	Heat output (MW)	Electricity output (MW)	Main fuel
Lassila	334	–	Natural gas
Patola	240	–	Natural gas
Salmisaari 1	120	–	Heavy fuel oil
Salmisaari 2	180	–	Coal
Salmisaari 3	7.7	–	Heavy fuel oil
Jakomäki	56	–	Heavy fuel oil
Myllypuro	240	–	Natural gas
Vuosaari	120	–	Natural gas
Hanasaari 1	56	–	Heavy fuel oil
Hanasaari 2	282	–	Heavy fuel oil
Salmisaari B (CHP)	300	160	Coal, wood pellet (7%)
Hanasaari B (CHP)	420	226	Coal, wood pellet (7%)
Vuosaari A (CHP)	160	160	Natural gas
Vuosaari B (CHP)	420	470	Natural gas
Katri Vala (heat pump)	90	–	Electricity
Vantaa, Owner: Vantaan Energia Oy			
Plant	Heat output (MW)	Electricity output (MW)	Main fuel
Koivukylä	145	–	Natural gas
Hakunila	80	–	Natural gas
Maarinkunnas	200	–	Natural gas
Lentokenttä	92	–	Heavy fuel oil
Varisto	92	–	Natural gas
Jussla	10	–	Light fuel oil
Martinlaakso 2 (CHP)	135	80	Heavy fuel oil
Martinlaakso 4 (CHP)	120	60	Natural gas
Jätevoimala	140	76.4	Waste
Martinlaakso Gt	75	58	Natural gas

Table A.2
Current heat production units and their properties in Warsaw [110,111].

Plant	Heat output (MW)	Electricity output (MW)	Main fuel
Owner: PGNiG Termika S.A.			
EC Zeran	1580	386	Coal
EC Siekierki	2078	620	Coal
EC Pruszków	186	9.1	Low-carbon coal
Heat Power Station Kaweczyn	465	–	Coal
Heat Power Station Wola	465	–	Light fuel oil
Owner: Energetyka Ursus Sp. z o.o.			
CHP Energetyka Ursus	110	6	Coal

Table A.3
Current heat production units and their properties in Kaunas [112,113].

Plant	Heat output (MW)	Electricity output (MW)	Main fuel
Owner: Independent heat producers			
'Danpower Baltic' JSC/“GECO Kaunas” JSC	20	–	Wood chips
“Lorizon Energy”JSC	13.3	–	Wood chips
“Aldec General” JSC	20	–	Wood chips
'Danpower Baltic' JSC/“Oneks invest”JSC	48.5	–	Wood chips
“Ekopartneris” JSC	17.5	–	Wood chips
Water heating boilers of Kaunas CHP	673	–	Gas
Pre-heaters	255	–	Gas
“Danpower Baltic Kaunas” JSC (CHP)	20	5	Wood chips
“Foksita” JSC	33	5	Wood chips
Turbines of Kaunas CHP	279	170	Gas
Owner: “Kauno energija” JSC			
“Petrasiunu katiline”	19.2	–	Wood chips
“Petrasiunu elektrine” Biomass boilers	30	–	Wood chips
“Petrasiunu elektrine” PTVM-100	207	–	Gas
“Petrasiunu elektrine” BKZ 75–39	57.8	–	Gas
“Silko katiline”	21	–	Wood chips
“Silko katiline”	23.5	–	Gas
“Inkaro katiline”	20	–	Wood chips
“Pergales katiline”	40.25	–	Gas
“Juozapaviciaus katiline”	10.8	–	Gas

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