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How do Long-term and Short-term Energy Crises Affect Low-Carbon District Heating Production?-A Case Study in Finland.

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Abstract— **This study examines how long-term and short-term energy crises may affect heat production in low-carbon District Heating (DH) networks. For this purpose, various scenarios decarbonizing DH network are investigated mainly in two groups, i.e., biomass combustion scenarios and waste heat-based scenarios. The duration of the hypothetical energy crisis is assumed as 3 years (Short-term Energy Crisis) and 10 years (Long-term Energy Crisis), and it is defined as a sharp increase in the electricity and biomass prices compared to the average prices over 2015-2020. Heat Production Cost (HPC), and Break-Even Price (BEP) are calculated and compared in various scenarios. The results show that in both long-term and short-term energy crises, biomass CHP has a significantly better performance compared to biomass HOB and waste heat-heat pump, but it provides much more expensive heat as the end-use product. Biomass HOB and waste heat-heat pump perform very similarly.**

Index Terms—**Biomass Combustion, Energy Crisis, Low-Carbon District Heating, Waste Heat Recovery.**

I. INTRODUCTION

District heating (DH) as an important part of heating sector plays a key role in reaching the target of carbon-neutral society by 2035 in Finland [1]. Biomass combustion and waste heat recovery from data centers with heat pumps are considered two available and efficient sources to develop low-carbon district heating networks in Finland [2]. However, the availability of these two sources for DH networks has been more vulnerable after Russia's invasion of Ukraine in early 2022 when the European wholesale electricity prices have increased dramatically [3]. Figure 1 compares the electricity spot price in 2022 with the average price in 2015-2020 for Finland [4]. The average spot price in 2022 (154 €/MWh) was almost 5 times higher compared to the average in 2015-2020 (36 €/MWh).

Russia's war of aggression has also affected the price of biomass fuel for DH networks in Finland [5]. While over the period of 2015-2020 in Finland, the average price for biomass was 21 €/MWh [6], in 2022 it increased by more than 25% [5]. Figure 3 shows that biomass is the most significant fuel in DH networks in Finland. In other words, the majority of biomass fired Heat-Only Boilers (HOB) in Figure 2.b. are operating at peak during the whole year while reserve boilers supplying by oil and natural gas operate in a very low-capacity factor. This study investigates how low-carbon district heating networks may be affected by hypothetical long-term and short-term energy crises in Finland. For this purpose, we define an energy crisis scenario in which electricity and biomass price are increased sharply compared to the average prices over 2015-2020. Different scenarios for biomass combustion and waste heat recovery are investigated under the energy crisis prices and compared with results from [2], which represents these scenarios before the energy crisis.

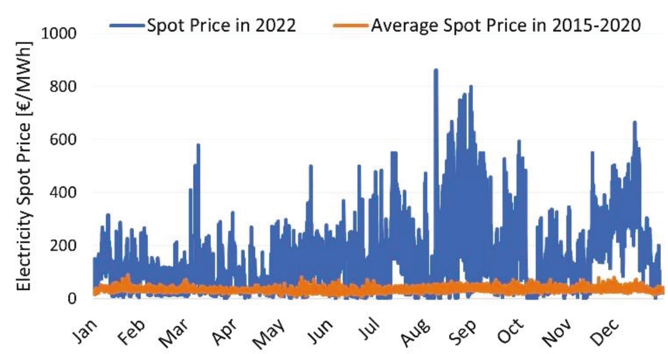

Figure 1. The electricity spot price in 2015-2020 compared to the spot price in 2022 as an energy crisis case. The average electricity spot price in 2015-2020 was about 36 €/MWh while this figure for 2022 is 154 €/MWh [4].

Like most of the European countries, Finland experienced an intense energy crisis in 2022. Figure 1 compares the electricity spot price in 2022 with the average price over the period of 2015-2020. As can be seen, in the second half of the year of 2022, the energy crisis was more severe. However, the average raise in the electricity spot price can be estimated by 500% for the whole year.

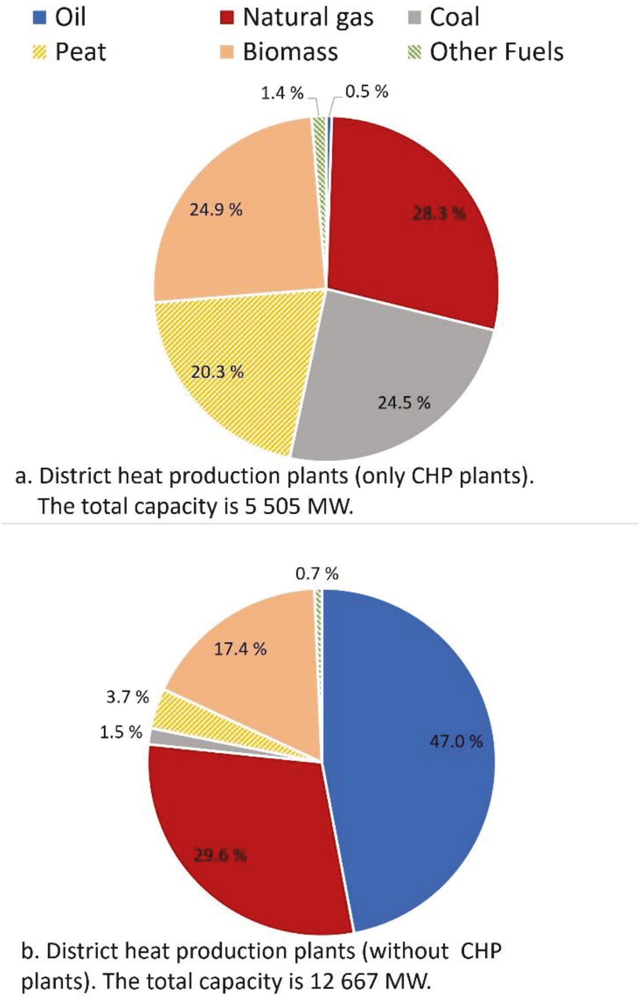

Figure 2. The capacity of DH production plants in Finland by different primary fuels in 2021. a represents the capacity distribution for the CHP plants, and b is for the rest of production plants in the Finnish DH networks [7].

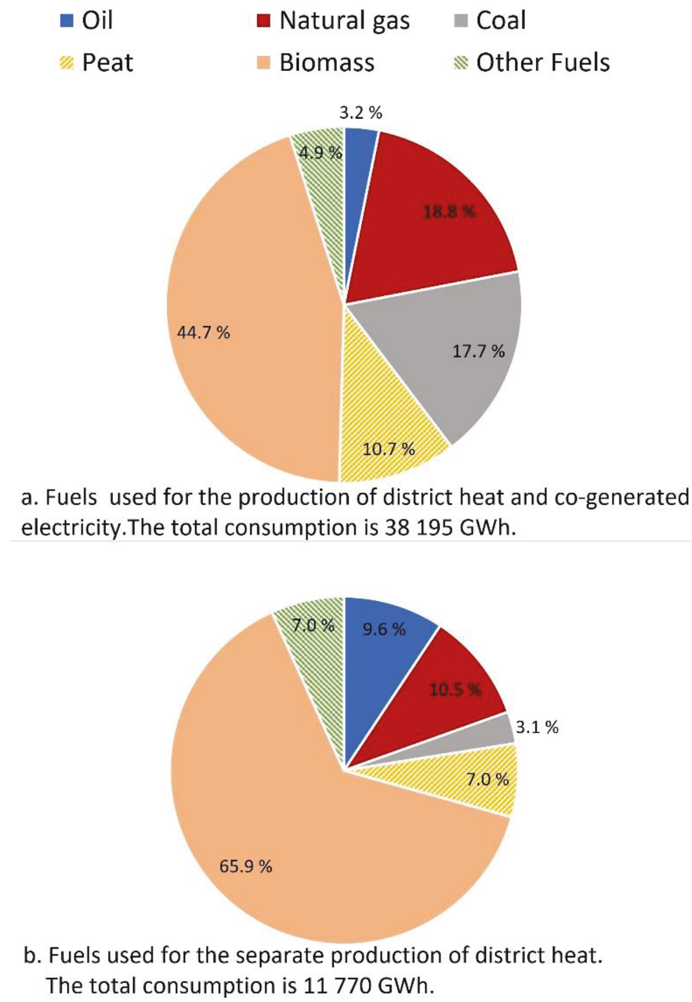

Figure 3. The distribution in fuel consumption by the Finnish DH network in 2021. a represents the distribution of fuel consumption by both DH and co-generated electricity plants and b is the share of different fuels used for separate production of district heat [7].

Figures 2a and 2b illustrate total available CHP and HOB plants supplying DH networks in 2021 in Finland, respectively. While almost half of HOB plants are supplied by oil as the primary fuel, natural gas has a significant share in both groups. Although, most plants supplying DH networks are based on fossil fuels, as Figure 3a and 3b show the majority of Finnish DH network was supplied by biomass fuels in 2021. According to these figures, almost 50% of heat produced by DH networks in 2021 in Finland came from biomass fuels. CHP plants had a significantly higher share compared to HOB plants.

II. Methods and Materials

A. DH Modeling

The investigated DH system is a hypothetical DH network with 10 000 inhabitants located in southern Finland which includes typical 1960s and 1970s apartment buildings. This DH network has been already modelled in different renovation levels by the authors of the current study in [2] with the aim of finding recommendable energy renovation strategies for national energy and climate policies in Finland. This study considers only the non-renovated level of the mentioned DH network. Figure 4 shows the heat demand by the non-renovated level of the hypothetical DH network which is investigated by this study. The district heating demand in these old buildings is 196 kWh/m^2, of which 42 kWh/m^2 is domestic hot water use, while the rest is used for space heating. The calculation of the hourly energy demand has been described in detail in [8].

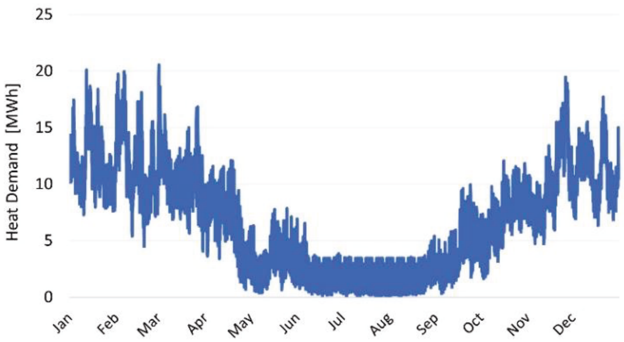

Figure 4. Annual heat demand by the hypothetical DH network [2].

In this study, the annual operation cost in different scenarios is calculated with the help of EnergyPRO software of EMD International A/S, Aalborg, Denmark, with hourly heat demand time series as the input. More information on EnergyPro can be found in [9].

B. DH supplying systems

The supply system of the studied hypothetical DH network includes three main group of scenarios, i.e., biomass combustion scenarios, waste heat recovery scenarios and direct electricity to heat scenario. In biomass combustion group we investigate three different scenarios based on different technologies as below (figures in parenthesis shows the plant size compared to the peak demand):

- Biomass fired CHP (100%)
- Biomass fired HOB (100%)
- Biomass fired CHP (50%) + Biomass fired HOB (50%)

in above mentioned scenarios, the thermal and electrical efficiency of the CHP plant are 57.4 % and 29.4 %, respectively. Moreover, the considered efficiency for biomass fired HOB is 92% [2].

The waste heat recovery scenarios are divided into two scenarios as below:

- Waste Heat-Heat Pump (100%)
- Waste Heat-Heat Pump (50%) + Electric Boiler (50%)

where data center has been considered as a possible waste heat source in this group of scenarios, and the price list is according to heat buy-in price reported by Fortum company for Espoo [10]. Furthermore, it is assumed that the heat pump is operating with a COP of 5, and the efficiency of the electric boiler is 98.5 % [2].

Finally, the direct electricity to heat scenario describes a scenario in which an electric boiler is used to cover 100 % of DH heat demand. To find the technical and economic data used in modeling different technologies in the mentioned scenarios please refer to [2].

Electricity in Finland is very low-carbon due to the extensive use of nuclear power, hydropower, biomass co-generation and rapidly increasing wind power. In 2022, the average CO_2 emission coefficient of electricity production in Finland was 55 gCO_2/kWh [11].

C. Energy Crisis Scenario

To define an energy crisis scenario, it is required to have a base scenario in which the prices are in a normal situation (before the energy crisis). In this study, the base scenario is according to the assumptions in [2], in which the electricity and biomass prices are the average prices over 2015-2020. The energy crisis scenario is defined by assuming 300% and 50% increases in electricity and biomass prices compared to the prices in the base scenario, respectively. The average hourly electricity spot price in 2015-2020 is according to Nord Pool spot price and it was 36 €/MWh [4]. Also, the average price for biomass in Finland over the period of 2015-2020 has been derived from [6], equaling 21 €/MWh.

It should be noted that the mentioned 300% increase for the energy crisis scenario is only applied to the electricity spot price, and it does not include neither electricity transmission fee nor electricity taxation. TABLE I shows the considered values for distribution fee and taxation that are based on the average values in Southern Finland over the period of 2015-2020 reported by Caruna company [12]. In this paper, we assumed that the energy crisis doesn't affect neither the electricity transmission fee nor its taxation, thus the values in TABLE I are valid for both the energy crisis scenario and the base scenario.

TABLE I. The electricity transmission fee and electricity taxation used by this paper [12].

Parameter		**Value (€/MWh)**
Distribution fee	Daily transmission, winter	11.12
	Other time transmission	7.27
Taxation (Electricity tax + VAT)		7.03

D. Economic Analysis

Heat Production Cost (HPC) and Net Present Value (NPV) in different scenarios are calculated according to (1) and (2), respectively:

$$\mathrm{HPC} = \mathrm{C}_{\mathrm{fuel}} + \mathrm{C}_{\mathrm{variable\ O\&M}} + \mathrm{C}_{\mathrm{Fixed\ O\&M}} - \mathrm{R}_{\mathrm{electricity}} \qquad (1)$$

$$\mathrm{NPV_n} = \sum_{t=1}^{t=n} \frac{\text{Net Income}}{(1+r)^t} - \text{Initial investment} \qquad (2)$$

in which C represent different costs while $\mathrm{R}_{\mathrm{electricity}}$ is the revenue from selling electricity in the CHP units, therefore according to (1) additional revenue from selling electricity declines the heat price. Break-Even Price (BEP) of heat produced is calculated by setting $\mathrm{NPV_n}$ shown in (2) to zero for a specific payback period (n) and interest rate of energy (r). In this study, BEP is calculated with the help of goal seek function in Excel software in which, n is considered as 20 years, and r is equal to 0.02 [13]. To find the initial investment in different scenarios please refer to [2]. It should be noted that since in the calculation of HPC by the CHP units, revenue from selling electricity is also included (see (1)), to have a fair analysis the initial investment for these units is the investment for the whole plant.

In the calculation of BEP, this study considers two different scenarios for the duration of the energy crisis as: 1-The short-term energy crisis (3 years), and 2- The long-term energy crisis (10 years). Figure 5 shows the assumed scenarios for the duration of energy crisis scenario more clearly.

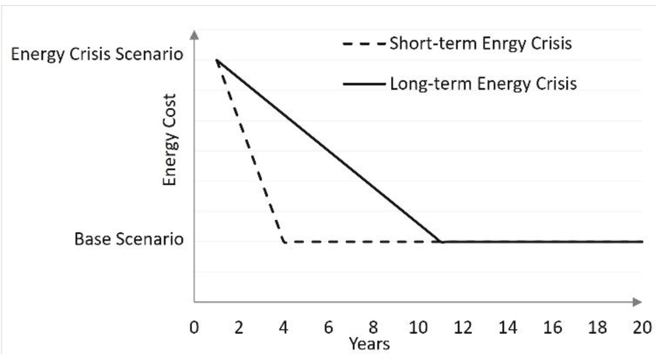

Figure 5. Two assumed scenarios describing how the energy crisis scenario will change in the next years.

III. Results and discussion

This section includes three subsections of heat production cost, break-even price, and sensitivity of HPC produced by different technologies to changes in electricity/biomass price.

A. Heat Production Cost (HPC)

Figure 6 compares the HPC by different scenarios supplying DH network in the energy crisis scenario and the base scenario. HPC has been defined and calculated according to (1). The higher fuel cost increases HPC but revenue from selling electricity decreases it. That is why by increasing electricity price, HPC in CHP units decreases dramatically. 300% increase in electricity price increases most the HPC by electric boiler. Biomass fired HOB has the lowest changes against 50% increase in biomass price.

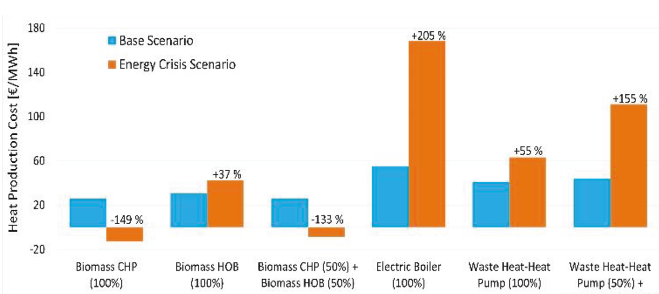

Figure 6. The impact of energy crisis on heat production cost (HPC) in different scenarios supplying the DH network in both renovated and non-renovated buildings.

B. Break-Even Price (BEP)

Figure 7 compares the BEP of heat produced by different scenarios supplying the DH network. As an interesting result, biomass HOB and waste heat-heat pump have very similar economics, however, biomass HOB shows a better performance especially in the long-term energy crisis. Although biomass CHP has the best performance in the short-term energy crisis scenarios, it provides heat with significantly higher costs compared to other scenarios supplying the DH network. This is due to the large investment and rather short (20 years) economic payback period assumed. Furthermore, while Biomass CHP (50%) + Biomass HOB (50%) and Biomass CHP (100%) have the same performance in a short-term energy crisis, but in a long-term energy crisis Biomass CHP (50%) + Biomass HOB (50%) has the best performance and provides heat with the lowest BEP compared to the other scenarios.

An interesting result which can be found in Figure 7, is the changes in different scenarios by shifting from a short-term energy crisis to a long-term energy crisis. As can be seen, Biomass HOB (100%) has the lowest changes by shifting from short-term to long-term energy crisis, and Waste Heat-Heat Pump (100%) is in the second place in this regard.

Comparing Waste Heat-Heat Pump (100%) and Waste Heat-Heat Pump (50%) + Electric Boiler (50%) reveals that Waste Heat-Heat Pump (100%) is less affected by both short-term and long-term energy crisis scenarios. As it could be predicted, the scenario with Electric Boiler (100%) experiences the highest costs in both short-term and long-term energy crisis scenarios.

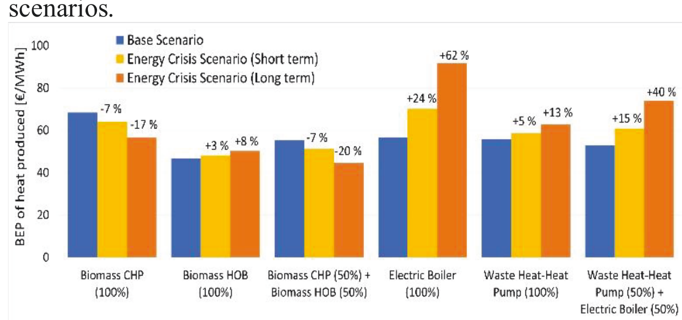

Figure 7. The impact of energy crisis on the BEP of heat produced by different scenarios supplying the DH network.

Furthermore, the rate of biomass consumption by the scenarios of Biomass CHP (100%), Biomass CHP (50%) + Biomass HOB (50%), and Biomass HOB (100%) in supplying the investigated DH network is 0.03, 0.025, and 0.02 Mt wood chips/year, respectively. In these calculations, the energy content of wood chips is 3.5 kWh/kg [14], and the thermal efficiencies for biomass CHP and biomass HOB are 57.6%, and 92%, respectively. It should be noted the total heat demand for the investigated DH network is 58.1 GWh/year.

C. Sensitivity of HPC produced by different technologies to changes in electricity/biomass price

Figure 8 shows the sensitivity of HPC produced by different technologies to changes in electricity/biomass price. While increasing the biomass price has only negative impacts on HPC, increasing electricity price in CHP can reduce HPC significantly. HPC by CHP is more affected by the biomass price than the electricity price. Biomass HOB is more sensitive to biomass price compared to waste-heat heat pump and its sensitivity to electricity price.

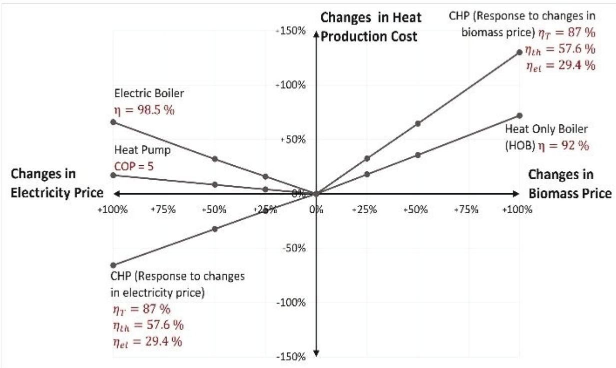

Figure 8. The sensitivity of HPC produced by different technologies to changes in the electricity/biomass price. η, η_T, η_{th}, and η_{el} represent efficiency, total efficiency, thermal efficiency, and electrical efficiency, respectively. COP represents the Coefficient of Performance for heat pump.

IV. Conclusion

This study aimed to find how an energy crisis in both short-term and long-term scenarios may affect the price of heat produced by low-carbon DH systems in Finland. For this purpose, various scenarios decarbonizing DH systems have been defined and investigated in a hypothetical energy crisis scenario. The investigated DH network located in southern Finland and included 10 000 inhabitants in typical 1960s and 1970s apartment buildings, which are common apartment buildings in this area.

In the 2022 energy crisis, the derivatives market did not have the normal liquidity, thus the higher electricity cost estimates of this paper are rather representative for the crisis situation. In the Finnish electricity market area, electricity market price is mostly determined by the availability of wind and nuclear power, in addition to electricity import and export. Thus, biomass price is rarely decisive for electricity market price, but important for DH price in many cities and towns.

The results revealed that in both short-term and long-term energy crisis scenarios, Biomass CHP (50%) + Biomass HOB (50%) has a significantly better performance compared to the other scenarios supplying the DH network. Biomass CHP (100%) has a good performance in the energy crisis, but it still provides heat in much higher prices compared to the other scenarios.

However, it is notable that in reality it is probable that DH companies do not sell all their electricity production to spot, but typically hedge the majority of the production. Thus, the assumed electricity sales fully to the spot market probably overestimates the income. Correspondingly, DH companies also aim to hedge their electricity purchases. Waste Heat-Heat Pump (100%) is less affected in both short-term and long-term energy crises compared to Waste Heat-Heat Pump (50%) + Electric Boiler (50%), however in the base scenario Waste Heat-Heat Pump (50%) + Electric Boiler (50%) produce cheaper heat.

Furthermore, the sensitivity of different technologies to changes in electricity/biomass price revealed that heat pump has the lowest sensitivity to electricity price while CHP has the highest sensitivity to biomass price. The sensitivity of CHP to biomass price is almost two times higher than its sensitivity to electricity price.

Based on economic calculations, Biomass CHP (50%) + Biomass HOB (50%) would be the best scenario supplying DH network in both short-term and long-term energy crises. However, increasing biomass usage has recently contributed to the loss of natural carbon sinks of the land use sector in Finland [15]. Taking this into account, this study recommends Waste Heat-Heat Pump (100%) as the most sustainable scenario supplying DH networks. This study shows that even in an extreme increase of electricity market prices, this option would remain economically competitive.

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