D4.2 Case study on district heat

February 2019

About this report

This report is part of EU Horizon project REEEM. The report presents case study, which analysed the possibilities of three city regions to transform their district heating systems to carbon neutrality. The city regions considered were Helsinki region, Warsaw in Poland and Kaunas in Lithuania. Work was done using energy system models and scenario analysis and in interaction with national and city-level stakeholders. The work is also reported as scientific articles and scientific conference presentations.

Authors

Dr. Aira Hast, Professor Sanna Syri, Aalto University
Dr. Arvydas Galinis, Dr. Vidas Lekavičius, Lithuanian Energy Institute

REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

The REEEM project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691739. This publication reflects only the views of its authors, and the European Commission cannot be held responsible for its content.

Contents

List of figures

List of tables

1 Task Description and Objectives

The main task description for work package 4.3 is defined as follows:

> One workshop with 10-15 participants is foreseen for to refine the scope of a case study on district heating, focusing on cities. The outputs will be used to evaluate how new, innovative district heating concepts can best contribute to lower expenditures and to reducing energy poverty. Technological choices for different pathways will be assessed regarding reliability, carbon neutrality and affordability.

The main objective of the task is thus to define and analyse district heating (DH) scenarios towards carbon neutrality by 2050. In order to reduce energy poverty and prevent the increase of consumer district heat price, this objective should be reached with minimum costs. The cities that were studied in the case study are Warsaw, Kaunas and Helsinki region (i.e. the cities of Helsinki, Espoo and Vantaa). In all of the studied cities district heating has a significant role but differences exist in the market structure, ownership, fuels and technologies used. In addition, the heat demands, housing stocks, and consumer profiles vary between the cities. The different national and city-level policies affecting energy producers and the possible changes in the energy production structure (fuels, technologies) are also different between the studied areas. A one-day workshop with 20 participants representing both academia and energy and district heat industry from all the studied countries was organised in Kaunas, Lithuania on 4th April 2017. The preliminary work plan of the District Heat Case study was presented, and feedback was received from the invited stakeholders. Stakeholders also presented their views on DH business and technology issues and other essential future issues from their respective viewpoints.

2 Scoping and Setting of Objectives

In order to identify the possible changes in the DH sector and to form the studied DH scenarios, national and city-level objectives and policies affecting the development of the DH systems were reviewed. In addition, the plans of the district heating companies supplying heat in the studied areas were considered. Expert opinions and feedback received in the DH workshop were also taken into account when the DH scenarios were developed further. The scenarios were modelled with EnergyPRO (Helsinki region and Warsaw) and MESSAGE (Kaunas). The reason for two different tools was the earlier experience of the teams with the respective models and the differences in DH market structure: the structure of MESSAGE model used in Kaunas case takes into account the fact that a large share of heat is produced by independent heat producers. In the cases of Helsinki region and Warsaw, DH scenarios were also built by interpreting the EU level energy system modelling results from TIMES PanEU to possible development of the DH systems.

2.1 The role of district heating in the context of decarbonisation

Reducing emissions in the energy sector is essential for climate change mitigation and for meeting EU's emission objectives. Study by Connolly et al. (2014) suggests that district heating could play an essential role in the cost-effective decarbonisation 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 lower cost (Connolly et al., 2014). A spread of renewable sources based DH is one of the important preconditions in reaching a goal to make Danish heating sector free of fossil fuel until 2035 (Brand and Svendsen, 2013). Other countries, especially those, which already have developed DH networks, consider DH as an important measure to reach their environmental goals. In many cases, DH helps to reach economy of scale and is more efficient heat generation option than individual alternatives (Lake et al., 2017). Along with economic advantages and ability to contribute to decarbonisation process, DH is an attractive option due to its convenience, safety, and comfort level provided. Therefore, willingness to pay for DH is 4.03–12.52% higher than for individual heating (Yoon et al., 2015).

Transformations of the network and new solutions are needed to make current DH systems suitable for the future needs. First of all, low-temperature DH systems are treated as more suitable for integration of renewable energy sources (Brand and Svendsen, 2013). Second, although technologically feasible, the integration of individual heat sources to the district heat network causes new challenges for management and control (Brand et al., 2014). Waste heat utilisation from industry and new sources, such as data centers, is an emerging trend in DH systems. Large heat pumps are usually used in combination with low-quality heat sources. Also heat generation by prosumers (i.e. consumers that are able to generate heat to the DH network), especially using solar energy, in many cases reaches its peak during in the summer, when heat demand is lowest (Brange et al., 2016). Therefore, seasonal heat storages are needed. As an answer to abovementioned and other challenges for DH in future energy system, the concept of so-called fourth generation DH is developed. Among the main features of it should be lower temperatures in a smart thermal grid, both centralized and decentralized generation sources, interaction with low-energy buildings, and close integration with other energy systems. The future development of DH could also include increased utilization of geothermal and waste heat. In addition to heating, district cooling is also likely to have an important role in the future energy systems (Lund et al., 2014).

In contrast to electricity generation from fossil fuels or nuclear, DH is very much associated with local conditions (urban demands, local resources, etc.) and locally specific features, as it is not economically viable to transport heat over long distances (Werner, 2017). Also, the decisions that are made at the municipal level are very important in DH (Chittum and Østergaard, 2014). It is not enough to perform country-level decision-making since objectives and situation in every municipality might be different. The peculiarities of different cities are addressed in the scientific literature by analysing cases of Turin (Guelpa et al., 2017), Geneva (Quiquerez et al., 2017), Göteborg (Romanchenko et al., 2017), Ludwigsburg-Sonnenberg (Uribarri et al., 2017) and four Austrian cases (Köfinger et al., 2016). 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 (Werner, 2017).

The general trends in DH sector are, however, likely to affect the development of separate DH systems but the impact of these trends depends on local peculiarities and political aims. Therefore, in the present research, the role of DH in future low-carbon energy system is analysed by studying the cases of Helsinki region, Kaunas and Warsaw.

2.2 Energy poverty and DH costs

In addition to emissions, it is important to take the costs and affordability of DH into consideration since even 11% of the EU's population may be affected by energy poverty. There is no one single European definition for energy poverty but it often refers to a situation in which individuals or households cannot afford to keep home adequately warm (European Commission, 2018; Pye et al., 2015). In our study, reducing energy poverty thus means cutting the emissions from DH production with least costs and thus prevent DH prices from increasing.

In Finland, DH price typically consists of initial connection fee and annually paid capacity and energy fees. The DH price varies between areas and in 2015, the average price of DH was 76 €/MWh (incl. VAT 24%) and since 2000, the average nominal price of DH has doubled (Finnish Energy Industries, 2016). DH prices vary within a range of roughly 60 €/MWh to 100 €/MWh in Finland for small-scale residential users, for example. Currently energy poverty is not a common problem in Finland and less than 4% of population is not able to keep home adequately warm (Pye et al., 2015). It should, however, be noted that energy poverty may become a more severe issue if the income of people at risk of energy poverty does not increase at the same rate as the price of energy (Runsten et al., 2015).

In Poland, the average DH price has increased from 21 €/MWh (excl. VAT) in 2000 to 44 €/MWh (excl. VAT) in 2013 (Werner, 2016). In the future, DH price may increase due to the need to modernize the system, which may weaken the competitiveness of DH compared to other heating options, as the pay-back of investments is included in the customer heating bills (Nuorkivi consulting and COWI, 2014). If Low Income High Costs measure is used, energy poverty affected 17% of the population in Poland in 2013. Yet, according to 13% of income threshold, almost third of the population is influenced by energy poverty (Miazga and Owczarek, 2015). Almost 28% of the population are not able to keep home adequately warm (Pye et al., 2015). It is estimated that without additional measures, energy poverty will remain at the current level by 2030 (Szpor, 2016).

It is estimated that 38% of population is not able to keep home adequately warm in Lithuania (Pye et al., 2015). Recent decision to revoke reduced VAT rate for DH at households will reduce attractiveness of DH as increase of VAT rate from 9 to 21 percent will considerably affect the expenses of DH. However, additional social security measures are being implemented to protect the most vulnerable consumers and keep the energy poverty not growing.

2.2.1 The impact of district heating price increase on energy poverty indicators

The role of district heating in energy poverty in studied cities has been analysed by employing detailed micro datasets of Household budget survey obtained from Eurostat. The Access to Eurostat microdata covering Household Budget Survey (HBS) (Eurostat, 2017) has been granted to Lithuanian Energy Institute by Eurostat to be used in REEEM Project. All the results of calculations using the datasets and conclusions are provided by the authors of this report and not those of Eurostat, the European Commission or any of the national statistical authorities whose data have been used. Although the dataset provides data for 2010, this is the most recent micro dataset about household budgets that covers all the EU countries (Eurostat, 2018).

Three energy poverty indicators are considered in this study:

- 2M indicator or the share of households whose share of expenditure on energy is twice the national median.
- As district heating price increases have an impact on the median, an additional indicator called 2Mfixed is introduced in this study and calculated by fixing the national energy expenditure share median at the base year level. In other words, simulated district heat price changes do not affect the value of national median for 2Mfixed, while for 2M national median is recalculated after each change of district heat price.
- 10pc indicator in which expenditure threshold is 10% and allows better expenditure comparison among cities in different countries.

As the datasets used provide anonymised data, there is no possibility to distinguish exactly which household belongs to which city. However, there is a possibility to use some proxies without any harm to the respondents. Rules used to select households to represent the cities under consideration are summarized in the table below.

Table 1: The description of cities in the dataset used for the analysis.

	NUTS region		Population density-level,	
	Actual NUTS region and local administrative unit in 2018	Based on possible values in HBS microdata	Actual (Eurostat, 2019)	Based on possible values in HBS microdata
Helsinki	FI1B1; 049 Espoo, 091 Helsinki, 092 Vantaa	FI1	520 inhabitants/km^2 in Espoo, 888 inhabitants/km^2 in Helsinki, 913 inhabitants/km^2 in Vantaa	1 Densely populated (at least 500 inhabitants/km^2)
Kaunas	LT022, LAU 19 Kauno miesto savivaldybė	LT0	1838 inhabitants/km^2	1 Densely populated (at least 500 inhabitants/km^2)
Warsaw	PL911, LAU 1007141286501 Warszawa	PL1	3412 inhabitants/km^2	1 Densely populated (at least 500 inhabitants/km^2)

The basic variables used to describe the cities were NUTS1 region and population density. The most exact representation is obtained for Warsaw due to the way Poland is divided into NUTS1 regions. NUTS1 FI1 represents entire Finland except for Åland, NUTS1 LT0 represents entire Lithuania. Thus, there were fewer possibilities to make an exact selection of households from the cities studied. However, this selection still allows analysing energy poverty properties in the cities of selected countries.

The values of energy poverty indicators without the changes in district heat prices are presented in Figure below.

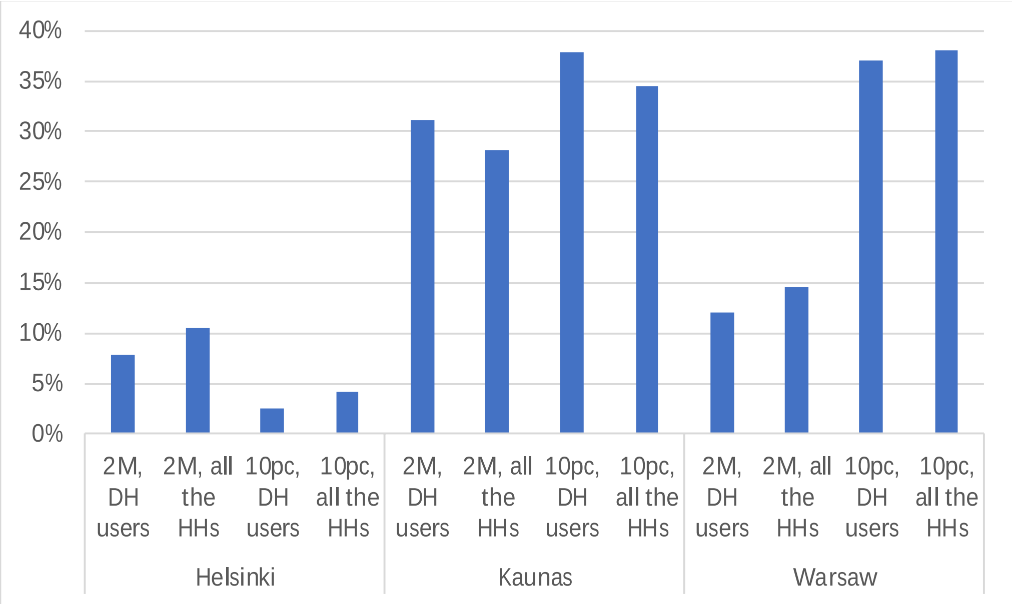

Figure 1: Energy poverty indicators in studied cities.

Despite the indicator considered, the energy poverty level in Helsinki is the lowest: only 4% of households spend more than 10% of their income for energy. The same indicator is much higher in Kaunas (34%) and Warsaw (38%). The situation among district heating users in Helsinki is even better as just 2% of households have to spend more than 10% of their income to pay energy bills. In contrast, the energy poverty level in Kaunas is higher among DH users than in the overall population.

The low energy poverty level in Helsinki can be explained not only by more advanced economic development and flatter income distribution but also by the fact that rent payments often include also heating cost and thus they are not reported separately as energy cost. There are considerable differences among countries considered with regard to housing tenure status: in Finland, 28.6% of the population are tenants, while in Poland this share is 15.8% and just 10.3% in Lithuania.

In principle, 2M indicator reflects the distribution of income shares that are needed to pay energy bills. Theoretically, there might be a situation when all the households spend a relatively large share of their income (e. g., 20%) on energy, but 2M will be zero when the distribution is flat. Thus, the most unequal shares of income are spent on energy in Kaunas (2M is 31% among DH users and 28% for the entire population). The variation of energy expenditure shares is much lower in Helsinki and Warsaw (2M is 8-15%). Also, 2M indicator is smaller among DH users in these cities.

Figures below show the relationships between district heat price and energy poverty indicators.

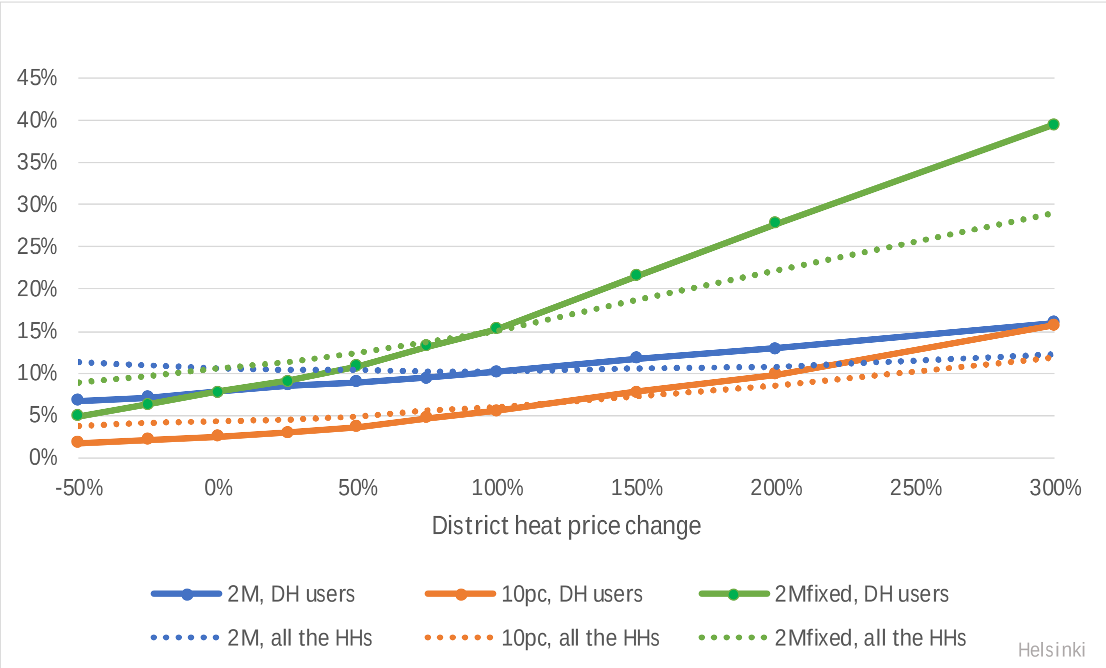

Figure 2: The relationship between district heat price level and energy poverty in Helsinki.

In Helsinki, district heating price increase would have a relatively low impact on the absolute number of energy-poor households: if DH price is twice higher than the baseline, 10pc indicator among DH users increases to 5.5%, which is still relatively low. If DH price is four times higher than base value, less than 16% of households that use DH would need to spend more than 10% of their income on energy bills.

Similar trends are observed with 2M indicators, but their general level is higher since median energy expenditure share was about 3.3% in Finland (twice median is 6.6% which is less than 10% used in 10pc indicator). In the case of a "pure" 2M, district heating price increase has an impact on the median share of energy expenses. Therefore, the energy poverty level is increasing not as remarkably as in the case when the median level is fixed at the base level (2Mfixed).

As mentioned, the general energy poverty level in Helsinki is higher than the energy poverty among DH users. The general energy poverty level among DH users would be reached only if DH prices increased by 50-70% depending on energy poverty indicator used.

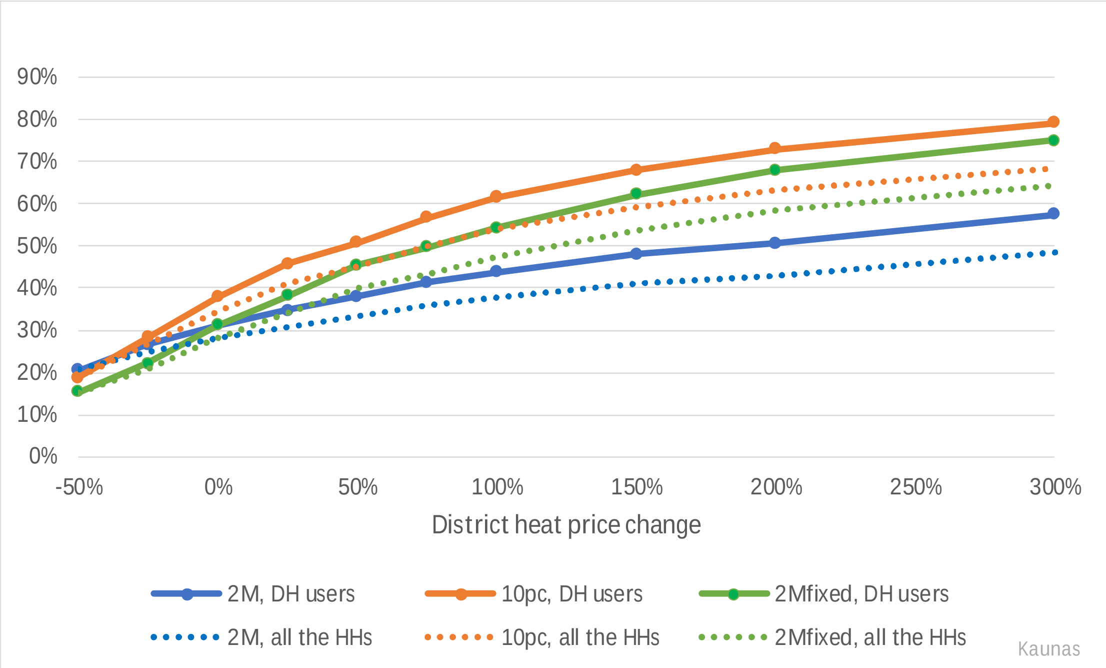

Figure 3: The relationship between district heat price level and energy poverty in Kaunas.

The national median energy expenditure share was 5.8% in Lithuania. Therefore, the trends of 10pc and 2Mfixed indicators are quite similar. District heat price increase by 100% would increase 2Mfixed to 54.4% and 10pc to 61.5%. As in the case of Helsinki, the value of 2M indicator grows slower and reaches 43.7% if DH price increases twice. If DH prices increase, the energy poverty level among DH users remains considerably higher than the general level in Kaunas. This shows that any decarbonization measure that has a negative impact on district heat prices must be taken with especial care.

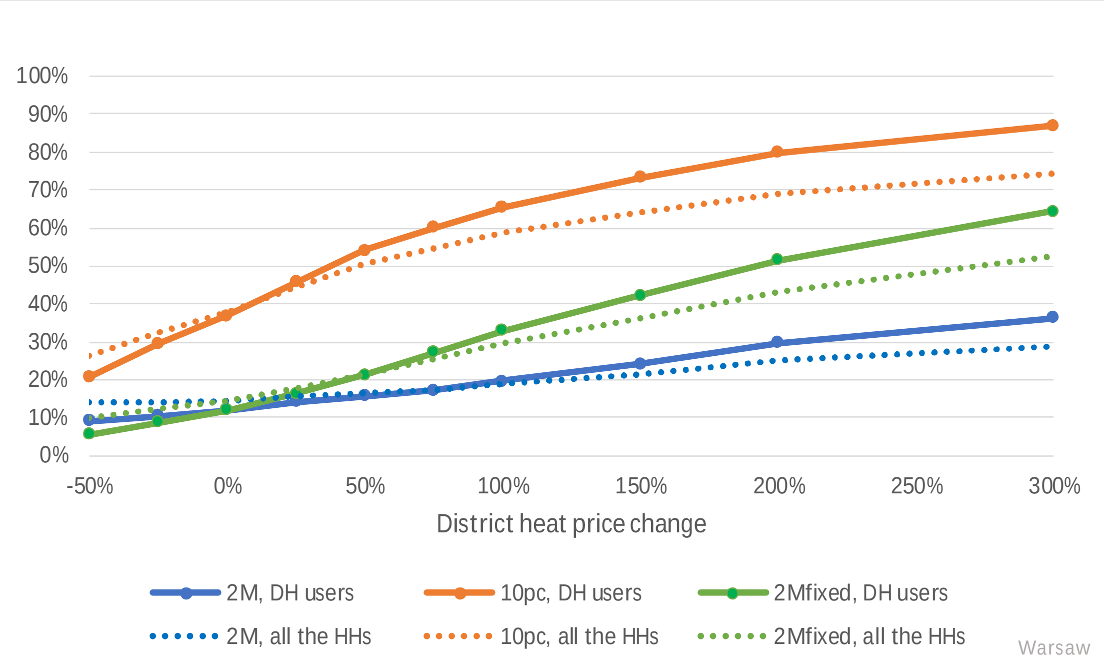

Figure 4: The relationship between district heat price level and energy poverty in Warsaw.

The highest national median of energy expenditure share was observed in Poland (8.7%). Thus, twice the median is 17.5% of the expenditure which is relatively high share and the reason for the difference in values of 10pc and 2M indicators. The increase of DH prices still has a considerable impact on the growth of energy poverty levels in Warsaw: if DH price increases twice, 10pc reaches 65.5% and 2M fixed is at 33.1% level.

The impact of DH price changes on energy poverty is an important factor in the decision-making process. There is no „acceptable" level of poverty and every society should seek to reduce it, this is the case for energy poverty as well. However, this study shows that there are considerable differences among cities studied and they may have some political implications on decarbonisation policies. In Kaunas and Warsaw, more than one-third of households spend more than 10% of their income to pay the energy bills, which makes the cost of energy socially sensible issue.

3 District heating in the studied cities

3.1 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% (Finnish Energy, 2015). According to analysis by Pöyry (Pöyry Management Consulting Oy, 2011) 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 which may further decrease the profitability and market share of DH in Finland (Paiho and Reda, 2016; Pöyry Management Consulting Oy, 2011).

Future development of the DH sector is also affected by national objectives. 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 (EU, 2009a, 2009b). In addition, the emission allowance price in the EU ETS also affects fuel costs. The Finnish government aims to abandon coal use in energy production and to halve the use of fossil oil by 2030 (Finnish Government, 2015). 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 (Ministry of Employment and the Economy of Finland, 2014).

Helsinki region consisting of three cities (i.e. Helsinki, Espoo and Vantaa) was investigated. There are around 1.1 million people living in the area and approximately 85% of the households are heated with DH (Finnish Energy Industries, 2016). In each city, DH is supplied by different company and in 2015 the total DH consumption in the area was approximately 10.3 TWh. The main fuels of DH and accompanied electricity production were coal (42%) and natural gas (46%) (Finnish Energy Industries, 2016) and there is thus a strong reliance on coal-fired CHP production in the area.

The climate strategy for the Helsinki Metropolitan area to 2030 sets carbon neutrality as a target by 2050. There is also an intermediate goal to reduce emissions by 20% by 2020 (HSY (Helsinki Region Environmental Services Authority), 2012). The city of Helsinki has announced in a strategy programme that the carbon dioxide emissions in Helsinki are reduced by 30% by 2020 compared to 1990 levels (Helsinki city council, 2013). Helen, the DH company 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 objectives, Helen has plans e.g. to increase the use of biomass and heat pumps. In addition, utilization of geothermal and solar heat is considered and possibilities of demand response, distributed generation and energy saving are evaluated (Helen, 2017a). Helen has already decided to close the Hanasaari coal CHP plant by 2024 and to replace Hanasaari CHP plant by bio-HOBs and use of other renewable energy sources. A new pellet-fired heating plant (heat output 92 MW) will also be built. In addition, Hanasaari and Salmisaari CHP plants will be equipped with pellet systems that allow approximately 5-7% of coal to be replaced by wood pellets (Helen, 2015, 2016, 2017b).

The city of Espoo and Fortum have announced to work in collaboration in order to achieve the goal of carbon neutral Espoo by 2050 and in developing carbon neutral district heating by 2030 (Fortum, 2017a; The city of Espoo, 2017). Development towards carbon neutral DH includes increased utilization of geothermal and waste heat as well as use of biofuels and recovered fuels in heat production (Fortum, 2016). Currently Fortum is already recovering heat from wastewater and from data centres in Espoo, and using pellets and bio-oil as fuels (Fortum, 2017b). In addition, Fortum plans to use excess heat from a new hospital and Matinkylä metro station. Fortum is also currently building a geothermal heat plant in Otaniemi (Fortum, 2017c, 2017d; Yle, 2016).

The city of Vantaa aims at reducing its emissions by 20% by 2020 compared to 1990 levels and at achieving carbon neutrality by 2050. Vantaan Energia has considered for example to increase the use of e.g. biochar, wood pellet and wood chips. In addition, possibilities to use geothermal and waste heat, and to build a seasonal heat storage have been analysed (Descombes et al., 2016; The city of Vantaa, 2011; Vantaan Energia, 2017). Vantaan Energia also plans to upgrade the gas- and oil-fired Martinlaakso 1 CHP plant and the modernized plant would be fired by biofuels (Vantaan Energia Oy, 2017).

3.2 Warsaw

In 2010, the market share of DH in Warsaw was around 80% (Nuorkivi consulting and COWI, 2014). 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 biofuels. There are also plans for example to build a new waste-to-energy facility and to replace coal-fired boilers with natural gas boilers in Zeran CHP plant. In addition, Pruszkow CHP plant will be upgraded and a new gas-fired production unit will be build (Gronkiewicz-Waltz, 2012; Polish Oil & Gas Company, 2017).

Coal dominates the energy production in Poland and in 2015, the share of coal in the total primary energy supply was around 50% and 80% in the electricity generation mix (IEA, 2017). The share of coal in heat production was around 74% in 2011 and during 2002-2011 the share of hard coal in heat production fell only by 5% (Szymczak, 2013). There is thus a need to diversify the energy production structure and Poland aims to introduce nuclear energy by 2022 (Ministry of Economy of Poland, 2009). However, this schedule might be unrealistic. Poland has large deposits of coal while gas and crude oil are mainly imported (Ministry of Economy of Poland, 2009). Energy security is considered as an important policy objective in Poland and energy security from Russia is regarded as an ultimate goal also by the Polish public opinion (Nuorkivi consulting and COWI, 2014). In addition, the cost of coal is significantly lower than that of natural gas and also of biofuels in DH production (Wojdyga, 2016), and the low price of EU ETS emission allowance does not increase the cost of coal remarkably. It is estimated that coal will have a prominent role in energy production also in the future decades in Poland (Remigiusz, 2015; Rojek and Regulski, 2012) and IEA estimates that coal will be the main fuel in DH production until 2050 even if it is partly replaced by natural gas (IEA, 2017). 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 (Huculak et al., 2015).

Especially many of the heat-only boilers are old and inefficient, and they could be replaced by more efficient CHP plants (IEA, 2017). The Energy Policy of Poland until 2030 further aims to improve energy efficiency and also sets a goal of doubling the amount of electricity produced in the CHPs (Ministry of Economy of Poland, 2009). Directive on Industrial Emissions (EU, 2010) also sets requirements for the plants and there is thus a need for modernization of the plants. The DH network systems are typically oversized and the heat losses of the network are approximately 12% (Rojek and Regulski, 2012).

3.3 Kaunas

Over half of the population is served by DH in Lithuania and the market share of DH has not changed significantly in recent years. In cities, the market share of DH is over 70% (Euroheat & Power, 2015). In 2015, the average heat loss in DH networks was around 15% (The Lithuanian District Heating Association, 2017a). During 2000-2013, the average DH price (excl. VAT) has increased from 30 €/MWh to 70 €/MWh (Werner, 2016) mainly due to increasing natural gas prices. Over the recent years, however, DH price decreased to 52.7 €/MWh in 2016. These changes are due to overall fuel price development in the market, introduction of biomass-fired heat generation capacities and increased competition among heat suppliers. The impact of intense competition among district heat producers is especially evident in Kaunas and Klaipėda during summer season, where DH generation prices in auctions fall even below average price for biomass component. On the other hand, head-to-head competition in summer season is posing serious problems for some heat producers who are unable to cover their cost by heat sales.

The share of biomass has significantly increased in the DH sector. In 1997 this share was 1.2% and in 2015 the share of biomass and municipal waste was 61%. It is expected that the share increases to 80% in 2020 (The Lithuanian District Heating Association, 2017a) and the Lithuanian Law on Energy from Renewable Energy Sources requires that the share of RES in DH should be 60% by 2020 (The Ministry of Energy of the Republic of Lithuania, 2011). The capacity of biomass has increased from 518 MW (in 2010) to 1589 MW (in 2015) (Ramanauskas, 2017). In 2015, the second most common fuel in DH production was natural gas (36%) (The Lithuanian District Heating Association, 2017a). The recently issued (and not approved yet) project of National Energy Strategy foresees new and more ambitious aims for district heating: in 2020 district heat from local and renewable resources shall make 70 percent of the total amount, in 2030 this share shall reach 90%. Also, it is foreseen that in 2050, 90% of buildings in cities shall take the heat from DH (Ministry of Energy of the Republic of Lithuania, 2017). In Kaunas, a new waste-to-energy CHP plant is being planned and there are also initial plans to build a gas-fired CHP plant.

4 Methods

The future DH scenarios (described in Section City-level approach) for Helsinki region and Warsaw were formed based on the review of the plans and goals of the DH companies, studied cities and countries. In addition, the feedback and expert opinions received in the DH workshop held in April 2017 were taken into account when these scenarios were formed. Future scenarios (described in Section Implications of EU level energy system modelling results to the city-level DH systems) were formed based on the EU level energy system modelling with TIMES PanEU so that national and local conditions and the findings from the city-level review were also considered. For instance, the future fuel use amounts were taken from TIMES results, but considering local political decisions, such as abandoning coal use in Finland by 2030. In both approaches, the operation of the DH system in each scenario was modelled with EnergyPRO software.

The scenarios for the Kaunas DH system are described in Section City-level approach. Two scenarios i.e. “Business as usual” (BAU) and “Carbon free” (C-Free) were considered and modelled with MESSAGE. In both scenarios optimal investment decisions and operation scheduling is allowed. In C-Free scenario, linear decrease of CO_2 emissions to zero until 2050 is assumed while in the BAU scenario, no emission limitation is set.

4.1 EnergyPRO

The DH systems of Helsinki region and Warsaw were modelled with EnergyPRO software. EnergyPRO is a commercial modelling software developed and maintained by EMD International A/S. It is designed for modelling and techno-economic operation optimisation of cogeneration and trigeneration projects. (EMD International A/S, 2017). In our analysis, hourly time step is used. EnergyPRO has been used for analysing various DH cases. It has been used for example to simulate DH systems based on heat pumps (Østergaard and Andersen, 2016). EnergyPRO has also been utilised to model the effects of different future electricity price scenarios in a Finnish DH system and in searching and determining the optimal dimensioning and combination of a heat storage and heat pump (Hast et al., 2017). The optimal size of a CHP plant with thermal storage in Germany has also been analysed with EnergyPRO by Streckienė et al. (2009) and the operation of CHP plants in the UK market by Fragaki and Andersen (2011).

EnergyPRO is an input/output model that determines the optimal operation strategy of the DH system by minimizing the total variable costs so that the hourly heat demand is met. Revenues from selling electricity are also taken into account in the variable costs. Inputs are for example the capacities and efficiencies of the production units. Inputs such as heat demand, electricity and fuel prices can be given as hourly time series. The outputs are e.g. which plants are running and when, how much heat is produced in each production unit, how much the heat and electricity production costs are and how much fuel is used for production. If a heat storage is included in the system, EnergyPRO also determines when the storage is charged and discharged.

Rule-based optimization is performed based on priority numbers indicating in which order new productions are entered. In the beginning of the simulation, EnergyPRO creates a matrix which contains the calculated priority numbers. Optimisation is performed in a non-chronological way so that the production units with the lowest priority numbers are entered first. EnergyPRO checks whether this production is possible and then tries to enter the production of the unit with the second lowest priority number (Hast et al., 2017; Lund and Andersen, 2005; Østergaard and Andersen, 2016).

4.2 MESSAGE

The DH system of Kaunas was modelled with MESSAGE modelling package. In contrast to EnergyPRO, MESSAGE provides optimal operation and development solution for the entire studied time period, and in addition to DH operation, investments are also taken into consideration (Connolly et al., 2010). The models created using MESSAGE package represent energy conversion and utilization processes of the energy system (or its part as in the case of district heating and electricity production in CHPs) and their environmental impacts and are mainly used for the development of medium to long term strategies. However, rather detailed operational analysis is also feasible by increasing the number of time slices. In that case, modelling time scope is limited not only by the uncertainties associated with future technological development, but also by the restrictions related with calculation capacity.

The energy system dynamics is modelled by multi period approach. The representation of the energy system in the model is based on a network concept. The activities and relationships of the energy system are described as an oriented graph, depicting the energy chain starting from extraction or supply of primary energy, passing through the several energy conversion processes (e.g., district heat generation, transmission and distribution to final consumers) in order to satisfy the demand for final energy in the industry, household, services and other demand segments. Using the notation of oriented graph, the links of the graph represent technologies or transportation and allocation processes of energy, while the nodes represent energy forms (like biomass, natural gas, and different stages of district heat supply).

For the case study on district heating, an especial specification mathematical model has been created using MESSAGE software. It gives an opportunity to take into account the peculiarities of district heating system that consists of different heat suppliers that are competing in the market. It is foreseen that different heat suppliers are competing for three different activities: a) the base load heat production, b) heat supply that is varying in each month due to changing outdoor temperature, c) reservation service.

4.3 Workshop

District heating workshop was held in April 2017 in Kaunas. Aim of the workshop was to refine the scope of the case study on district heating. Preliminary scenarios and results were presented, and feedback and comments were received. Altogether 20 people participated the workshop and there were participants from the energy industry operating in Lithuania, Poland and Finland. The participants were for example from Fortum, Kauno energija and industry associations.

For example, the prospective investments in the DH systems were discussed and their viability assessed. A questionnaire on the future of district heating in Kaunas was performed in connection to the workshop and the questions dealt with prices and costs, technologies as well as regulations and market conditions. Feedback concerning Helsinki and Warsaw regions was collected by in-depth discussions with stakeholders. In the workshop, regulations affecting the DH sector and its development in each country was addressed and issues caused for example by the commonly changing regulations in Poland were discussed. The feedback and comments received in the workshop were taken into account when the studied DH scenarios were formed and refined.

5 Scenarios

5.1 City-level approach

In the city-level approach, the scenarios for Helsinki region and Warsaw were formed based on the review of the plans and goals of the cities and DH companies. In addition, expert opinions and feedback received in the DH workshop were taken into consideration when scenarios were formed. The main assumptions concerning the changes in heat and electricity production capacities in the studied scenarios in the Helsinki region and Warsaw are summarized in Appendix A.

In the case of Kaunas DH system, two scenarios (i.e. “Business as usual” (BAU) and “Carbon free” (C-Free) scenario) were studied. Both scenarios were modelled with MESSAGE and optimal investment decisions and operation scheduling is allowed. 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 were considered among new candidate heat producing technologies in both scenarios. In the BAU scenario, no emission limitation is set while in the C-Free scenario, linear decrease of CO_2 emissions from the current level to zero in 2050 is set.

In the cases of Helsinki region and Warsaw, the total annual heat demand was assumed to remain at current level. The profile depends on outdoor temperature and a reference temperature of 17ºC was applied. It was also further assumed that 20% of the annual heat demand i.e. used for hot water generation (Statistics Finland, 2016; Szymczak, 2013). In Kaunas, DH demand projections were prepared taking into account energy efficiency improvements such as buildings’ renovation, demographic developments and other factors.

5.2 Implications of EU level energy system modelling results to the city-level DH systems

The implications of the wider EU level energy system modelling were reflected to the city level development of the DH systems of Helsinki region and Warsaw. The shares of different fuels and the changes in these shares in the heat production according to TIMES PanEU results were interpreted as the DH production capacities given as inputs in the EnergyPRO model in the 2030 and 2050 DH scenarios. The optimization performed with EnergyPRO determines which plants are run and when i.e. which of the available heat production units are utilized and which fuels are used in the DH production. It should, however, be noted that the goals and plans of the cities and countries also need to be considered when scenarios are formed. In addition, the starting point i.e. the currently existing capacity differs from that assumed in the wider energy system model. The power plant capacities in the studied cities are not according to national averages. For instance, in Helsinki, coal-fired CHP is in significant position, which is not the case at national level.

The current heat and electricity production capacities cannot be changed rapidly which is why the reference DH scenarios were formed based on the city-level review described in earlier. The reference DH scenarios thus include the current system and the projects currently planned by the DH companies. It should further be noted that due to the investment costs the DH systems cannot be entirely changed rapidly without high cost increase. In addition, the current structure of the DH system, the capacities of the plants and the age of the plants (i.e. the remaining plant lifetime) affect the possible changes and their costs. In addition, the national and city level policies and plans affect the development of the system. For these reasons, the shares of different capacities by fuel in the studied DH systems are not equal to the shares of fuels used in heat production in TIMES PanEU especially in the 2030 scenarios which are not in too distant future. The 2030 DH scenarios were formed based on the reference DH scenarios so that the changes in the shares of fuels used in TIMES PanEU between 2020 and

2030 were reflected to similar changes in the shares of DH production capacities by fuel in the EnergyPRO model. In the 2050 scenarios the capacities by fuel in the DH system correspond closer to the shares in TIMES PanEU results since there is more time to alter the existing DH production infrastructure. The assumptions of the DH scenarios are described in Appendix B. In addition to the assumptions concerning DH production capacities by fuel, TIMES PanEU results and assumptions regarding e.g. the variable costs and efficiencies of the plants were utilized also in the EnergyPRO model. The prices for CO_2 and most fuels as well as investment costs were also taken from TIMES PanEU results. Yet, the prices for fuels such as waste and wood were collected from literature as they are largely affected by the local conditions. The current levels for fuel taxes were assumed in EnergyPRO model.

Electricity and DH sectors are closely linked e.g. through CHP plants and heat pumps and electricity price variation thus affects the optimal operation of DH systems. Heat storages can help balancing the timing between heat production and demand, and thus be beneficial especially when there is more variation in electricity prices due to higher share of RES in the energy system. In addition, heat pumps could also balance the operation of energy systems and produce heat when electricity price is low. Therefore, two electricity price variation scenarios, formed based on the study by Helistö et al. (Helistö et al., 2017), were tested and optimal capacities for heat storages and heat pumps searched.

6 Results from the city-level approach

6.1 Fuel consumption

The consumption of different fuels in the studied regions is presented in Figure 5 - Figure 7. In Helsinki region (Figure 5), coal use is abandoned by 2030, according to the present national policy, and the consumption of natural gas also reduced significantly. The modelling is used to find viable alternatives to replace the retiring capacities and also to investigate the best technology and heat storage combinations to maintain reliable supply without excessive cost increases.The consumption of wood pellet increases significantly in the future scenarios. In addition, the use of electricity in heat pumps increases especially by 2050. The fuel consumption in Warsaw is illustrated in Figure 6. As can be seen, the consumption of coal, natural gas as well as oil decreases significantly by 2050 while there is a considerable increase in the consumption of waste and biomass.

In Kaunas, the share of biomass and municipal waste in heat production is already high and in 2015, their share was already 61% (The Lithuanian District Heating Association, 2017b). The fuel consumption in the BAU and C-Free scenarios is Kaunas is presented in Figure 7. By 2030, especially the utilization of waste increases and the heat production is also more diversified due to use of solar energy and electricity in heat pumps. Natural gas and waste are abandoned and replaced with biomass and heat pumps in the C-Free 2050 scenario while in the BAU 2050 scenario heat is produced mainly with waste, gas and wood. The Figure 7 also shows that there is a significant decrease in the fuel consumption by 2050 due to the assumed energy efficiency improvements.

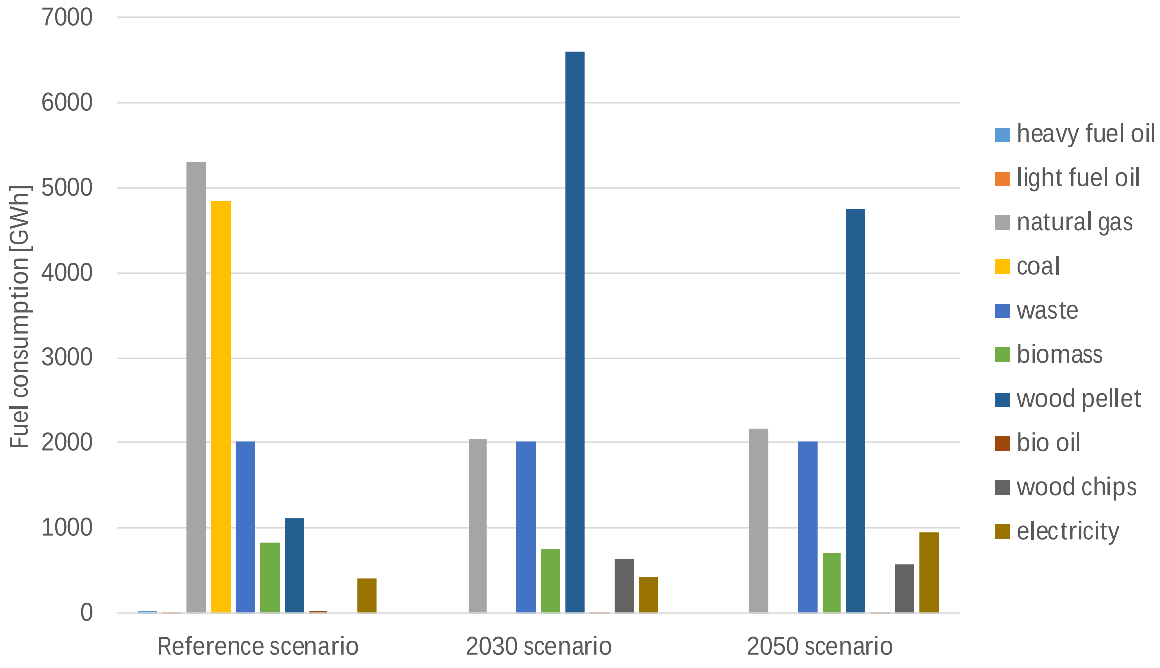

Figure 5: Fuel and electricity consumption in the DH system of Helsinki region in different scenarios.

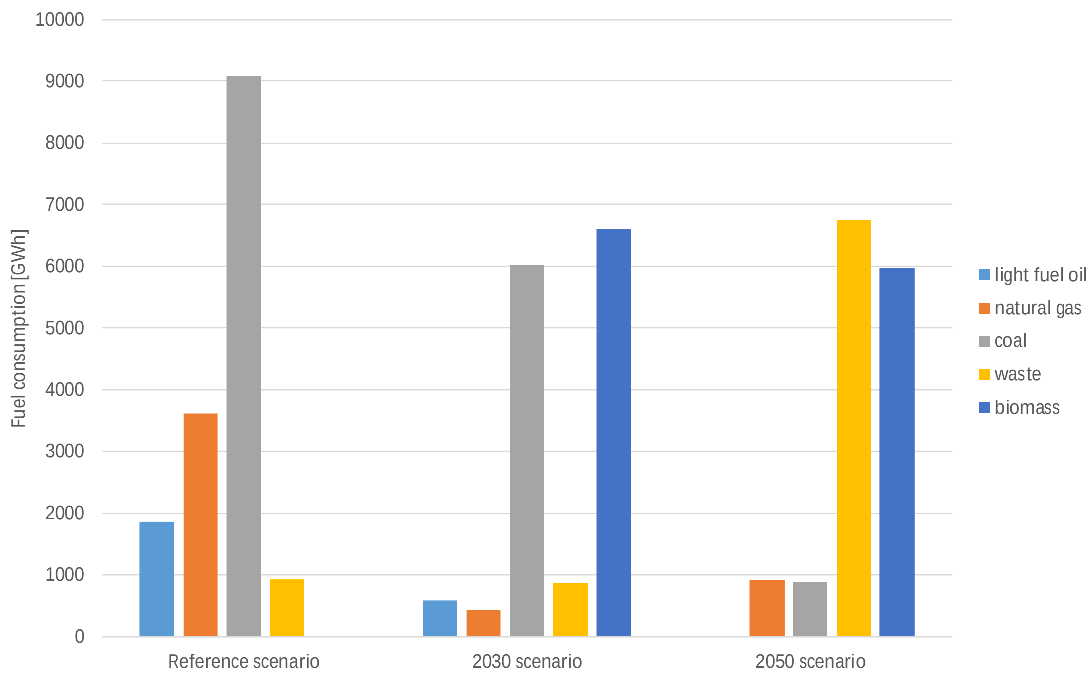

Figure 6: Fuel consumption in Warsaw DH system in different scenarios.

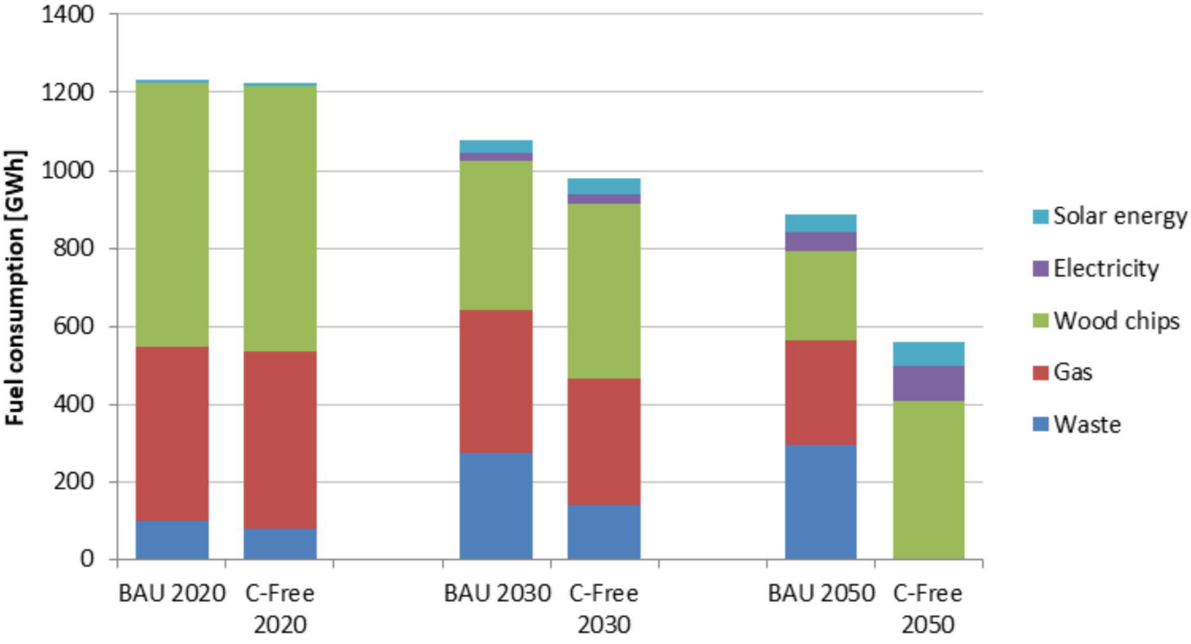

Figure 7: Fuel consumption in Kaunas DH system in different scenarios.

6.2 Heat production costs

Key results from the simulations are summarized in Table 2 and especially GHG emissions and heat production costs are presented. In addition, the shares of heat production with CHPs, heat-only boilers (HOBs) and heat pumps are given in Table 2. The results show especially that in Helsinki region, emissions can be cut with moderate cost increase (16%) while in Warsaw higher cost increase can be expected (40%). The high cost increase in Warsaw is especially due to the high investment costs of CCS technologies. In the case of Kaunas, the costs increase especially in the C-Free scenario which is due to the need to replace peaking gas boilers with carbon free technologies. Yet, in both scenarios, the heat production costs increase especially due to growing fuel prices. Research thus suggests that the emission reduction costs depend rather strongly on the studied area and the actions that are assumed.

The annual emissions of DH production in each case and scenario are also presented in Table 2. It is important to note that the emissions from waste depend on the type of waste and emission factor of 114 $kgCO_2$/MWh (1 in Table 2) and of 0 $kgCO_2$/MWh (2 in Table 2) is assumed for waste in the cases of Helsinki region and Warsaw. In Kaunas case, the emission factor of 114 $kgCO_2$/MWh was assumed since the emission factor plays an important role in the choice of technologies. The results indicate that the type of waste has large impact on the emissions especially in Warsaw where the use of waste increases significantly by 2050. In Kaunas BAU scenario, use of municipal waste increases by 2030 which increases the emissions. By 2050, this increase is compensated by reduced use of natural gas.

It can be also seen that in Helsinki region, there is a significant increase in the use of heat pumps due to the increased utilization of waste heat and geothermal energy. The utilization of heat pumps increases also in the C-Free scenario in the Kaunas case. In Warsaw, the CHP production increases only slightly from the already high level (80%) in the reference scenario until 2030 and 2050 scenarios.

Table 2: Heat production costs and annual emissions in each scenario. The shares of energy produced with CHP plants, HOBs and heat pumps are also presented.

Region	Scenario	Annual GHG emissions [$MtCO_2$-eq]	Heat production costs [€/MWh_{heat}][1]	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

[1] 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.

C-Free scenario 2020	0.101	60	17	83	
2030	0.082	77	30	50	20
2050	0	93	7	27	66

Heat production cost fails to fully reflect district heat price for households since an important role is played by heat transmission as well as market structure and price setting mechanisms. However, combining analysis of district heat price changes impact on energy poverty and generation cost results presented here allows setting general conclusions. Decarbonisation scenarios in the district heating sector have little impact on energy poverty in Helsinki. In Warsaw, production cost decrease in 2030 might have a positive impact on energy poverty. However, more ambitious emission reduction targets for 2050 might be challenging from point of view of energy poverty for both Kaunas and Warsaw.

6.3 Sensitivity analysis

Sensitivity analysis concerning the assumed fuel prices and the amount of DH demand was performed. The effects of a 15% increase and decrease in these parameters were examined. In the Kaunas case, the price increase and decrease were assumed for the year 2050 and the 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. This, for example, means that fuel prices are 6,4% higher or lower in 2030 in comparison with the price in 2015. (2015 was assumed as the first year of the study period). The changes in the average heat production costs in the Helsinki region are shown in Figure 8 and the changes in the Warsaw in Figure 9. In Helsinki region, the prices of natural gas and coal have rather large impact in the reference case and the effect of wood pellet is more significant in the 2030 and 2050 scenarios. In Warsaw, the effect of coal price is largest in the reference scenario. Yet, the impact of coal price decreases in the 2030 and 2050 scenarios and the influence of electricity and biomass prices increases. The figures also show that both in Helsinki region and Warsaw, heat demand has a very significant impact on the costs especially in the reference scenario. It is thus also important to take possible energy efficiency improvements into account. In addition, energy efficiency improvements can help reducing consumer heating costs and thus contribute to reducing energy poverty.

The changes in the average annual heat production costs in Kaunas case are shown in Figure 10. The figure shows that in the BAU scenario, the prices of natural gas and biomass have the largest contribution to the average annual heat production costs. A 15% increase in the biomass price would increase the average heat production costs by 2.6% and similar rise in the price of natural gas would increase the heat production prices by 2.2% in 2050. A 15% decrease in the natural gas price reduces the average annual heat production costs by 4.7% while a similar decrease in biomass price lowers the heat production costs only by 2.1%. In the C-Free scenario, changes in biomass price affect most the average annual heat production cost which is due to the changes in the structure of heat production technologies and shift in proportions of fuel use. 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 prices have minor impact to heat cost.

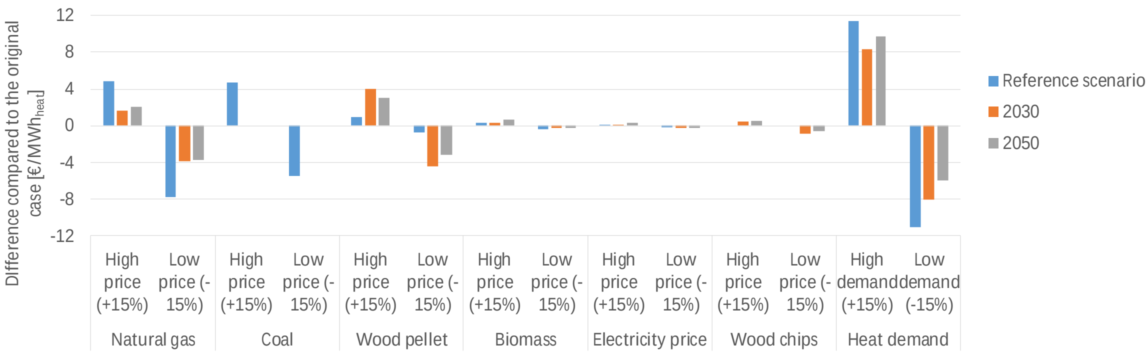

Figure 8: Difference in the average annual heat production cost compared to the case with the original fuel prices in the Helsinki region. The effects of higher and lower heat demand are also presented.

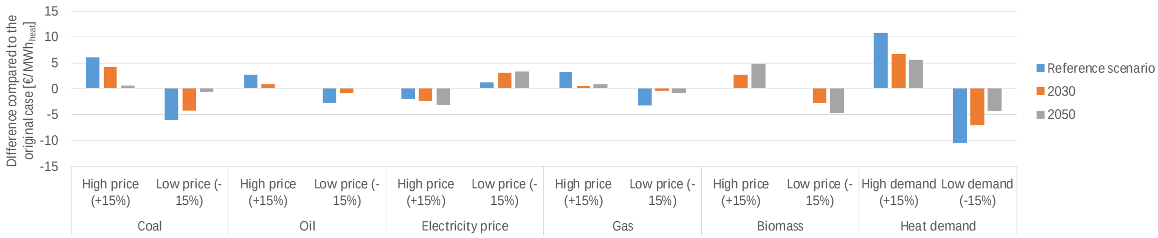

Figure 9: Difference in the average annual heat production cost compared to the case with the original fuel prices in Warsaw. The effects of higher and lower heat demand are also presented.

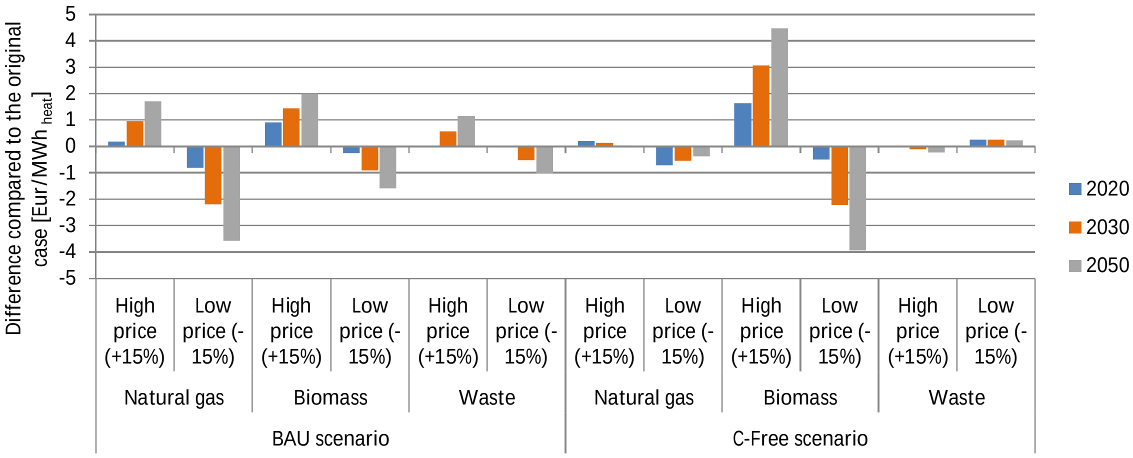

Figure 10: Difference in the average annual heat production costs compared to the case with original fuel prices in Kaunas case. Results are presented for both scenarios.

7 Results from the approach interpreting TIMES PanEU results to the city-level DH system development

The wider EU energy system level results were interpreted to the development of the DH systems of Helsinki region and Warsaw. The DH systems were then modelled with EnergyPRO and the results from the analysis of the specific DH systems are described in this Section. Since electricity price affects the optimal operation of DH systems e.g. through CHP plants and heat pumps, two electricity price variation scenarios ("traditional" and "high variation") were examined. In these scenarios, the average electricity price is the same but in the "high variation" scenario, electricity price varies stronger. Heat storages may be beneficial in DH systems by balancing the timing between production and demand which is why the option of increasing the heat storage capacity from that already assumed in the DH scenarios was taken into consideration.

7.1 Heat production costs

The average heat production costs for one MWh of consumed heat in Helsinki region and Warsaw according to the EnergyPRO calculations are presented in Table 3. In the heat production costs, revenues from electricity sales and investment annuities are also taken into account. It was also investigated whether it is beneficial to include additional heat storages in the DH systems and the optimal capacities of additional heat storages are shown in the Table 3. In addition, the effect of additional heat storage on the costs is also presented when additional heat storage is profitable. Revenues from electricity sales are presented in the Appendix C.

The results show that in Warsaw heat production costs decrease slightly in 2030 scenario compared to the reference scenario which is largely due to higher electricity price and increased electricity production i.e. higher revenues from electricity sales. In 2050 scenario, heat production costs increase rather much since large changes and investments are required in the DH system. In Helsinki region, cost increase until 2050 is rather modest. In Helsinki region, revenues from electricity sales also increase significantly by 2050 which further hinders cost increase.

It can also be seen that additional heat storage is often beneficial in both regions. In Warsaw, heat storage is economical in the reference and 2050 scenarios, and it can lower heat production costs even with 5-7%. In Helsinki region, additional heat storage is beneficial in 2030 and 2050 scenarios. The results also suggest that in Helsinki region the benefit of additional heat storage is higher when electricity price varies more. In addition, heat storages are profitable in both regions in the 2050 scenarios.

Table 3: Heat production costs in different scenarios.

Electricity price scenario	DH scenario	Heat production cost without additional heat storage [€/MWh_{heat}]	Heat production cost with additional heat storage [€/MWh_{heat}]	Cost decrease with additional heat storage [%]	Optimal additional heat storage capacity [GWh]
Warsaw					
Reference scenario		26.0	24.6	5.6%	60
Traditional	2030	23.9	-	-	-
	2050	68.5	63.9	6.7%	55
High variation	2030	21.9	-	-	-
	2050	69.1	64.8	6.3%	42.5
Helsinki region					
Reference scenario		33.4	-	-	-
Traditional	2030	33.6	33.5	0.38%	9
	2050	44.5	44.5	0.07%	18
High variation	2030	32.1	31.7	1.17%	9
	2050	42.2	40.6	3.85%	9

In addition to heat storages, heat pumps may also be beneficial in lowering heat production costs and the effects of additional heat pump capacity were also investigated. It was found that in Warsaw, additional heat pump capacity of 570 MW_{th} was beneficial in the reference scenario and it lowered the heat production costs by 8.8%. In the high variation electricity price scenario, additional heat pump capacity of 420 MW_{th} decreased the heat production costs by 2.9% in 2050. In the traditional electricity price variation scenario, heat production costs lowered by 4.2% in the 2050 scenario when 270 MW_{th} of additional heat pump capacity was added to the DH system. In Finland, additional heat pump capacity of 900 MW_{th} in the reference case lowered the heat production costs by 15 %. In the traditional electricity price variation scenario, heat production costs could be decreased by 4% with additional heat pump capacity of 1170 MW_{th}.

7.2 Fuel consumption

The consumption of the main fuels is illustrated in Figure 11 in Helsinki region and in Figure 12 in Warsaw. As can be seen, heat is produced especially with waste and wood pellet in Helsinki region in 2050. In addition, heat is also produced using electricity i.e. utilizing geothermal and waste heat recovered e.g. from wastewater, hospitals and data centers. In the case of heat pumps, it was assumed that the COP is between 3 and 3.5 depending on the case. It is thus important to note that even though the electricity consumption is rather low compared to other fuels, the amount of heat produced with electricity is higher due to the high efficiency of heat pumps. In Warsaw, especially the utilization of biomass and waste increases rather much by 2050. In the 2050 scenarios, natural gas is also used in plants equipped with CCS. Additional heat storage can, however, lower the consumption of natural gas.

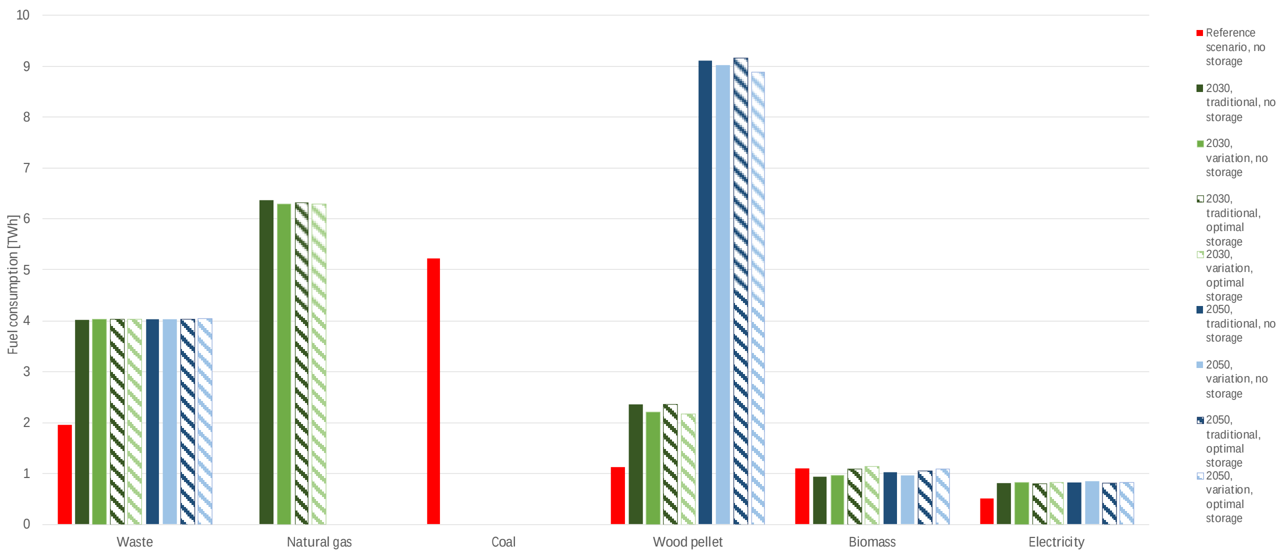

Figure 11: Consumption of the main fuels used in Helsinki region in different DH and electricity price variation scenarios. In addition, the effects of additional heat storage are illustrated.

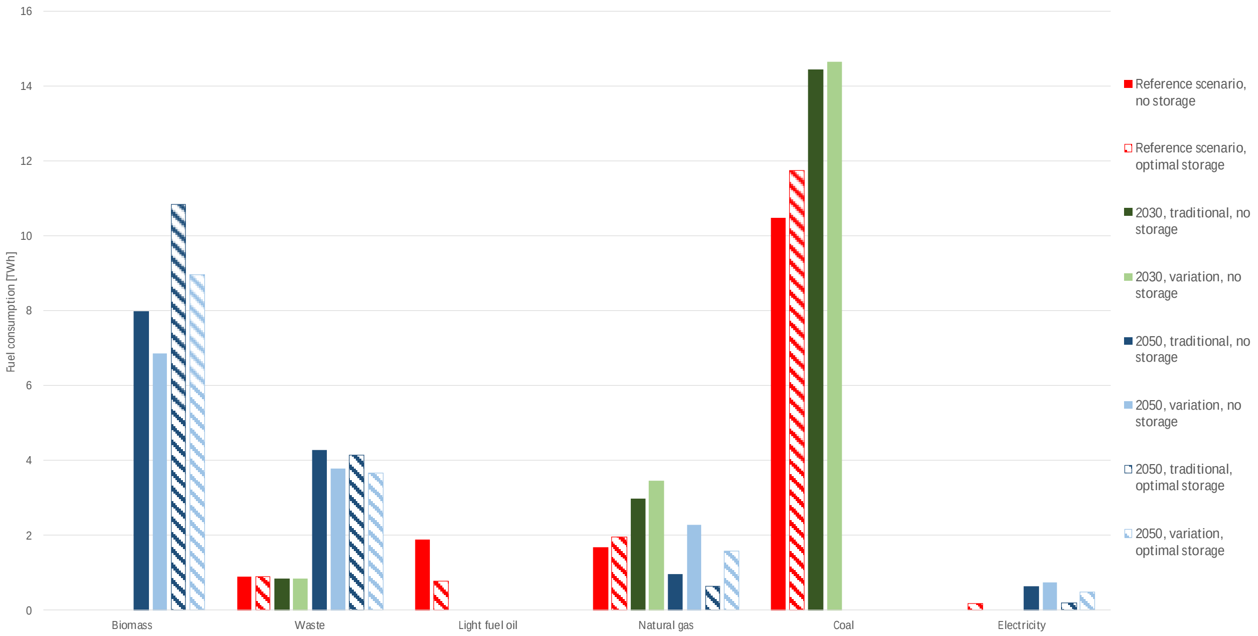

Figure 12: Consumption of the main fuels used in Warsaw in different DH and electricity price variation scenarios. In addition, the effects of additional heat storage are illustrated.

7.3 Sensitivity analysis

District heating and electricity sectors are linked e.g. through CHP plants and heat pumps. Electricity price thus plays a key role in the optimal operation of DH systems. Therefore, the effects of 15% higher and 15% lower electricity prices were investigated. The impact of higher and lower electricity prices in Warsaw are illustrated in Figure 13 and in Helsinki region in Figure 14. When the difference is positive, heat production costs increase compared to the corresponding case with original electricity price and when the difference is negative, heat production costs decrease.

In both regions, lower electricity price typically increases the heat production costs while higher electricity price lowers them. This is due to the revenues gained from electricity sales. In Warsaw, the impact of electricity price was largest in the 2030 scenario i.e. the scenario with the high revenues from electricity sales in the original case. It was also found that additional heat storage is a profitable investment in the reference and 2050 scenarios even with lower and higher electricity prices. In Helsinki region, higher electricity price lowers the heat production costs especially in the 2050 scenarios, and additional heat storage can further decrease the heat production costs significantly. Higher electricity price typically lowers the heat production costs more than lower electricity price increases the costs. The effect of higher electricity price is thus more significant than the impact of lower electricity price. Sensitivity analysis also showed that additional heat storages were in most cases profitable with lower and higher electricity prices. When electricity price was higher, heat storage could provide even 15% decrease in the heat production costs in the 2050 scenario.

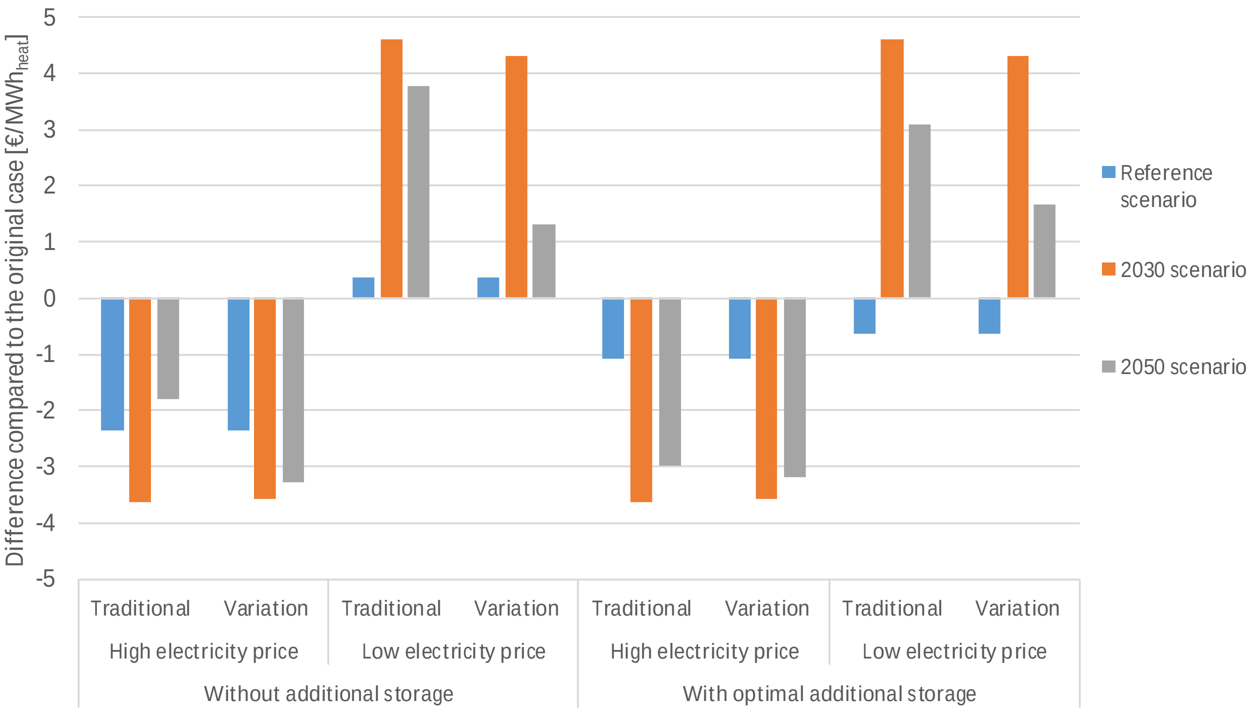

Figure 13: Difference in the average annual heat production cost compared to the case with original electricity price in Warsaw.

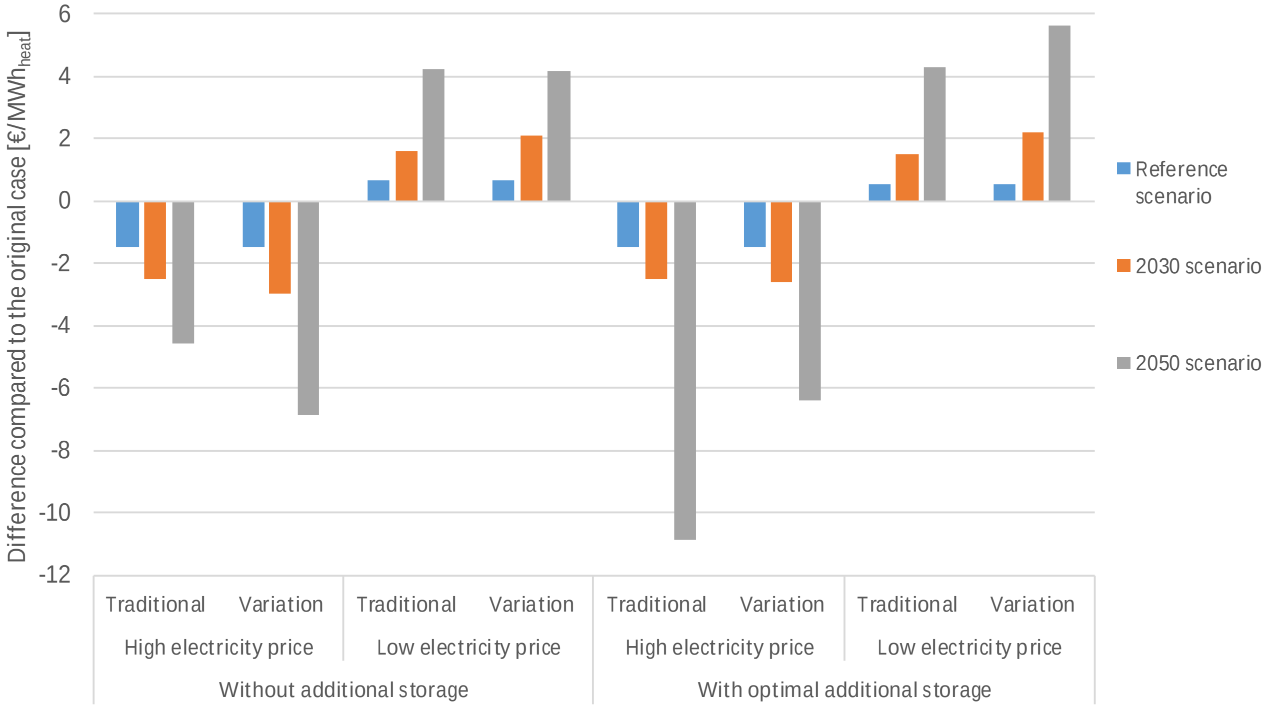

Figure 14: Difference in the average annual heat production cost compared to the case with original electricity price in Helsinki region.

8 Conclusions and recommendations

The key aim of this analysis was to investigate how carbon neutral DH production could be reached in three European regions i.e. Helsinki region, Kaunas and Warsaw. The results suggest that even though there is potential to cut the CO_2 emissions, rather large changes may be needed in the studied DH systems, which can further increase the heat production costs. The studied DH system differ from each other, e.g., in the fuels currently used for DH production, which further affect the changes required. The heat production costs are prone to increase through the investments required for reaching the emission target. The increase in the heat production costs until 2050 thus varies between the regions. In Kaunas where the share of biomass and municipal waste has increased rather much in recent years, emissions can be cut by 15% with modest cost increase. Yet, if emissions are cut to zero, the marginal heat production cost increases by 55%. According to this analysis, the changes required in the DH system of Warsaw are large and increase the heat production costs rather much. In Helsinki region, costs increase rather modestly by 2050. Cost increase is hindered by significant revenues from electricity sales, use of heat pumps in heat production and utilization of inexpensive fuels such as waste and wood pellet.

The analysis showed that in order to reduce emissions, rather large changes are needed in the DH systems. These changes include especially increased use of biomass, waste, heat storages and heat pumps. In addition, the use of CCS technologies could be considered and energy efficiency improved. According to the results of this analysis, heat production in Kaunas would be based solely on wood chips and waste in 2050. In Warsaw, biomass, waste and electricity would be the main fuels for DH production. In addition, natural gas is also used in plants equipped with CCS, as was also indicated by TIMES PanEU results. The results suggest that in Helsinki region heat and electricity production is mostly based on wood pellet and waste in 2050. In addition, electricity is used in the utilization of geothermal and excess heat. Increased use of wood, biomass and waste as well as diminished dependence on fossil fuels also contribute to the energy security goals. It should, however, be noted that the availability of these fuels may limit the possibilities to increase their utilization in DH production in the future. In addition, their price may increase due to the increased demand. It is also important to take energy efficiency into account both in the DH production and in the buildings. The results from the sensitivity analysis show that the level of DH demand has a large impact on the costs i.e. DH should be used efficiently. Energy efficiency improvements can also help lowering consumer energy bill and thus reducing energy poverty.

Heat storages can also help balance the timing between production and demand, and thus decrease the production costs. It was found that heat storage was beneficial in both regions in most scenarios. In addition, the benefit of additional heat storages is higher in Helsinki region when electricity price varies stronger. Sensitivity analysis showed that additional heat storages are beneficial in most DH and electricity price variation scenarios even with lower and higher electricity prices. It was also found that in both regions additional heat pumps were often profitable and could help lower heat production costs by 3% to 15% depending on the scenario.

Decarbonisation scenarios in the district heating sector have little impact on energy poverty in Helsinki. However, ambitious emission reduction targets for 2050 might be challenging from point of view of energy poverty for both Kaunas and Warsaw, where more than one-third of households spend more than 10% of their income to pay the energy bills. Any measure that increases energy cost would be very sensitive in social terms and might require a considerable amount of funding to compensate the price increases at least for the most vulnerable consumers. New approaches to district heating market structure and price setting might be employed along with technical improvements in DH system as possible tools reduce the energy poverty along with the decarbonisation process.

9 References

Brand, L., Calvén, A., Englund, J., Landersjö, H., Lauenburg, P., 2014. Smart district heating networks – A simulation study of prosumers' impact on technical parameters in distribution networks. Appl. Energy 129, 39–48. https://doi.org/10.1016/j.apenergy.2014.04.079

Brand, M., Svendsen, S., 2013. Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment. Energy 62, 311–319. https://doi.org/10.1016/j.energy.2013.09.027

Brange, L., Englund, J., Lauenburg, P., 2016. Prosumers in district heating networks – A Swedish case study. Appl. Energy 164, 492–500. https://doi.org/10.1016/j.apenergy.2015.12.020

Chittum, A., Østergaard, P.A., 2014. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Policy 74, 465–474. https://doi.org/10.1016/j.enpol.2014.08.001

Connolly, D., Lund, H., Mathiesen, B.V., Leahy, M., 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl. Energy 87, 1059–1082. https://doi.org/10.1016/j.apenergy.2009.09.026

Connolly, D., Lund, H., Mathiesen, B.V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P.A., Nielsen, S., 2014. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 65, 475–489. https://doi.org/10.1016/j.enpol.2013.10.035

Descombes, L., Autio, M., Vehviläinen, I., 2016. Vantaan kasvihuonekaasujen päästövähennysselvitys.

EMD International A/S, 2017. energyPRO - User's guide.

EU, 2010. Directive 2010/75/EC of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). Official Journal of the European Union 334/17.

EU, 2009a. Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020 (No. 140/136). Official Journal of the European Union.

EU, 2009b. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union 140/16.

Euroheat & Power, 2015. District Energy in Lithuania [WWW Document]. Euroheat Power. URL https://www.euroheat.org/knowledge-centre/district-energy-lithuania/ (accessed 6.30.17).

European Commission, 2018. Introduction - Energy - European Commission [WWW Document]. Energy. URL /energy/en/content/introduction-5 (accessed 10.15.18).

Eurostat, 2019. URL https://ec.europa.eu/eurostat/documents/345175/501971/EU-28-LAU-2018-NUTS-2016.xlsx (accessed 2.4.19).

Eurostat, 2018. Household Budget Survey [WWW Document]. URL https://ec.europa.eu/eurostat/web/microdata/household-budget-survey (accessed 2.4.19).

Eurostat, 2017. HBS Household Budget Survey microdata. Survey 2010.

Finnish Energy, 2015. District Heating [WWW Document]. Energiateollisuus. URL http://energia.fi/en/en/home-and-heating/district-heating

Finnish Energy Industries, 2016. District Heating in Finland 2015.

Finnish Government, 2015. Finland, a land of solutions. Strategic Programme of Prime Minister Juha Sipilä's Government (Government Publications No. 12/2015).

Fortum, 2017a. City of Espoo and Fortum continue efforts towards making Espoo a low-carbon city | Fortum [WWW Document]. URL https://www.fortum.com/en/mediaroom/Pages/City-of-Espoo-and-Fortum-continue-efforts-towards-making-Espoo-a-low-carbon-city.aspx (accessed 6.12.17).

Fortum, 2017b. Lämpöä yhä puhtaammin| fortum.fi [WWW Document]. URL https://www.fortum.com/countries/fi/lampo/tulevaisuuden-lampo/pages/default.aspx (accessed 6.12.17).
Fortum, 2017c. Espoon sairaala ensimmäisiä avoimen kaukolämmön kohteita| fortum.fi [WWW Document]. URL http://www.fortum.com/countries/fi/lampo/tulevaisuuden-lampo/espoon-sairaala/pages/default.aspx (accessed 5.19.17).
Fortum, 2017d. Geoterminen lämpö| fortum.fi [WWW Document]. URL http://www.fortum.com/countries/fi/lampo/tulevaisuuden-lampo/geoterminen-lampo/pages/default.aspx (accessed 5.19.17).
Fortum, 2016. Kolme visiota kaukolämmöstä| fortum.fi [WWW Document]. URL https://www.fortum.com/countries/fi/lampo/tulevaisuuden-lampo/kolme-visiota-kaukolammosta/Pages/default.aspx (accessed 6.12.17).
Fragaki, A., Andersen, A.N., 2011. Conditions for aggregation of CHP plants in the UK electricity market and exploration of plant size. Appl. Energy 88, 3930–3940. https://doi.org/10.1016/j.apenergy.2011.04.004
Gronkiewicz-Waltz, H., 2012. Powering the city through cogeneration - Warsaw (Covenant of Mayors).
Guelpa, E., Mutani, G., Todeschi, V., Verda, V., 2017. A feasibility study on the potential expansion of the district heating network of Turin. Energy Procedia, CISBAT 2017 International ConferenceFuture Buildings & Districts – Energy Efficiency from Nano to Urban Scale 122, 847–852. https://doi.org/10.1016/j.egypro.2017.07.446
Hast, A., Rinne, S., Syri, S., Kiviluoma, J., 2017. The role of heat storages in facilitating the adaptation of district heating systems to large amount of variable renewable electricity. Energy 137, 775–788. https://doi.org/10.1016/j.energy.2017.05.113
Hast, A., Rinne, S., Syri, S., Kiviluoma, J., 2016. The role of heat storages in facilitating the adaptation of DH systems to large amount of variable RES electricity. Proc. 29th Int. Conf. Effic. Cost Optim. Simul. Environ. Impact Energy Syst.
Helen, 2018a. Finland's largest rock cavern heat storage planned for Helsinki | Helen [WWW Document]. URL https://www.helen.fi/en/news/2017/rock-cavern-heat-storage-planned-for-Helsinki/ (accessed 3.27.18).
Helen, 2018b. The world's first seasonal energy storage facility of its kind is planned for the Kruunuvuorenranta rock caverns | Helen [WWW Document]. URL https://www.helen.fi/en/news/2018/Seasonal-energy-storage-facility-is-planned-for-the-Kruunuvuorenranta-rock-caverns/ (accessed 3.27.18).
Helen, 2017a. A carbon neutral future | Helen [WWW Document]. URL https://www.helen.fi/en/helen-oy/responsibility/carbon-neutral-future/ (accessed 5.8.17).
Helen, 2017b. Pellettien jatkuva seospoltto käynnissä Hanasaaressa | Helen [WWW Document]. URL https://www.helen.fi/helen-oy/ajankohtaista/blogi/2016/pellettien-jatkuva-seospoltto-kaynnissa-hanasaaressa/ (accessed 5.19.17).
Helen, 2017c. Large heat pumps arrive in Helsinki | Helen [WWW Document]. URL https://www.helen.fi/en/news/2017/large-heat-pumps-arrive-in-helsinki/ (accessed 3.27.18).
Helen, 2016. Salmisaareen Suomen suurin pellettikattila | Helen [WWW Document]. URL https://www.helen.fi/uutiset/2016/suomen-suurin-pellettikattila/ (accessed 5.19.17).
Helen, 2015. Kaupunginhallituksen päätös: Hanasaari suljetaan | Helen [WWW Document]. URL https://www.helen.fi/helen-oy/ajankohtaista/blogi/2015/kaupunginhallituksen-paatos-hanasaari-suljetaan/ (accessed 5.19.17).

Helistö, N., Kiviluoma, J., Holttinen, H., 2017. Sensitivity of electricity prices in energy-only markets with large amounts of zero marginal cost generation. EEM 2017 (14th International Conference on the European Energy Market).

Helsinki city council, 2013. The City of Helsinki, Strategy Programme 2013-2016.

HSY (Helsinki Region Environmental Services Authority), 2012. Pääkaupunkiseudun ilmastostrategia 2030 - Tavoitteiden tarkistaminen 2012.

Huculak, M., Jarczewski, W., Dej, M., 2015. Economic aspects of the use of deep geothermal heat in district heating in Poland. Renew. Sustain. Energy Rev. 49, 29–40. https://doi.org/10.1016/j.rser.2015.04.057

IEA, 2017. Energy Policies of IEA Countries - Poland 2016 Review.

Köfinger, M., Basciotti, D., Schmidt, R.R., Meissner, E., Doczekal, C., Giovannini, A., 2016. Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies. Energy, Special issue on Smart Energy Systems and 4th Generation District Heating 110, 95–104. https://doi.org/10.1016/j.energy.2015.12.103

Kość, W., 2014. PGNiG Termika to build WtE plant in Warsaw [WWW Document]. URL https://www.endswasteandbioenergy.com/article/1295124/pgnig-termika-build-wte-plant-warsaw (accessed 3.2.18).

Lake, A., Rezaie, B., Beyerlein, S., 2017. Review of district heating and cooling systems for a sustainable future. Renew. Sustain. Energy Rev. 67, 417–425. https://doi.org/10.1016/j.rser.2016.09.061

Lund, H., Andersen, A.N., 2005. Optimal designs of small CHP plants in a market with fluctuating electricity prices. Energy Convers. Manag. 46, 893–904. https://doi.org/10.1016/j.enconman.2004.06.007

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., Mathiesen, B.V., 2014. 4th Generation District Heating (4GDH). Energy 68, 1–11. https://doi.org/10.1016/j.energy.2014.02.089

Miazga, A., Owczarek, D., 2015. It's cold inside - energy poverty in Poland (IBS working paper No. 16/2015).

Ministry of Economy of Poland, 2009. Energy Policy of Poland until 2030.

Ministry of Employment and the Economy of Finland, 2014. Energy and Climate Roadmap 2050. Energy and the climate.

Ministry of Energy of the Republic of Lithuania, 2017. Energetika konkurencingai Lietuvai.

Nuorkivi consulting, COWI, 2014. District Heating and Cooling, Combined Heat and Power and Renewable Energy Sources, BASREC - BEST PRACTICES SURVEY, APPENDIX - COUNTRY SURVEY.

Østergaard, P.A., Andersen, A.N., 2016. Booster heat pumps and central heat pumps in district heating. Appl. Energy 184, 1374–1388. https://doi.org/10.1016/j.apenergy.2016.02.144

Paiho, S., Reda, F., 2016. Towards next generation district heating in Finland. Renew. Sustain. Energy Rev. 65, 915–924. https://doi.org/10.1016/j.rser.2016.07.049

Polish Oil & Gas Company, 2017. Power Generation - Annual Report 2012 [WWW Document]. URL https://www.pgnig.pl/reports/annualreport2012/en/ar-energetyka.html (accessed 5.8.17).

Pöyry Management Consulting Oy, 2011. Kaukolämmön asema Suomen energiajärjestelmässä tulevaisuudessa (Role of district heat in Finland's future energy system).

Pye, S., Dobbins, A., Baffert, C., Brajković, J., Grgurev, I., De Miglio, R., Deane, P., 2015. Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures (Policy Report).

Quiquerez, L., Lachal, B., Monnard, M., Faessler, J., 2017. The role of district heating in achieving sustainable cities: comparative analysis of different heat scenarios for Geneva. Energy Procedia, 15th International Symposium on District Heating and Cooling, DHC15-2016, 4-7 September 2016, Seoul, South Korea 116, 78–90. https://doi.org/10.1016/j.egypro.2017.05.057

Ramanauskas, V., 2017. Biokuro panaudojimas šilumos ūkyje: pasiekimai, tendencijos, reali nauda.

Remigiusz, R., 2015. The energy policy of Poland up to 2050 - a critical analysis. Środkowoeuropejskie Studia Polityczne.
Rojek, N., Regulski, B., 2012. Polish district heating.
Romanchenko, D., Odenberger, M., Göransson, L., Johnsson, F., 2017. Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden. Appl. Energy 204, 16–30. https://doi.org/10.1016/j.apenergy.2017.06.092
Runsten, S., Berninger, K., Heljo, J., Sorvali, J., Kasanen, P., Vihola, J., Uotila, U., 2015. Pienituloisen omistusasujan energiaköyhyys, Energiaköyhyyden jatkoselvitys liittyen asuntojen lämmitysremontteihin ja energiakuluihin (Energy poverty among low-income homeowners. The continuation report on energy poverty related to heating-system renovations and energy expenditure). Ministry of the Environment.
Statistics Finland, 2016. Energy 2016 table service - 8.1 Energy consumption in households.
Streckienė, G., Martinaitis, V., Andersen, A.N., Katz, J., 2009. Feasibility of CHP-plants with thermal stores in the German spot market. Appl. Energy 86, 2308–2316. https://doi.org/10.1016/j.apenergy.2009.03.023
Szpor, A., 2016. Energy poverty in Poland - Buzzword or a real problem? (ibs policy paper No. 2).
Szymczak, J., 2013. Poland, country by country, 2013 survey.
The city of Espoo, 2017. Climate goals aim for carbon neutrality [WWW Document]. espoo.fi. URL http://www.espoo.fi/en-US/Housing_and_environment/Sustainable_development/Climate_goals (accessed 3.14.17).
The city of Vantaa, 2011. Vantaan kaupungin kestävän energiankäytön toimenpidesuunnitelma vuosille 2010-2020.
The Lithuanian District Heating Association, 2017a. DH review [WWW Document]. URL http://www.lsta.lt/en/pages/about-heating-economy/statistics (accessed 6.30.17).
The Lithuanian District Heating Association, 2017b. DH review [WWW Document]. URL http://www.lsta.lt/en/pages/about-heating-economy/statistics (accessed 6.30.17).
The Ministry of Energy of the Republic of Lithuania, 2011. Law on Energy from Renewable Sources.
Uribarri, P.M.Á. de, Eicker, U., Robinson, D., 2017. Energy performance of decentralized solar thermal feed-in to district heating networks. Energy Procedia, 15th International Symposium on District Heating and Cooling, DHC15-2016, 4-7 September 2016, Seoul, South Korea 116, 285–296. https://doi.org/10.1016/j.egypro.2017.05.075
Vantaan Energia, 2017. Isojen vaihtoehtojen äärellä [WWW Document]. Vantaan Energ. URL https://www.vantaanenergia.fi/lampo/nykylampo/isojen-vaihtoehtojen-aarella/ (accessed 6.13.17).
Vantaan Energia Oy, 2017. Vantaan Energia aikoo siirtyä kaasusta ja kivihiilestä biovoimaan [WWW Document]. Vantaan Energ. URL https://www.vantaanenergia.fi/vantaan-energia-aikoo-siirtya-kaasusta-kivihiilesta-biovoimaan/ (accessed 5.19.17).
Werner, S., 2017. International review of district heating and cooling. Energy. https://doi.org/10.1016/j.energy.2017.04.045
Werner, S., 2016. European district heating price series (No. 316). Energiforsk.
Wojdyga, K., 2016. Polish District Heating System — Development Perspectives. J. Civ. Eng. Archit. 10, 268–279.
Yle, 2016. Espoon kaukolämpö vihertyy hurjaa vauhtia – merkittäviä harppauksia edessä ja takana [WWW Document]. Yle Uut. URL http://yle.fi/uutiset/3-8697555 (accessed 6.22.17).
Yoon, T., Ma, Y., Rhodes, C., 2015. Individual Heating systems vs. District Heating systems: What will consumers pay for convenience? Energy Policy 86, 73–81. https://doi.org/10.1016/j.enpol.2015.06.024

Appendix A

Table 4: Studied DH scenarios for Helsinki region and Warsaw in the city-level approach. Key assumptions i.e. changes in the heat production capacities are presented.

Region	Scenario	Assumptions
Helsinki region	Reference scenario	Planned projects are implemented. The 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) (Fortum, 2017c). Use of geothermal heat in Otaniemi. Heat output around 40 MW (Fortum, 2017d). 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 (Vantaan Energia Oy, 2017). Plans of Helen Ltd in Helsinki: Helen has decided to close Hanasaari coal CHP plant by 2024 (Helen, 2015). New pellet-fired heating plant will be built. Heat output of the plant is 92 MW (Helen, 2016). Pellet systems will be used in Hanasaari and Salmisaari CHP plants. Approximately 5-7% of coal can be replaced by wood pellets (Helen, 2017b).
	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 (Hast et al., 2016). CCS in gas-fired plants.

Warsaw	Reference scenario	Planned projects are implemented i.e.: Building a new waste-to-energy facility. Electricity output of the plant is 50 MW and heat output 25 MW (Kość, 2014). 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 $MW_{electricity}$ (Polish Oil & Gas Company, 2017). Building a new Pruszkow CHP plant. Plant will be fired by gas, electricity output is 16 MW and heat output 15 MW (Polish Oil & Gas Company, 2017). CHP plants Zeran and Siekierki are being fitted with measures which will allow them to use bio fuels (Gronkiewicz-Waltz, 2012).
	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%).

Appendix B

Table 5: Main assumptions in the scenarios formed based on the results from the EU level energy system modelling.

Region	Scenario	Assumptions
Helsinki region	Reference scenario	Plans of Fortum Oyj in Espoo (Fortum, 2017c) (Fortum, 2017d): 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 (Vantaan Energia Oy, 2017): 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 (Helen, 2015) (Helen, 2016) (Helen, 2017b): 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. Heat storage in Mustikkamaa. The effective volume of the storage is around 260,000 m^3 and the amount of energy stored is 11.6 GWh (Helen, 2018a). Seasonal heat storage in Kruunuvuori, the volume of the storage is 300,000 m^3 (Helen, 2018b). Two new heat pumps. Cooling output of the pumps is 2 * 7.5 MW and heat output 2 * 11 MW (Helen, 2017c).
	2030	Projects assumed in the 2020 scenario. Coal is replaced by wood (50%) and natural gas (50%). A new waste CHP plant is built (heat output 140 MW, electricity output 75 MW). Use of waste heat is increased to 15%.
	2050	Projects assumed in the 2020 and 2030 scenarios. Natural gas and oil replaced by wood (60%) and heat pumps (40%). Geothermal energy unit built in Helsinki (heat output 40 MW).

		Capacity of solar thermal increased to 270 MW. Utilization of waste heat increased to 20% of heat demand.
Warsaw	Reference scenario	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.
	2030	Projects assumed in the 2020 scenario. Oil replaced by gas-fired CHP. Solar thermal capacity increased to 190 MW.
	2050	Projects assumed in the 2020 and 2030 scenarios. Coal use is abandoned. Heat capacity of gas-fired plants equipped with CCS is increased to 480 MW, electrical capacity to 400 MW. Increased utilization of geothermal heat (heat output 810 MW). Heat capacity of biomass-fired CHP plants increased to 1800 MW, electrical capacity to 770 MW. Heat capacity of biomass-fired HOBs increased to 1000 MW. Heat capacity of waste-fired CHP plants increased to 280 MW, electrical capacity to 165 MW. Capacity of heat pumps increased to 150 MW. Solar thermal capacity increased to 430 MW.

Appendix C

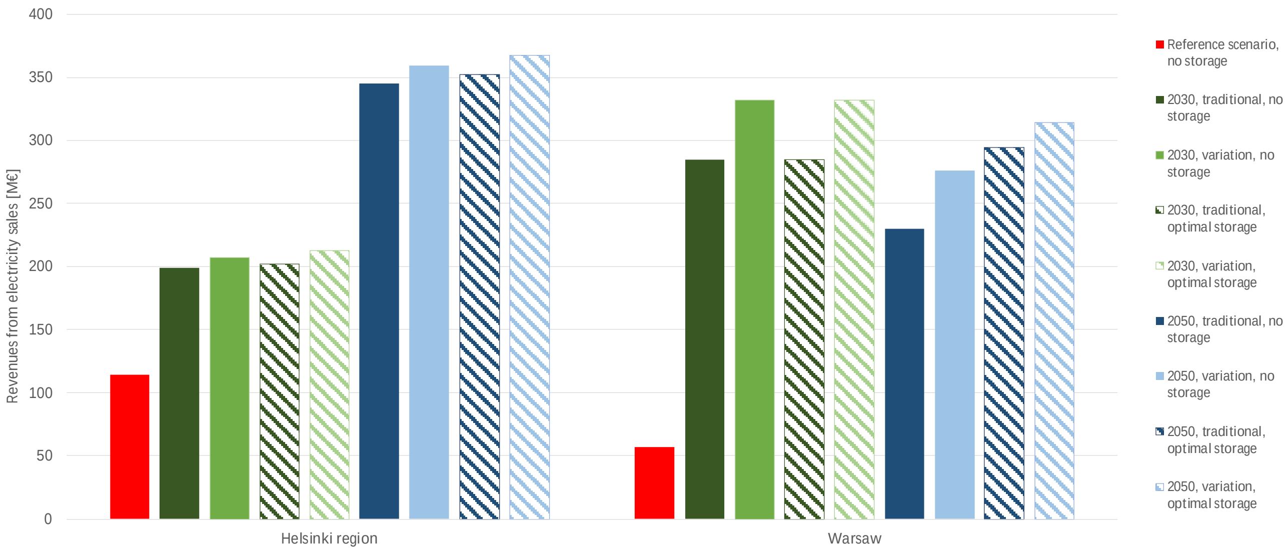

Figure 15: Revenues from electricity sales in Helsinki region and Warsaw. Revenues are presented in each scenario with and without possible additional heat storage capacity.