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Transition to carbon neutral energy systems – implications to district heating in cities

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***Abstract*— In this paper, the results from EU level energy system modelling with TIMES PanEU are interpreted to the city level development of the district heating (DH) systems of Warsaw and Helsinki region until 2050. In the future, there is probably more variation in the electricity prices due to the higher share of renewable energy sources in the electricity production which further affects the operation of DH systems. The results presented in this paper indicate that heat storages were almost always profitable investments and the optimal heat storage capacity was highest in 2050. The benefit of the heat storage increased with the variation in electricity prices. In Warsaw, heat pumps were also profitable. Heat production with wood and waste fuels as well as utilization of geothermal and waste heat increased in Helsinki region by 2050. In Warsaw, the consumption of biomass, waste and electricity in heat production increased by 2050.**

***Keywords:* District heat, decarbonisation, costs, Helsinki, Warsaw**

I. INTRODUCTION

In order to reduce CO_2 emissions and mitigate climate change, decarbonisation of the energy sector is essential. District heating (DH) could play a key role in the decarbonisation of the energy system [1]. In the future, there is probably more variation in the electricity production and price due to higher share of variable renewable energy sources (VRES). This can further affect the optimal operation of DH systems which often include combined heat and power (CHP) plants producing both heat and electricity. Heat storages can be used to balance the timing between heat production and demand. In addition, heat pumps running especially when electricity price is low, could be used in balancing the energy system. Electricity and DH sectors are thus linked, and DH components such as heat pumps and heat storages could help reaching the longer term decarbonisation and RES targets. The effects of electricity price variation on the DH systems have been studied e.g. in the DH systems of Göteborg [2] and Järvenpää [3]. Hast et al. [3] found that heat storage is a profitable investment especially with a heat pump and these components help balancing the operation of energy system in different electricity price scenarios.

This paper presents initial modelling results of the EU Horizon project REEEM (Role of technologies in an energy efficient economy – model-based analysis of policy measures and transformation pathways to a sustainable energy system). 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, given the objectives and framework outlined in the Strategic Energy Technology Plan (SET-Plan). The provisions of the energy services in this society will be defined by their sustainability, affordability, efficiency, energy security and reliability. In support of this overall aim, the project is developed e.g. to address defining pathways towards a low-carbon society and assess their potential implications. In addition to SET-Plan, the European Commission has also launched Energy Union the aim of which is to ensure that the European consumers have secure, affordable and clean energy. It includes five closely related dimensions and the progress against these dimensions should be measured through key indicators. These dimensions include for example energy security, solidarity and trust, and decarbonizing the economy [4].

The development of European energy systems until 2050 is modelled with TIMES PanEU in the REEEM project. In this paper, the results from this EU level development are further interpreted to city level development of district heating systems in two European regions, Warsaw in Poland and Helsinki region in Finland. The main goal of this study is therefore to examine what kinds of implications the wider EU level energy system development towards carbon neutrality could have in the city level DH systems.

In both of the studied regions, DH plays a significant role. There are, however, significant differences between the areas in the fuels and technologies used, as well as in the heat demand and housing stocks. It should also be noted, that the development of a specific DH system is affected by the plans of the DH companies as well as the national and city level policies. These policies may also affect the behavior of the consumers and heat demand. In an earlier research [5], the plans and goals of the studied cities and DH companies were reviewed, and possible future DH scenarios towards carbon neutrality were formed based on that review. The analysis also showed that there are differences in the possible future development pathways towards carbon neutrality in the studied DH systems. When the EU level energy system development is reflected to the city level DH system development, this earlier research focusing particularly on the studied DH systems is also considered.

The studied DH systems could include in the future for example a higher share of biomass in heat production and increased utilization of geothermal and solar thermal technologies. Changes in heat demand due to climate change are modelled and taken into account in the analysis. The optimal operation of the DH systems are determined by minimizing the heat production costs, and the studied DH scenarios are assessed based on their fuel consumption and costs in particular. Heat storages and heat pumps are also important in balancing the timing between production and demand. Therefore the optimal operation and dimensioning of heat pumps and heat storages in the studied DH systems is determined. The results presented in this paper thus provide insight about how DH in cities can contribute to meeting ambitious climate and energy goals. The progress towards Energy Union objective i.e. providing affordable, clean and secure energy can be assessed in the studied DH cases.

II. METHODS AND ASSUMPTIONS

EnergyPRO is used for modelling the DH systems of Warsaw and Helsinki region. It is an input/output model that solves the optimal operation of the heat production units by minimizing the total variable costs so that the hourly heat demand is met. Inputs are for example hourly heat demand, electricity and fuel prices and capacities of heat and electricity production units.

The city level DH scenarios were formed based on the results from TIMES PanEU modelling. TIMES is an energy system model generator which is a further development of the model generators MARKAL and EFOM-ENV, written in GAMS. TIMES is a bottom-up linear optimization model based on a technical approach. The aim of the model is to optimize the energy system cost according to the given energy demands, energy technologies, and policy requirements. The Pan-European TIMES energy system model (TIMES PanEU) is a 30 region partial equilibrium energy system model. The model covers the EU-28 countries, with addition of Norway and Switzerland. The base year is 2010 and the time horizon ends in 2050. The current structure accounts for 12 time slices, 4 seasonal and 3 daily. The model is split in 5-year time steps. Both greenhouse gas emissions (CO_2, CH_4, N_2O, SF_6) and local air pollutant emissions (SO_2, CO, NOx, NMVOC, PM_{10}, $PM_{2.5}$) are included. TIMES PanEU contains the country specific data covering all the sectors related to energy supply and demand. The system commences from the potential of different energy sources in a particular country and includes public and industrial generation of electricity, industry, agriculture, refineries, inventory power stations and the end-use service demands such as heating, lighting and transportation.

The future heating demands in EnergyPRO are scaled using the results from Larsen et al. [6]. They estimate mean heating/cooling degree days until 2050 according to [7] using the outputs of several climate models for RCP 2.6 and 4.5 [8]. The annual heating/cooling degree days are calculated as 5-year averages to account for natural variability (cold/hot years).

A. Assumptions

The CO_2 and fuel prices as well as the fuel taxes assumed in the DH modelling are presented in Table 1. Since the electricity price variation affects especially the operation of CHP plants and heat pumps, two electricity price scenarios i.e. traditional and high variation scenarios were tested in the DH modelling. The average electricity price was assumed the same in both scenarios and the hourly profile of the prices were formed based on the study by Helistö et al. [9]. In the DH modelling, it was assumed that the minimum operation time for CHP plants is one week.

Table 1: Assumed CO_2 prices and import prices of the fuels including delivery costs. Fuel taxes (excluding VAT) assumed in the DH modelling are also shown.

Fuel	**2020**	**2030**	**2050**	**Fuel tax (excl. VAT)**
Carbon price [€/tCO_2]	15	30	68	
Finland				
Coal [€/MWh]	9.3	10.5	7.7	Heat only boilers (HOB): 27 €/MWh [10] CHP: 17.1 €/MWh [10]
Oil [€/MWh]	44.5	61	41.5	HOB, light fuel oil: 22.9 €/MWh [10] HOB, heavy fuel oil: 23.7 €/MWh [10] CHP, light fuel oil: 15.1 €/MWh [10] CHP, heavy fuel oil: 15.5 €/MWh [10]
Gas [€/MWh]	23.2	32.4	32.1	HOB: 18.6 €/MWh [10] CHP: 12.9 €/MWh [10]
Wood fuels [€/MWh]	10.8	10.8	10.8	
Wood chips [€/MWh] [5]	24	32	40	
Wood pellets [€/MWh] [5]	30	38	46	
Biomass [€/MWh]	10.8	10.8	10.8	
Biodiesel [€/MWh] [11]	67	67	67	48 €/MWh [11]
Waste [€/t_{waste}] (i.e. gate fee) [12]	-45	-45	-45	
Average electricity price [€/MWh]	43	77	76	Electricity distribution cost: 21 €/MWh [11] Electricity tax: 22.5 €/MWh [13]
Poland				
Coal [€/MWh]	9.8	10.9	8.1	1.1 €/MWh [13]
Oil [€/MWh]	46.6	63.1	44	Light fuel oil tax: 5.4 €/MWh [13]
Gas [€/MWh]	23.2	32.4	32.1	1.1 €/MWh [13]
Wood fuels [€/MWh]	10.8	10.8	10.8	
Wood chips [€/MWh] [5]	24	32	40	
Wood pellets [€/MWh] [5]	30	38	46	
Biomass [€/MWh]	10.8	10.8	10.8	
Waste [€/t_{waste}] (i.e.	-50	-50	-50	

gate fee) [14]				
Average electricity price [€/MWh]	32	48	64	

Currently the total annual DH demand in Helsinki region is around 11.4 TWh [15] and 11.5 TWh in Warsaw [16]. It is assumed that in the 2020 scenario, heat demand is at current level. It is assumed that the DH demand in the cities develops as the heat demand in Finland and Poland, and the assumed DH demands in different years and climate scenarios are presented in Table 2. The profile of the demand is determined based on outdoor temperature and the reference temperature i.e. when heating is needed is 17 °C. It is also assumed that energy used for hot water generation is approximately 20% of the annual heating demand and remains constant throughout the year.

Table 2: Development of the district heating demand in the studied regions.

Region	Climate scenario	2020 scenario [TWh]	2030 scenario [TWh]	2050 scenario [TWh]
Helsinki region	RCP 2.6	11.4	11.0	10.3
	RCP 4.5	11.4	10.7	10.2
Warsaw	RCP 2.6	11.5	10.7	10.4
	RCP 4.5	11.5	10.9	10.4

III. STUDIED DISTRICT HEAT SCENARIOS

1) 2020 DH scenario

In an earlier research [5], the plans and goals of the cities and DH companies supplying district heat in the studied regions were reviewed. Based on that review, the 2020 scenarios were formed so that the currently planned projects are included in them. The 2030 and 2050 scenarios i.e. changes in the heat and electricity production capacities were formed based on the TIMES PanEU results. In the Helsinki region, the projects currently planned and included in the 2020 scenario are listed below.

Plans of Fortum Oyj in Espoo [17] [18]:

- 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 [19]:

- 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 [20] [21] [22]:

- 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 [23].
- Seasonal heat storage in Kruunuvuori, the volume of the storage is 300,000 m^3 [24].
- Two new heat pumps. Cooling output of the pumps is 2 * 7.5 MW and heat output 2 * 11 MW [25].

In Warsaw DH system, the planned projects included in the 2020 scenario are listed below.

- 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.

2) 2030 DH scenario

Helsinki region:

- 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%.
- Different heat pump and heat storage capacities are tested.

Warsaw:

- Projects assumed in the 2020 scenario.
- Oil replaced by gas-fired CHP.
- Solar thermal capacity increased to 190 MW.
- Different heat pump and heat storage capacities are tested.

3) 2050 DH scenario

Helsinki region:

- 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.
- Different heat pump and heat storage capacities are tested.

Warsaw:

- 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 240 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 70 MW.
- Capacity of heat pumps increased to 150 MW.
- Solar thermal capacity increased to 430 MW.
- Different heat pump and heat storage capacities are tested.

IV. RESULTS

The average heat production costs for one MWh of consumed heat without heat storage capacity additional to those already assumed in the studied DH scenarios are presented in Table 3. In addition, the optimal additional heat storage capacities and their impacts on the heat production costs are shown. The results indicate that in almost all cases including additional heat storage in the DH system is profitable. In both regions, the optimal heat storage capacity is largest in the 2050 scenario and the benefit of including additional heat storage in the system was largest when electricity price variation was higher.

In the 2030 scenario in Helsinki region, the revenues from electricity sales increase rather much compared to the 2020 scenario which lowers the heat production costs in the 2030 scenario with heat storage. It should, however, also be noted that in the 2030 scenario the use of inexpensive fuels such as waste increases which also decreases the costs. In the 2050 scenario, the cost increase is somewhat modest compared to the 2020 scenario especially in the high variation electricity price scenario in Helsinki region. In Warsaw, the cost increase compared to the 2020 scenario is small in the 2030 scenario but in the 2050 scenario, the cost increase is high mainly due to the investment costs.

With our assumptions, increasing the heat pump capacity of those already assumed in the studied DH scenarios did not significantly decrease the heat production costs in Helsinki region and in the high electricity price variation scenario in Warsaw. Yet, in the traditional electricity price scenario additional heat pump capacity of 180 MW_{th} decreased the costs by 5.5 €/MWh in the 2030 scenario in Warsaw. In the 2050 scenario, the costs decreased by 2.8 €/MWh when heat pump capacity was increased by 270 MW_{th}.

The impact of the assumed climate scenario on the heat production costs was in the range of 0-5% in Warsaw and 0-15% in Helsinki region.

Table 3: Optimal additional heat storage capacities in different electricity price and DH scenarios. Average heat production costs for one MWh of consumed heat without additional heat storage and cost decrease with the optimal heat storage capacity are also shown. In the heat production costs, revenues from electricity sales and investment annuities are taken into consideration.

Electricity price scenario	DH scenario	Heat production cost without additional heat storage [€/MWh]	Cost decrease in the heat production costs with additional heat storage	Optimal heat storage capacity [GWh]	Storage capacity as a share of annual heat demand
Warsaw					
Traditional	2020	20.2	1.7%	10.6	0.1%
	2030	23.1	0%	0	0%
	2050	78.7	0.9%	12.6	0.12%
High variation	2020	20.2	1.7%	10.6	0.1%
	2030	28.5	2.1%	4.6	0.04%
	2050	82.7	1.2%	12.6	0.1%
Helsinki region					
Traditional	2020	32	0.1%	9	0.1%
	2030	15.7	2.3%	15	0.1%
	2050	58.9	0.2%	55.5	0.5%
High variation	2020	32	0.3%	9	0.1%
	2030	10.1	11.5%	82.5	0.8%
	2050	52.1	2.8%	157.5	1.5%

Fuel consumption in the studied scenarios are presented in Figures 1-2. As can be seen, in Helsinki region especially the consumption of wood increases by 2050 which also contributes to the Energy Union goal of energy security. In addition, the use of waste and electricity due to the increased utilization of geothermal and waste heat increases in the DH production. In Warsaw, the use of biomass, waste and electricity increases significantly by 2050.

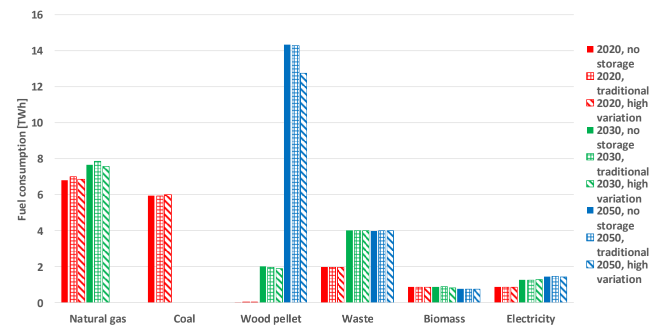

Figure 1: Fuel consumption in Helsinki region in different DH and electricity price scenarios. Solid bars indicate situation without additional heat storage capacity and dashed bars represent situation with optimal heat storage capacity.

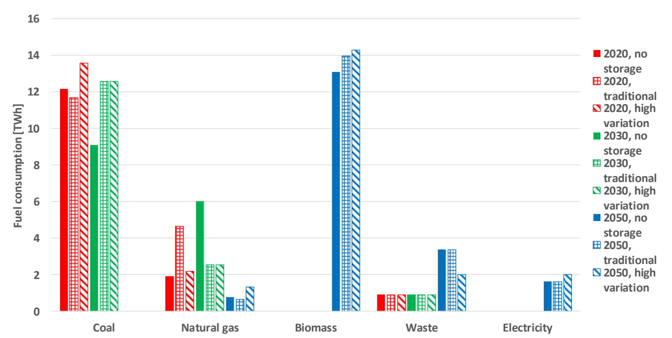

Figure 2: Fuel consumption in Warsaw in different DH and electricity price scenarios. Solid bars indicate situation without additional heat storage capacity and dashed bars represent situation with optimal heat storage capacity.

V. CONCLUSIONS

In this paper, city level DH scenarios for Warsaw and Helsinki region were formed based on the modelling of European energy system until 2050. The results indicate that including additional heat storage in the DH systems was profitable in almost all scenarios. In both regions, heat storages were more beneficial when electricity price variation was higher and the optimal heat storage capacity was largest in the 2050 scenario. The results thus suggest that heat storages are beneficial in balancing the operation of the studied DH systems in the future especially when there is more variation in the electricity prices due to the higher share of RES in energy system. In Warsaw, the heat production costs increased significantly by 2050 while in Helsinki region the cost increase was rather modest especially in the electricity price scenario with high variation.

The consumption of wood and waste fuels increased in Helsinki region by 2050 which both reduces emissions from heat production and contributes to energy security. Heat production with electricity i.e. utilization of geothermal and waste heat also increased in 2050 scenario. In Warsaw, coal was abandoned by 2050 and the consumption of natural gas also decreased significantly in the 2050 scenario which lowers the emissions from heat production. In the 2050 scenario, heat was produced especially with biomass and waste. Electricity consumption also increased significantly due to the increased utilization of geothermal and heat pumps.

In Helsinki region, heat pumps did not decrease the heat production costs significantly. Yet, in Warsaw where the assumed electricity price was lower, heat pumps decreased the heat production costs in the traditional electricity price scenario. Heat pumps are thus economical in DH systems if electricity prices are modest. Improvement of the coefficient of performance could also increase the profitability of heat pumps in district heat production.

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