Master's Thesis

Integration of Waste Heat from Power to X in District Heating Systems

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Abstract:

Power-to-X is a promising technology for decarbonising parts of the industry and the transport sector. The former Danish government formulated a national strategy for Power-to-X to reach a capacity of 4-6GW of electrolysis capacity by 2030. The capacity would result in a large waste heat stream due to heat loss. Since the existing research on the utilisation of waste heat is limited, this thesis investigated how the integration of waste heat from Power-to-X can be utilised in the district heating systems of Sønderborg. Waste heat from Power-to-X differs from the dominant technologies since it is a fluctuating heat source that cannot be controlled directly by the district heating companies and the utilisation may require a stronger cooperation of the district heating companies in the area. The quantitative analyses showed that there is a potential for expanding the district heating system and the total expansions could increase the annual heat demand by 15%. The utilisation of the waste heat depends on whether the system is interconnected or two separate systems. Compared to the existing system, the utilisation of the waste heat is feasible from both a business and socioeconomic perspective if the two district heating systems are connected by a transmission line. Depending on the size of the Power-to-X plant, waste heat could contribute 34-56% of the annual heat production if the systems are interconnected.

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Summary

The technology Power-to-X is a promising technology for decarbonising parts of the industry and the transport sector. Through electrolysis, hydrogen can be produced from electricity and water, which can be used directly or combined with a carbon source to produce a gaseous or liquid fuel that can be utilised in the transport sector. The former Danish government formulated a national strategy for Power-to-X to reach a capacity of 4-6GW of electrolysis capacity by 2030. A goal of the strategy is for Power-to-X as a technology to ensure the coupling of different sectors in the energy system. An electrolysis capacity of 4-6 GW would result in a large waste heat stream since electrolysis production results in a heat loss of approximately 20% of electricity input depending on the technology. This waste heat could potentially be integrated into the district heating system if planned appropriately. While existing research on waste heat for Power-to-X mainly focuses on strategic development to support the development of the technology, focuses on the technology itself or waste heat integration on a national energy system level, little research focuses on the integration of waste heat in specific district heating systems.

This thesis investigated how the integration of waste heat from Power-to-X can be utilised in the district heating systems of Sønderborg. The analyses are based on energy system modelling in energyPRO and distribution grids in Qgis to assess the utilisation quantitatively. Qualitative interviews were conducted to analyse how waste heat differs from the existing production units. The results of the qualitative interviews are that the district heating systems of Sønderborg are mainly supplied by dominant technologies like combined heat and power plants and boilers. Waste heat from Power-to-X differs from the dominant technologies since it is a fluctuating heat source that cannot be controlled directly by the district heating companies and the utilisation may require a stronger cooperation of the district heating companies in the area. The quantitative analyses showed that there is a potential for expanding the district heating system, and the total expansions could increase the annual heat demand by 15%. The utilisation of the waste heat depends on whether the system is interconnected or two separate systems. Compared to the existing system, the utilisation of the waste heat is feasible from both a business and socioeconomic perspective if the two district heating systems are connected by a transmission line. Depending on the size of the Power-to-X plant, waste heat could contribute 34-56% of the annual heat production. However, if the waste heat is only utilised in the district heating grid in Nordborg closest to the Power-to-X plant the utilisation is unfeasible, and the waste heat would only account for 15% of the annual heat production of the total

district heating demand in Sønderborg Municipality. It has not been assessed whether it would be feasible to integrate a smaller amount of waste heat in the district heating system in Nordborg.

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The writing of this thesis has been accomplished with supervision and guidance from several people. The authors would like to thank our supervisor Iva Ridjan Skov and co-supervisor Frederik Dahl Nielsen from AAU for constructive supervision during the semester. We would also like to thank Esben Lauesen from Sønderborg Forsyning for participating in an interview and hosting a meeting and a guided tour of the straw plant in Nordborg. Thank you to Tue Gejl Christensen from Sønderborg Varme for participating in an interview and providing us with data for our energy system analysis. Moreover, a thank you to Lene Sternsdorf from Sønderborg Municipality and Michael Kurt from Broager Varme for participating in an interview. Christian Rechter Zenas helped us with the modelling of distribution grids, and we would like to thank you for the dialogue during this process. Thank you to Steffen Nielsen from AAU who helped us with our GIS modelling and Leif Holm Tambjerg from EMD who provided guidance on energyPRO modelling as well as the required licenses. Last but not least thank you to Ea Energy Analyses who provided us data on fuel and electricity prices.

Reading Guide

References in this thesis are applied with APA reference style. References are written with the authors' last name followed by the year. E.g., (Hansen, 2019). When there are three or more authors *et al.* is shown after the last name of the. E.g., (Connolly, et al., 2014). If a reference does not include a year *n.d.* (no date) is applied. When a reference includes the same author(s) and year the reference is followed by a letter. E.g., (Danish Energy Agency, 2022a) and (Danish Energy Agency, 2022b). A complete list of references is found in the chapter Bibliography at the end of the thesis. Appendices are uploaded separately and contain minutes of the interviews and GIS models, energyPRO models and Microsoft Excel sheets.

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Abbreviations

AEC: Alkaline electrolysis cells

BBR: Danish Building and Housing register

CC: Carbon capture

CCS: Carbon capture and storage

CCU: Carbon capture and utilisation

COP: Coefficient of Power

GHG: Greenhouse Gas

GIS: Geographic Information Systems

GJ: Gigajoule

GW: Gigawatt

GWh: Gigawatt hours

HWHT: High Waste Heat Transmission Scenario

Kr.: Danish kroner

KW: Kilowatt

kWh: Kilowatt hours

LCOE: Levelized Cost of Energy

LHV: Lower heating value

LWHN: Low Waste Heat Nordborg Scenario

LWHT: Low Waste Heat Transmission Scenario

MW: Megawatt

MWh: Megawatt hours

MWHT: Medium Waste Heat Transmission Scenario

NHPC: Net Heat Production Costs

NPV: Net Present Value

ORC: Organic Rankine Cycle

O&M: Operation and maintenance expenditures

PEM: Polymer electrolyte membrane electrolysis cells

PtX: Power-to-X

REF: Reference Scenario

SOEC: Solid oxide electrolysis cells

Problem Analysis

Power to X

Power-to-X (PtX) is a technology concept, which covers the conversion of power (electricity) into different energy carriers. Existing research on the topic defines the 'x' as electrofuels for the transport sector and industry or a heat pump for heat production mainly in the district heating sector (Araya, et al., 2022). Since PtX utilises power to generate different energy outputs, the technology as a concept is effective for sector coupling the electricity sector with both heat and/or the transport sector and thus the entire energy sector (Lund, et al., 2021). Different from converting power to heat, the production of electrofuels from PtX for the transport sector requires an electrolysis process, where water is split into hydrogen and oxygen using electricity. When hydrogen has been isolated, it can be combined with a carbon source, resulting in a gaseous or liquid fuel that can be utilised in the transport sector. (Araya, et al., 2022) However, hydrogen can be utilised directly for different purposes in both transport and industry (Danish Energy Agency, 2022a). Depending on the origin of the electricity, the hydrogen from the electrolysis process can be categorised as either brown, grey, blue or green hydrogen. According to (Danish Ministry of Climate, Energy, and Utilities, 2021a), brown hydrogen is produced by utilising electricity originated from coal, grey hydrogen from natural gas, blue hydrogen is produced with the same approach as grey or brown hydrogen but the CO2 is captured and/or stored also known as carbon capture (CC) and stored (CCS). Green hydrogen is produced from electricity from renewable energy sources (e.g., solar photovoltaic, wind turbines, hydropower etc.). According to the literature in the field, three technologies are the most common for producing hydrogen: Alkaline electrolysis cells (AEC), polymer electrolyte membrane (PEM) and solid oxide electrolysis (SOEC) cells (Mathiesen, et al., 2013) (Araya, et al., 2022) (Danish Energy Agency, 2022a). For all three types of electrolysis cells the inputs are electricity and water. (Danish Energy Agency, 2022a)

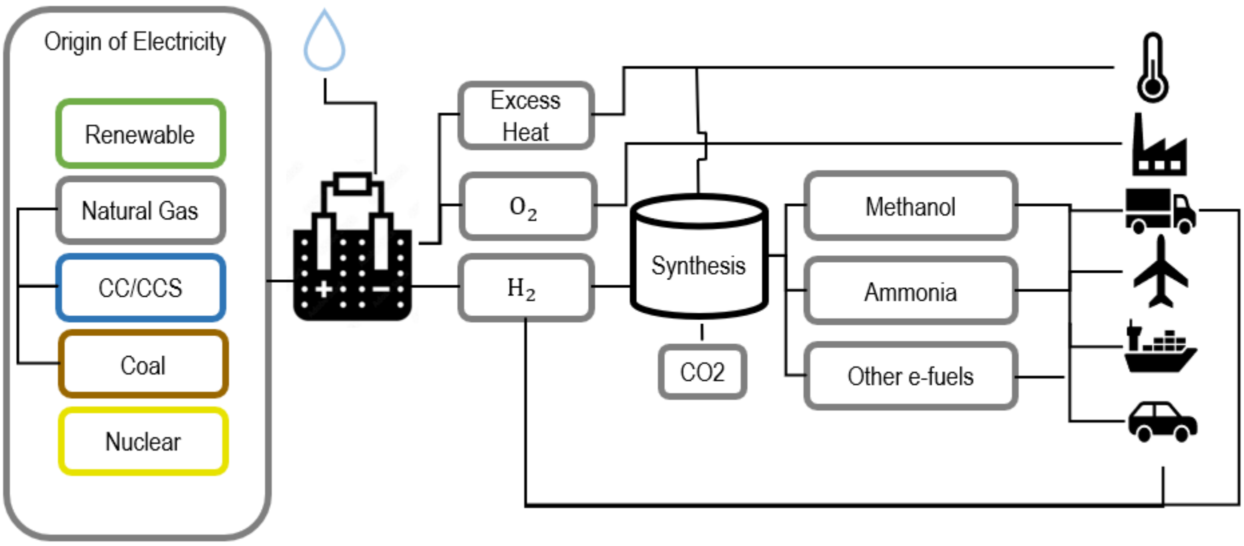

Figure 1: Illustration of PtX technology concept. Own figure based on: (EnergiNet, 2020) (Danish Energy Agency, 2022) (Ministry of Climate, Energy, and Utilities, 2021) (Araya, et al., 2022) (Connolly, Mathiesen, & Ridjan, 2014)

The PtX technology concept is illustrated in a flow chart in Figure 1, meaning the inputs are to the left and the outputs to the right. The centre of the figure illustrates conversion technologies such as an electrolysis plant. As observed in the figure, the origin of the electricity production is marked with its respective colours. Moreover, the electrolysis requires an input of water as illustrated in the figure, and the outputs of the electrolysis are oxygen, hydrogen and waste heat where waste heat can be utilised in district heating. The synthesis process produces electrofuels for multiple types of vehicles in the transport sector. The synthesis process utilises CO2 as well as hydrogen for the process as illustrated in Figure 1.

Alkaline Electrolysis Cells

According to (Danish Energy Agency, 2022a), the most common electrolyser is alkaline electrolysis cells (AEC). The inputs are electricity and water where water is split into hydrogen and oxygen by utilising electricity in a separator where the water is fed into a cathode and led to an anode. The output of AEC is both hydrogen and oxygen from the feed-in water and according to (Danish Energy Agency, 2022a) it currently has an efficiency of 66.5% (lower heating value of hydrogen). However, since the electrolysis process operates at a rather high temperature, waste heat is a product that can be utilised for heating purposes (Danish Energy Agency, 2022a).

Polymer Electrolyte Membrane

The concept of AEC and PEM is rather the same. However, in PEM the split of feed-in water is done in a membrane where the hydrogen is isolated from the anode into the cathode (Danish Energy Agency, 2022a). The efficiency of PEM is currently 58% hydrogen (lower heating value) and like AEC, waste heat can be extracted from the process. (Danish Energy Agency, 2022a)

Solid Oxide Electrolysis Cells

SOEC are somewhat different from AEC and PEM technologies even though the output is the same. About 78% of the output is hydrogen (lower heating value), which makes the efficiency higher compared to AEC and PEM (Danish Energy Agency, 2022a). SOEC operates with an input of electricity, heat and water. The temperature required to isolate the hydrogen is higher, and the feed-in water has to be converted into steam. This means that SOEC requires about 80% input of electricity and 20% heat to convert the feed-in water into steam. Moreover, SOEC is, contrary to PEM and AEC, still under development. (Danish Energy Agency, 2022a)

According to the literature, it is likely that a large share of hydrogen will be converted to either ammonia or methanol as a fuel or product for the transport sector and industry (Araya, et al., 2022) (Danish Energy Agency, 2022a). The production of electrofuels to substitute fossil fuels in the transport sector has been discussed broadly in existing literature (Ridjan, et al., 2013) (Brynolf, et al., 2022) (Connolly, et al., 2014). Overall, the production of fuels can be divided into two major categories: biofuels and electrofuels, whereas biofuels originate from biomass through pyrolysis, electrofuels are produced in combination with an electrolyser and synthesis reactor (Danish Energy Agency, 2022a). A study by (Ridjan, et al., 2013) points to issues of applying biofuels over electrofuels due to the reliance on biomass. This thesis investigates waste heat processes from PtX plants and the term fuels will refer to electrofuels that are produced by electrolysis and/or a synthetic reactor. Methanol can be produced in a synthesis reactor from hydrogen and CO2 and is in the literature considered valuable for the transport sector since methanol can be utilised in both combustion engines as well as fuel cells (Araya, et al., 2022). Ammonia like methanol can be used in the transport sector and may replace fossil fuels in combustion engines (Araya, et al., 2022). Additionally, Ammonia is a useful resource as a fertiliser for the industry (Araya, et al., 2022). Even though both ammonia and methanol can be used as substitute fuel in the transport sector, the utilisation may vary for transportation types. A study from (Brynolf, et al., 2022) states that on one hand both methanol and ammonia are suitable fuels for heavy-duty transport. However, the study concludes that the utilisation of ammonia and methanol is difficult to determine for each transportation type like shipping and aviation. Moreover, the study finds that the utilisation of ammonia requires further processes to utilise ammonia for aviation as a so-called jet fuel. (Brynolf, et al., 2022). An analysis by Energinet (the Danish TSO for electricity and gas) of the utilisation of both hydrogen, ammonia and methanol has been assessed. The analysis concludes that the largest potential consumption of electrofuels is for aviation and marine shipping (EnergiNet, 2020). In addition to the conclusions of (Brynolf, et al., 2022), the analysis by (EnergiNet, 2020) states that it is unrealistic to utilise ammonia for both domestic and foreign aviation transport in Denmark since engines (e.g., fuel cells etc.) that utilise ammonia are not yet commercialised. In addition to this, the potential for utilising methanol is assumed to be larger since the engines that can utilise methanol are already commercialised (EnergiNet, 2020).

Trends in Danish Regulation

In 2021, the former Danish Government formulated a strategy for the future PtX development in Denmark. The main points of the strategy are to ensure that PtX must contribute to the goals in the Danish Climate Act and that PtX as a technology must support the sector coupling in the energy sector. Moreover, the strategy states that Denmark in the future will be an exporter of PtX products and technologies, which the strategy aims to reach by formulating regulatory conditions as well as establishing market conditions for the infrastructure. (Danish Ministry of Climate, Energy, and Utilities, 2021a) With the strategy, the aim is that Denmark will have 4-6 GW electrolysis capacity by 2030. The capacity is expected to be reached by establishing a public bidding round where developers can bid for government subsidies that should cover parts of the costs related to the production of hydrogen (Danish Ministry of Climate, Energy, and Utilities, 2021a). Besides the expected need for 4-6 GW electrolysis capacity from the strategy, the Danish Energy Agency published a report in 2023 where the final electricity consumption is expected to increase by five- to six-fold in 2050 compared to 2022 (Danish Energy Agency, 2023a). The increase in electricity consumption is mainly due to the large increase in electricity consumption for PtX plants (Danish Energy Agency, 2023a). The electrolysis capacity in Denmark was <100 MW in 2022, however, the expectation is that the capacity will increase rapidly in both the short term (towards 2030) and long term (towards 2050) to meet the political goals of the PtX strategy. According to (Danish Ministry of Climate, Energy, and Utilities, 2021a) the portfolio of pipeline projects, which means PtX plants that are not currently established, will exceed the expectations of 4-6 GW by 2030 since the portfolio consists of 7 GW electrolysis capacity towards 2030. Moreover, a recent publication from the Danish Energy Agency expects that the

PtX capacity in the long term will be 15-35 GW (Danish Energy Agency, 2023a). The expected capacity of 15-35 GW is seen as a contributor to the common goal from the European Parliament of at least 40 GW PtX capacity by 2040 (Danish Ministry of Climate, Energy, and Utilities, 2021a).

According to (Danish Ministry of Climate, Energy, and Utilities, 2021a), pipeline projects are primarily located in Jutland with only a few on Zealand due to the areas in Jutland being dominated by electricity production rather than consumption. Moreover, The strategy states that especially the southern part of Jutland (Syd Jylland) is a suitable location for PtX and hydrogen production due to both gas transmissions pipes to export hydrogen to Germany and the integration of waste heat processes to the local district heating grid (Danish Ministry of Climate, Energy, and Utilities, 2021a). Since the political strategy for PtX states that PtX is a technology that should be applied to ensure sector coupling, the placement of PtX plants should be planned close to district heating grids. However, an analysis from the Danish Energy Agency concludes that the socioeconomic benefits of placing a PtX plant close to the electricity infrastructure often is more feasible than utilising the waste heat from the PtX plant (Danish Ministry of Climate, Energy, and Utilities, 2021a). If PtX plants are placed closer to electricity infrastructure, the consequences could be that PtX does not contribute to the sector coupling of the electricity and heat sectors but only a coupling of the electricity and transport sector. If waste heat from PtX is not utilised, this would result in higher fuel and energy consumption in the district heating sector and a greater loss in the energy system.

Utilisation of Waste Heat from PtX Production

The district heating sector in Denmark has reduced fossil fuel consumption significantly in the previous decades. Fossil fuels in the sector has primarily been replaced by solid biomass, like wood, straw, and biomass in waste. By 2021, biomass excl. biomass in waste accounted for 50.4% of total fuel consumption for district heating. Electricity for heat pumps, electric boilers etc. only accounted for 3.5% of production, while surplus heat only accounted 3.5% of fuel consumption. Both have increased in recent years, with electricity experiencing the largest increase. (Danish Energy Agency, 2022b) However, surplus heat could supply substantially more in the future (Mathiesen, et al., 2021). When one considers the plans for PtX in Denmark, surplus heat could potentially supply a significant share of the future district heating demand. Production of electrofuels from PtX results in significant losses regardless of the specific technology used or fuel that is produced (Danish Energy Agency, 2022a). The three major technologies for producing hydrogen through electrolysis, AEC, PEM and SOEC vary in efficiency and therefore in the amount of waste heat. *Table 1* shows the efficiency of the three electrolyser technologies stated in the lower heating value of hydrogen.

Table 1 - Expected efficiency and waste heat potential of electrolyser technologies by 2030 (Danish Energy Agency, 2022a). The efficiencies do not sum to 100%, since the LHV of hydrogen is used.

Technology	Efficiency (LHV of hydrogen)	Recoverable heat loss	Unrecoverable heat loss
AEC	68%	16.6%	3%
PEM	65.5%	19.6%	3%
SOEC	80.5%	0%	4.8%

SOEC electrolysers are the most efficient at converting electricity to hydrogen. As a result, there is a lower heat loss, and it is not possible to utilise waste heat from the process in district heating (Danish Energy Agency, 2022a). AEC and PEM electrolysers, however, do have significantly lower efficiency and greater heat loss. At a recoverable heat loss of 16.6% and 19.6% respectively, there is a significant potential for utilising the waste heat in district heating systems. If hydrogen is used to produce electrofuels like ammonia or methanol, additional losses would occur (Danish Energy Agency, 2022a). Today the waste heat from PEM and AEC electrolysers is available at 50°C, which is expected to rise to 70°C by 2024 (Danish Energy Agency, 2022a). This is important since low waste heat temperatures require heat pumps to boost the temperature to the required level of the district heating systems, which is typically are defined as 3rd generation district heating that operates at 80°C or above (Sorknæs, et al., 2020). Heat pumps add cost to the utilisation of the waste heat. If the waste heat could be utilised directly without the need for heat pumps, the heating cost would be lower and a larger share of waste heat from PtX production would theoretically become feasible. Low-temperature district heating, such as 4th generation district heating, which is often defined at operating temperatures of 55°C or lower (Sorknæs, et al., 2020), would also allow for greater direct integration of waste heat from PtX. In an analysis of the effects of implementing 4th generation district heating in Aalborg (Sorknæs, et al., 2020) showed, that a lower supply temperature allows for the utilisation of more waste heat sources and an increased energy efficiency and heat production due to higher heat pump efficiencies as well as increased thermal efficiencies for CHP plants.

Politically there is broad consensus that more waste heat from various sources, including PtX, needs to be utilised for district heating. In a political agreement from 2019, the Danish parliament agreed to increase the use of waste heat in district heating by reducing bureaucracy and simplifying rules (Regeringen, 2019). It is estimated that the deal would increase the use of waste heat in general by 35% from 2019-levels (Regeringen, 2019). Currently, district heating companies are subject to a price ceiling when they buy waste heat of 93kr./GJ in total costs related to the waste heat (Danish Ministry of Climate, Energy and Utilities, 2021c). This means that district heating companies are not allowed to utilise waste heat if the total cost is above this limit. This is to protect consumers from high district heating prices and is set based on the cost of alternative heat from wood chip boilers or air source heat pumps, which would often be the relevant alternative to waste heat. Additionally, utilisation of waste heat is taxed at 25kr./GJ, however, companies that deliver waste heat may be exempt from this tax if they are part of the Danish Energy Agency's energy efficiency scheme, which aims at ensuring efficient use of energy including investments in energy efficiency measures (Danish Ministry of Climate, Energy and Utilities, 2021c).

If the former government's strategy of 4-6 GW of electrolyser capacity laid out in (Danish Ministry of Climate, Energy, and Utilities, 2021a) is realised, this would lead to a recoverable heat loss potential of 2.12-3.18TWh if AEC electrolysers are used, while the heat loss could be as high as 4.63-6.94TWh using PEM electrolysers, considering average annual full load hours of 4.380. However, SOEC electrolysers could potentially lower the overall heat loss, but this technology is less developed and not likely to contribute significantly to the 4-6GW by 2030 laid out in the strategy, meaning there will likely be a significant heat loss from PtX by 2030 in Denmark. The existing research on waste heat utilisation from PtX is limited. There are some reports and studies published on the subject. In an analysis by (Mathiesen, et al., 2021), researchers modelled scenarios for the Danish heating sector by 2030 and 2045. The scenarios include a significant amount of waste heat from PtX production. The researchers estimate that the maximum waste heat potential from electrolyser is 2.96-3.86TWh annually by 2045 (Mathiesen, et al., 2021). Although not all of the potential can be utilised due to various local factors, PtX could potentially contribute significantly to the future district heating supply in Denmark if sites for PtX production are planned appropriately. The Danish District Heating Association estimates that waste heat, including waste heat from PtX production, can contribute about 20% of the total district heating demand in Denmark in the future (Grøn Energi, 2021). The analysis by (Burrin, et al., 2021) modelled a small, combined heat and hydrogen generator using the PEM technology at an efficiency of 60-70% and utilising the waste heat in a district heating network. By utilising the waste heat, a combined hydrogen and heat efficiency of 94.6% was achieved in the model. By restriction of the flow rate in the cooling circuit, a waste heat water temperature of 75°C was achieved making it suitable for direct integration in some district heating networks (Burrin, et al., 2021). A waste heat temperature of 45°C was achieved in the non-restricted operation of the cooling network (Burrin, et al., 2021). In this case, a heat pump would be needed to integrate the waste heat in district heating networks to reach the desired supply temperature. Another study by (Li, et al., 2019) studied the effect of PEM electrolysers in electricity distribution networks including waste heat recovery from hydrogen production. The study found that the electrolyser increased the operational efficiency of the CHP plant in the system, while the waste heat recovery increased the overall energy efficiency of the system by 15% (Li, et al., 2019). (Böhm, et al., 2021) analysed the future sector coupling potentials between power-to-hydrogen production and district heating, through existing literature and interviews with experts. The study finds that to integrate waste heat from power-to-hydrogen production in district heating the following requirements apply:

- *"Low cost of recovery*
- *Sufficient temperatures and/or low preparation costs*
- *Low costs of supply infrastructure (pipelines, transfer station)*
- *Short-term constancy (low production fluctuations, i.e., low need for storage)*
- *Long-term availability (no risk of bankruptcy, no serious process modifications that avoid waste heat, no relocation to more efficient locations)*
- *Presence of backup systems*
- *Low value of alternative use of waste heat (i.e., that there is no cost-efficient use, e.g., on the site or for electricity generation)"*

(Böhm, et al., 2021)

The study also estimates that 6-10% of the EU's district heating demand could be supplied by waste heat from electrolysis based on the EU's electrolysis distribution plans (Böhm, et al., 2021). Additionally, the researchers conducted a SWOT analysis (analysis of Strengths, Weaknesses, Opportunities and Threats) of the utilisation of waste heat from power to hydrogen. Amongst other things, they conclude that waste heat temperatures from power-to-electrolysis are sufficient for many district heating networks, however, the temperature could be too low for other networks and low compared to conventional sources of heat like combustion of fuels. The authors also highlight the fact that the seasonality of hydrogen production and district heating demand might not overlap, which could pose an issue for integration. (Böhm, et al., 2021)

(Francesco, et al., 2021) studied the waste heat utilisation from PtX production in a decarbonised scenario of the Italian energy system. The article considers both high-temperature waste heat (above 150°C) and low (50-90°C) temperature waste heat for either power generation via Organic Rankine Cycle (ORC) or direct use for District Heating. They consider PEM electrolysis for hydrogen production, along with the production of several other electrofuels like methanol, ammonia, jet fuel etc. The results show that the model prefers to use high temperatures in the ORC for power generation during summer at night since Solar PV covers more than the demand during the day and the demand for district heating is low. During winter the model prefers to use high-temperature waste heat directly for district heating since the demand is higher (Francesco, et al., 2021). In general, the model shows that waste heat is concentrated during the summer months. This is because the model of the Italian energy systems is heavily reliant on Solar PV for power generation, which is concentrated in the summer months (Francesco, et al., 2021). The study shows that a total of 31.7TWh of high-temperature waste heat and 37.7TWh of low-temperature waste heat was generated, which could roughly cover one-quarter of the total heat demand in the civil sector in Italy (Francesco, et al., 2021). The study mostly focused on high-temperature waste heat for power generation and did not focus on specific district heating systems, but the complete Italian energy system, which presents some limitations in the real-world application of waste heat utilisation from PtX. The study also did not consider any investment costs, but only commodity costs (fuel).

District heating in Sønderborg Municipality

This thesis investigates the district heating systems of Sønderborg Municipality with regards to integration of waste heat from a PtX plant. The current heating system in Sønderborg Municipality is split into district heating areas, individual natural gas boilers and other heating solutions. The district heating system is illustrated on Figure 2. The district heating grids are split into four distinct grids, which are not currently connected by transmission lines. However, a transmission line will be built between Graasten and Sønderborg (Christensen, 2023). In the west of Sønderborg Municipality is the district heating grid of Graasten, Egernsund to the east and Overby south of Graasten. Broager District Heating is the smallest of the district heating systems in the municipality and only supplies the city of Broager. Sønderborg Varme is by far the largest of the district heating systems and supplies the cities of Sønderborg, Dybbøl, Vollerup, Hørup and Augustenborg. In the northern part of Als, Sønderborg Forsyning supplies Nordborg, Havnbjerg, Svenstrup and Guderup.

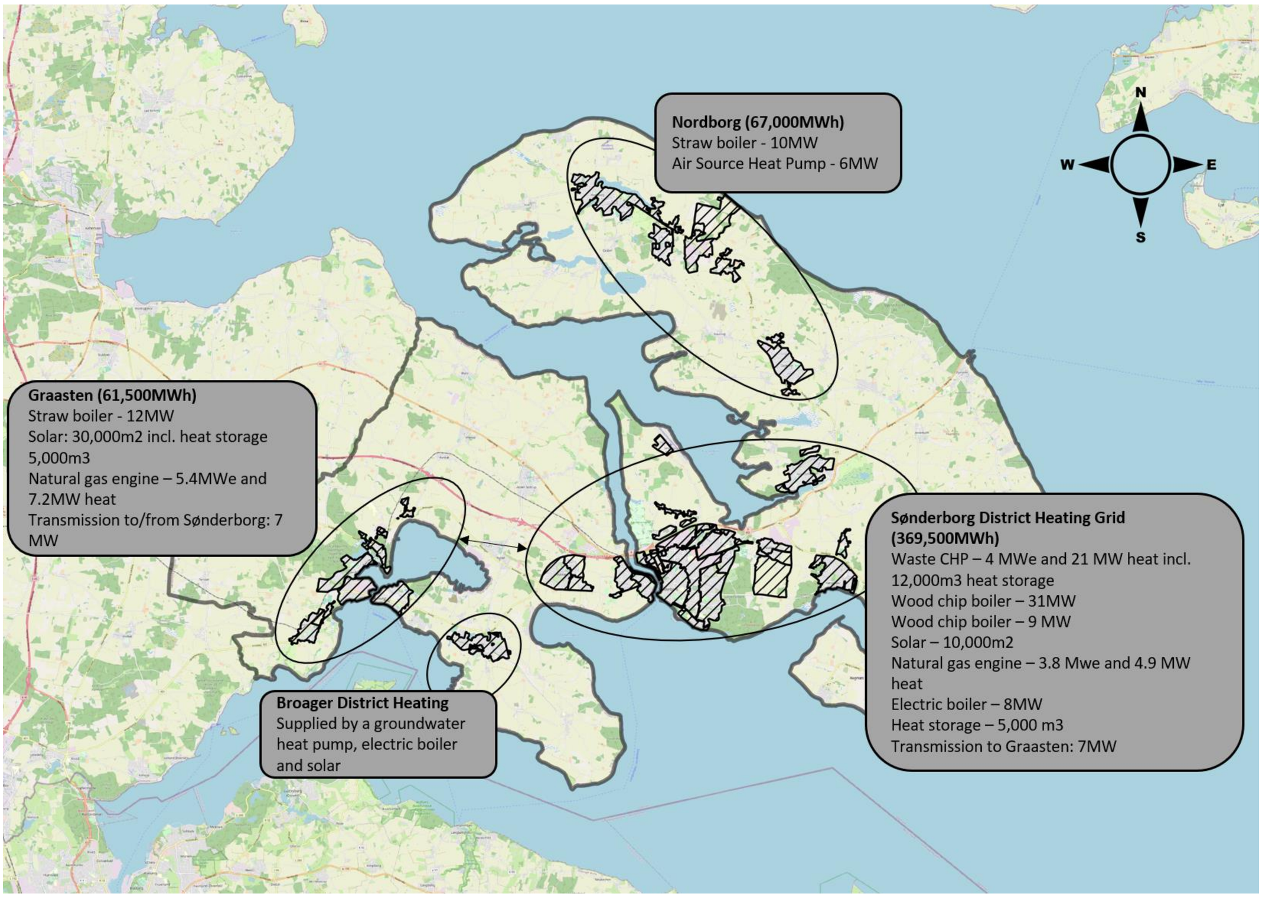

Figure 2: Overview of the existing district heating systems in Sønderborg and existing heat production units. All areas have natural gas boilers to cover peak demand.

Together, the four district heating grids supply around 500,000 MWh annually. According to (Sønderborg Varme, 2023c), the share of renewable energy in heat production at Sønderborg Varme (which covers the district heating grids in Graasten and Sønderborg) was 73.96% in 2022. Wood chips accounted for >40% of the fuel consumption, biogenic waste for almost 20%, straw >10% and solar thermal and electricity for both <5%. The share of fossil fuel was from waste, oil, and natural gas. (Sønderborg Varme, 2023c) According to an interview with Broager Varme, they supply heat almost exclusively with a heat pump, electric boiler, and solar collector, with natural gas as reserve capacity. The district heating grid in northern Als is entirely supplied by straw and natural gas for peak load (Nordals Fjernvarme A/S, 2022).

In August of 2020, Sønderborg Varme formulated a strategy to support the company's strategic sustainability goals. The goal is to support the green transition by operating the company in a socially as well as economically sustainable manner. The company seeks to reach its strategic sustainability goals through several focus areas, of which some are an *expansion of the existing grid and increase of customer base*, *formalised partnerships*, *stable heating costs* etc. (Sønderborg Varme, 2020) With the 2025 strategy Sønderborg Varme has the ambition of reducing energy consumption through energy savings and thereby lowering the heat loss in the district heating grid. Moreover, the company seeks to investigate the potential of innovative technologies like PtX, CCS and industrial excess heat as a supplement to the current heat supply. (Sønderborg Varme, 2020)

In addition to Sønderborg Varme's 2025 strategy, the company is part of the *ProjectZero* partnership, which aims to achieve carbon neutrality in the energy system by 2029 in Sønderborg Municipality (ProjectZero, 2021a). Set in 2007, the goal is a long-running commitment from citizens, companies, educational institutions, utility companies and Sønderborg Municipality to work towards achieving the goal. As of 2020, the project has resulted in a CO2 reduction of 52% (ProjectZero, 2021a). The plan to reduce further and achieve the goal is outlined in the Masterplan2029 (ProjectZero, 2021b). The plan includes energy efficiency measures and electrification of heat production, conversion to electric cars, investments into biogas plants, an offshore wind farm, PtX, expansion of district heating and a focus on sector coupling (ProjectZero, 2021b) The biggest contribution to reducing emissions will be the biogas plant, offshore wind farm, PtX plant and district heating expansion (ProjectZero, 2021b). Sector coupling between these plants becomes important since this could increase energy efficiency by utilising waste heat from PtX or by optimising the operation of the PtX plant according to the renewable electricity production from the offshore wind farm or other local renewable electricity production.

The expansion of district heating is described in the heating plan of Sønderborg Municipality (Sønderborg Municipality, 2022a). A map of the expansion areas is shown in Figure 3.

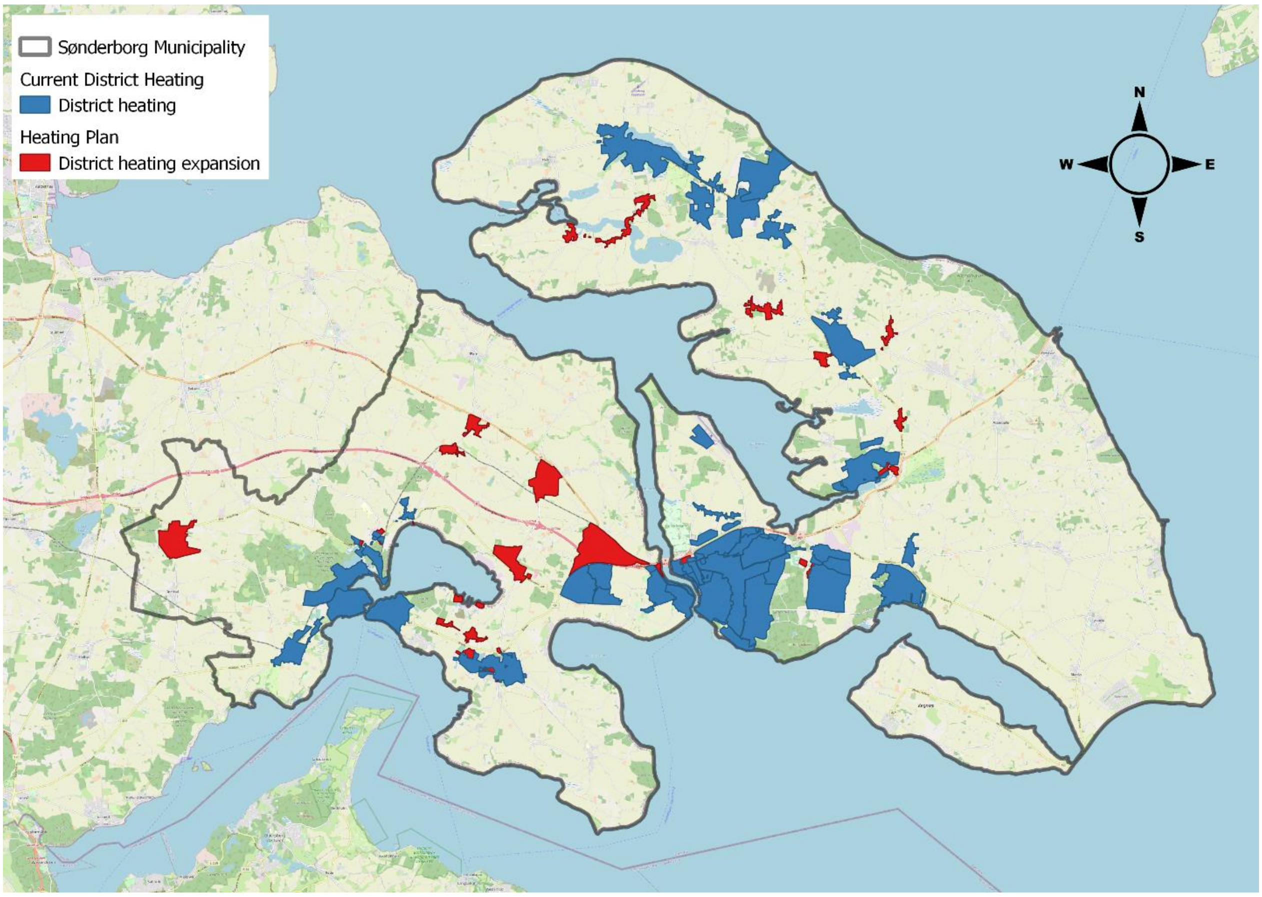

Figure 3: Own map. Map of district heating expansion in Sønderborg Municipality. Expansion detailed in (Sønderborg Municipality, 2022b)

As Figure 3 illustrates, there are multiple expansion areas all over Sønderborg Municipality. This will lead to an increase in district heating demand, which will need to be covered by non-fossil fuel sources for the district heating expansion to contribute to the overall goal of ProjectZero, which is to achieve net zero emissions by 2029. According to an interview with Sønderborg Varme there are also plans to connect the district heating grid in Graasten to the grid that supplies Sønderborg.

Research Question

With the ambition to reach an electrolysis capacity of 4-6GW by 2030 in Denmark, there is a potential to investigate the sector coupling possibilities of PtX plants in the Danish energy sector. Moreover, the previous chapter showed that electrolysis technologies have a significant heat loss that can be utilised in the district heating sector to ensure coupling of sectors. Estimations of waste heat from PtX plants showed a waste heat potential of 2-7TWh depending on the specific electrolysis technology. According to the existing research in the field, the potential of waste heat from PtX plants is around 3TWh. However, existing research on the integration of waste heat from PtX plants is limited and focuses on national energy models or theoretical modelling of PtX plants with limited focus on integration in concrete district heating systems. This presents an area of interest for future research since the location of PtX production in relation to existing district heating systems is critical to the cost-effective utilisation of the waste heat. Specific temperature levels and existing production units will also influence the feasibility of waste heat integration.

It is expected that most PtX projects will be placed in Jutland, and the southern part of Jutland has been pointed out as a suitable area for the location of PtX plants. In the municipality of Sønderborg, a goal of net zero CO2 emissions has been set within the framework of ProjectZero. A significant contribution to reaching the ProjectZero goal of net zero CO2 emissions in Sønderborg Municipality is the establishment of a PtX plant in the region, supplied by local renewable energy, including a nearshore wind farm. At the same time, the district heating in the municipality is expanding towards 2030. Careful planning and analysis must occur to ensure the coupling of electricity, transport, and heat sectors. Therefore, this thesis will analyse the possibilities of integrating waste heat from a PtX plant in Sønderborg Municipality.

This leads to the research question and sub-questions of this thesis.

Research question

How can the integration of waste heat from PtX support a feasible transition of the district heating systems in Sønderborg Municipality, and how does the technology fit into the existing local district heating system?

Sub questions

1. *What is the potential for expanding district heating in Sønderborg, and what is the feasibility of the expansion?*
2. *What are the potentials of integrating waste heat from PtX in the local district heating system of Sønderborg Municipality, and how does it compare in a feasibility study?*
3. *How does waste heat from PtX differ from the existing production units as a technology, and how does it influence the implementation of waste heat from PtX?*

Research Design

This thesis seeks to investigate how waste heat from a PtX plant in Sønderborg Municipality can be integrated into the existing district heating systems by conducting an energy system analysis of the district heating systems as well as how waste heat as a technology fits into the system by conducting a qualitative analysis. To assess the consequences of implementing waste heat into the energy system, this thesis delves into a case study of a PtX plant located in Nordborg in Sønderborg Municipality, which is expected to operate from 2029. The purpose of the case study is both to assess the energy system by quantitative modelling as well as analyse the system by conducting interviews to analyse how waste heat from PtX differs from existing technologies as well as what consequences it might have to implement it. When conducting both quantitative and qualitative analyses, the research is a mixed method approach where the energy system has been assessed as a socio-technical system with both quantitative and qualitative methods. The theoretical framework includes a theoretical conceptualisation of '*technology´* defined by (Lund, H., 2014), and the purpose is to establish an analytical framework to analyse the existing technologies and waste heat as well as discuss whether the integration of waste heat from PtX could cause a radical technological change compared to the system as it is today.

Besides the analytical framework and the mixed method approach, this thesis is organised logically meaning that the analyses feed into each other, and that the methodology is applied in more than one analysis. This is clear in the quantitative analyses of the energy system where the system as it is today and as it is expected to be, are analysed. Moreover, different scenarios are analysed where the potential of implementing different capacities of waste heat is analysed to test the feasibility of the scenarios. The first analysis will present the PtX case in Nordborg as well as analyse how waste heat as a technology is different from existing technologies.

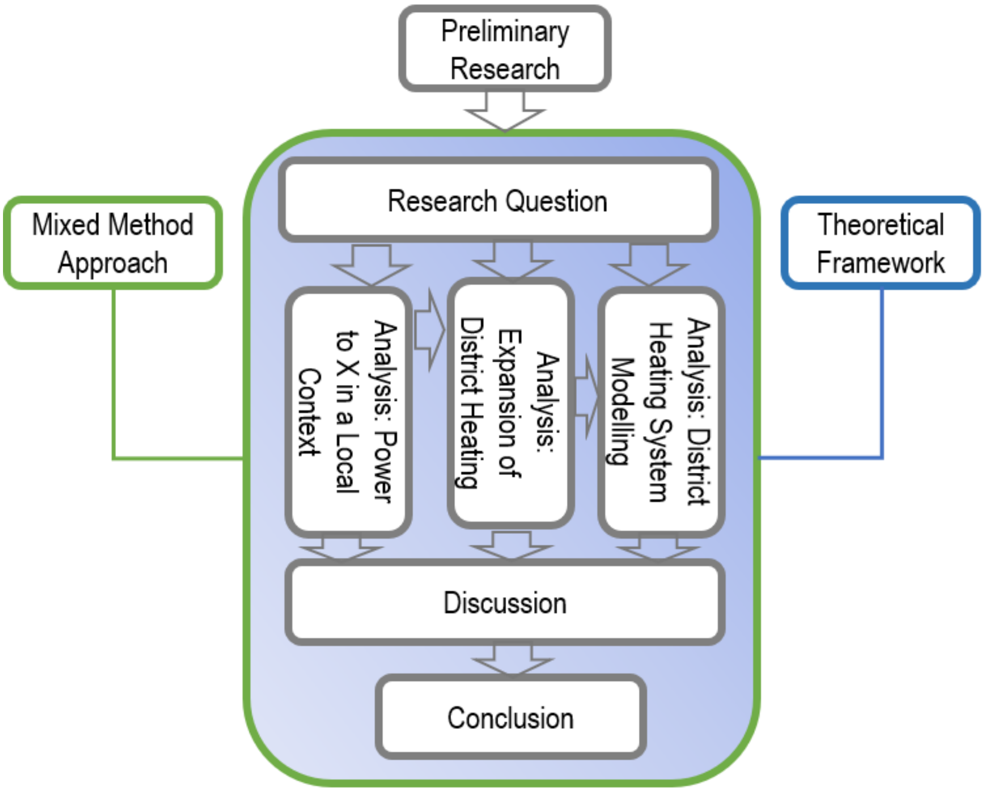

Figure 4: Structure and design of this thesis

In addition to the previous section, Figure 4 illustrates the design and logical setup of this thesis. The conclusion of the preliminary research is used to define the actual scope and purpose of this thesis which is stated in the research question. Both the mixed method approach and the theoretical framework define the approach for the analyses, which is illustrated with the blue square with a green border surrounding the research question, analyses, discussion, and conclusion. This means that the theoretical framework defines the perception and framework of the conducted research and that the methodological approach is applied as tools to analyse and model the research. The theoretical framework is, e.g., applied to conceptualise the term *'technology'* and to conceptualise the district heating sector in Denmark where it can be defined as different generations. The methodology is understood as a toolbox that is applied to assist the analytical approach of this thesis. Since the methodological approach of mixed methods and the theoretical framework are bases for the analyses, it means that the district heating system of Sønderborg Municipality is analysed as a socio-technical system where both qualitative and quantitative methods are applied. The results and findings of the analyses will be stated in partial conclusions where the sub-questions are answered, in addition to this, the results and conclusion of the analyses are discussed before the final conclusions are stated to answer the research question.

Theoretical Framework

This section will present the theoretical framework. The purpose of the section is to describe how the theoretical framework defines the structure of the analyses and to explain how the analytical structures are related to the theoretical framework.

According to research, there seems to be consensus on the need for the integration and utilisation of waste heat from various sources, like industrial excess heat and waste heat from PtX plants in the district heating grid to reach a *100% renewable energy system* in Denmark in the future (Lund, et al., 2021) (Mathiesen, et al., 2021). The main purpose of (Lund, H., 2014) is to present a technological system design of a *100% renewable energy system* on a national scale as well as a theoretical framework, which can be applied to analyse the social and political institutions that are responsible for implementing the needed technological changes in order to reach *100% renewable energy system* (Lund, H., 2014). In other words, the theoretical framework deals with discourse, power, and the fact that people have a choice to choose from other technologies than the dominant ones (Lund, H., 2014).
Moreover, (Lund, H., 2014) introduces the phrase *Radical Technological Change,* which this thesis will apply in its' theoretical framework to analyse utilisation of waste heat from PtX and how it is different from the existing district heating systems in Sønderborg.

Radical Technological Change

Since (Lund, H., 2014) considers the energy system affected by both political norms and institutions as well as dominant technologies the book develops a theoretical framework, which defines technology with five elements: *Technique, Knowledge, Organisation, Products* and *Profit*. These five elements encompass both the arena of political decisions and the technological perspective, among other things. When (Lund, H., 2014) addresses the energy system from multiple perspectives, the system can be defined as a socio-technical system, meaning it contains technical components as well as societal and political perspectives. From this point of view, the district heating systems in Sønderborg are more than the transmission and distribution lines and production units. It also includes aspects like regulation, political goals etc.

The technological perspective is directly related to the technique and product and the political perspective is directly related to an organisation where the focus is to change the norms within the organisation to establish a 100% renewable energy system (Lund, H., 2014). (Lund, H., 2014) defines institutions as social structures and mechanisms that formalise the behaviour and rules of organisations. The theoretical concept of radical technological change is that the societal and technological perspectives and institutions must change in order to reach a 100% renewable energy system. The changes are related to the five elements of the technology definition and the hypothesis is that at least one of these elements must change to cause a radical technological change (Lund, H., 2014). However, if only one of the elements changes and the others do not it will not cause a radical technological change since the technology and related institutions have not been fundamentally changed, which will ultimately cause the change to abandon over time (Lund, H., 2014).

This thesis has not applied the definition of institutions but only organisations. However, the understanding of institutions is that it is related to organisation since institutions are defining the norms of organisations whereas norms can be defined as a set of "values" or a "codex" which defines how people act. In more detail, norms define people's ethical values one could say. This means that norms vary between institutions, but norms also define institutions since they establish structures and mechanisms in which people act and "are" together. This corresponds to the definition by (Lund, H., 2014) since institutions can govern organisations by defining rules and values. E.g., institutions can develop a regulative framework to either support or prevent development by providing subsidies or collecting taxes. The definition of organisation is directly related to (Lund, H., 2014), which means that organisations are understood to be specific and tangible things like companies, non-governmental organisations (NGOs), municipalities, the state etc. (Lund, H., 2014). This thesis will analyse the organisations which are defined as relevant actors of the district heating system in Sønderborg Municipality.

The understanding of the five elements of technology from (Lund, H., 2014) will be elaborated on and the application of the elements will be discussed in the following sections.

Technique

Technique is referring to a technology's technical purposes and components. E.g., a heat pump's technical purpose of converting electricity to heat through technical components like an evaporator, compressor, and condenser. The Technique in PtX is a water purifier, pumps, electrolyser stacks, heat exchanger etc. as described in the chapter Problem Analysis. A heat pump to utilise the waste heat in higher temperature district heating grids could also be part of the technique. The major difference between technique and technology is understood to be that technique solely concerns technical components and technology is a conceptualisation of all five elements.

Products

Products are directly related to the technique and are seen as the output(s) of the technique. For a wind turbine, the output would be fluctuating electricity production and for a heat pump, the output would be heat. PtX as a technology concept involves more sectors, and the product may vary from sector to sector. The product of PtX for the transport sector is various kinds of electrofuels to replace fossil fuels. For the heating sector, the product is waste heat, which is a by-product of the fuel production process.

Organisation

Organisations can be defined as relevant actors within the technology, and they are directly related to political agendas and decision arenas. For a PtX plant, relevant actors could be the owners of the PtX plant, the municipality since the plant could impact political goals for reduction of CO2 emissions from transport or district heating companies that aim for utilising waste heat or reduction of emissions.

Knowledge

Knowledge is the knowledge required to achieve the product of the technique as well as the knowledge required to operate the technique itself. Moreover, knowledge is related to organisations since organisations need knowledge on how to implement a technique but also what the technique is and what it can provide for society. For PtX plants, knowledge of different sectors is crucial since it is considered a useful sector coupling technique. This means that actors and organisations from different sectors need knowledge of PtX as a technology to benefit from the products. One could argue from the perspective of (Lund, H., 2014) that actors with limited knowledge could oversee beneficial achievements and products in the value chain of PtX plants like the utilisation of waste heat.

Profit

Profit is an element that relates to the economic achievements of technology. When considering the energy system as a socio-technical system, more actors become relevant when analysing the potential profit of a technology. When addressing PtX plants, the profit(s) becomes more complicated since more organisations and actors are involved due to various products. An example is the economic value of products (electrofuels) for the transport sector where the economic value is distributed to the owner of the PtX plant. When waste heat is integrated into district heating systems, another economic value could be gained from the PtX plant. One could argue, that in a situation where waste heat is a feasible solution for the district heating company, the profit is not left solely for the owner of the PtX plant since the district heating company would buy heat at a lower cost compared to alternative production methods. Thereby, multiple profit streams are created for more than one organisation.

Application of Theoretical Framework and Analytical Structures

The theoretical framework of radical technological change is directly applied as a structure of the analysis of the utilisation of waste heat from PtX and the implementation in Sønderborg Municipality. The analysis is conducted by analysing the five elements of technology which have been discussed in the previous sections to identify if waste heat from PtX is a different technology compared to the existing technologies. Moreover, the conducted interviews have granted the authors of this thesis technical knowledge of the techniques and products such as existing production technologies, existing grid etc. which is applied in the energy system analysis. With the analysis of the five elements of technology, this thesis seeks to analyse the energy system of Sønderborg as a socio-technical system considering the five elements of technology as an analytical structure based on the theoretical framework.

Methodology

Data Collection

This thesis has collected data by using both qualitative and quantitative methods, primarily in a form of interviews and literature review.

Qualitative Data: Interviews

According to (Creswell & Creswell, 2017), qualitative research is applicable when analyses research problems that relate to social aspects such as groups or individuals. This thesis seeks to investigate if waste heat as a technology is different from the existing technologies in the district heating system of Sønderborg Municipality and to do so qualitative interviews have been conducted to research the differences. Moreover, the purpose of the interviews has been to collect empirical data regarding quantitative data such as data on energy conversion units, heat demands etc.

Four actors have been interviewed: Sønderborg Varme, Broager Varme, Sønderborg Forsyning, Sønderborg Municipality and ProjectZero. Common for all interviews was that an interview guide containing questions and an agenda was formulated before the interview and emailed to the respondent(s). The questions from the interview guide included both open and closed-ended questions and according to (Creswell & Creswell, 2017) open questions are suitable on collecting qualitative data since it allows for an open conversation where the respondent can elaborate their views and understanding of a subject. Close-ended questions are suitable for collecting quantitative data as known in surveys (Creswell & Creswell, 2017). Since the purpose of the interviews was to obtain empirical findings of both qualitative and quantitative data both open- and close-ended questions have been raised.

For the two district heating companies Sønderborg Varme and Sønderborg Forsyning, the interview guide were identical and contained both questions regarding qualitative data and quantitative data. For the quantitative data, questions were about energy conversion units, plans for expanding the district heating grid and other data collected for the energy system modelling to model the reference scenario. The interview with Sønderborg Varme was held on Microsoft Teams and the interview lasted for approximately 1.5 hours. The interview with Sønderborg Forsyning was held as a physical meeting in Sønderborg and in addition to the interview, Sønderborg Varme arranged a guided tour of the straw plant located on Nordals. For the qualitative data, the questions related to whether the two companies cooperate, and what their thoughts in general are on waste heat from PtX as an energy source. The interview with Sønderborg Municipality also had a mix of methods of qualitative and quantitative approach and the interview was held on Microsoft Teams. However, the municipality was not able to provide any quantitative data, so the interview developed into a conversion regarding PtX as well as the municipality's plans for the energy sector in the future. The interview with ProjectZero was conducted with a different approach. The organisation was contacted regarding the same date as the other companies. A 20-minute interview by phone was conducted and contained both qualitative and quantitative data collection questions. However, most of the quantitative data were confidential and considered not useful due to issues of publishing this thesis.

Minutes of the meetings have been noted and may be found in appendices. Since the minutes of the meetings have been noted as a summary, direct quotes from the meetings are not included in the analyses.

Quantitative Data: Literature Review

Besides empirical findings gathered and obtained from interviews with local actors, research of existing literature has an impact on the research. According to (Creswell & Creswell, 2017), literature review is an important part of the research since it allows the research to be limited to the preferred scope of the research. Moreover, the literature review can prove whether the research is worth studying and to determine what can and should be studied, which is related to finding gaps in the existing research and thereby identifying a need for new research. (Creswell & Creswell, 2017)

This thesis researches how waste heat from PtX can be utilised in the district heating sector. The preliminary research highlighted that the existing research of utilisation of waste heat from PtX is limited and a simple estimate of potential waste heat from PtX is 2-6TWh depending on the technology of the electrolysis. The identified potential only concerns electrolysis technologies and does not include synthetic fuel production which would increase the potential. Existing research on the integration of waste heat from PtX plants is limited and focuses on national energy models or theoretical modelling of PtX plants with limited focus on integration in concrete district heating systems. In this way, this thesis contributes to fill gaps in the research.

According to (Creswell & Creswell, 2017), a literature review can be conducted by following certain steps.

1. Identify keywords.
2. Apply keywords in databases to search for literature.
3. Locate and prioritise the literature.
4. Skim the literature and arrange the literature based on topics.

The first point is to identify keywords which for this thesis have been: Power to X, Power to x excess heat, Power to x heat, electrolyser excess heat, Hydrogen excess heat, Methanol excess heat, Green Methanol Production, Cooling of electrolysis etc.

The second point is to apply the keywords in a database. The databases used have been Aalborg University's online library database which has been deemed relevant since it allows the authors to gain access to other journals like Energies and other databases like Elsevier. Google Scholar has also been used, but only sparsely.

The third and fourth points are to locate, prioritise and skim the literature. Abstracts of literature have been read to prioritise between papers and organise relevant ones. The literature has been prioritised in folders with names corresponding to the topics of the literature. E.g., literature on heat from PtX, literature on specific PtX plants, reports on PtX (e.g., national strategies) etc.

Modelling of District Heating Expansions in Geographic Information Systems

This thesis analyses the feasibility of integrating waste heat from PtX in the district heating systems of Sønderborg Municipality. To analyse this, future expansions of the district heating systems have been analysed to determine the extent of the expansions and the likely increase in heat demand, which has an influence on the integration of waste heat from PtX. A model of the future district heating grids has been built in the tool Qgis model district heating grids and to assess the feasibility of district heating expansions. Qgis is a free and open-source geographic information system (GIS) software (Qgis, 2023). The Qgis model is upload in the appendix. Future district heating areas have been chosen based on the heating plan of Sønderborg Municipality (Sønderborg Municipality, 2022a) and interviews with the local district heating companies. Currently, there are plans to extend the district heating to several areas, but there are no official project proposals for each area. Therefore, the analysis will determine the feasibility of each area.

One area for district heating has been considered at a time in Qgis. For each area the model has 1) estimated the annual heat demand of the buildings for hot water and space heating, 2) estimated the peak heat demand and service line capacities, 3) mapped the district heating grid from a chosen location in the area and estimated the required district heating pipe capacities in the district heating grid and 4) estimated the investment cost of the district heating grid and heat loss. Some data management and calculations have been carried out in Microsoft Excel, e.g., data on investment costs are not included directly in the Qgis model. These four parts of the model are described in detail below:

1) Estimation of the annual heat demand of buildings for space heating and hot water

The heat demand in buildings has been estimated using data from the Danish Building and Housing register (BBR) (Dataforsyningen, 2023) and Varmeplan Danmark (Mathiesen, et al., 2021). The BBR registry is publicly available and contains various types of information like size, building type, year of construction, roof material, heating sources etc. on all buildings in Denmark. Varmeplan Danmark contains data on the heating demand pr. m2 in all specific building types and years of construction or renovation (Mathiesen, et al., 2021). The authors of Varmeplan Danmark use data from energy companies to calculate average consumption in kWh/m2 for specific building types and years of construction. The heat demands per m2 for specific types of buildings are included in the appendix E. In case a building has been renovated, it is assumed that the demand is equal to a house constructed in the year of renovation. The data is then imported to Qgis.

2) Estimation of peak demand of buildings and service line capacities

An annual usage of 1800 full load hours has been used to estimate the required connection effect (Andreasen, et al., 2021). This includes heat for space heating and domestic hot water and assumes that the building is fitted with a hot water tank, instead of an instantaneous water heater. The required effect for a specific building is calculated using the following formula and an example calculation is given:

Annual heat demand [kWh] / 1,800 hours = Required effect [kW] (Andreasen, et al., 2021)

18,100 kWh / 1,800 hours = 10 kW

The calculated required effect is imported to Qgis and merged with the BBR and heat consumption data.

3) Mapping of a district heating grid from a chosen location in the area and estimation of required district heating pipe capacities in the district heating grid

Each district heating grid has been modelled in Qgis using BBR data, the required effect to supply the buildings incl. a hot water tank, the public road network, and an outline of the area in question. From these data sources, the shortest route along the public road network has been determined from a user-defined starting point. The Qgis tool 'Shortest path (point to layer)' has been used, which computes individual lines from the defined starting point (start of the district heating grid) to all buildings with heat demand. Each line contains information on the building that it connects to. Additionally, the result has been processed into one single line that represents the district heating network and then split into many single line segments a few meters in length. Secondly, another version of the district heating grid has been created where the individual lines to the buildings are divided into many single segments a few meters in length, that contain the building data. This results in a grid with lines to each building, where each line is split into many smaller lines of a few meters in length, resulting in a very large number of total lines. For each of these small lines, a sum of the required capacity can be calculated based on the capacity of each of the individual line segments (Capacity for each building calculated in step 2 of this section). The number of houses that the line supplies is also calculated. However, all buildings do not consume heat at the same time, and therefore a simple sum of required capacities is not correct. Therefore, a capacity factor is introduced to correct this. The following formula is used to correct the sum of capacities in specific line segments:

Capacity factor = 0.62 + 0.38/N (Andreasen, et al., 2021)

And the total effect of an area can be calculated using the following formula:

$$N * C_{house} * Capacity\ factor = required\ district\ heating\ pipe\ capacity\ [kW]$$

Where N is the number of houses on the line, C_{house} is the required capacity for the building. E.g., if 6 houses, which are supplied by a single district heating pipe, have a required effect of 10 kW each, a total required effect to supply the houses can be calculated:

$$6 * 10\ kW * (0.62+0.38/6) = 41kW$$

The capacity calculated for each line segment is merged with the district heating grid that consists of one line that is split into line segments resulting in a district heating grid, with a specific capacity for all pipe segments in the system. From this grid, the length of the segments and the total grid can be calculated. The model is illustrated in Figure 5. The blue lines represent the road network, the black dot represents the starting point of the district heating grid, and the black lines represent the district heating grid to the houses. The capacity requirement for each building is displayed by the house icon. The capacities between the buildings represent the calculated capacity of each segment of the distribution grid. Transmission from the existing district heating grid is included in the town it connects to. The cost of transmission is split if two towns are connected using the same transmission line.

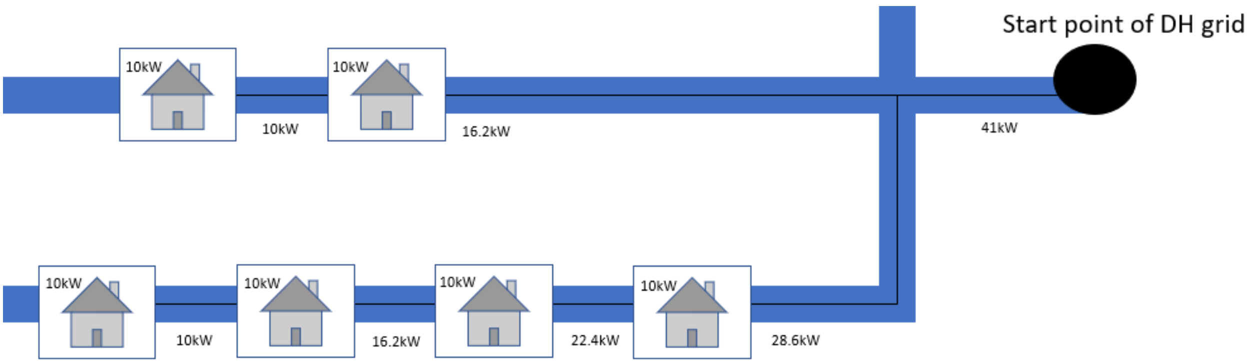

Figure 5: Modelling of district heating grid in Qgis.

4) <u>Estimations of district heating grid investment costs and heat loss</u>

The outputs from the previous steps have been exported from Qgis to Microsoft Excel. In excel, the cost of the district heating pipes has been calculated using the length and capacity of the pipes calculated in Qgis and reference cost for specific district heating pipes. The heat loss is calculated using a factor for heat loss in district heating pipes based on the tables from (Andreasen, et al., 2021) and (Mathiesen, et al., 2021).

Cost for installation of district heating uses data from (Mathiesen, et al., 2021), which have been adjusted based on interviews with the local district heating companies. Based on their experience, total installation costs are generally lower in the local area compared to (Mathiesen, et al., 2021). However, a cost of 2500 kr./m is used as a minimum cost, based on local experience from Sønderborg Forsyning (Lauesen, 2023). Data for substation are based on (Danish Energy Agency, 2021a).

Table 2: District heating installation costs and heat losses applied in the analysis.

DN-size	Internal Pipe Dimension [mm]	Investment costs [Kr./m]	Capacity [MW]	Heat loss [W/m]
DN25	33.7	2,500	0.04	5.30
DN32	42.4	2,500	0.08	6.60
DN40	48.3	2,500	0.17	8.30
DN50	60.3	2,559	0.31	9.70
DN65	76.1	3,064	0.59	12.50
DN80	88.9	3,624	0.90	15.30
DN100	114.3	4,351	1.74	18.40
DN125	139.7	5,152	2.99	24.00
DN150	168.3	5,694	4.90	29.90
DN200	219.1	6,504	9.88	35.50
DN250	273	7,789	17.60	44.50
DN300	323.9	9,429	28.10	55.60
DN400	406.4	11,240	50.99	66.80
DN500	508	13,312	91.94	77.90

Costs for individual heat pumps and heat exchangers incl. a hot water tank are described in Table 3.

Table 3: Cost of individual heat pumps and heat exchangers for district heating.

Technology	Cost	Lifetime	O&M costs	Source
The individual heat pump (Buildings with a required effect under 16 kw)	75,220 kr./unit	16 years	1,695 kr./annually	(Danish Energy Agency, 2022b)
The individual heat pump (Buildings with a required effect over 16 kw)	4,702 kr./kW	16 years	1,695 kr./annually	Based on the unit cost of individual heat pumps divided by stated capacity incl. resistance heater (16kW).
Heat exchanger for district heating	17,427 kr./unit	25 years	270 kr./annually	(Danish Energy Agency, 2022b)

Energy System Modelling

The tool energyPRO has been applied for energy system modelling. energyPRO is a dispatch optimisation tool, which allows optimisation and thus prioritisation of energy-producing units by minimising the marginal costs of heat production. The optimisation is carried out by taking all variable costs like hourly electricity prices, tariffs etc. and other constraints into account and thereby minimising net heat production costs (NHPC). For this thesis, energyPRO is applied to optimise the business economy meaning the total system costs related to supply the total heat demand including losses from a consumer perspective. Socioeconomics will be calculated based on the outputs excluding taxes and tariffs from energyPRO but processed in a separate Microsoft Excel sheet. Although energyPRO offers the ability to include costs for investments and fixed costs e.g., fixed O&M, the modelling only includes variable costs that directly affect the optimisation process. Investments and other fixed costs are included after the optimisation.

The tool has been chosen among several applicable tools since it allows the modeller to model and optimise PtX-plants as well as energy-producing units like CHP units and storage technologies like large hot water tanks. Moreover, literature has shown that energyPRO is an applicable tool for integrating waste heat from processes related to PtX plants (Østergaard, et al., 2022). The tool offers a temporal resolution ranging from 5 minutes to 1 hour, where the temporal resolution for this thesis will be 1 hour due to several factors, which include the temporal resolution of the hourly electricity prices, hourly heat demands etc. Since electricity prices and electricity-producing units are a factor for minimising NHPC., the temporal resolution has been defined as hourly. As mentioned, other tools offer similar procedures as energyPRO, but the tools vary in certain aspects like the scale. E.g., the tool energyPLAN offers a deterministic input-output simulation approach (Connolly, et al., 2010) which allows any modeller to reach the same results given the input is the same. However, energyPLAN does not offer the modeller the option of implementing changes and details on the local and regional scale and since energyPRO allows the modeller to implement local scale details the modelling has been conducted in energyPRO.

The modelling of the district heating systems and the optimisation PtX have been carried out in separate energyPRO files. The waste heat output from the PtX model has then been soft-linked to the district heating model. This means that the district heating system has no influence on the operation of the PtX plant. If there is an income from the methanol production, it would influence the marginal costs which could influence the operation of the PtX plant and influence the distribution of the waste heat. The models do not take this in account since this is difficult to model due to uncertainties of methanol prices.

Energy System Scenarios

A central part of this thesis is to determine the feasibility of utilising waste heat from PtX. To do so the methodological approach includes defining scenarios for the utilisation of waste heat and the development of heat demand. In addition to this, the scenarios as well as the determination of the feasibility of the very same become a central part of the analyses this thesis. The methodological approach to the development of scenarios for the district heating system builds on the theoretical and analytical structure as defined in the section Theoretical Framework. This means that scenarios have been defined with the inspiration of (Lund, H., 2014)'s approach to designing technical alternatives as well as designing the analyses as a business case according to Danish legislation *Bekendtgørelse af lov om varmeforsyning* (the Danish Heat Supply Act) and *Bekendtgørelse om godkendelse af projekter for kollektive varmeforsyningsanlæg* (the Danish Executive Order on Approval of Collective Heat Infrastructures) (Danish Ministry of Climate, 2021b) (Danish Ministry of Climate, Energy and Utilities, 2021d).

To elaborate, one important factor is that the scenarios must be comparable which is the case for this thesis since the alternatives are compared to the same reference and the only change from the reference is the utilisation of waste heat from PtX as an added heat production capacity to investigate the feasibility. E.g., if more than one change occurs between the scenarios, the scenarios have been analysed incrementally to determine the feasibility of each change in the scenarios. In addition, the scenarios are based on the same input data and delimitations, which eases the comparison. E.g., the implementation of PtX will occur in 2029 in every scenario based on interviews with Sønderborg Forsyning. The definition of the reference is especially important since it can distort the feasibility of the scenarios. Especially if the reference is set up as a *worst-case scenario* with for instance deficit base load capacity making the system operate a lot of peak load boilers, which will ultimately increase the total system costs and thereby make almost any change that will lead to more baseload operation in each scenario compared to the reference feasible. In other words, the system must be in balance. When including the development of the system the definition of the investigation period becomes relevant. The investigation period for all scenarios including the reference has been set to 20 years (2025-2044).

The names of the modelled scenarios can be observed in Table 4. Besides the application of the same input data and investigation period of 20 years, the scenarios include a simulation of capacities, meaning that the capacity of the waste heat is modelled incrementally with increasing capacity to establish a sample space of different possible choices for the district heating companies in Sønderborg. This incremental simulation is found in scenarios 2, 3 and 4.

Table 4: Energy System Scenarios

Reference: *As is* (REF)	Scenario 1: Low Waste Heat from PtX Nordals (LWHN)	Scenario 2: Low Waste Heat Transmission (LWHT)	Scenario 3: Medium Waste Heat Transmission (MWHT)	Scenario 4: High Waste Heat Transmission (HWHT)

Reference: As is

The reference is modelled as a baseline scenario meaning that the other scenarios are compared to REF. The REF is modelled and analysed throughout the same investigation period as the following scenarios, the calculation period is 2025-2044. Defining a baseline scenario can be complicated due to the expected developments of the system. A reason for including the expected development of the system is that the PtX plant is expected to operate from 2029 according to interviews with Sønderborg Forsyning. This means that the period 2025-2028 is identical for both the reference and the scenarios. To model a realistic situation for the reference, units that are expected before 2025 have been included. This includes a heat storage and an air source heat pump in Nordborg. Moreover, the increase of heat demand due to expansions of the district heating systems has been included in the reference and the scenarios. As described in the section District heating in Sønderborg Municipality the total heat demand of the system is around 500,000MWh/yr. and according to data from the district heating companies and calculations of the expected heat demand carried out in Qgis, the heat demand is expected to increase by 15% (Christensen, 2023) (Lauesen, 2023). This increase means that the district heating company Sønderborg Forsyning is investing in an air-source heat pump with a heat production capacity of 6 MW as well as storage of 5,500m3 ~ 255MWh to meet the increasing heat demand. According to data from (Christensen, 2023), the waste CHP is expected to supply most of the increasing heat demand in Sønderborg Varme's grid, so no extra investments in base load units are needed to cover the expected expansions. According to an analysis of the waste CHP, the plant is currently cooling its heat production in some hours during the year, which could indicate that there is available heat production capacity from the waste incineration plant. (Rambøll & Dansk Affaldsforening, 2020)

Scenario 1: Low Waste Heat from PtX integrated into Nordals

The first scenario models the reference but with a low capacity of waste heat in the district heating grid of Nordborg only in 2029. The low capacity corresponds to 33MW waste heat at peak production which is generated by a PtX plant with the capacities of 100MW electrolysis and 65MW methanol synthesis. The purpose of the scenario is to assess the potential of utilising the waste heat only in Sønderborg Forsyning's district heating grid on Nordals.

The waste heat output is modelled as an independent model and soft-linked to the reference model. This means that the PtX model is not hard-linked or implemented directly in the reference model, but the generated fluctuating heat from the PtX plant is implemented as an independent hourly time series as the only output from the PtX model. In more detail, the first scenario includes the reference and a heat pump to utilise the generated waste heat as well as heat transmission to distribute the waste heat to Nordborg.

Scenario 2: Low Waste Heat Transmission

The second scenario is identical to the first scenario but with the implementation of heat transmission line between Sønderborg Forsyning and Sønderborg Varme's district heating grids. This means that the hourly fluctuating waste heat profile is the same as for the previous scenario. The purpose of the scenario is to analyse the consequences of allowing heat exchange between the two companies as well as to assess the potential of utilising the waste heat generated from PtX in an interconnected district heating system. It is worth noting that the scenario will not draw a clear conclusion on the feasibility of the heat transmission itself since it is combined with waste heat from the PtX plant. However, the isolated feasibility of the heat transmission will be assessed later in the analyses.

Scenario 3: Medium Waste Heat Transmission

The third scenario builds on the second scenario with an increase in waste heat. This means that the scenario includes 49.5MW waste heat at peak load which is generated by a PtX plant with the capacities of 150MW electrolysis and a 97.5MW methanol synthesis reactor, which is an increase of 50% of the capacities from the previous scenarios. The scenario also includes heat transmission between the two district heating grids. The purpose of the scenario is to test whether a larger amount of waste heat could be a feasible solution.

Scenario 4: High Waste Heat Transmission

As for the third scenario, the fourth scenario is a further increase in capacity. The capacity of the waste heat at a peak is 66MW, the electrolysis is 200MW, and the methanol synthesis reactor has a capacity of

130MW. The scenario also includes heat transmission between the two grids and is modelled to test a further increase in waste heat capacity.

Transmission line capacity and length

For the scenarios LWHT, MWHT and HWHT, a transmission line is included in the model. Either from the PtX plant to Nordals or from the PtX plant to Nordals and Sønderborg. The transmission costs are documented in Table 2. Because the transmission pipes in the table are stated in fixed capacities a larger transmission pipe is always chosen based on the waste heat capacity of the PtX plant in the given scenario. The length is calculated in Qgis. The transmission between the two district heating areas is based on the distance from the PtX plant to the waste CHP in Sønderborg. This is because it is assumed that grid capacity in that area is sufficient to implement the waste heat there, as opposed to the edge of the district heating grids, where the grid is thinner.

Energy System Model of Sønderborg District Heating System

This section will describe the energy system model which has been modelled in energyPRO. Furthermore, the section will describe the assumptions of the modelling and the input data of the modelling. In general, if data have been available from the local actors in Sønderborg it has been directly implemented in the model. However, some of the data are confidential which makes it not applicable. In case of a lack of data, general assumptions have been made based on existing literature and technology data from Danish Energy Agency.

The energy system model is a model that contains all heat production units that currently exist in both Sønderborg Varme’s as well as Sønderborg Forsyning’s district heating systems. The model is a complete model meaning that both companies’ energy conversion units operate in the model, which results in a total system cost based on the two district heating grids. The purpose of the model is to optimise the operation of the energy conversion to minimise the NHPC. The model contains specific data such as capacities of the grid, energy conversion units, heat demands etc. Most of the data have its origin based on empirical findings from interviews and data exchange from the two companies Sønderborg Varme and Sønderborg Forsyning. Data on fuel prices have been provided by EA Energy Analyses. However, some fuel prices were not listed by EA Energy Analyses, such as waste price, straw and biogas. Sources on those prices are obtained from (Danish Energy Agency, 2023a), (Danish Energy Agency, 2022c) & (CTR, et al., 2021). A figure of the energy system model can be observed in Figure 6.

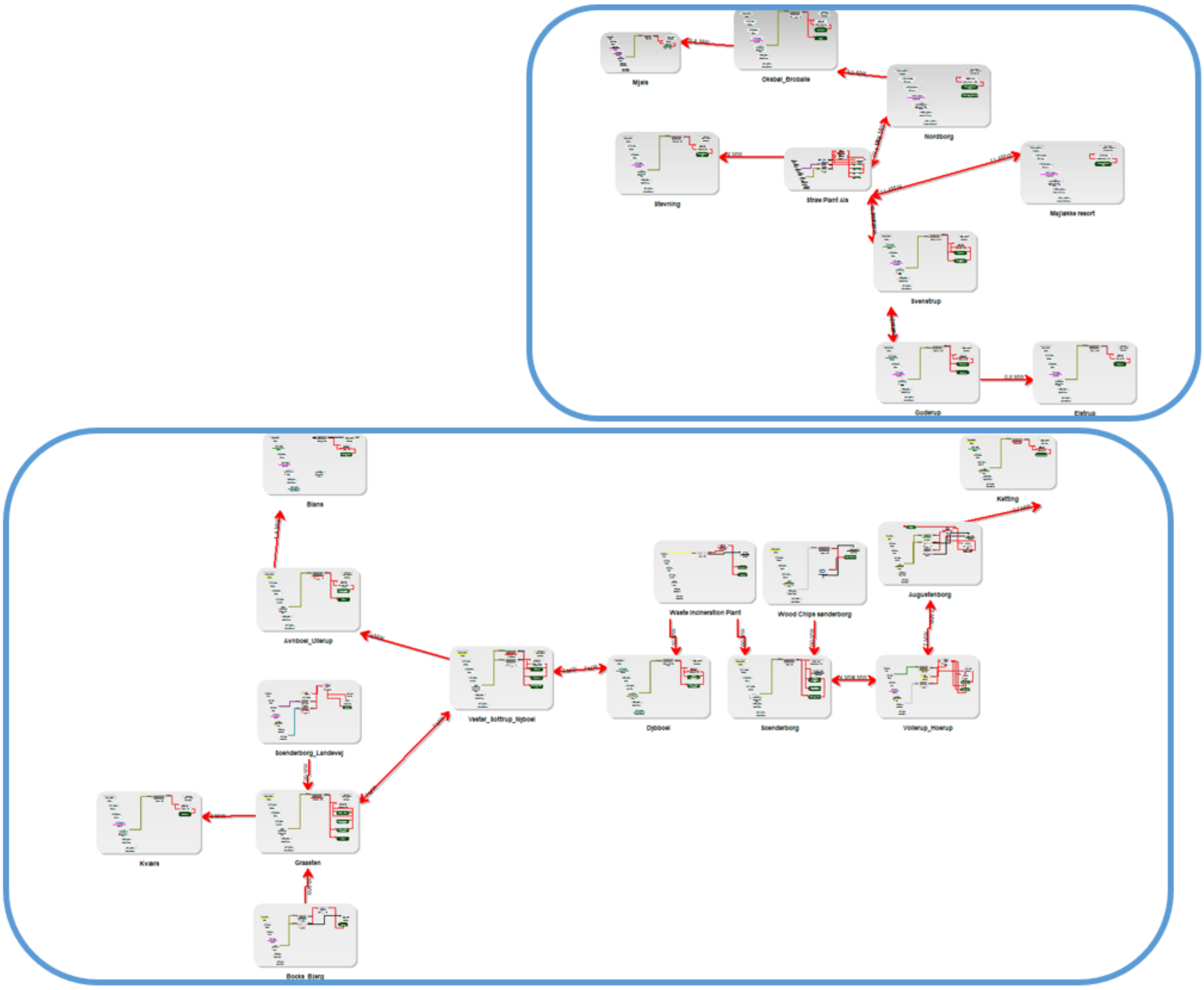

Figure 6: Overview of Energy System Model in energyPRO

The figure illustrates the energy system model as computed in energyPRO. The model is defined as the reference which includes all planned expansions from the district heating companies as well as planned new energy conversion units but without transmission between the two companies. The top right blue square illustrates the district heating grid of Sønderborg Forsyning and the centre blue box illustrates Sønderborg Varme's grid. The model is somewhat complex in terms of calculation time, where a calculation of 20 years takes roughly 4 hours. The model includes around 30 energy conversion units and 7 heat storages. According to data from statistics on energy producers in Denmark by (Danish Energy Agency, 2022d) there were around 20 energy conversion units in 2021 units in Sønderborg Municipality, which is contrary to the 30 heat conversion units in the model. However, an assumption has been made to add more units to ensure the heat demand is met at all hours of the year. According to data from (Christensen,

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2023), the assumption is that peak load boilers operate on natural gas, so the deviation from the existing 20 units to the 30 is due to the implementation of more peak-load natural gas boilers. However, since energyPRO is an optimisation tool the model would only allow heat production on peak load boilers when no other heat production is available due to higher variable heat production costs. As stated, the system must be in balance to establish a true comparison of the reference and scenarios. The implementation of extra peak load boilers is implemented from a model perspective to let the model operate. A validation of this has been carried out and the reference does not operate a significant amount of peak and the average peak heat production from the natural gas peak load boilers is on average 10% of annual heat production for the reference in total for both district heating companies. According to an analysis of the district heating in Sønderborg, the current heat production from natural gas peak load boilers is approximately 14 %/yr. (Ea Energy Analyses, 2020) Moreover, the annual report from Sønderborg Varme (Sønderborg Varme, 2023a) states that the historical heat production from peak load boilers has been 6% and the latest declaration of district heating from the company states fossil fuels accounts for <5% of the heat production (Sønderborg Varme, 2023c). It is worth noting that data on peak load have not been available from Sønderborg Forsyning, so the model is validated by taking Sønderborg Varme's natural gas peak load heat production into account, this has been deemed relevant since Sønderborg Varme accounts for the largest share of the heat demand. The result of 10% annual peak load heat production is assumed valid since it is lower than the analysis from (Ea Energy Analyses, 2020) which includes a foresight of the operation and a little higher than the historical data from (Sønderborg Varme, 2023a). With the validation in mind, the reference as a baseline is deemed to be in balance meaning that the system does not run a deficit in baseload heat production capacity and that it creates a base for a fair comparison of the scenarios.

Heat Demand

The number of heat conversion units is not the only deviation from the current energy system. The annual heat demand is assumed to be higher than it is today due to expectations of the district heating grid. The implementation of the expected district heating expansion has been carried out in different ways. Firstly, data obtained from (Christensen, 2023) and (Lauesen, 2023) have been implemented into the model. The implementation led to an increase in annual heat demand from around 465,000MWh before 2025 to 512,000MWh in 2025. The total annual heat demand of the model is around 555,500MWh in 2028 due to the implementation of data from both district heating companies and this thesis' analysis of district heating expansion. The annual heat demand is distributed to an hourly profile in energyPRO based on the outdoor temperature and demand for domestic hot water. An example of the hourly heat demand profile can be observed in Figure 7. The figure illustrates the distribution of the entire system's hourly heat demand profile including grid losses.

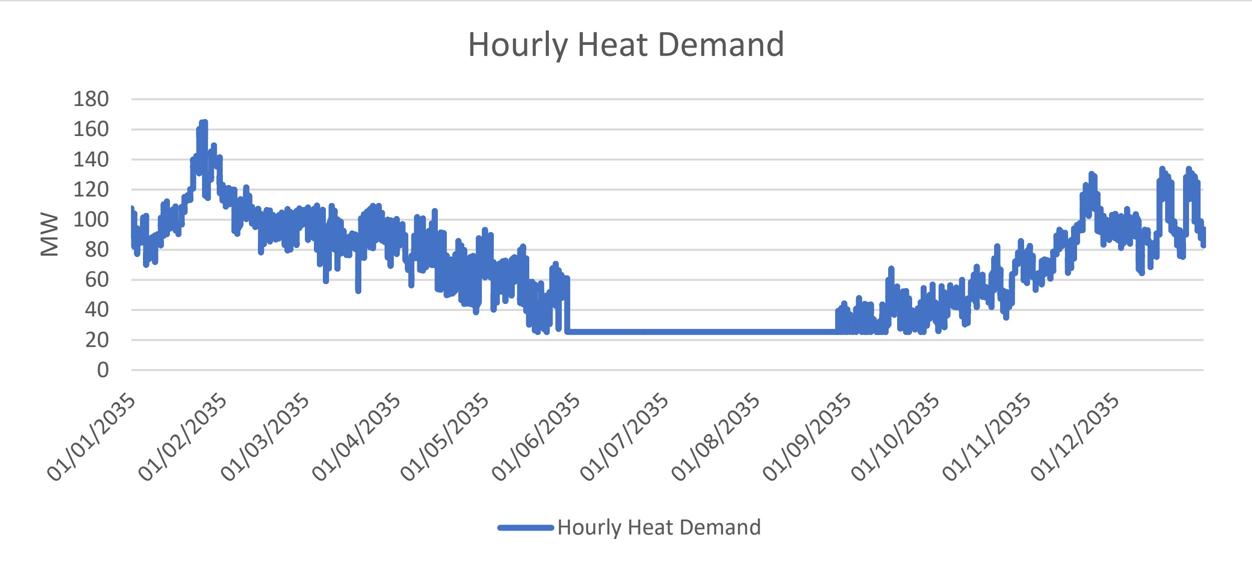

Figure 7: Illustration of Hourly Heat Demand Profile generated by energyPRO. With an example of 2035.

As observed in the figure, the peak is in February and the highest demands are during the winter periods. During summer there is still a heat demand for domestic hot water.

It is assumed that most of the expansions have been carried out by the start of the calculation period in 2025. However, some of the expansions are carried out during 2025-2028, which has been implemented linearly in that period. When the district heating expansions have been carried out, the heat demand remains the same throughout the investigation period until 2044. Heat savings are not considered in the development of heat demand. If a significant amount of heat savings is implemented this could influence the feasibility of large amounts of waste heat negatively. The development can be observed in Figure 8.

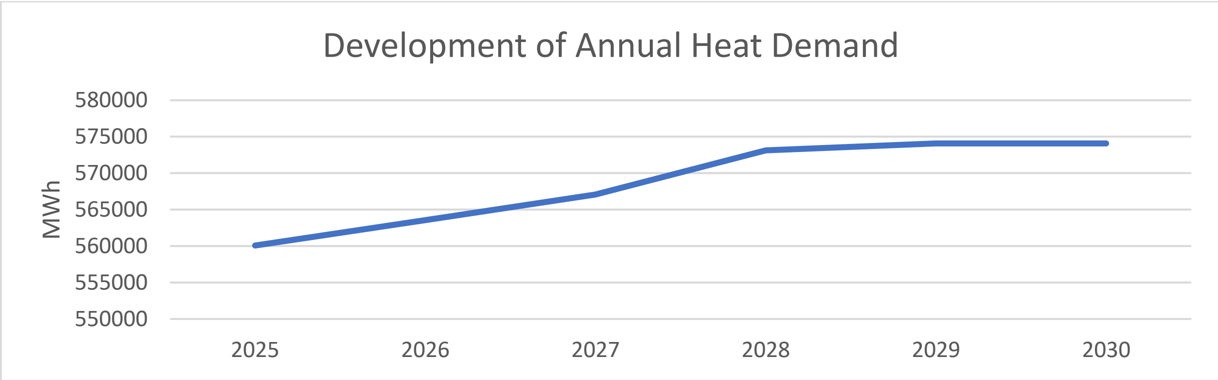

Figure 8: Development of Annual Heat Demand. Note that the Y axis starts at 550,000 MWh.

Fuel Prices

The development of fuel prices can be seen in Figure 9.

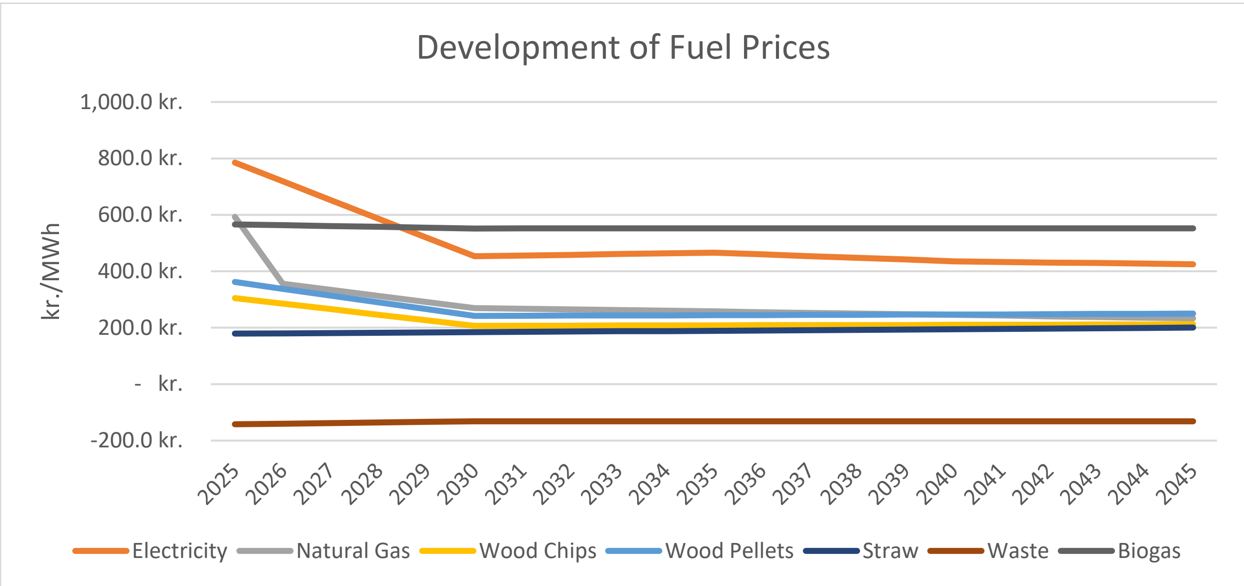

Figure 9: Development of Fuel Price (kr./MWh) (Ea Energy Analyses, 2023)

As observed in the figure, most of the fuel prices are expected to decrease in the short term. A reason for this is that the energy sector has faced high fuel prices in 2022 according to market data on solid fuels from *Trading Economics* and electricity from *NordPool*. The decrease is significant for electricity, natural gas, wood pellets and wood chips. These prices have been provided by (Ea Energy Analyses, 2023) and for all prices except for electricity, the prices have a yearly cost that develops throughout the calculation periods due to external market conditions. The electricity price has been provided as hourly values throughout the period. The waste price is based on data from Greater Copenhagen's district heating system (CTR, et al., 2021) which is a delimitation. A reason for the delimitation is that the negative price is not considered as the true costs for the waste CHP in Sønderborg since it is based on other waste incineration plants in Denmark. However, the price is assumed to be negative due to the fact the waste incineration plants are to be paid for treating the waste by a so-called *modtagegebyr* (charge for collecting waste) (CTR, et al., 2021). The waste CHP is modelled as a prioritised unit in the model due to fact that Danish waste incineration plants must treat the collected waste within a timespan according to Danish regulation (Danish Ministry of Environment, 2017). This means that the waste CHP do not affect the calculation strategy. However, a prioritisation of the waste CHP would result in 8760 full load hours excluding the planned outages. This has been restricted by limiting the available amounts of waste. A reason for this is due to empirical findings from (Christensen, 2023), which state that the waste incineration plant has a fuel consumption of around 55,000tons/yr. However, it is assumed that that fuel consumption is expected to decrease because of political goals of reductions in waste for incineration. This is assumed to result in a lower waste amount for the waste CHP in Sønderborg of around 30,000tons/yr. according to an interview with Sønderborg Municipality.

CO2 Quota Price

As with the fuel prices, the CO2 quota price projection has been provided by EA Energy Analyses. The price can be observed in *Figure* 10.

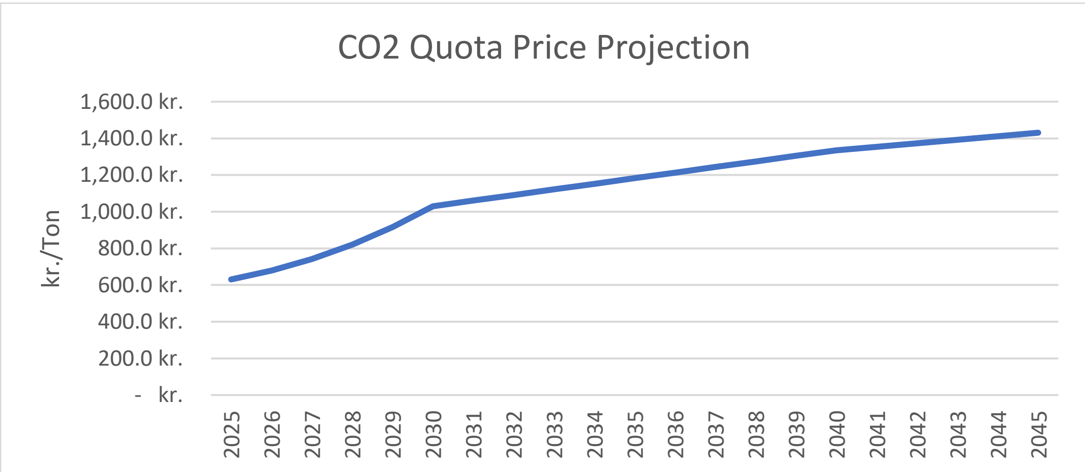

Figure 10: Development of CO2 Quota Price

As one can observe from the figure, the CO2 quota price is expected to increase throughout the investigation period. This is due to the assumption that actors within the CO2 quota market must incur higher costs for emitting CO2. The European Union monitors the *Emissions Trading Scheme* (ETS) where the CO2 quota price is set. According to market data from Trading Economics the 15th of May 2023, the ETS price is 91.9 EUR/ton ~ 685 kr./ton. This illustrates that the current price is higher than the expected ~600 kr./ton in 2025. The reason for this could be the increasing prices in end 2021 and end 2022. However, the price decreased end 2022 and as of 2023 the price has decreased further. Based on this, the CO2 quota price is assumed to be within the range of the prices of 2025 according to the figure.

Taxes and Tariffs

The tariffs applied in the modelling are both for electricity and for gas from the gas grid. The tariffs for electricity include tariffs for both the DSO and TSO. The tariff for TSO is 112kr./MWh as a fixed cost for consumed electricity. (EnergiNet, n.d) The local DSO N1 has a variable tariff, which should incentivise the use of electricity for periods with reduced usage in the distribution grid. The tariff ranges from around 3 kr./MWh in baseload hours, 5.5kr./MWh in high load hours to 8 kr./MWh in peak load hours (N1, n.d.). The gas tariff is based on the TSO tariff of 30kr./MWh (EnergiNet, n.d).

For taxes, the Danish national rates have been applied. The taxes concern an energy tax as well as a CO2 tax. The energy taxes have been obtained from (Danish Ministry of Taxation, 2022) and are expressed as a tax per MWh of consumed fuel. E.g., the energy tax on natural gas is 230kr./MWh. The CO2 tax is further based on (Danish Ministry of Taxation, 2022) and varies from fuel to fuel. Besides taxes on fuels, the model includes the electricity for heat tax of 8kr./MWh (Danish Ministry of Taxation, 2022).

Grid Temperature

Data on grid temperatures have been provided by (Lauesen, 2023) and the annual profile on an hourly basis can be observed in Figure 11.

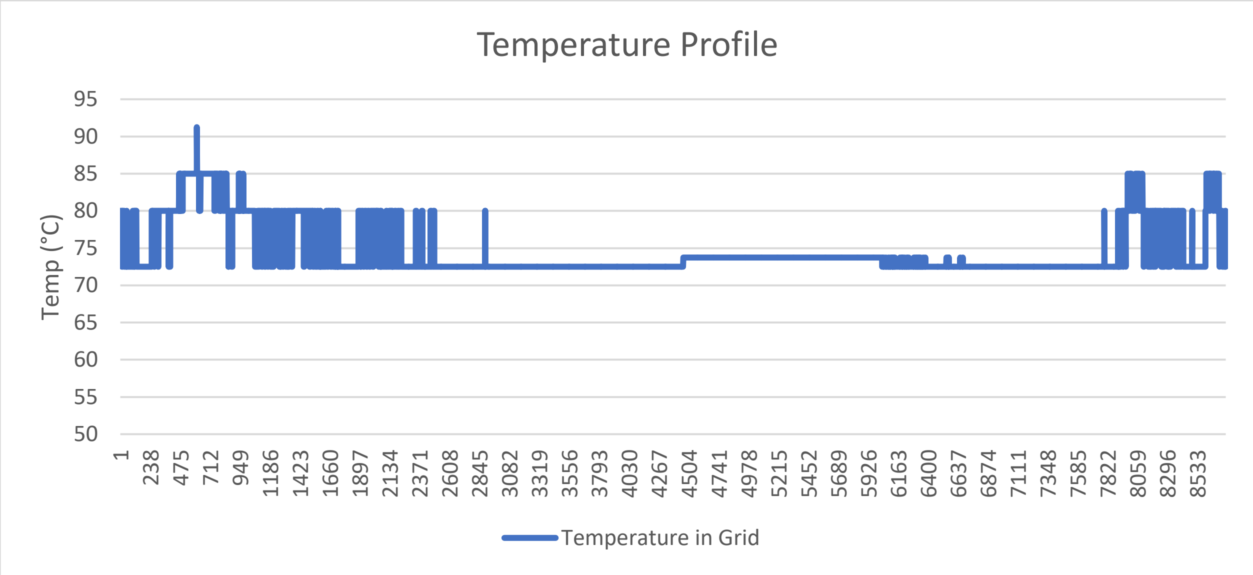

Figure 11: Temperature Profile on an Hourly Basis. Note that the Y axis starts at 50°C

As one can observe in the figure, the temperature profile fluctuates in the winter and early spring and is nearly constant during the summer. Moreover, one can observe that the temperature is higher than stated for 4th generation district heating indicating that the existing district heating system would be defined as a 3rd generation district heating system. The temperature profile will be included in the calculation of the utilisation of waste heat from PtX. This will be discussed later in this chapter.

Operation of Energy Conversion Units

The overall purpose of the modelling is to let energyPRO optimise the operation of the energy conversion units to minimise the total system cost. However, there are some delimitations and constraints to that assumption. One is that all energy conversion units are not always available during the optimisation due to technicalities such as planned outages. For baseload units, meaning all conversion units that are not natural gas peak load boilers it is assumed that the base load units will have the restriction of planned outage for maintenance based on (Danish Energy Agency, 2023b). This means that planned outage is included for larger baseload units, and these are the waste CHP, straw boiler, wood chip boiler, and the planned air source heat pump. The planned outage ranges from 1 week up to 4 weeks depending on the unit (Danish Energy Agency, 2023b). Minimum load and restrictions on ramping, meaning how fast an energy conversion unit can increase or decrease its operation have not been included due to the simplicity and run time of models. Moreover, the waste CHP is restricted to operate based on available fuel. As stated earlier this is reduced linearly from 55,000tons/yr. to 30,000tons/yr. by 2030 and remains at this level towards 2044. From a modelling perspective, this means that the waste CHP has been prioritised to incinerate the available fuel every year.

Power-to-X modelling in energyPRO

The PtX model has been modelled in a separate file from the energy system including the district heating grid due to various reasons. The purpose of modelling the PtX plant is to ensure the plant is operating as expected to reflect a realistic operation pattern. This means that the operation of the plant should not be influenced by the operation of other energy conversion units. Since energyPRO is optimising NHPC the objective of the tool is not to optimise fuel production but heat production, which would distort the optimisation of the hydrogen and methanol production of the PtX plant. Several tests of hard-linking the PtX model directly to the district heating model have been tested and found unnecessary since the calculation time has been heavily increased and the operation of the PtX plant was false. Hard-linking the two models would increase the calculation time from about 4 hours to 8 hours. Moreover, the operation of the PtX plant is distorted when hard-linking the two models. This means that the PtX plant would have fewer full load hours due to various factors. One of them is the modelling environment which allows electricity-producing units to produce electricity directly to electricity-consuming units whenever feasible. This has been observed in hours with low electricity prices where the model prioritises electric for the heat pump before hydrogen or methanol production due to the objective of minimising NHPC.

The modelling of the PtX plant can be observed in Figure *12*.

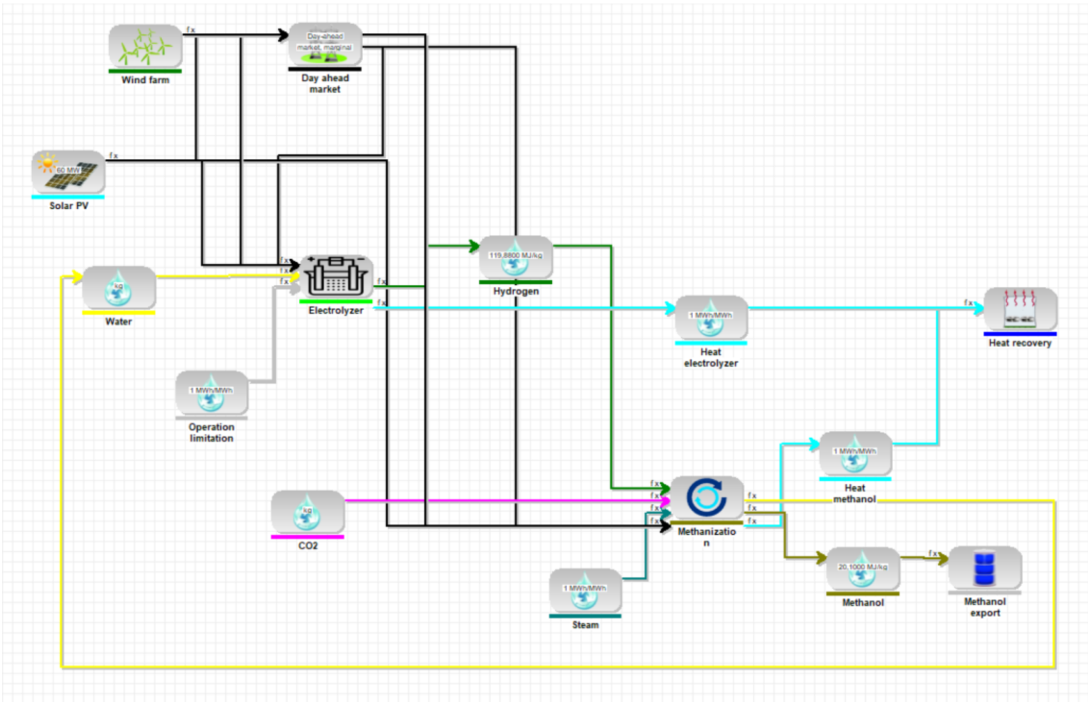

Figure 12: Modelling of PtX plant in energyPRO

As observed in Figure *12*, the PtX plant is a complex technology to model. In the top left corner, the renewable electricity production (solar PV and Offshore wind turbines) units can be observed as well as the day ahead market. The centre of the figure illustrates the electrolyser with water, 'operation fuel' and electricity inputs. The electricity input for the electrolyser can be delivered directly with no cost from solar PV and/or wind turbines or purchased from the electricity market. The operation fuel is part of the computation due to expectations of full load hours. The electrolyser produces hydrogen for the methanol synthesis process and waste heat for district heating. The methanol synthesis process can be observed in the lower right corner and the process requires CO2, steam, electricity, and hydrogen as inputs. The main inputs are hydrogen and CO2. For the CO2 and steam inputs, no restrictions have been set. However, one could argue that the CO2 input would require CC technology close to the PtX plant or at least infrastructure to carry the CO2 to the PtX plant. Electricity and steam only account for a minor share of the total input for methanol synthesis. The hydrogen input for the methanol synthesis is produced directly from the electrolyser. Both waste heat and methanol production are outputs of the methanol synthesis, and methanol production is considered the 'final product' of the value chain. Waste heat is also generated from the methanol synthesis process.

Data Input for Power-to-X Model

Input data have been collected by various approaches and most of the data have been gathered by literature studies where specific data for various types of electrolysers and methanol synthesis processes have been assessed. However, some data have been difficult to obtain. The main source of the input data for the PtX plant has been (Danish Energy Agency, 2022a) which includes data on both AEC and methanol synthesis from hydrogen production. Moreover, data on a specific PtX plant have been obtained from (COWI, 2021), where project-specific data on operation have been implemented in this thesis' PtX model. The data and assumptions for the PtX model can be observed in Table *5*

Table 5: Data Inputs and Assumptions for PtX Model

Data	Input	Source
Expected uptime. (Full load hours) for PtX plant	73% expected uptime. The PtX plant is expected to operate 73% during the year	(COWI, 2021)
Wind Farm Lillebælt South (Lillebælt Syd Vindmøllepark)	160MW electricity production capacity 4,500 full load hours based on (Murcia, et al., 2022)	(Lauesen, 2023) & (Lillebælt Syd, n.d.) Wind profile based on DKE1 dataset from (Murcia, et al., 2022)
Solar PV	60MW 1,300 full load hours based on calculations in energyPRO.	Own assumption and (COWI, 2021)
	Electrolyser	
Alkaline (AEC) electrolyser	100, 150 & 200MW electricity input	Own assumption
Water input for electrolyser	184kg/h pr. MW electrolyser capacity	(Danish Energy Agency, 2022a)
Hydrogen output from electrolysis	20.42kg/h pr. MW electrolyser	(Danish Energy Agency, 2022a)
Waste heat from electrolyser to district heating	16.6% of electrolyser electricity input (100MW AEC equals ~16MW)	(Danish Energy Agency, 2022a)
Hydrogen Price	N/A	Own assumption
	Methanol Synthesis	
Methanol process	65% of AEC electrolyser capacity	Based on the efficiency/output of the electrolyser. (Danish Energy Agency, 2022a)
Hydrogen Input for methanol production	1.13MW hydrogen pr. MW methanol synthesis capacity	(Danish Energy Agency, 2022a)

CO2 input	1.25kg/h pr. MW methanol synthesis capacity	(Danish Energy Agency, 2022a)
Steam input	0.1MW pr. MW methanol synthesis capacity	(Danish Energy Agency, 2022a)
Electricity input	0.018MW pr. MW methanol synthesis capacity	(Danish Energy Agency, 2022a)
Methanol Price	N/A	Own assumption
Waste heat from methanol synthesis to district heating	25% of total inputs (65MW methanol equals ~16MW)	(Danish Energy Agency, 2022a)

As observed in Table *5*, data inputs have been obtained from various sources as well as assumptions stated. Some of the important assumptions are the expected uptime of the PtX plant, capacities of RES and prices for methanol and hydrogen production as well as the waste heat generated by the PtX plant. Firstly, the generated waste heat is assumed constant across every year, meaning that the model does not include a larger waste heat potential as the stacks of the electrolysis ages. Secondly, the prices of hydrogen and methanol can be relatively hard to determine from a Danish market perspective. The hydrogen and methanol prices are discussed later in this thesis. For the modelling, the prices will not impact the optimisation of the PtX plant since the model is restricted to the assumption of 73% expected uptime. The uptime and availability of the plant are key assumptions that have been made to let the model reflect a realistic pattern of operation where the district heating companies have the waste heat at their disposal. The uptime is based on a project description of the PtX plant in Kassø (COWI, 2021). This means that the optimisation of the PtX model is restricted to 73% of 8,760 hours every year. For electrolysis, the operation is restricted to 6,395 full load hours during the year. When restricting the model to full load hours, the prices of both hydrogen and methanol become unimportant since the model will identify the 6,395 hours with the either lowest electricity price from the day-ahead market or when RES is available from solar PV and/or the wind farm. The capacity of RES is based on empirical findings and literature on wind farms. The solar PV is included based on the assumption that the PtX plant would not obtain the assumed full load hours due to a lack of RES in some periods, especially during summer. The capacity of the solar PV has been analysed by assessing the area close to the assumed location of the PtX plant in GIS where 60MW corresponds to 75 ha.

Soft-linking PtX model and Energy System Model

As described earlier, the process of implementing the waste heat from the PtX model to the energy system model has been done by soft-linking the two models. This means that the PtX model is not directly implemented in the energy system modelling due to various reasons. One of them being that the financial results of the energy system modelling would interfere with the financial results of the energy system model since it is assumed that the financial results of the energy system should reflect the cost of the district heating system to determine the feasibility of the waste heat. Moreover, the analysis of energy flows in the PtX model will be presented as a stand-alone analysis to illustrate how the PtX plant is assumed to operate.

The soft-link itself consists of the generated waste heat on an hourly basis from both the methanol synthesis and electrolysis. This means that the waste heat is implemented as a time series with hourly resolution for 20 years. To assess the potential of the waste heat, several calculations on temperatures have been conducted. The current district heating grid is a 3^{rd} generation district heating system with rather high temperatures and the temperature of the waste heat is expected to be 65°C. This is based on (Danish Energy Agency, 2022a), which states that it is expected that waste heat from PtX is available at 70°C from AEC electrolysis by 2024. 65°C is chosen as a more conservative approach.

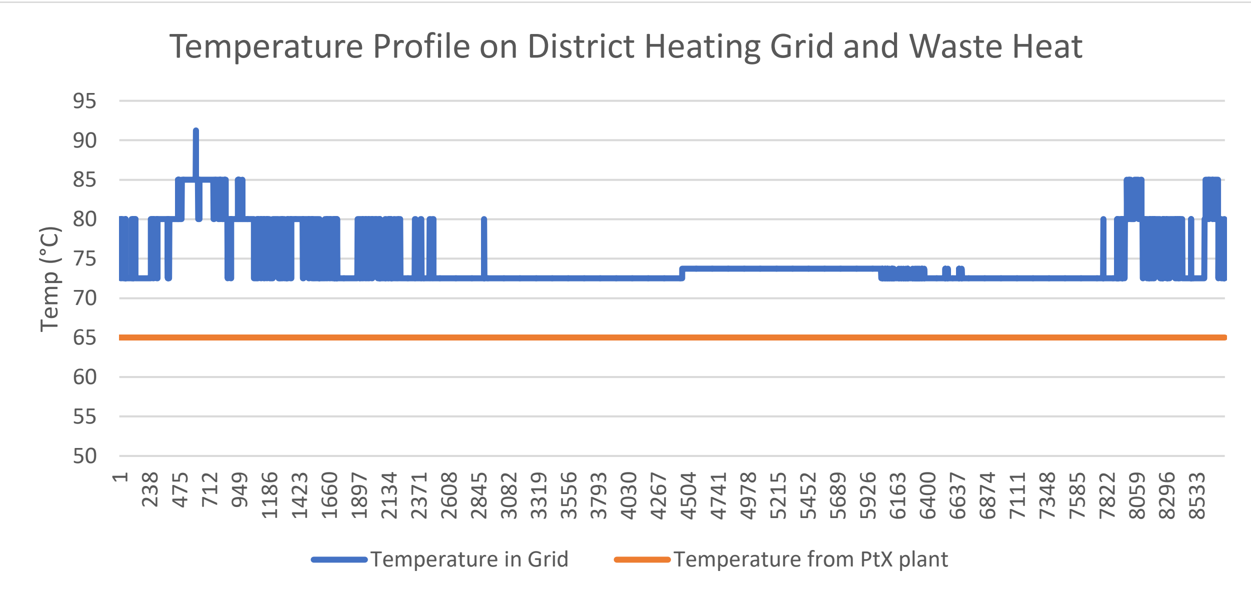

Figure 13: Hourly Temperature Profile from District Heating and Waste Heat. Note: Y axis starts at 50°C

As one can observe from Figure 13, the temperature of the district heating grid exceeds the temperature of the waste heat from the PtX plant. This means that the utilisation of the waste heat would require a temperature boost. A heat pump is assumed to boost the temperature from 65°C to the desired temperature in the given hour. The waste heat from PtX is cooled from 65°C to 18°C. To calculate the energy required to boost the temperature, the Coefficient of Power (COP) Lorenz formular has been applied from (Danish Energy Agency, 2023b)

$$COP_{Lorenz} = \frac{T_{lmSink}}{T_{lmSink} - T_{lmSource}}$$

Where, T_{lm} is defined as:

$$T_{lm} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)}$$

T_{lmSink} is based on the hourly temperatures of the district heating grid in Kelvin, $T_{lmSource}$ is the hourly temperature in Kelvin of the PtX plant and 18°C after cooling of the waste heat stream. (Danish Energy Agency, 2023b). In addition, the COP value has been adjusted with a correction factor since the COP Lorenz is a theoretical value. The correction factor that has been applied is 53% (Danish Energy Agency, 2023b).

Based on the formulas and the correction factor, the hourly COP for the heat pump to utilise the waste heat is presented in Figure 14

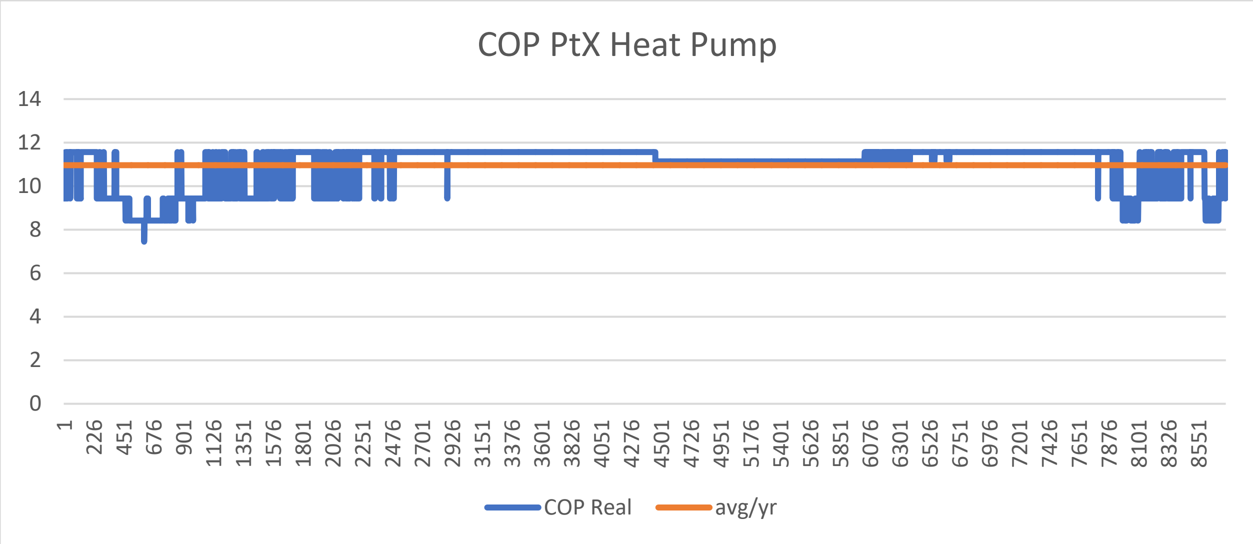

Figure 14: Hourly COP value of Heat Pump

The hourly COP can be observed in Figure 14 as the fluctuating blue line. The COP fluctuates based on the flow temperature of the district heating grid. Since the temperature in the grid fluctuates the COP fluctuates and because of this, the higher flow temperature required in the grid the lowers the COP value of the heat pump. This can also be observed by comparing the two figures Figure 13 and Figure 14. The average COP value is marked with orange to illustrate the difference between applying variable COP values and fluctuating COP values.

Financial Calculations

This section will describe the applied formulas for financial calculations for business and socioeconomics.

Business Economics

The business economics are presented as NPV of total system business economic cost, system LCOE and LCOE across production units.

Investment Costs, Technological Lifetime and Annuity

The investment costs applied in this thesis are obtained from data catalogues from the Danish Energy Agency. The data catalogues have been deemed applicable since it has not been the purpose to perform a market analysis of investment costs and accordingly to guide on both business and socioeconomics it is applicable when no market data are available (Danish Energy Agency, 2022c). To compare different technologies, the methodology of annuity has been applied. This allows for a comparison of technologies with diverse lifetimes and a comparison of technologies where lifetime is either longer or shorter than the investigation period. (Danish Energy Agency, 2022c)

The annuity formula is presented in the following:

$$Annuity = \frac{r}{1-(1+r)^{-n}} * G$$

Where n is the lifetime of the technology, G is the investment cost and r are the rate. (Danish Energy Agency, 2022c) Annuity of the investment has been applied both for socioeconomics as well as business economics. A discount rate of 3.5% has been applied and an interest rate of 3.5% has been applied.

Net Present Value and Levelized Cost of Energy

To determine the economic feasibility of both the reference and the scenarios, two formulas have been applied. The total costs are expressed by net present value (NPV) and the levelized cost of energy (LCOE) is a calculation where all discounted costs of a technology are allocated to its discounted heat production. The LCOE calculation is based solely on heat production rather than distinguishing between the type of energy like electricity.

The formula of NPV is as follows:

$$NPV = \sum \frac{B-C}{(1+r)^t}$$

The formula is used to express the benefits and the costs of the reference and the scenarios. The summation symbols define that the formula is applied to calculate the costs and benefits for each year. B is used for benefits and the costs C are subtracted from the benefits. r is used for the rate and t for the calculation period of 20 years.

According to (Hansen, 2019), LCOE calculations are applicable when assessing energy systems because it allows the results to presented for each unit rather than an aggregated total system costs like NPV. This means that changes applied in the scenarios will be presented for each unit and ultimately make the results more transparent.

The applied formula for LCOE is:

$$LCOE = \frac{\sum \frac{I + M + F}{(1 + r)^t}}{\sum \frac{E}{(1 + r)^t}}$$

As mentioned above, LCOE includes all costs related to the technology. This means that I is the annualised investment costs, M represents both fixed and variable O&M expenditures. F is fuel costs. E is the energy (heat) produced by each unit. Both costs and heat production are expressed by a NPV value. For the socioeconomic calculations similar calculations have been made. However, the LCOE is expressed as costs of heat production for the entire system. The formular is as follows:

$$Total\ System\ LCOE = \frac{NPV(Total\ System\ Costs)}{NPV(Heat\ Production)}$$

Socioeconomics

To assess the socioeconomics of the investigated scenarios, certain assumptions have been applied. Firstly, to assess whether the investigated scenarios prove a socioeconomic beneficial solution the NPV of the scenarios are compared to the reference. The socioeconomic calculations of this thesis are conducted in accordance with the Danish Energy Agency's guide and assumptions (Danish Energy Agency, 2022c). A reason for this is that Danish legislation states that investments in the Danish district heating sector must prove that the proposed solution is a socioeconomically beneficial solution, or at least make it probable that it is (Danish Ministry of Climate, 2021b) (Danish Energy Agency, 2022c). The socioeconomic calculations are based on the business economic outputs from energyPRO and treated in an independent Microsoft Excel sheet. Taxes are kept out of the socioeconomic calculations. This means that the excel sheet uses the data output on heat production and fuel consumption from energyPRO to assess the socioeconomic benefits or drawbacks. To calculate and translate the data outputs from energyPRO, the guide on socioeconomics from the Danish Energy Agency has been applied. The guide includes data on coefficients of emissions (CO2, CH4, N2O, SO2, NOx and PM2.5) as well as monetarisation of emissions, discount rate, distortion loss factor, net tax factor etc. (Danish Energy Agency, 2022c)

Discount Rate, Net Tax Factor and Distortion Loss Factor

A discount rate of 3.5% has been applied in the socioeconomic analyses. The rate is defined by the Danish Ministry of Finance (Danish Ministry of Finance, 2021). A net tax factor of 28% have been applied to adjust prices from raw prices without taxes and duties to prices that corresponds to the socioeconomic value (Danish Energy Agency, 2022c). A distortion loss factor has been applied to assess the tax revenue of the scenarios, meaning that if the system ends up paying less tax to the Danish state, the loss of tax revenue must be covered elsewhere or that taxes should be allocated to other goods. According to (Danish Ministry of Finance, 2021) the distortion loss factor is 10%.

Analyses

This chapter is composed of three analyses in chronological order starting from Analysis 1 to Analysis 3. The purpose of the analyses is to answer the sub-questions related to the analysis as well as contribute to answering the research question.

Analysis 1: PtX Technology in a Local Context of District Heating

The analytical structure defined in the section Theoretical Framework will be applied to analyse how the existing technologies differ from PtX waste heat as well as assessing how the differences might affect the implementation of waste heat. The analysis is based on interviews with relevant actors, these are: Sønderborg Forsyning, Sønderborg Varme, Sønderborg Municipality and ProjectZero.

PtX case in Nordborg

The interview with ProjectZero have showed that there are concrete plans for establishing a PtX plant close to the town Nordborg in Sønderborg Municipality in 2029. The PtX will contribute to the masterplan by ProjectZero (ProjectZero, 2021b). The purpose is that the PtX plant will contribute to sector coupling the energy sector in Sønderborg and thereby reduce CO2 emissions.

The plan is that the PtX plant will be supplied with electricity from the nearby wind farm *Lillebælt Syd* which Sønderborg Forsyning will own 50% of according to an interview. The wind farm will be in operation from 2027 and the PtX plant is expected to operate from 2029. The plant is supplied by 160 MW from the wind farm and according to an interview with ProjectZero most likely electricity produced from solar PV. The plant is assumed to produce hydrogen and methanol or jet fuel in the long term according to interview with Sønderborg Forsyning and (ProjectZero, 2021b). Since the PtX plant utilises electricity produced from Lillebælt Syd, the plant is assumably located close to the transformer station on Nordals close to Nordborg which will influence the utilisation of waste heat due to a requirement of heat transmission lines. The exact capacity of the PtX plant is not determined yet capacities (MW), c.f. section Data Input for Power-to-X Model.

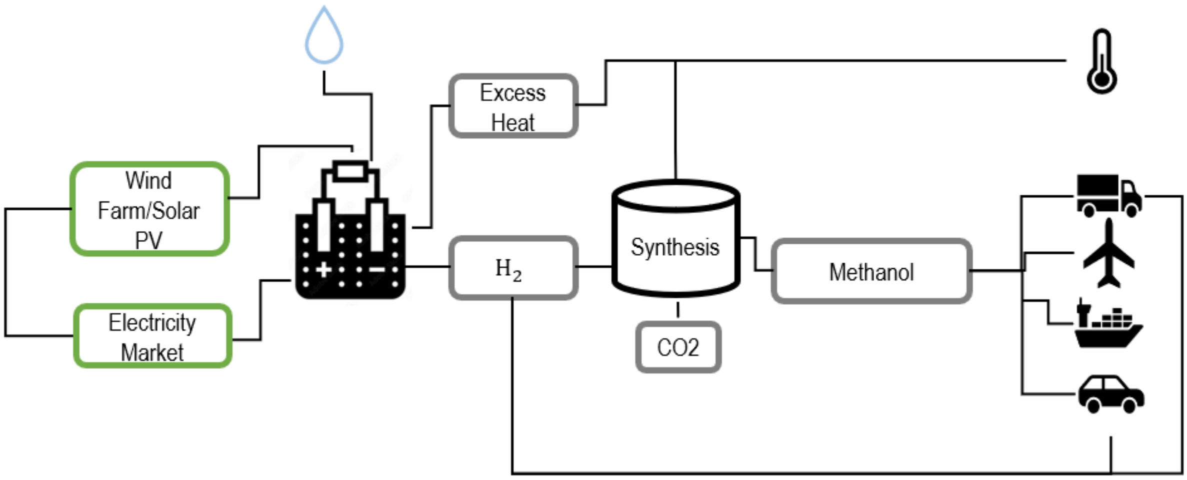

Figure 15: PtX Plant in Nordborg. Based on: Interviews and (ProjectZero, 2021b)

The conceptualisation of the PtX plant in Sønderborg can be observed in Figure 15. The plant is assumed to be provided with electricity from local wind and solar and the electricity market. The electrolyser is assumed to use the technology AEC which is connected directly to the methanol production in the synthesis reactor. Waste heat is utilised from both the AEC and synthesis reactor. It has not been possible to get data on the origin of the CO2 and water inputs but according to interviews with Sønderborg Varme which own the local waste CHP '*there are hopes for CC'*. Additionally, there are two biogas plants in the municipality (ProjectZero, 2023), which could be a source of CO2.

Products

The products of the current system are primarily heat and electricity produced from the existing dominant techniques like boilers and waste CHP. The products of a PtX plant are multiple but for the district heating companies the product would be waste heat and according to interviews with Sønderborg Varme and Sønderborg Forsyning the companies expect a large amount of waste heat from the PtX plant. However, the waste heat product is unlike the product from the dominant technologies since the waste heat is a fluctuating source. The fluctuation of the product could be a concern for the companies since they cannot control and directly manage the waste heat. Moreover, the companies worry that the waste heat would exceed the heat demand many hours during the year and especially during the summer months when there is no need for the waste heat. This means that the waste heat product could become unusable for some hours or even longer periods. In addition to this, Sønderborg Forsyning states in an interview that they are considering providing the PtX plant with cooling which would change their products from solely concerning heat to also providing cooling. Sønderborg Varme, however, is somewhat familiar with fluctuations in heat production since the company owns solar capacity. According to the company, they are currently analysing waste heat from local tileworks which could gain experience with a product of fluctuating waste heat. One could argue that the district heating companies have concerns regarding fluctuating waste heat since it is a product the companies do not directly control and manage compared to heat products from dominant boilers that can produce heat rapidly when needed. The fluctuating waste heat product is intermittent due to fluctuations in the electricity prices and/or local RES production. Additionally, a fluctuating heat product could be hard to implement in a system that is based on waste CHP due to the fact that the waste has to be incinerated and is therefore prioritised, cf. section *Fuel Prices*. The issues of waste CHP producing heat at a near constant rate in combination with a fluctuating waste heat product will be analysed later in the thesis.

Technique

The current technique in the district heating systems includes dominant technologies like boilers and CHP units. The supply of heat is primarily based on waste incineration, wood chip boilers, natural gas boilers and natural gas engines, solar, heat pumps, electric boilers etc. Generally, the systems are supplied by techniques that are common and dominant in the heating sector (Danish Energy Agency, 2022b). Sønderborg Forsyning has also invested in a geothermal unit, however, it did not produce as expected and is currently not in operation. The utilisation of waste heat would require different techniques. First of all, a heat pump is required to boost the temperature of the waste heat. Additionally, a transmission line is a technique that could be required to utilise more of the waste heat. The heat pump to utilise the waste heat from the PtX plant in Nordborg is not a substantial change of the existing techniques in the system since the interview with Sønderborg Forsyning has shown that they will invest in an air source heat pump to supply heat when the companies expand. This emphasises that Sønderborg Forsyning will presumably have experience with a heat pump as a technique to utilise the waste heat with a heat pump when the waste heat from PtX is integrated in the system in 2029. Moreover, according to an interview with Sønderborg Forsyning a transmission line would presumably be required to utilise larger shares of the waste heat due to surplus capacity compared to the heat demand in Nordborg. The companies are familiar with transmission lines as a technique and both Sønderborg Varme and Sønderborg Forsyning are currently working and investing in transmission lines in their grid due to expansions. According to the interview with Sønderborg Varme, there are concerns regarding investments in new techniques in the short term since the waste heat generated from the PtX plant in Nordborg could cause faulty investments if the waste heat from PtX results in lower heating costs. This could cause an unfeasible utilisation of the waste heat or short-term investments in new heat production units due to surplus heat production capacity. For example, if investments in other production units are carried out before 2029, where the PtX plant is expected, the heat production on units that have been invested in beforehand could become unfeasible due to displacement of the units.

Organisation

Interviews have shown that the local district heating companies are currently two independent companies that do not directly cooperate. This means that Sønderborg Varme is controlling and managing its techniques and products independently from Sønderborg Forsyning and vice versa. Currently, Sønderborg Varme supplies Augustenborg in the east and all the way to the west in Graasten. Sønderborg Forsyning is primarily suppling Nordborg and the surrounding towns, cf. Figure 1. However, the interview with Sønderborg Municipality showed that the Municipality and the district heating companies are cooperating in *working groups* managed by ProjectZero. The main purpose of cooperation is to reach the targets of the masterplan by ProjectZero that defines a net zero emission target by 2029 (ProjectZero, 2021b). According to the interview with the municipality, the working group managed by ProjectZero is a forum where knowledge sharing and experiences of techniques can be shared to reach the net zero emission target. However, cooperation in the working group is different from direct cooperation where the companies are planning and co-investing in new techniques. Additionally, the interview with Sønderborg Forsyning showed that the company is currently analysing a transmission line to interconnect the grid in Nordborg with the grid in Sønderborg. One could argue that the interconnection of the two grids would require stronger cooperation from the two district heating companies since they presumably would co-invest in the transmission line. A co-investment in a transmission line could presumably lead to the displacement of marginal costly heating techniques which could improve the feasibility of the transmission line. However, the exchange of heat via the transmission line would require a formalised cooperation and organisation which could be formulated in an "*exchange of heat*" agreement where the purpose is the displacement of marginal unfeasible heat production units by hourly or daily optimisation of heat production. i.e., daily or hourly heat optimisation would need to be carried out to displace marginal costly units in either

Sønderborg Varme's or Sønderborg Forsyning's grid. If such an agreement was formulated and the co-investment of the transmission line was implemented the organisational structure would change and one could argue that the utilisation of waste heat could become more feasible due to the identification of units with higher marginal costs than the waste heat and better utilisation of the waste heat. The co-investment and interconnection of the district heating grid will be analysed in the following analyses of this thesis.

Knowledge

Currently, the district heating companies' knowledge concerns the control and management of their techniques to provide the product of heat to supply its customers with heat. The knowledge of the system is closely related to the management of techniques. This means that the companies currently are managing the system based on dominant techniques that are almost solely operated by the companies themselves to supply heat whenever needed except for heat production from solar. This is in contrast to a fluctuating waste heat product that is operated by a third party and only available whenever the PtX plant is operating. According to the interview with Sønderborg Varme the existing biogas plant in Glansager has a PtX pilot project that could provide the system with waste heat. However, there are no current plans for utilising the waste heat from the plant. One could argue that if the waste heat from the methanol synthesis process from the biogas plant is utilised the companies would have knowledge of managing fluctuating waste heat streams, but since Sønderborg Varme is not doing so, the knowledge of fluctuating waste heat is considered low which could be a barrier to utilise the waste heat from the PtX plant Nordborg. Moreover, the interview with Sønderborg Varme showed that the company have concerns about utilising waste heat from PtX due to the surplus capacity of waste CHP. Waste CHP could be a barrier to implementing waste heat from PtX due to the priority of waste CHP in the system. Additionally, Sønderborg Varme does not have the knowledge of waste heat being a feasible technology for the system since the company have not assessed whether the waste heat would provide savings compared to the existing system. This means that there is potential for investigating whether the utilisation will generate an economic surplus or deficit from a business and socioeconomic perspective. In addition to this, the interconnection of the two grids becomes apparent since a lower marginal heat cost could provide a feasible alternative to the waste incineration or other higher marginal cost heat production units even when taking the costs for the transmissions line into account.

Profit

The profit of the district heating companies is defined by Danish legislation, cf. section *Energy System Scenarios*. This means that the economic profit must be returned to the customers in terms of lower heating prices or an economic deficit must be incurred by the costumers in terms of higher heating prices. Implementation of waste heat would not change the fundamentals and legal definitions of the profit for the district heating companies. However, the assessment of waste heat could either provide an economic deficit or a surplus compared to the reference. To assess the economic deficit or surplus this thesis conducts a feasibility study to determine whether the implementation of waste heat from PtX is economically feasible. The interview with Sønderborg Varme showed that the company is currently analysing the feasibility of utilising waste heat from local tileworks which could provide feasible heating from a business and socioeconomic perspective. This means that Sønderborg Varme will gain experience in assessing the potential profit of waste heat sources when it comes to determining the feasibility of utilising the waste heat. However, Sønderborg Forsyning does not have the same experience since interviews have shown that the profitability of utilisation of waste heat might depend on the interconnection of the two district heating grids due to the waste heat capacity. On the other hand, Sønderborg Forsyning is considering a profit from delivering cooling to the PtX plant rather than utilising the waste heat as a heat source alone. Currently, it is not decided whether the district heating companies would have to pay the PtX plant for the waste heat. If so, the total cost of waste heat including the cost of utilisation and transmission would still have to be lower than alternative means of heat production according to Danish legislation. Particularly for Sønderborg Varme the profits of the waste CHP could be challenged if large amounts of waste heat from PtX are integrated due to surplus heat production during summer. Sønderborg Varme would have to either decommission the waste CHP or limit the amount of waste heat from PtX integrated into the system to maintain a balance between heat demand and heat production during summer since the system runs a surplus of capacity. For Sønderborg Forsyning the potential financial benefits of utilising the waste heat from PtX in an interconnected system could cause the upcoming air source heat pump to operate less full load hours which would make the waste heat cannibalise the heat production and ultimately increase the payback time of the air source heat pump which could cause a faulty investment.

Partial Conclusion

The purpose of the last analysis was to analyse the differences in waste heat from PtX compared to the existing technologies in the system as well as analyse potential barriers to implementing the waste heat in the current system. The waste heat from PtX was found to differ in several aspects and especially product and technique where waste heat from PtX is considered a fluctuating source that the district heating companies cannot control themselves. This is contrary to the primary dominant technologies which for the current system are woodchip boilers, straw boilers, and waste CHP. However, the analysis showed that the actors have some knowledge of fluctuating heat sources since the system consists of solar and there are plans to utilise waste heat from tileworks which could improve their knowledge of managing fluctuating heat sources. Moreover, the utilisation of waste heat is considered to become more useful for district heating in Sønderborg if the two systems are connected, because the capacity of waste heat is too high for Nordborg alone. The barrier to implementing the waste heat from PtX is the organisation of the two district heating companies that does not cooperate in a formalised setup but only through *working groups* managed by ProjectZero. The barriers could be removed by reorganising the organisation by formulating an exchange of heat agreement. This would require knowledge of optimising the heat production in an interconnected system based on marginal where the hourly marginal heating costs are known.

Analysis 2: Expansion of the District Heating Networks in Sønderborg Municipality

This analysis will analyse the feasibility of expanding the two district heating systems of Sønderborg Varme and Sønderborg Forsyning in Sønderborg Municipality. The purpose of the analysis is to investigate the potential for expanding district heating in the municipality and estimate the feasibility of the expansion because an expansion of the district heating demand could help increase the integration of waste heat from PtX due to higher heat demand. Currently, there are plans to extend the district heating to several areas, but there are no official project proposals for each area. Therefore, the analysis will determine the feasibility of each area. The analysis is a direct input for the following analysis.

The heating plan of Sønderborg Municipality points out areas for district heating expansion (Sønderborg Municipality, 2022a). The modelled district heating grids incl. transmission and substations are shown in Figure 16.

Figure 16: Map of district heating expansion in Sønderborg Municipality.

The blue areas show the existing district heating grid. The modelled district heating grids are shown within the red areas. Black lines indicate higher capacity distribution lines, while lighter grey lines indicate lower capacity lines. Figure 17 shows an example of a grid in Vester Sottrup. All modelled grids are documented individually in appendix F.

Figure 17: Example of a modelled district heating grid for a town. Vester Sottrup is given as an example.

The areas in the heating plan are modelled using GIS software following the method described in the section Modelling of District Heating Expansions in Geographic Information Systems. All areas from the heating plan are included in the analyses as well as the town of Blans. The cost of producing heat in the district heating system is determined by the average variable cost of heat production calculated in the energyPRO model. The variable cost has been used since the expansion can be carried out using existing production capacity in the system, resulting in a higher number of full load hours on existing production units, including baseload units. This has been assumed since the interviews with Sønderborg Varme showed that there is a surplus of heat production capacity as well as the analysis (Rambøll & Dansk Affaldsforening, 2020) which have analysed the heat production from the waste CHP in Sønderborg. The feasibility of district heating is each area is compared to individual heat pumps. A 90% connection rate is assumed for district heating expansions and a heat production cost of 311 kr./MWh, which is the current average variable cost of the district heating systems found in the energyPRO model of the system.

The total expansion includes 2,800 buildings in Sønderborg Municipality and will result in an increase in heat demand by 75,000 MWh annually including losses, which is an increase of roughly 15% compared to the current heat demand. The heat losses in the new areas are estimated at an average of 15%, with some areas having a heat loss as low as 4%, while the highest heat loss is 41%, due to the distance and heat density of the areas. The results show that district heating is 16% more expensive than individual heat pumps, with large differences in cost between areas. Table 6 shows economic results in the 18 individual areas sorted by the priority value, which states the cost of expanding district heating to the area compared to the annual heat demand in the area. A lower priority value the better. The priority value is an indicator of whether district heating is feasible in the area, however, a specific or fixed value for the feasibility of the project area cannot be determined since it depends on the cost of alternatives and the heat production cost of the specific district heating system.

Table 6: Economic results of the GIS district heating model. Areas marked with bold are deemed close to feasibility (<15%).

Area	Heat demand [MWh/annually]	Priority value [Kr./MWh]	Increase (-%) or decrease (+%) in total costs compared to individual heat pumps
Augustenborg C	60	3,546	**21%**
Sønderborg Ø and Ø2	11,624	3,881	**-3%**
Vollerup S and Ø	802	4,641	**-4%**
Graasten N	528	4,973	**-11%**
Guderup V	1,826	5,533	**-2%**
Augustenborg Ø and CØ	1,493	5,628	**-11%**
Adsbøl S	60	5,681	**7%**
Elstrup and Elstrup S	2,104	6,363	**-14%**
Nybøl	8,775	7,204	**2%**
Stevning	5,185	7,207	**-14%**
Vester Sottrup	12,914	7,345	**-9%**
Avnbøl	3,876	7,885	**-13%**
Oksbøl and Broballe	5,901	8,183	-27%
Mjels	2,153	8,400	-21%
Ullerup	3,823	9,353	-26%
Blans	4,728	9,549	-17%
Ketting	2,102	9,883	-34%
Kværs	6,389	14,573	-77%
Total expansion	**Total: 74,342 MWh**	**Average: 7,213 Kr./MWh**	**-16%**

The table shows the heat demand, the priority number and the percentage showing the increase or decrease in cost compared to individual heat pumps. A positive percentage indicates that district heating is cheaper than individual heat pumps and a negative value indicates that district heating is more expensive than individual heat pumps. The results show that many areas are feasible or close to it (<-15%) while a few areas are significantly more expensive than individual heat pumps. For areas such as Oksbøl and Broballe, Mjels, Ullerup, Ketting and Kværs district heating would likely be more expensive than individual heat pumps.

A sensitivity analysis is carried out to analyse how robust the results are to changes in various assumptions. The main result shows that district heating is 16% more expensive than individual heat pumps.

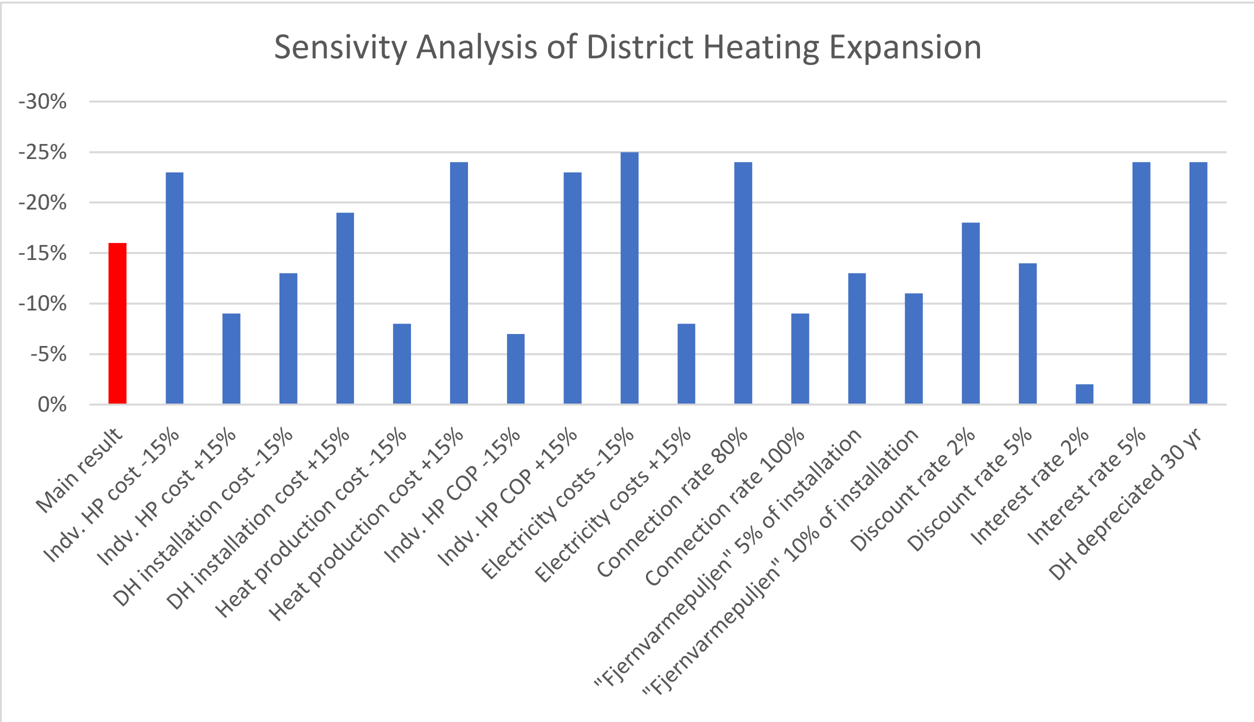

Figure 18: shows the results of the sensitivity analysis.

District heating remains more expensive than individual heat pumps when analysing the sensitivity of the total expansion. The cost of individual heat pumps, district heating heat production costs, COP of individual heat pumps, electricity costs, connection rate to district heating, the interest rate and depreciation district heating grid have a large effect on the result., showing the result is sensitive to these changes.

Based on an interview with Sønderborg Forsyning, the company expects that *'fjernvarmepuljen'* (Danish Energy Agency, 2023c) will subsidise the areas. The result would therefore likely be that district heating is 11 to 13% more expensive than individual heat pumps assuming 5 or 10% of the installation cost is covered by the subsidy.

In conclusion, the analysis shows that district heating is 16% more expensive than individual heat pumps without government subsidies. If subsidies are included from "Fjernvarmepuljen" district heating would be 11 to 13% more expensive than individual heat pumps. In the following analysis of the integration of waste heat from PtX, all areas will be included in the energyPRO model. However, since the expansions do not show a clear feasibility there is some uncertainty in this.

Integration of waste heat from PtX could potentially lower the cost of producing heat in the system. Therefore, some of the areas that are not feasible with the current production units could be after the integration of waste heat from PtX is implemented. This will be analysed in Influence of Heat Production Cost on Feasibility of Expansion of District Heating.

Partial Conclusion

The analysis showed that the total potential for district heating is roughly 75,000MWh/yr. based on the areas from the heating plan, which would be an increase of 15% to the existing district heat demand of the municipality. The total district heating expansion showed an increase of 16% in the total costs compared to individual heat pumps, with large fluctuations in feasibility between areas. From interviews with Sønderborg Forsyning, it is known that 'f*jernvarmepuljen*' will cover some of the cost of establishing district heating. If so, the costs would be -11 to -13% higher than individual heat pumps. Therefore, it is assumed that the total expansion can be carried out since the business economic feasibility is comparable to individual heat pumps. All areas will be included in the energy system analysis of waste heat from PtX. However, since the feasibility does not show a clear benefit, the inclusion of all areas will be discussed in a later section.

Analysis 3: Energy System Model of Waste Heat from PtX

This analysis will analyse the potential of integrating waste heat from PtX in Sønderborg. The analysis will first present the results of the modelling of the PtX case with a focus on the inputs required for the generation of waste heat, secondly, the analysis will present the results of the modelling of both the current district heating system as well as the system including the waste heat generated from the PtX plant. Finally, the economics will be assessed on both business and socioeconomics to test the scenario's economic feasibility.

Results of PtX Modelling

This section is a presentation of the results from the PtX model prior to soft-linking the model to the district heating model. As stated previously a PtX plant requires certain inputs to produce hydrogen, methanol, and waste heat. Both the inputs and outputs can be observed in Table 7. The table illustrates the input and outputs for all modelled scenarios, and it is worth noting that the input and outputs are the same for LWHN and LWHT.

Table 7: Results of PtX model. Numbers are average for 2025-2044. Please note the units of each row. Values are expressed as annual averages as each year can vary from the next.

	LWHN & LWHT	**MWHT**	**HWHT**
PtX plant capacity			
AEC [MW]	100	150	200
Methanol Synthesis [MW]	65	97.5	130
Input			
Electricity from Wind Farm [GWh]	705	727	730
Electricity from Solar PV [GWh]	72	77	82
Electricity from Market [GWh]	162	336	620
Electricity Consumption PtX plant Total [GWh]	646	970	1293
Water [Kton]	118	176	235
CO2 [Ton]	481	722	963
Output			
Export of Electricity [GWh]	293	170	140
Hydrogen Production [Kton]	13	20	26
Methanol Production [Kton]	69	103	138
Waste Heat Production [GWh]	219	328	438
Waste Heat Capacity [MW]	33	49,5	66

As one can observe from the table the RES production from the wind farm and solar PV are similar when comparing the three simulations, because the same RES sources are assumed for each scenario. However, the slight increases in local RES production are due to the precision of the solver applied in energyPRO.

Additionally, the full load hours of the wind farm are on average 4,400-4,500 and 1,200-1,300 on average for the solar PV which do not change significantly across the scenarios. On the other hand, the electricity input from the market has a significant increase when the capacity of the PtX plant increases. Moreover, as the capacity of the PtX plant increases the water input increases as well due to a larger hydrogen production. Both the hydrogen and methanol production increases linearly e.g., if the electrolysis capacity increases from 100MW to 150MW in the MWHT scenario and to 200 MW in the HWHT scenario. All other inputs and outputs increase proportionally to the capacity increase of the electrolyser. For electricity the total consumption increases proportionally, but the individual sources does not since the wind and solar capacity remain constant.

The waste heat generated from the simulations is 219GWh, 328GWh and 438GWh for respectively LWHT, MWHT and HWHT on an annual average. The waste heat production is including the waste heat generated from both the electrolysis and the methanol synthesis. The contribution of the waste heat production from the electrolysis and the methanol synthesis is approximately 50/50, cf. section *Power-to-X modelling in energyPRO*. The full load hours of the waste heat production are 6,636 for all scenarios which is approximately 4% higher than the assumption of 73% uptime. The reason for this is the precision of the solver in energyPRO.

The waste heat from the PtX plant is a fluctuating source that is produced at the same time as the hydrogen and methanol production. This causes hours with little or no waste heat as well as hours with waste heat corresponding to the capacity of the PtX plant.

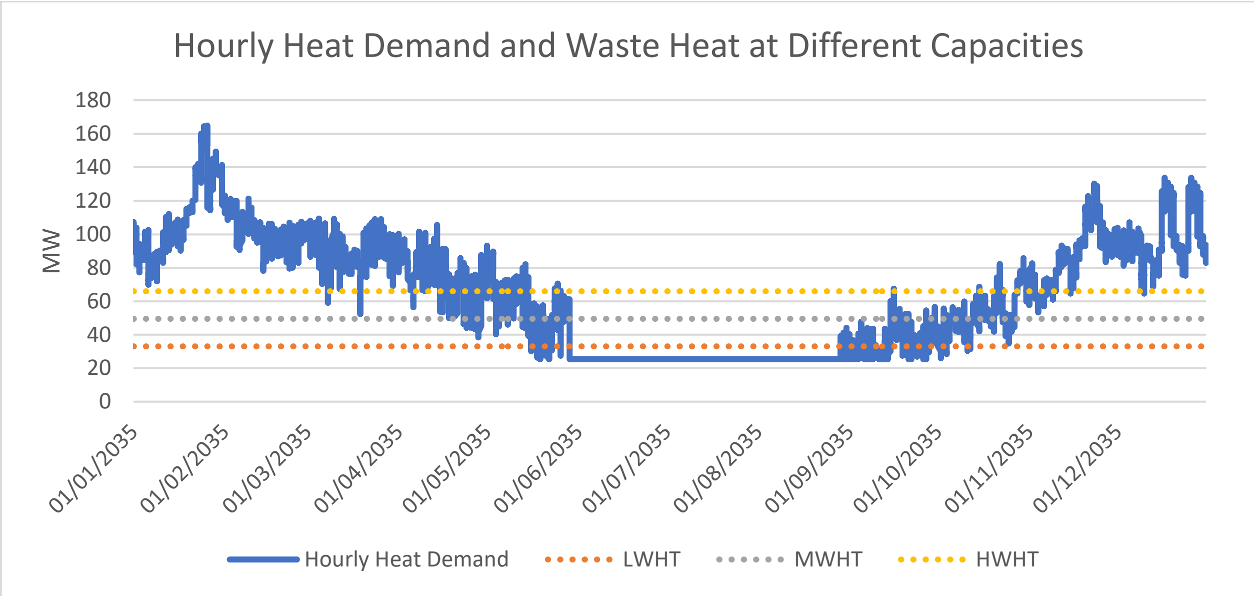

Figure 19: Hourly heat demand and PtX waste heat at different capacities

The hourly heat demand as well as the potential capacities of the waste heat can be observed in Figure 19. As observed, the waste heat capacities are marked with a dotted line and the hourly heat demand with a fluctuating blue line. The waste heat capacity from the PtX plant varies from scenario to scenario. The capacity of LWHT is maximum of 33MW waste heat whereas electrolysis accounts for 16.6MW and the methanol synthesis for 16.4MW. The following capacities are 49.5MW for MWHT and 66MW for HWHT. Moreover, it can be observed that all simulated capacities will exceed the heat demand during the summer as well as parts of spring and autumn. However, the capacity will not be able to cover the heat demand during peaks in the winter and heating season.

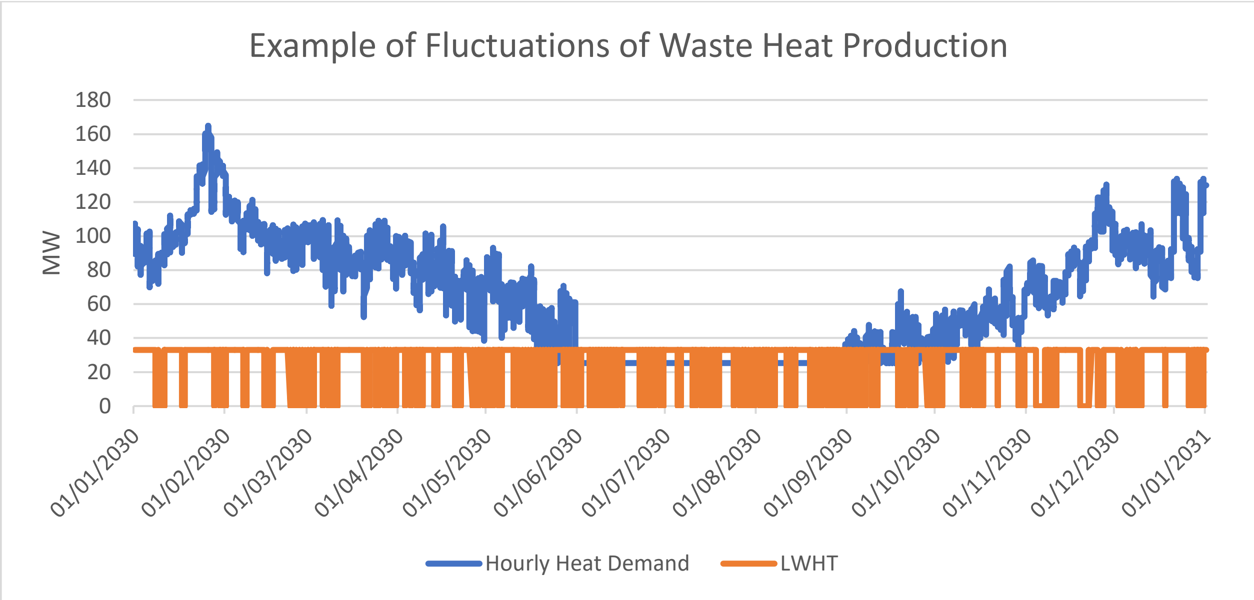

Figure 20: Fluctuating Waste Heat Production in 2030

An example of the simulation of LWHT in the year 2030 the fluctuations of the waste heat production are illustrated in Figure 20. As one can observe in the figure, the fluctuations of the waste heat are clear during the summer months and the heat production is more stable during the heating season. A reason for this is more local wind production during winter. From a district heating perspective, waste heat is more valuable during the winter months due to higher heat demand. Moreover, waste heat could become counterproductive during the summer if for instance heat from waste incineration is available due to priority or simply if the waste heat source is exceeding the heat demand as in the present case.

Heat production

Based on the results of the modelling as well as the simulations of different PtX capacities this section will analyse the heat production based on different heat production units for every scenario. The heat production is presented for each year throughout the investigation period for all scenarios.

Heat Production: REF

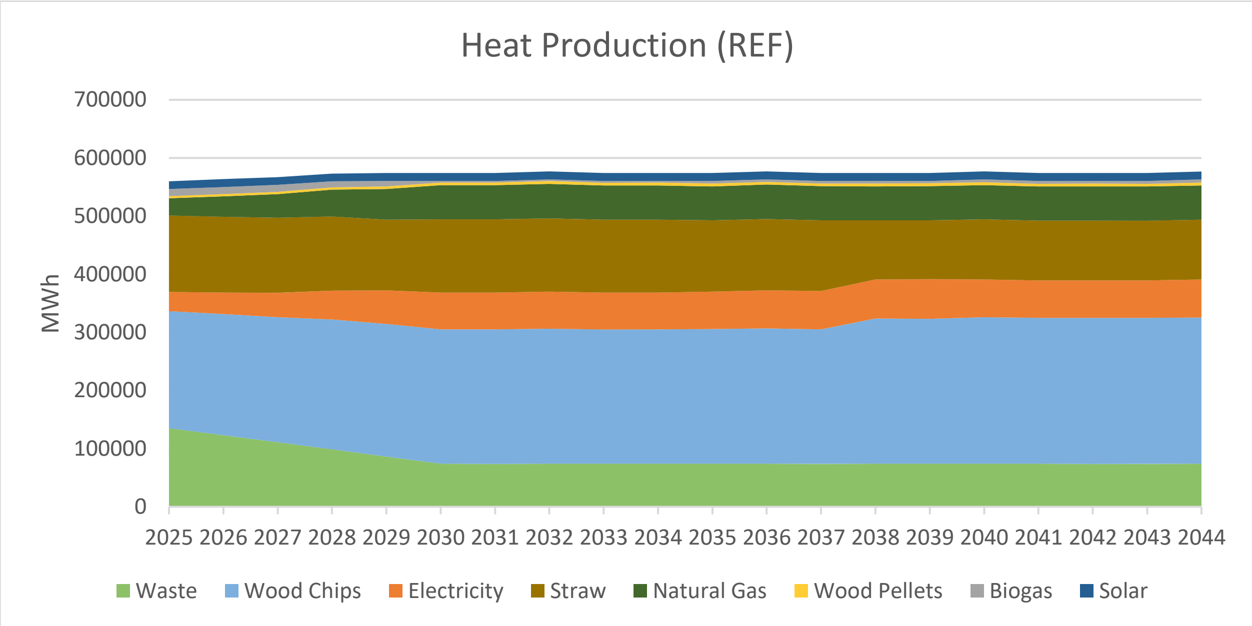

Figure 21: Share of Heat Production in the REF

The mix of heat production from the existing and planned units in the reference can be observed in Figure 21. In general, the total heat production is increasing slightly, due to the expectations of expanding the district heating grid towards 2028. Moreover, heat production from waste CHP is declining due to the limitations of available fuel towards 2030 where it is expected to have a cap of 30,000 tons/yr. compared to 55,000ton/yr in 2025. This means that heat production from waste CHP is displaced by woodchips from the boiler in Sønderborg. Heat production from waste CHP is contributing 24% of the total heat production in 2025 to 13% in 2030 and wood chips are increasing from 36% to 40% during the same period. Moreover, the share of peak load in the system increases from around 5% of the total heat production to 10% from 2030. This means that the reference could be less feasible in the future due to a presumably higher share of peak load in the system. Whether it is due to increased heat demand or limitations of available amounts of waste is hard to conclude. The heat production from electricity from air source heat pump and electric boiler increases in both the short and long term due to lower electricity prices. This can be observed by the orange area in the middle. If observing the long-term perspective, the heat production from waste is flat due to prioritisation of the unit in the model, but wood chips are increasing around 2037. Straw, however, is decreasing from 2037 which means that the decline is displaced by the wood chips in Sønderborg. The displacement occurs in Sønderborg because Sønderborg Varme has both wood chips and straw whereas Sønderborg Forsyning only has heat production based on straw and electricity and results show no changes in the units' heat production.

Heat Production: LWHN

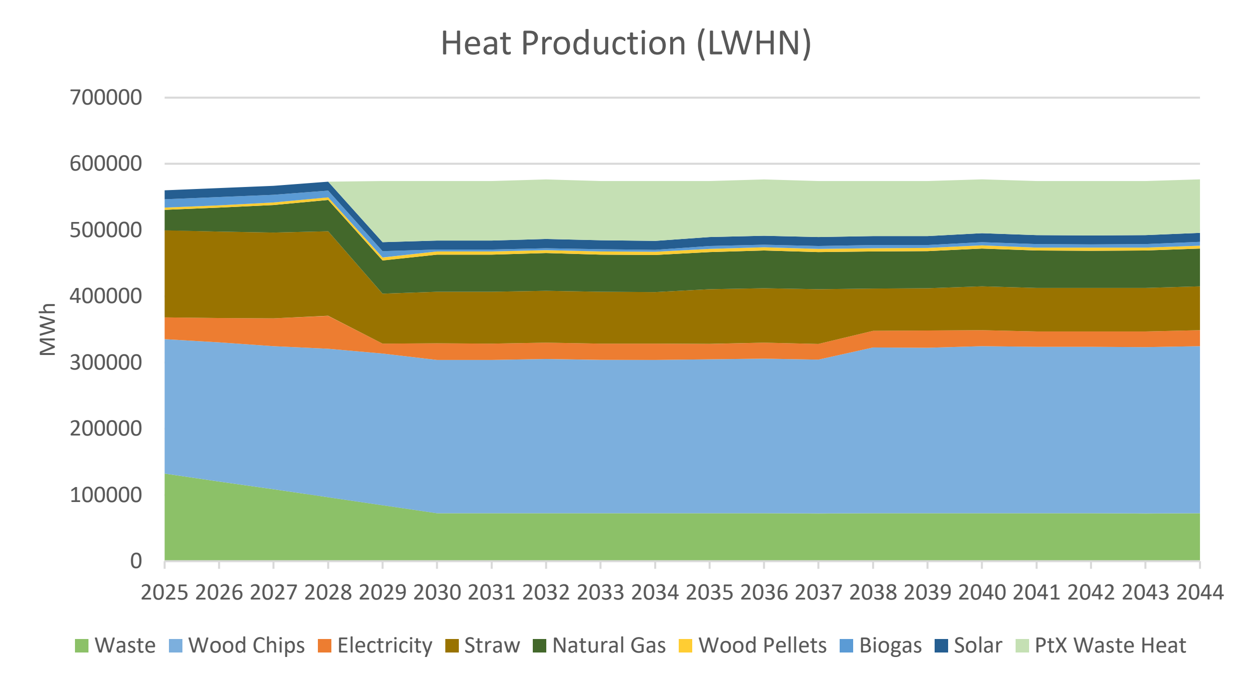

Figure 22: Heat Production in LWHN

Until 2029, the heat production for LWHN is identical to the reference. This can be observed in Figure 22. The reason for this is because the waste heat from PtX is assumed to be available from 2029. When observing the waste heat production to Sønderborg Forsyning's grid, the heat production seems rather constant. A reason for this could simply be due to the surplus of waste heat from the PtX plant compared to heat demand. Sønderborg Forsyning's heat demand accounts for approximately 17% of the total system heat demand and as illustrated in Figure 19 and Figure 20 the potential of waste heat exceed the total system heat demand in some hours. This is supporting the fact that mostly the heat production from straw is displaced in Figure 22, where the straw plant in Sønderborg Forsyning has lower heat production compared to REF. Moreover, heat production from electricity seems to be displaced when the waste heat is penetrating Sønderborg Forsyning's grid. This is due to less heat production from the air source heat pump. In LWHN waste heat accounts for 15% of the heat production when implemented on average. As for the reference, the share of heat production from natural gas peak load is approximately 10% throughout the investigation period which indicates that the peak load boilers in Sønderborg Varme's grid are operating more than in Sønderborg Forsyning's grid.

Heat Production: LWHT

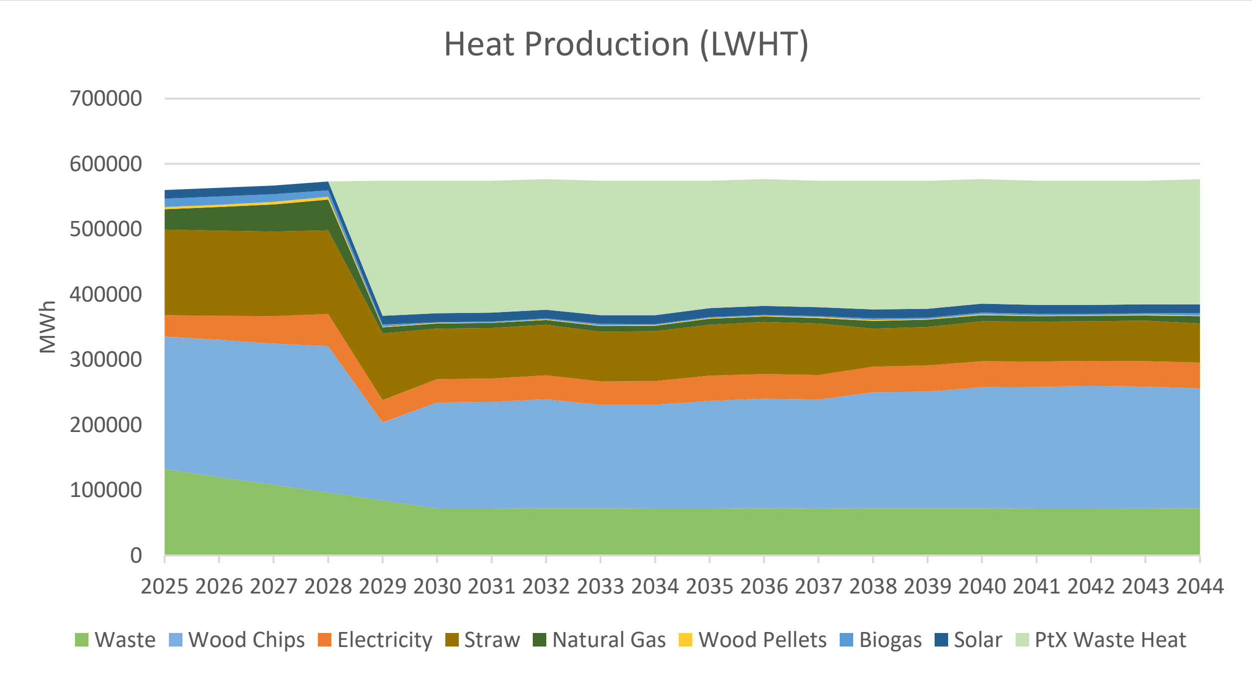

Figure 23: Heat Production in LWHT

As per the previous figure, the share of heat production is similar to REF in the period 2025-2029 for LWHT. However, the difference between LWHN and LWHT is the interconnection of the district heating grids. This means that the model can transmit heat from Sønderborg Varme's and Sønderborg Forsyning's grid which gives the ability to optimise the heat production of the entire system based on marginal costs. The share of waste heat is significant from 2029 when interconnecting the grids which leads to a displacement of straw boilers and wood chip boilers. This means that the waste heat is considered a baseload unit in an interconnected system and that it displaces other baseload units. However, natural gas sees a significant decrease where it contributed with 10% of the heat production in REF on annual average to only 3% in LWHT. Waste heat is contributing 34% of the heat produced when implemented on average which is more than a factor of 2 compared to LWHN.

Heat Production: MWHT

The third scenario is a simulation of the PtX capacity to assess whether an increase in capacity could lead to a more feasible solution than LWHT.

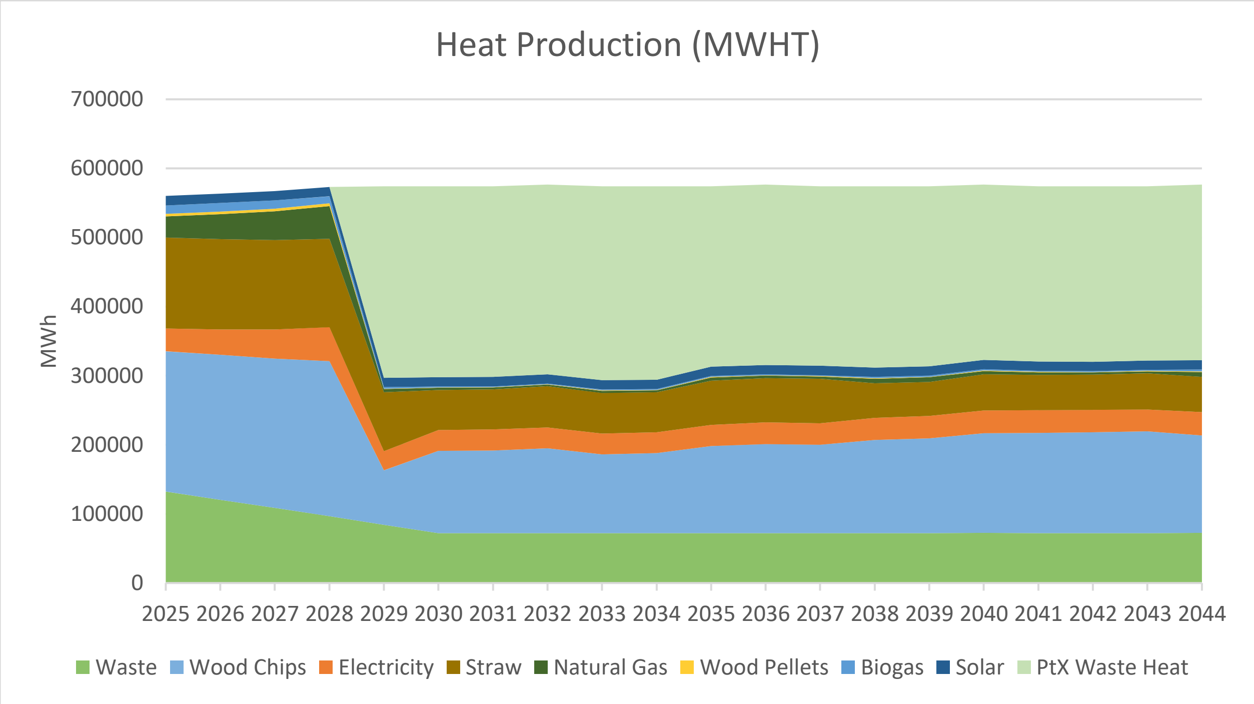

Figure 24: Heat Production MWHT

As one can observe in Figure 24 the difference between LWHT and MWHT is the increase in waste heat from PtX. In the present scenario, waste heat accounts for 46% of the total heat production on average from 2029 to 2044. This leads to a further displacement of units with higher marginal costs than the waste heat as presumed. In addition to this, both straw and wood chips seem to decrease the most which supports the terminations stated in LWHT where the waste heat displaces baseload units due to higher marginal costs. Moreover, the share of heat production from natural gas peak load boilers decreases from a 3% annual average in LWHT to 2% in MWHT. It is worth noting in some years the peak load boilers account for only 0.4-0.5% of the total heat production.

Heat Production: HWHT

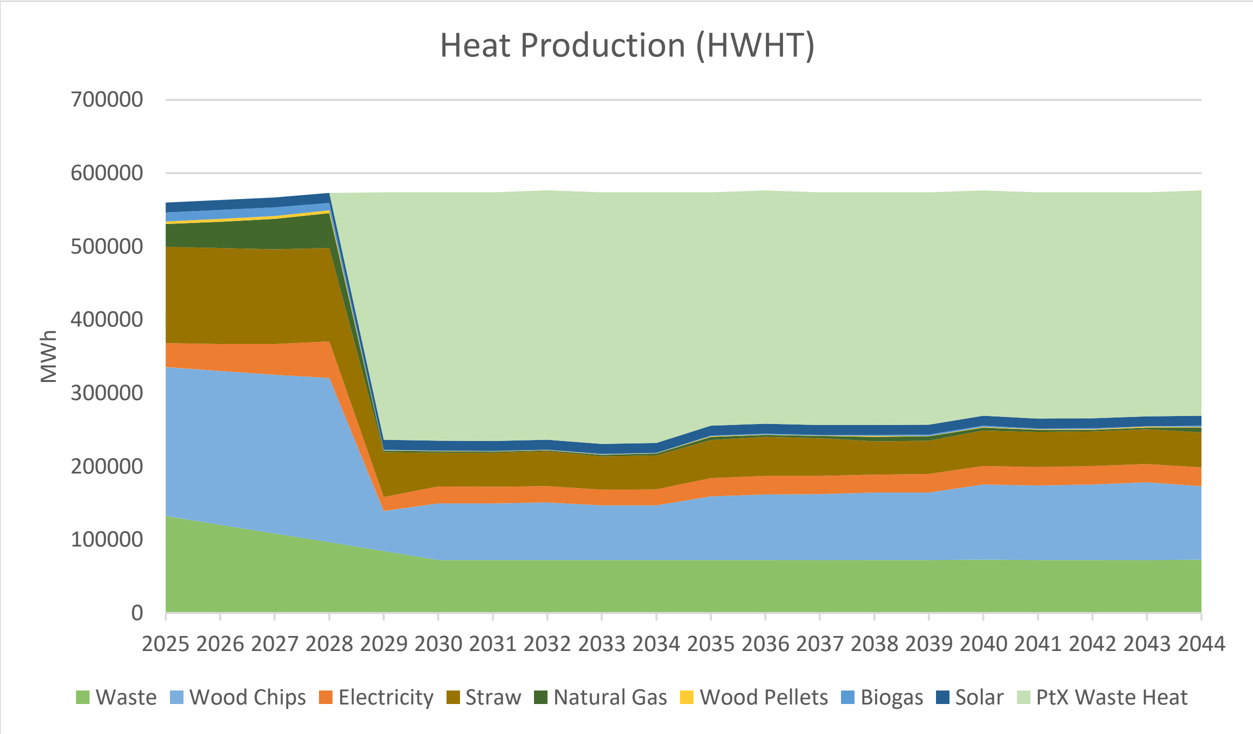

Figure 25: Heat Production HWHT

The primary difference between Figure 24 and Figure 25 is the increase in heat production from waste heat from 2029. Moreover, the same patterns can be observed in Figure 25 where waste heat is displacing heat production from the wood chip boiler in Sønderborg as well as the straw plant in Sønderborg and the straw plant in Nordborg. Waste heat is contributing 56% of the total heat production and the share of heat production from natural gas peak load boilers is approximately 2% on average, but in several years the heat production from natural gas is less than 0.4% of the annual heat production.

Full Load Hours

To support the results of the heat production this section will present the results of the full load hours of the heat production units. The full load hours are expressed as an annual average throughout the investigation period. However, for waste heat production, the average starts when the unit is operating in 2029-2044.

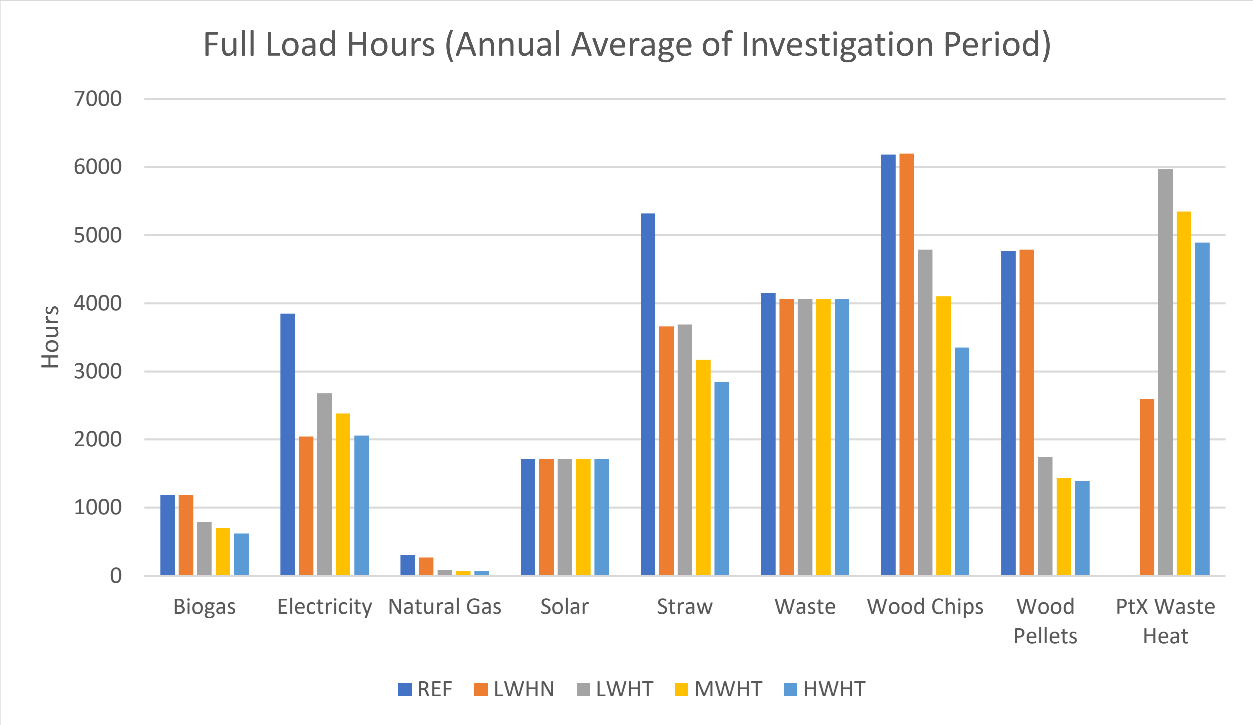

Figure 26: Full Load Hours of Heat Production Units Across Scenarios. Electricity is both for heat pump and electric boiler.

The primary baseload units in the district heating system are the CHP and wood chip boiler in Sønderborg as well as the straw boiler in Nordborg. When observing the reference (dark blue bars) it is clear that these units have the highest number of full load hours. Furthermore, the waste incineration plant is assumed a baseload. However, the baseload is assumed since the plant is prioritised in the optimisation due to the legal framework of Danish waste incineration plants and not solely because of its full load hours, cf. section *Energy System Model of Sønderborg District Heating System*. In LWHN where waste heat is implemented in the grid of Sønderborg Forsyning, the results of full load hours support the conclusions of the heat production since the full load hours on straw boilers decrease the most as well as electricity for heat pump and electric boilers, which influences the operation of the straw boiler as well as the air source heat pump in Nordborg. When implementing the same share of waste heat but in an interconnected system as for LWHT, the full load hours of straw increase slightly, this is due to displacement of units with a higher marginal cost like biogas or natural gas as illustrated with the grey bars in Figure 26. Moreover, LWHT compared to LWHN will lead to an increase in full load hours on units utilising electricity like the air source heat pump in Nordborg and the electric boiler in Augustenborg. Finally, the full load hours on wood chip boilers decrease significantly when utilising waste heat in an interconnected grid. When increasing the capacity of the waste heat from the PtX plant, the same patterns are shown for MWHT and HWHT but a more significant change the larger the capacity. This can be observed by the yellow and light blue bars in Figure 26. The pattern is that both scenarios will lead to a decrease in full load hours on all units including the PtX waste heat. A reason for this could be that the system runs a surplus of capacity, which is an expression of a saturated system where the system operates with little to zero peak load and due to low consumption during summer compared to waste heat and waste CHP capacity. The highest amount of full load hours from the PtX waste heat will be achieved by implementing LWHT and the lowest by only utilising waste heat in Nordborg.

Table 8: Full Load Hours of PtX Waste Heat

	LWHN	LWHT	MWHT	HWHT
Waste Heat Full Load Hours	2,594	5,968	5,348	4,894
% of available hours	$41\% = \frac{2{,}594}{8{,}760 * 73\%}$	$93\% = \frac{5{,}968}{8{,}760 * 73\%}$	$84\% = \frac{5{,}348}{8{,}760 * 73\%}$	$77\% = \frac{4{,}894}{8{,}760 * 73\%}$

Table 8 compares the full load hours of the waste heat to the availability of the PtX heat to calculate how much of the waste heat is utilised in the scenarios. The PtX waste heat is available 73% of 8,760 hours for every year meaning that the actual available full load hours are 6,394.5 hours/yr. When comparing the full load hours of the PtX model and district heating model it becomes clear that the system does not utilise all the available heat in the scenarios. 93% of the heat is utilised in LWHT but as the capacity increases the full load hours decrease, which supports the assumption of the system being saturated. On the other hand, when observing LWHN only 41% of the heat is utilised from the PtX plant. This further supports the assumptions of Sønderborg Forsyning's district heating demand being too low compared to the capacity of the PtX plant. It is not possible to utilise 100% of the available waste heat due a surplus of waste heat generation in combination with low heat demand during summer. It has not been analysed whether integration of a smaller amount of waste heat in Nordborg could be a feasible solution. Moreover, the generated waste heat from the PtX model was shown to be 219 GWh, 328 GWh and 438 GWh on average for the three simulated capacities, respectively. The actual utilised heat was 86 GWh for LWHN, 197 GWh for LWHT, 265 GWh for MWHT, and 323 GWh for HWHT, which corresponds to the shown full load hours.

Business economics

This section will present the business economic results of the scenarios. Figure 27 shows the business economic result of the scenarios. Results are presented as NPV discounted at 3.5% and presented for the investigation period from 2025-2044.

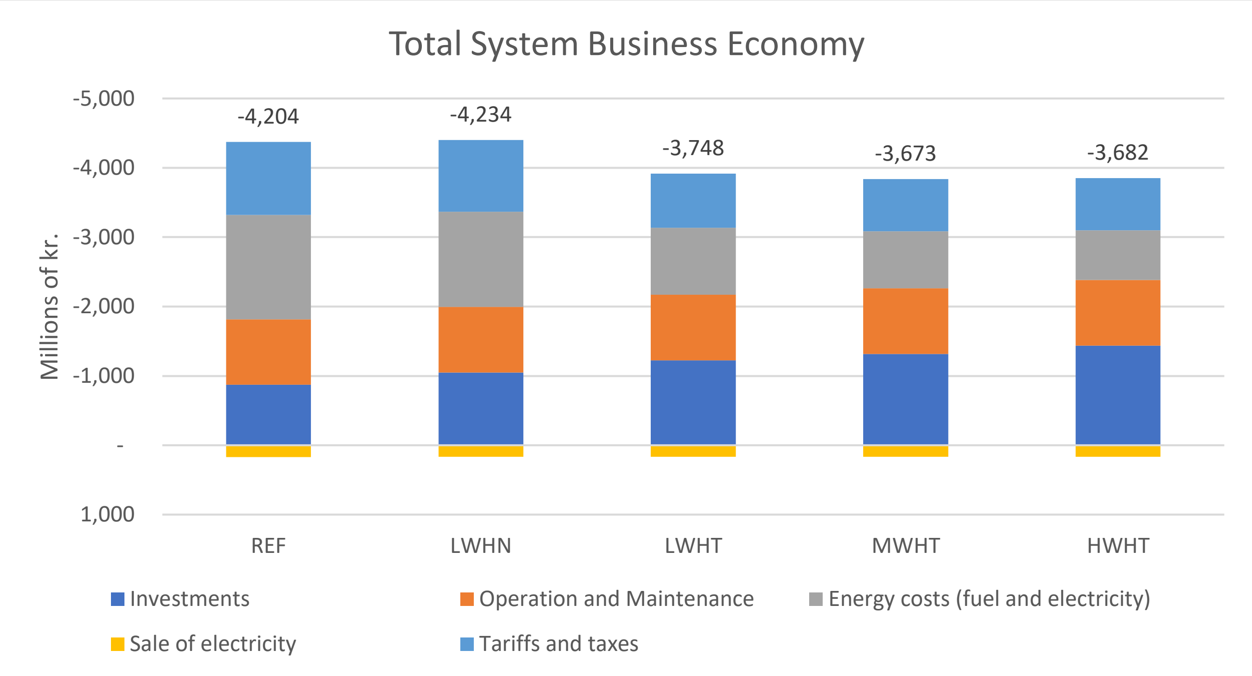

Figure 27: NPV of total system business economy during the 20-year investigation period. Results are discounted at 3.5%. Each stacked column shows the cost of each scenario. Note: Values are in millions.

The results show a total cost of 4.204 billion kr. for the reference. For LWHN, where waste heat is implemented only in Nordborg, the result is increasing the total system costs compared to REF. This is because the district heating grid in Nordborg can only utilise a small amount of the waste heat from the plant due to the relatively low heat demand in the grid and compared to increasing investment costs. This is also reflected in the full load hours of the waste heat from PtX in this scenario. The grid in Nordborg is only able to utilise 41% of the available waste heat. If waste heat is implemented only in Nordborg, without a transmission line to Sønderborg, it would be more feasible to utilise a smaller amount of waste heat from the PtX plant. If a transmission line is built from Nordborg to Sønderborg, which is the case for LWHT, the business economic result improves significantly to 3.75 billion and would, from business economic perspective be feasible compared to the reference. The transmission line makes it possible to utilise 93% of the available waste heat from the PtX plant, displacing production from existing units in Sønderborg.

However, the results show that the NPV can be improved further with larger shares of waste heat in the MWHT and HWHT scenario. In MWHT, the district heating system is only able to utilise 84% of the waste heat, while the percentage falls to 77% in HWHT. Even though a smaller share of waste heat can be utilised the NPV improves compared to LWHT.

The results show feasibility when implementing both transmission and waste heat from PtX as seen for the LWHT, MWHT and HWHT scenarios. However, the economic value of the transmission line between Sønderborg Forsyning and Sønderborg Varme is distorted by the economic value of the waste heat in the results. This means that the feasibility of the waste heat scenarios is added to the possibility of displacing units in hours where the waste heat might not be available and vice versa. To assess the economic value of the transmission line without the waste heat a calculation has been carried out where the transmission line is available from 2029-2044 without waste heat from PtX. This means that the model is identical to the reference but including the transmission line.

The costs for transmission lines for the scenarios and reference can be observed in Table 9.

Table 9: NPV, capacity and lengths of transmission lines Costs

	Reference + transmission	LWHN	LWHT	MWHT	HWHT
NPV of transmission line [Million kr.]	240	63	240	277	338
DN-size	400	400	400	400	500
Length of transmission line [km]	23.5	4	23.5	23.5	23.5

It can be observed that the reference model and LWHT have the same costs for the transmission line. The reason for this is that the reference model including transmission is a model that interconnects the two district heating grids making the transmission line longer than for LWHN. Moreover, the costs increase as the capacity of the PtX waste heat increases. This is due to a need for higher flow and capacity of the transmission line.

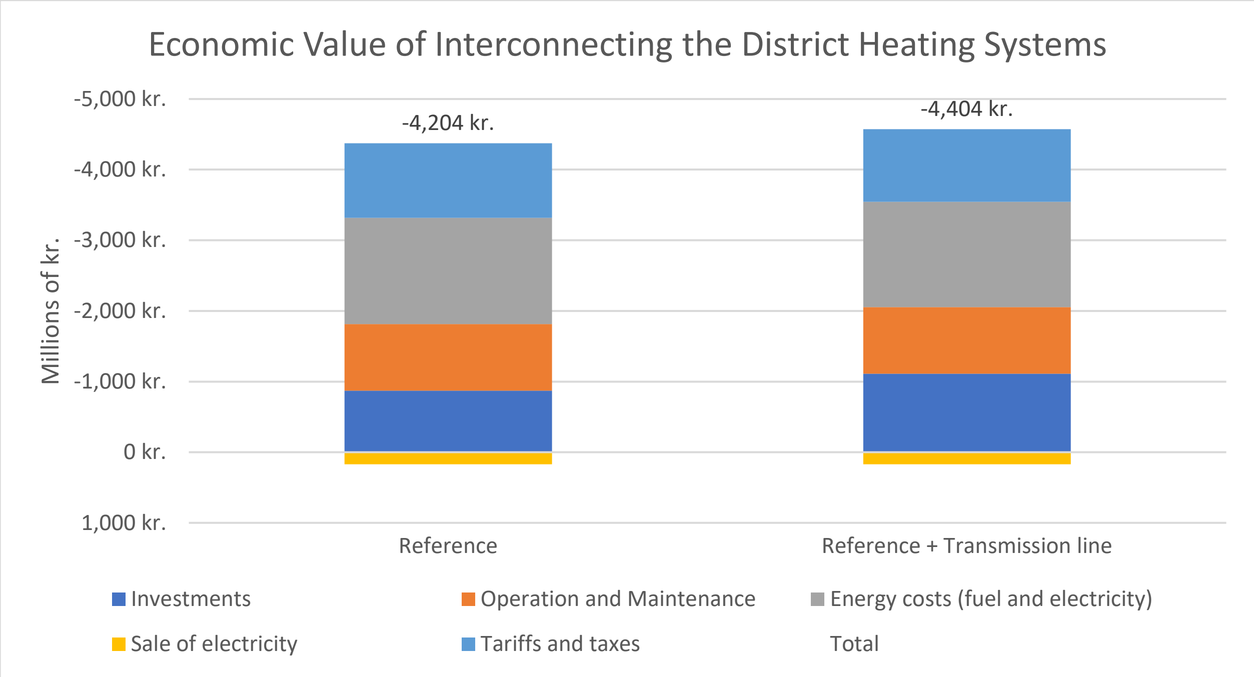

Figure 28: Total system costs of reference with and without transmission. Note that values are in millions of kr.

The total system costs of the reference and the reference including an interconnection of the grids can be observed in Figure 28. The results show that the reference result in a total system cost of 4.204 billion kr. where the result of implementing a transmission line results in a total system cost of 4.404 billion kr. which includes the investment of 240 million kr. When assessing the economic value of the transmission line the difference of the total system costs is performed, this leads to an NPV of -200 million kr. throughout the investigation period. Moreover, the isolated value of the transmission line, meaning the difference between the total system costs without investment is +41.6 million kr. throughout the investigation period. The result of 41.6 million kr. can be translated as the willingness to pay for the transmission line since it is assumed that the difference between the total system costs is the marginal value of adding transmission. Finally, it can be stated that a transmission line itself would not be able to provide the system with an economic benefit and that the economic value of the transmission line is ascribed to the dynamics of exchanging the heat as well as utilising the waste heat from PtX since the waste heat has a low variable heating cost. In addition to this, the fuel costs do not change significantly when implementing a transmission line to the reference where the costs decrease by 18 million kr. throughout the investigation period.

It has not been analysed whether a smaller transmission line between the two district heating systems could be a feasible solution.

Levelized Costs of Energy

The LCOE of each heat production unit is presented across all scenarios including the reference. The LCOE of each unknit vary across scenarios due to variations in the number of full load hours for the same units, c.f. section *Net Present Value and Levelized Cost of Energy*. The calculation is based on the variable business economic output from energyPRO as well as fixed costs like annualised reinvestments and fixed O&M expenditures.

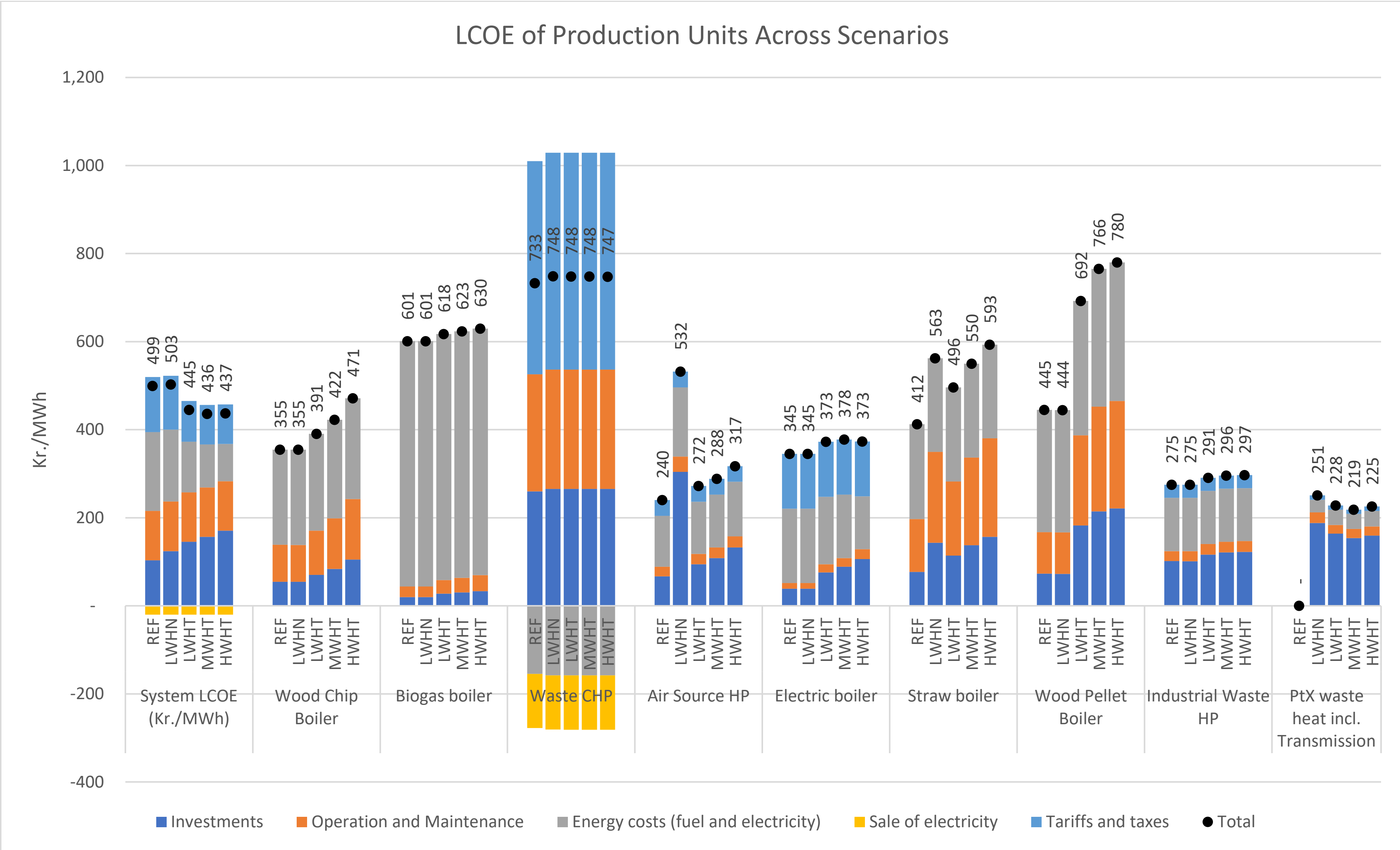

Figure 29: LCOE of each production unit across scenarios presented in Kr./MWh. Variations in LCOE for each unit are a result of the number of full load hours.

It is clear from Figure 29 that the LCOE of existing units increase when more PtX is included in the system. This is because of the lower utilisation of existing units. For example, the wood chip boiler in Sønderborg will only operate 4,800 full load hours in LWHT, while the operation falls to 4,000 and 3,300 full load hours in MWHT and HWHT, respectively. This brings up the question of whether waste heat from PtX cannibalises existing units, due to a saturated system. The total heat production capacity of the reference system is 115 MW, excluding natural gas boilers for peak demand and solar. As shown in Figure 19, the peak demand is 165 MW, which can be supplied by the system if the natural gas boilers also produce heat. However, most of the demand is below 115 MW, with the coldest months averaging around 100 MW. Decommissioning existing units to replace them with waste heat from PtX would naturally involve some risk for the district heating companies because they lack direct control of the waste heat stream.

The LCOE of the waste CHP is very high. This is mainly due to the restrictions on the annual waste stream of 30,000 tons annually from 2030. The current waste stream is roughly 55,000 tons annually, which corresponds to roughly 83% of the capacity of the plant. 30,000 tons annually would only utilise the plant's waste capacity at 45%. If the utilisation is this low, one could argue that the plant should be decommissioned, or that waste would have to be imported from other regions or countries to improve the utilisation of the plant.

The LCOE of the PtX waste heat is generally low at 219-251 kr./MWh including costs for the transmission line. The lowest LCOE for waste heat is achieved in MWHT at 219 Kr./MWh. The highest LCOE of PtX waste heat is in LWHN at 251 Kr./MWh, since the system in Nordborg cannot utilise most of the waste heat stream.

Influence of Heat Production Cost on Feasibility of Expansion of District Heating

The heat production cost of a district heating system has a large influence on the feasibility of expansions. The LCOE and marginal costs of the scenarios are shown in Figure 30.

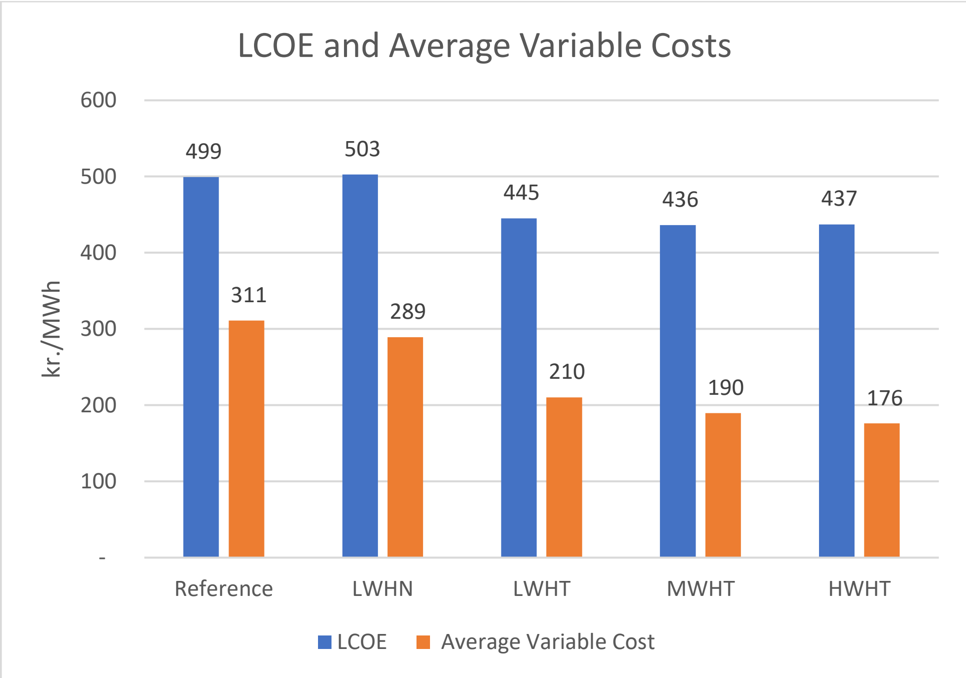

Figure 30: LCOE and average variable costs of the district heating system

The figure illustrates a significant decrease in average variable costs with increasing amounts of PtX waste heat. The average variable costs are based on the total system costs and heat consumption. Only variable costs e.g., fuel prices, tariffs, electricity prices etc. are included. The average variable costs could influence the economic feasibility of district heating expansions. With an average heat production price of 311 Kr./MWh, the total district heating expansion is 16% more expensive than individual heat pumps, cf. *Analysis 2: Expansion of the District Heating Networks in Sønderborg Municipality*. If the average heat production cost of MWHT (190kr./MWh) is applied, district heating is 5% cheaper compared to individual heat pumps. This highlights the impact of the heat production costs on the district heating system, and that the results of the expansions are sensitive towards changes in heat costs.

Waste heat from PtX must be compared to other relevant alternatives to evaluate whether integration is feasible. In the case of Sønderborg, only electricity-based or other renewable fuel technologies are relevant if the political goals of the municipality and ProjectZero (ProjectZero, 2021b) of a climate neutral energy system by 2029 are to be achieved. A relevant alternative could be an air source heat pump. The reference shows an LCOE of an air source heat pump at 240 kr./MWh at an annual average of 6,600 full load hours, showing that air source heat pumps are close to the same cost as waste heat from PtX including transmission costs. Depending on the specific implementation of waste heat from PtX, the cost could be the same as air source heat pumps or heat pumps with other heat sources. This is discussed further in a sensitivity analysis.

Sensitivity Analysis of Business Economics

The following sensitivity analyses are carried out:

- Fuel and electricity costs (±20%)
- Waste heat HP COP value (20% lower than the main assumption of 10.9 on annual basis)
- Full load hours of PtX of 8,000 and 5,000 instead of ~6,400
- Cost of HP for waste heat from PtX (+50% and ±20%)
- Depreciation of transmission costs over 25 years instead of 40 years
- District heating system without waste incineration

The sensitivity analysis of full load hours of PtX is only carried out for LWHT and MWHT due to calculation time. Additionally, the total system business economy does not improve significantly when increasing waste heat from PtX from this level. The model is not reoptimised in the sensitivity analyses, except for the sensitivity analysis where the waste CHP is removed as well as the test of full load hours for PtX waste heat. This is to limit calculation time. This is a limitation of the sensitivity analyses since it does not change the operation from the model due to changes in marginal costs when increasing or decreasing, for instance fuel costs.

Fuel and Electricity Costs

A sensitivity analysis of ±20% fuel and electricity costs has been conducted. The results are illustrated in Figure 31 and it shows a robustness with increasing amounts of waste heat from PtX in the system. This is due to the low marginal costs of the waste heat from PtX, which are less impacted by changes to electricity prices.

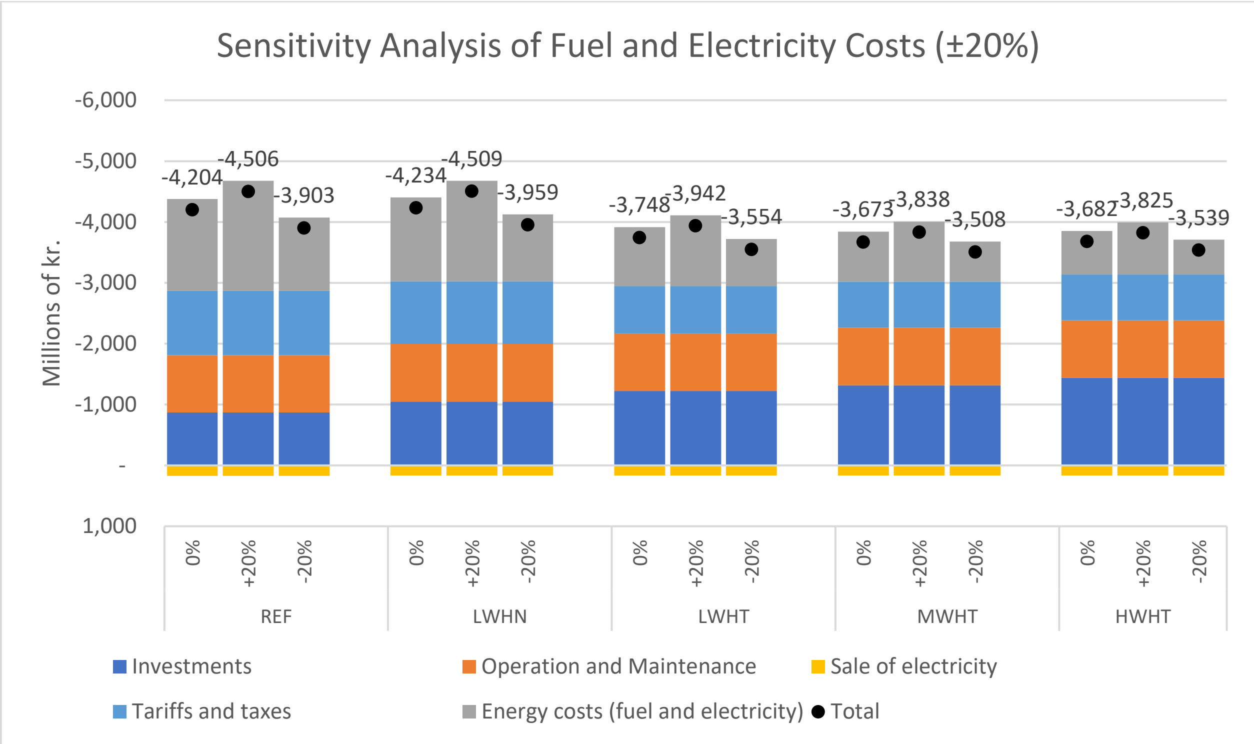

Figure 31: Sensitivity analysis of fuel and electricity costs. A change of ±20% is carried out. Note that values are in millions of kr.

Moreover, it can be observed that an increase in fuel and electricity costs for LWHN would move the result closer to the reference. This illustrates that the reference is more sensitive towards changes in fuel and electricity costs. Finally, it can be observed that the MWHT is the scenario that provides the system with the most feasible solution.

Waste Heat COP Value

A sensitivity analysis of the COP value of the HP for waste heat has been carried out. The main assumption is 10.9 on yearly basis. Changes to the COP value of ±20% has been carried out.

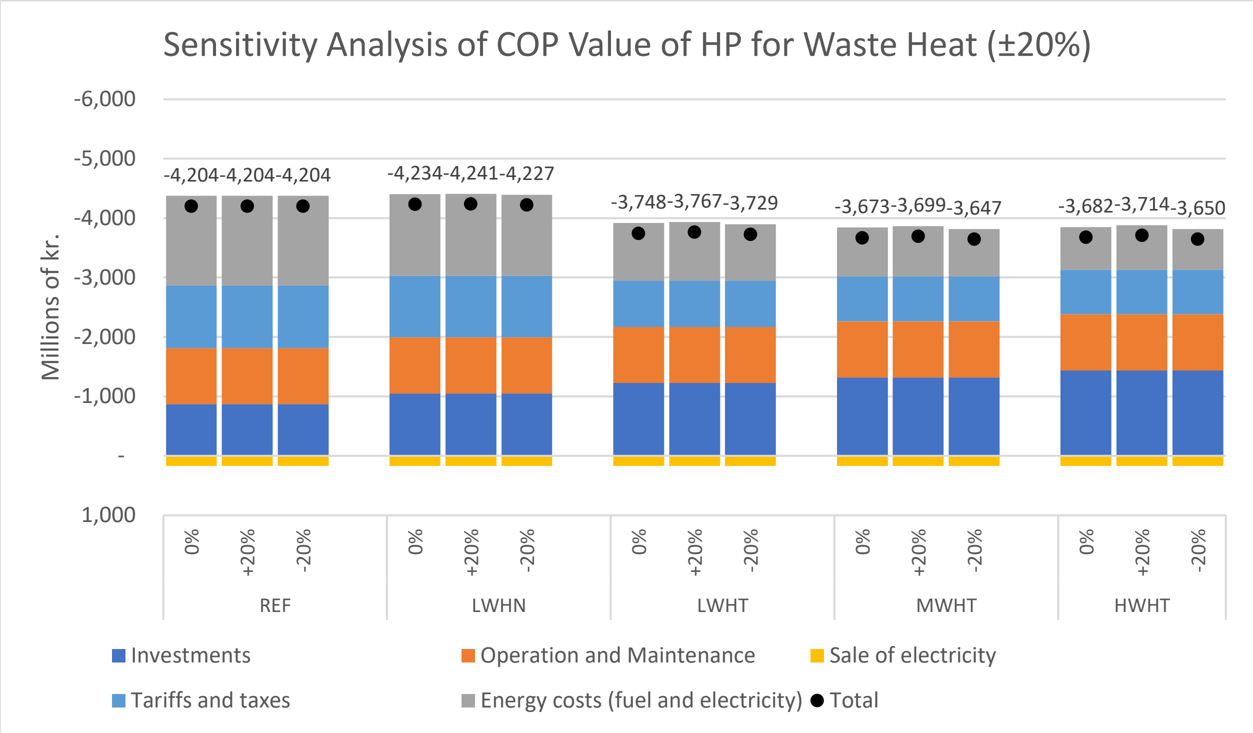

Figure 32: Sensitivity analysis of the COP value of the HP for waste heat. A change of ±20% is carried out. Note that values are in Millions of kr.

The results illustrated in Figure 32 show that the COP value only has a small impact on the system business economy. However, the sensitivity increases as the amount of waste heat from PtX increases. A reason for this is the larger share of heat production from waste heat.

Full Load Hours of PtX

A sensitivity analysis of the full load hours of the PtX plant is carried out. The main assumption is ~6,400 full load hours. 8,000 and 5,000 full load hours are analysed. The sensitivity analysis is carried out for LWHT and MWHT. The results show that the operation of the PtX plant has a larger effect on systems costs compared to the COP value of the heat pump or electricity costs. Higher full load hours result in a better NPV, while lower full load hours result in higher NPV.

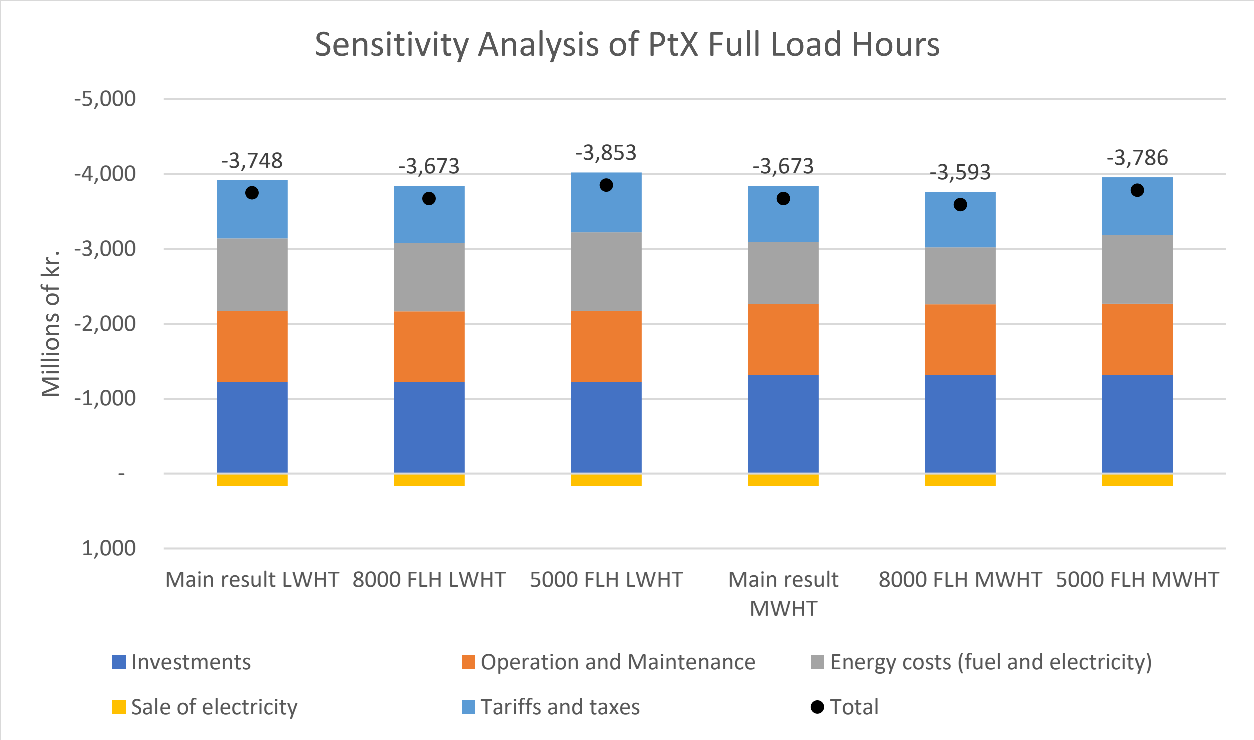

Figure 33: Sensitivity analysis of the number of full load hours of the PtX plant. An analysis of 8000 and 5000 full load hours is carried out for LWHT and MWHT. Values are in Millions of kr. and represent NPV of total system costs.

Investment costs for PtX waste heat Heat pump

A sensitivity analysis of the cost of the HP for waste heat from PtX is carried out. An increase and decrease of 20% are analysed.

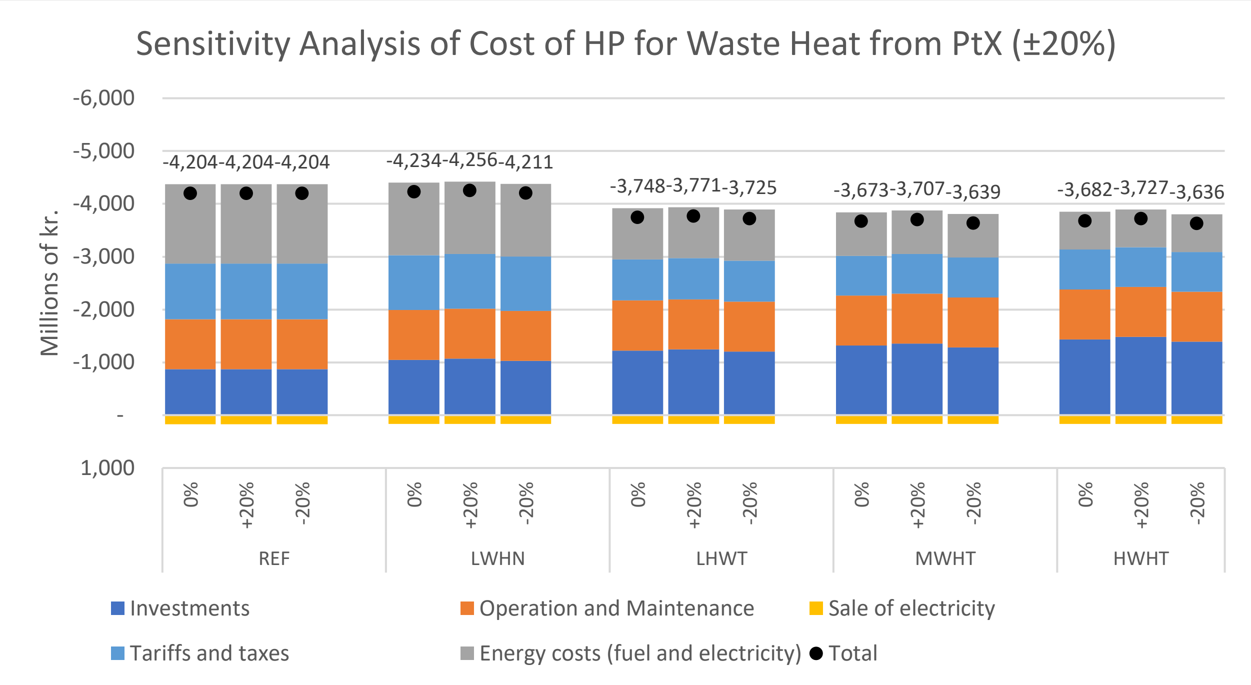

Figure 34: Sensitivity analysis of Cost of HP for Waste Heat from PtX. A change of ±20% is carried out. Note that Millions of kr.

The results show that the investment cost for the heat pump has a larger influence than the COP value of the heat pump. This means that there are no changes to the reference but the sensitivity increases as the investment costs increase. This is especially clear when observing HWHT. However, the changes are not substantial but there is still a change.

Depreciation of Transmission Costs

A sensitivity analysis of the depreciation of the transmission line has been carried out. The main assumption of depreciation over 40 years, is set to the lifetime of the transmission line. A depreciation period of 25 years is tested, which is the lifetime of the PtX plant.

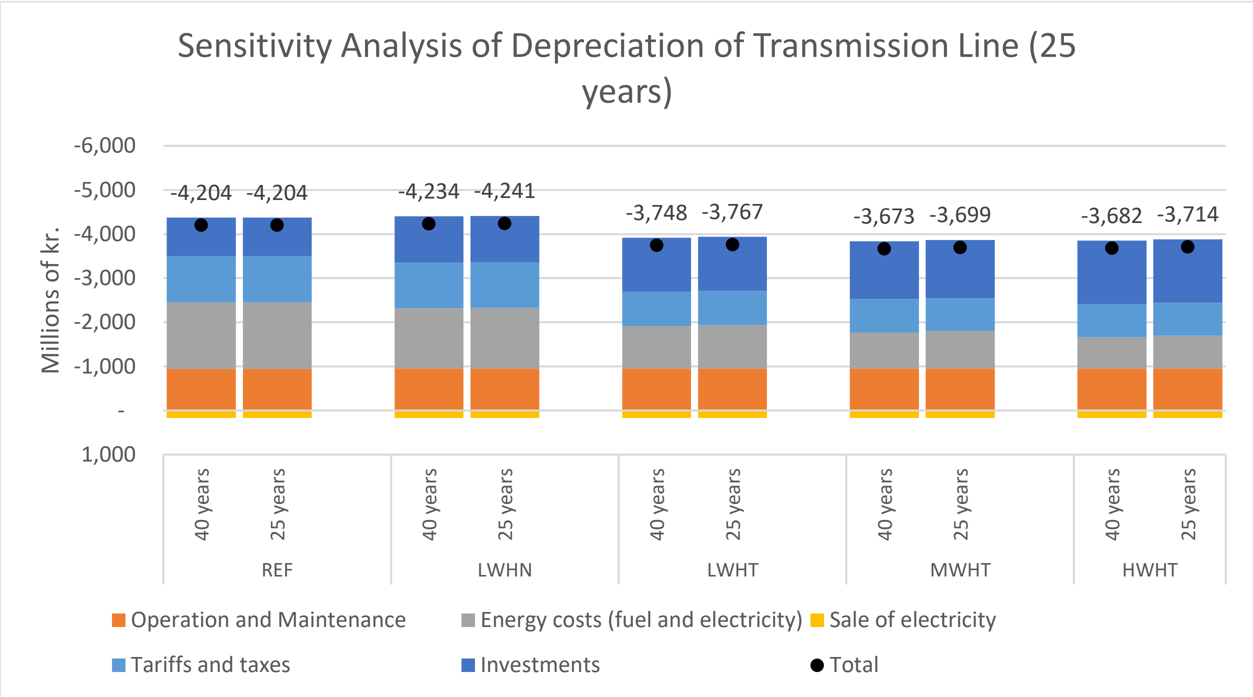

Figure 35: Sensitivity analysis of depreciation of the transmission line for waste heat from PtX. 25 years is tested. The main assumption is 40 years. Note that values are in millions of kr.

The reason for testing the sensitivity of changing the depreciation of the transmission line is to show the economy if the PtX plant is only located in Northen Als for 25 years, which would decrease usefull lifetime of the transmission line. An important point to note in this sensitivity analysis is that it does not include the potential value of the transmission line without the PtX plant. As shown ealier this value was shown to be minimal. The reference sees no changes due to no investments. The other of the scenarios sees small changes in the total system costs.

District heating system Without Waste Incineration Plant

A sensitivity analysis of the district heating system without the waste CHP from the start of 2029 has been carried out for LWHT and MWTH. The waste CHP plant is included in the model for the period from 2025 to 2029. This is to show the impact of the PtX waste heat replaced by waste CHP. The analysis is only carried out for two scenarios to limit calculation time. Figure 36 shows that the total system business economic costs are lower without the waste CHP plant.

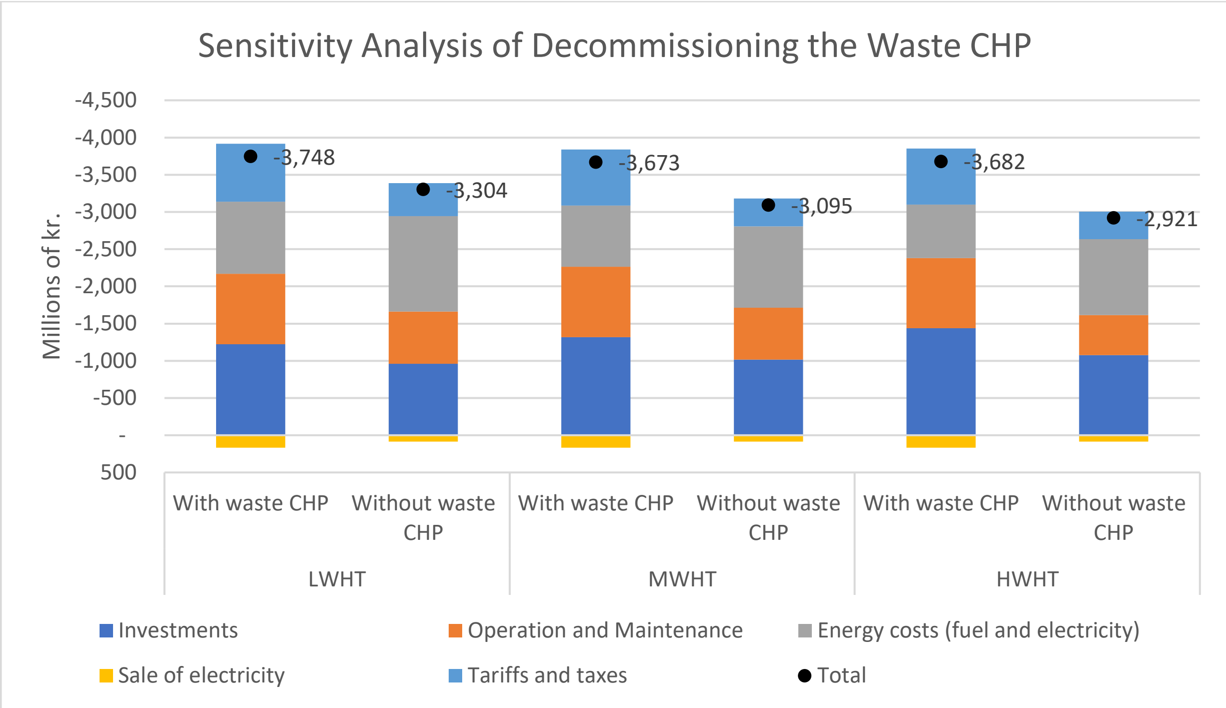

Figure 36: Sensitivity analysis of the district heating system without waste incineration plant in LWHT and MWHT. Note that values are in millions of kr.

The costs for the waste CHP are largely reinvestments, fixed maintenance, and taxes. It is assumed for all units that reinvestments are needed to maintain the current production units. The waste CHP is currently 29 years old (Sønderborg Varme, 2023b), which is more than the technical lifetime of 25 years of a waste CHP plant (Danish Energy Agency, 2023b). Therefore, it is reasonable to assume that reinvestments are required to maintain the plant throughout the investigation period from 2025-2044. The exact levels of reinvestments needed, however, are outside the scope of this thesis, which is why general investment costs for waste CHP plants are used. If the waste CHP plant is removed, the district heating companies would lose the capacity that they control as opposed to waste heat from PtX, which is controlled by third parties. When the waste CHP plant is removed in 2029 other units increase production to make up for the waste CHP. Table 10 shows the change in production.

The results illustrated in Figure 36 show that a decommissioning of the waste CHP would increase the feasibility of all investigated scenarios with waste heat from PtX. The priority of the waste incineration plant has a large impact on the how the model optimises since a removal of the unit would lead to an economically feasible solution. Moreover, it can be observed that both taxes and investment and O&M

costs are reduced significantly when decommissioning the waste CHP. The results show that a decommissioning of the waste CHP would decrease the total system costs of 12%, 17%, and 21% for LWHT, MWHT, HWHT, respectively.

Table 10: Shares of heat production with and without waste CHP in MWHT. Units marked with bold text indicates an increase after the waste CHP is removed.

	Share of heat production with waste CHP	Share of heat production without waste CHP from 2029	Change
Biogas Boiler	0.7%	0.7%	**2.1%**
Electric Boiler	1.5%	1.4%	-7.9%
Heat Pump	4.8%	4.5%	-6.1%
Industrial Excess Heat	0.4%	0.4%	-1.3%
Natural Gas Boiler	2.4%	2.6%	**6.6%**
Natural Gas CHP	0.2%	0.2%	**0.4%**
PtX Waste Heat	27.5%	40.2%	**46.3%**
Solar	2.4%	2.4%	0.0%
Straw Boiler	14.5%	14.0%	-3.6%
Waste CHP	14.2%	4.0%	-71.9%
Wood Chip Boiler	31.1%	29.4%	-5.6%
Wood Pellet Boiler	0.3%	0.3%	-7.7%

The table shows the change in heat production across different types of production units (excluding solar) in MWHT in a system where waste CHP is included throughout the investigation period and one where waste CHP is decommissioned in 2029.

The percentage change is a relative change from the previous results of MWHT to the new results of MWHT excluding waste. The most significant change is the increase of PtX waste heat and waste CHP. However, waste CHP produces 4% due to the decommissioning from 2029 when PtX waste heat penetrates the system. Moreover, the heat production from natural gas peak load increases but remains low <5% overall.

Sensitivity analysis of LCOE of waste heat from PtX

Figure 37 illustrates the results of the sensitivity analysis compared to an air source HP. The grey line is the LCOE of the air source HP in REF with a cost of 240 kr./MWh, while the yellow line is the LCOE of the air source HP in MWHT with a cost of 288 kr./MW. The difference between the lines is mainly due to the number of full load hours at 6,600 in REF and 3,900 in MWHT.

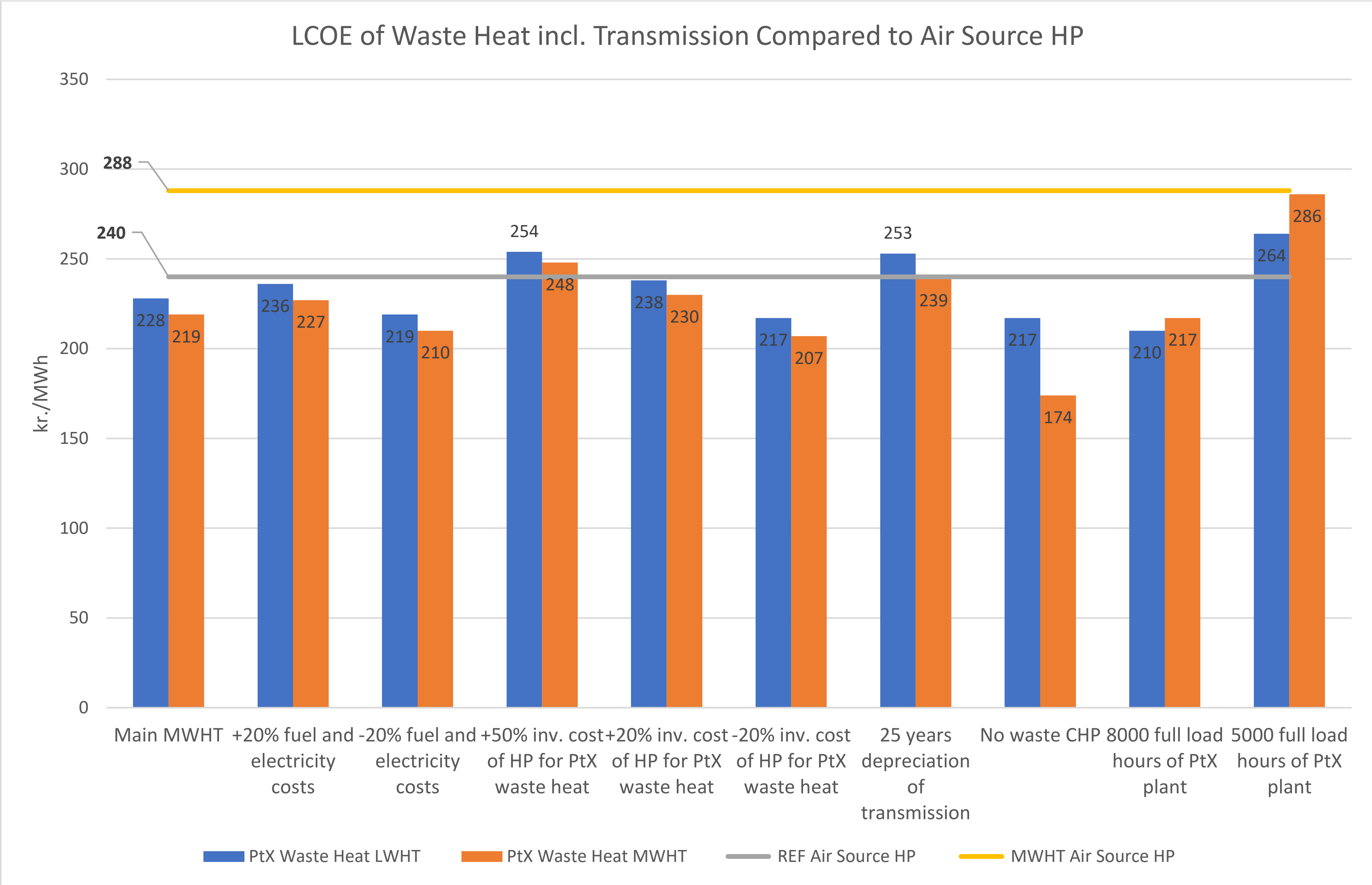

Figure 37: Results of the sensitivity analysis. The table shows the impact of various assumptions on the LCOE of waste heat from PtX in LWHT and MWHT compared to air source HP. The grey line is the LCOE of the air source HP in REF (6600 full load hours), while the yellow line is the LCOE of the air source HP in MWHT (3900 full load hours).

The results of the sensitivity analysis can be observed as LCOE in Figure 37. The results of the sensitivity analyses show that the LCOE of waste heat from PtX varies between 174 kr./MWh and 286 kr./MWh for MWHT and 210 kr./MWh and 264 kr./MWh for LWHT. The waste heat from PtX has a lower LCOE than an air source HP in most cases. However, the LCOE of PtX waste heat could potentially be higher compared with the air source HP from the reference, if the investment costs of the HP for waste heat are significantly higher or if the transmission pipe is depreciated over 25 years instead of 40 years. A lower number of full load hours for the PtX plant could also increase costs to a level above the air source heat pump from the reference at 6,600 full load hours. The lower full load hours of the PtX plant would increase the cost of waste heat significantly due to the lower utilisation of the waste heat.

Generally, the LCOE remains lower than an air source heat pump. It is worth noting that the cost of the air source heat pump is influenced by the number of full load hours and the availability of heat storage in the system. Therefore, an air source HP of comparable capacity to the waste heat from PtX, would likely run at a different number of full load hours and the LCOE would be different. Furthermore, the lowest LCOE of waste heat can be achieved by decommissioning the waste incineration plant. This is mainly due to the priority of the unit in the model so the implementation and utilisation of waste heat would directly lead to a marginal displacement of waste heat. In addition to this MWHT would lead to significantly lower LCOE for the waste heat without waste CHP.

Socioeconomics

An analysis of the socioeconomic feasibility of the scenarios has been conducted to identify whether the scenarios will provide the system with a feasible solution. The socioeconomic calculations have only been conducted for the main results of scenarios and the reference. Which means the total system costs excluding taxes and tariffs. The analysis will present the socioeconomic cost of the total system cost as well as a simplified socioeconomic LCOE meaning that it is the socioeconomic value of 1 MWh produced heat. This means that this analysis will differ from the previous analysis of business economics where an analysis of all units' LCOE were presented. The following figures include socioeconomic values of investment and O&M, fuel and electricity costs, distortion loss, revenues (sale of electricity), environmental costs (CO2 and other GHG-emissions), and total NPV according to (Danish Energy Agency, 2022c).

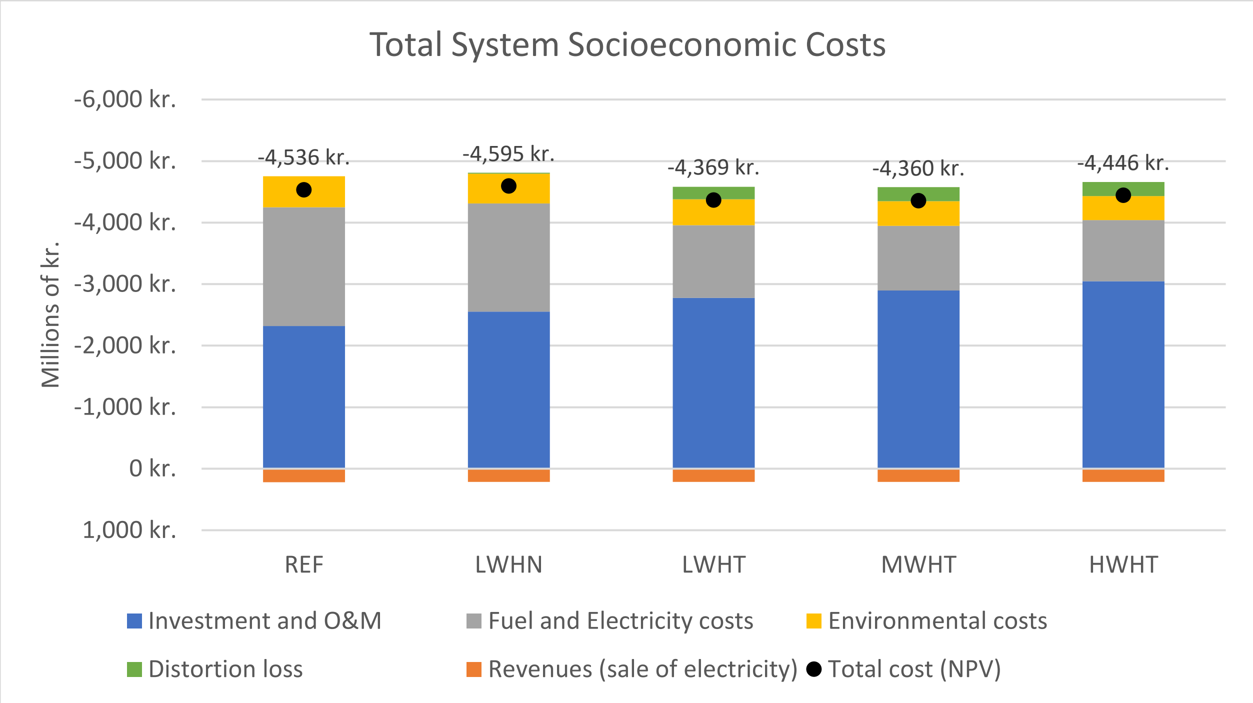

Figure 38: Socioeconomic Results of System Costs. Note: Values are in millions of kr.

The socioeconomic results can be observed in Figure 38. When observing the total costs, it becomes clear that all analysed scenarios except LWHN will provide the system with a feasible solution compared to the reference. MWHT will provide the biggest saving in terms of total system costs, and the scenario will from a socioeconomic perspective save society for 176 million kr. throughout the investigation period. However, all scenarios where waste heat from PtX is utilised in an interconnected system will provide the system with a feasible solution and the differences are not significant. Moreover, Figure 38 clarifies that the investments and O&M account for the largest share of the total costs and those expenses will increase for the investigated scenarios, which is due to investments in a heat pump as well as a transmission line and substations to utilise the waste heat from PtX. If observing the fuel and electricity costs, there is a significant decrease when comparing the reference to the scenarios. A reason for this is the displacement of units utilising fuels with higher marginal costs e.g., natural gas peak load. The environmental costs are expected to decrease the larger the share of waste heat becomes. A reason for this could be due to the assumptions stated in (Danish Energy Agency, 2022c) where fixed coefficients of emissions have a fixed value for some solid fuels. E.g., the coefficients for straw and biomass boilers for CH4 are respectively 108 g/MWh and 39,6 g/MWh, respectively. This is in contrast to coefficients of emissions on electricity which develop over the years due to the expectations of more RES in the electricity sector in the future. When observing the decrease of costs related to emissions, it becomes clear that a system based on heat production from electricity will decrease the socioeconomic costs. In addition to this, a heat pump has a significantly higher efficiency compared to for instance boilers, which also favours less consumption and thus lower emissions. If observing the distortion loss, it becomes clear that the scenarios will result in a negative tax balance and from a socioeconomic perspective it could cause an unfeasible solution. The decrease of tax revenue, however, is incurred by the socioeconomic savings of both fuel consumption and environmental costs for emissions where especially savings in fuel and electricity costs are the largest contributor. The revenue of sold electricity remains somewhat the same for all scenarios, which is due to the operation of the waste incineration, which is the largest contributor to electricity production in the district heating system of Sønderborg.

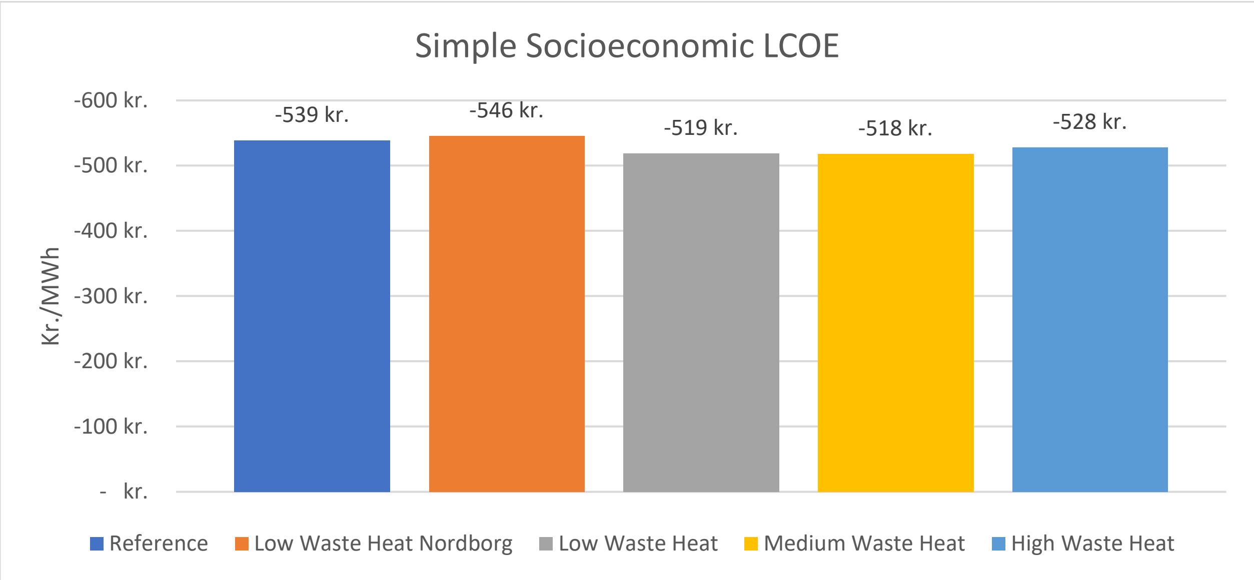

Figure 39: Socioeconomic Simple System LCOE (kr./MWh)

It can be observed that the socioeconomic LCOE as presented in Figure 39 have the same pattern as the socioeconomic results illustrated in Figure 38. The lowest LCOE can be achieved from the scenario of MWHT and the highest LCOE in LWHN. The other scenarios with PtX in an interconnected system would result in a slightly higher socioeconomic LCOE compared to MWHT.

Sensitivity of Socioeconomics

To test the robustness of the scenarios from a socioeconomic perspective, a sensitivity analysis of the investment and O&M, environmental costs and fuel costs has been conducted with the factor of ±20%. The following figures are designed as a stacked bar chart showing the expenses and revenues of the scenarios in one single bar. The purpose is to illustrate the changes in the parameters as the costs either increase or decrease by 20%.

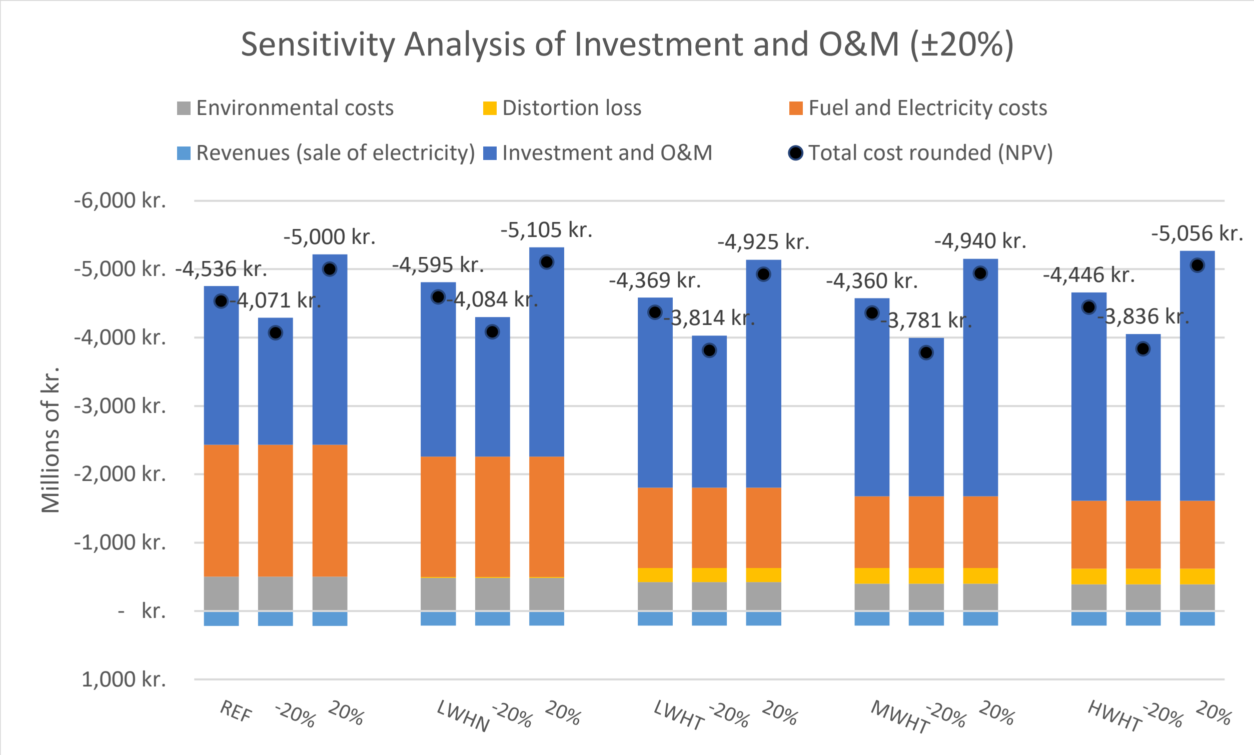

Figure 40: Socioeconomic Sensitivity Analysis of Investment and O&M. Note: Values are in millions of kr.

The sensitivity of investment and O&M for the reference and for the investigated scenarios can be observed in Figure 40. The top dark blue bar illustrates the investment and O&M and the first stacked bar to the far left is the baseline expenditures, meaning the results as observed in Figure 38 followed by a change of -20% in the middle and to the right a change of +20% can be observed. In Figure 40 it can be observed that the robustness of the reference and the scenarios are rather similar when comparing the total costs. However, a change of +20% would lead HWHT being more costly compared to the reference and the total costs would increase with 14% compared to the main results of HWHT and the reference would increase with 10%. When observing the investigated scenarios, it becomes clear that the robustness of the scenarios decreases as the share of investment and O&M expenditures of the total costs increases. I.e., it can be observed that the results of both HWTH and MWHT are the most sensitive towards changes in investment and O&M and a reason for this is that 66-69% of the total costs is investment and O&M. The robustness of LWHN is remarkably close to the reference. Finally, it can be observed that changes in investment and O&M would not change the conclusion of MWHT being the most feasible solution.

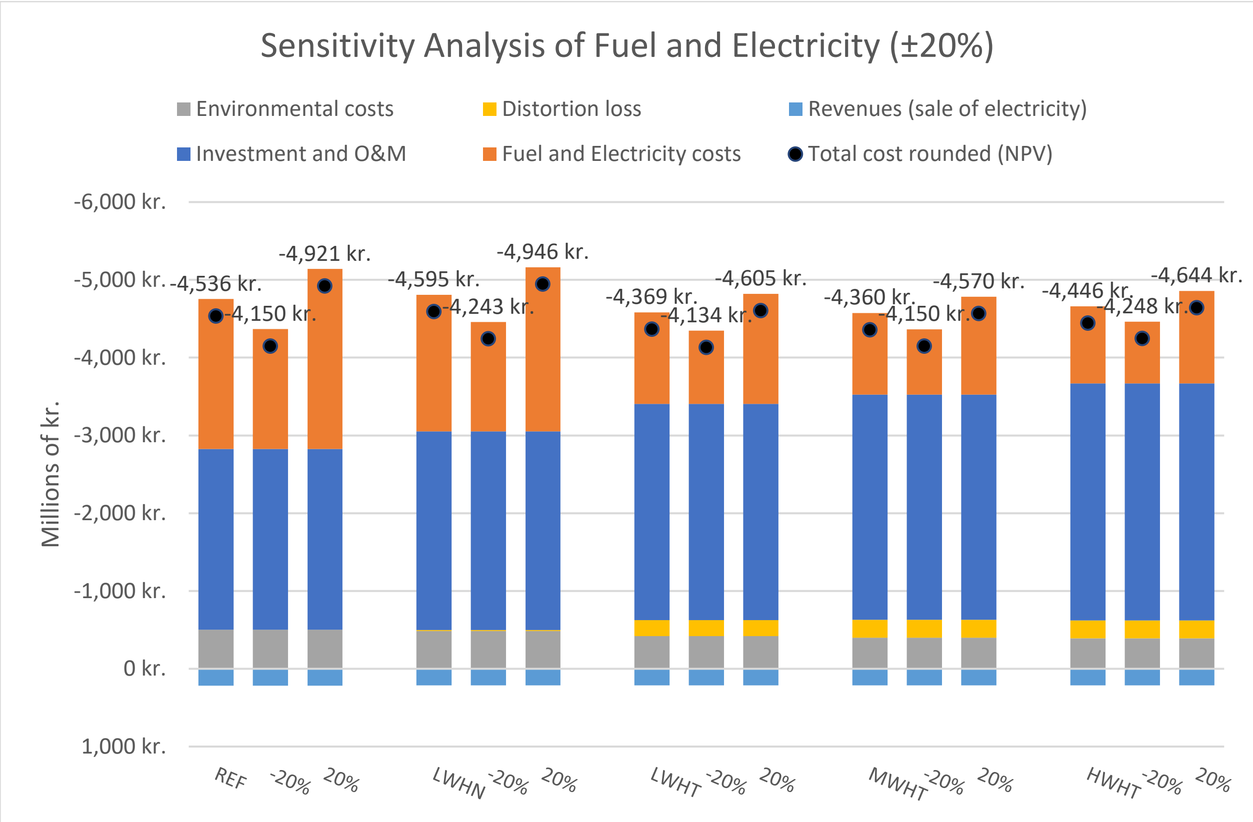

Figure 41: Socioeconomic Sensitivity Analysis of Fuel and Electricity Costs. Note: Values are in millions of kr.

In Figure 41 the sensitivity analysis of fuel and electricity costs can be observed by the orange bars. As with the previous sensitivity analysis the pattern is that the larger the share of the fuel expenditure accounts for in the total costs, the less robust the scenario or reference is. It becomes clear when observing the reference where the fuel expenditures account for a larger share of the total costs, the sensitivity is more significant than compared to HWHT. For the reference the fuel costs account for 43% of the total costs and a change of ±20% would result in ±4-6% change of the total costs whereas the same changes for HWHT would result in ±3-4% change of the total costs. Where the robustness of LWHT and MWHT is almost identical and close to HWHT, the result of LWHN is remarkably close to the reference's robustness. Finally, it can be observed that changes in fuel costs would change the conclusion of MWHT being the most feasible solution where LWHT results a lower total cost and MWHT results in the same total costs as the reference. The reference is most sensitive to change in fuel costs.

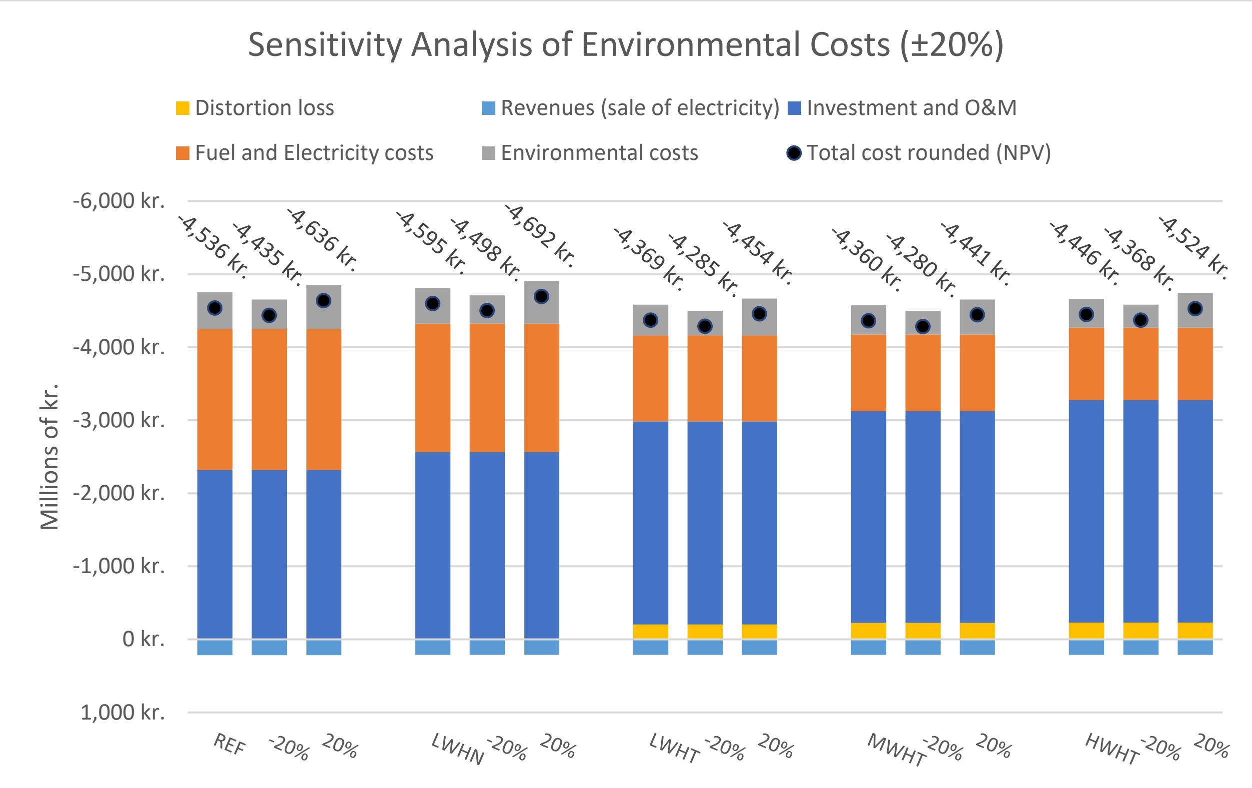

Figure 42: Sensitivity Analysis of Environmental Costs. Note: Values are in millions of kr.

In general, the robustness of both the reference and the scenarios when changing the environmental costs ±20% is similar. Environmental costs are socioeconomic costs for emitting CO2, CH4, N2O, SO2, NOx, and PM2,5 according to (Danish Energy Agency, 2022c). It is clear that environmental costs account for a smaller share for MWHT and HWHT compared to the reference and LWHN scenario. However, the shares are relatively close and across the reference and scenarios the shares are 9-11% from the original results. Change of ±20% would lead to a change of 2-3% of the total costs. The feasibility of MWHT is sustained, and the robustness of the scenarios is almost similar.

Partial Conclusion

The purpose of the analysis was to analyse the potential of integrating waste heat from PtX in Sønderborg and as well compare it with the current system by conducting a feasibility study. First of all, the waste heat from PtX was found to exceed the heat demand during the summer period and thereby causing a saturated system. For the LWHN scenario, the waste heat was utilised 41% of the available hours on average and the heat production from waste heat accounts for 15% of the heat demand on average in this scenario. For the interconnected scenarios: LWHT, MWHT and HWHT the potentials for integrating the waste heat are greater. The waste heat is utilised 77-93% of the available hours on average and the lower the capacity of the waste heat the greater the utilisation. The heat production accounts for 34-56% of the heat production on the annual average and the greater the capacity, the larger the shares.

From a business economics perspective, the feasibility of utilising waste heat from PtX shows an economic saving compared to the reference. However, the feasibility of utilising the waste heat in only Nordborg provides a business economically worse situation than the reference due to large investments. Additionally, it cannot be concluded whether a smaller capacity of the waste heat, e.g., only utilising waste heat from the electrolysis stack will provide a feasible solution in Nordborg. Moreover, the interconnection of the two district heating grids without waste heat from PtX will not from a business economic perspective provide a sufficient solution for the two companies. However, it cannot be concluded that a smaller capacity of the transmission line will provide a feasible solution for an interconnected system. The LCOE of the waste heat showed low costs compared to the existing units. From a socioeconomic perspective, all interconnected scenarios would be beneficial for the system and the results showed similar NPV and system LCOE.

Discussion

Discussion of Results and Modelling

This section will discuss the delimitations and assumptions of the modelling and energy system analysis.

The modelling of the PtX plant is bound with uncertainties and delimitations. Firstly, the availability of the PtX plant is assumed to be identical to a planned PtX plant in Kassø (COWI, 2021). This means that the operation of the PtX plant is restricted to operate ~6,400 full load hours annually and the operation is based on an optimisation of local production of RES and the electricity market. This means that the model finds an equilibrium of the operation by calculating the most optimal solution based on RES production and the fixed full load hours of ~6,400. Another approach to modelling the PtX plant would have been to include several prices in order to let energyPRO optimise the operation solely based on variable costs and thereby identify the potential full load hours and generate an hourly profile of the waste heat. However, prices for hydrogen and methanol have been hard to determine due to a lack of market data and according to (IRENA, 2021) the prices of hydrogen and methanol are primarily determined by the production costs. For methanol, the prices are linked to the hydrogen production costs due to the reliance on hydrogen for methanol production. The report states that the price for hydrogen through electrolysis is about 16.65-20kr./kg. This means that the methanol production costs would likely be 8,000-16,000kr./t when considering all required inputs including CO2. (IRENA, 2021) Another study has applied a cost for methanol of 6,000kr./ton (Bos, et al., 2020). The prices of hydrogen and methanol could have been implemented in the modelling of the PtX plant to find an optimal operation based on market mechanism. This, however, would lead to an assumption that the production costs reflect the minimum income for the methanol and hydrogen. For the PtX plant in Kassø, the companies Lego and Novo Nordisk will be the purchaser of the methanol production (Energiwatch, 2023) and one could argue that the price of methanol might not only reflect the production costs but also include a certain willingness to pay if the companies consider a branding value of utilising *green methanol* for their plastic production. The income from selling the methanol to a market could potentially shift the production in some hours and as shown in Table 7 the market accounts for 25-48% of the electricity consumption. This means that an income from selling the methanol from an optimisation approach could increase the share of electricity from the market due to operation in hours with higher electricity costs where it would be feasible to operate on electricity from the market compared to the net income of producing the methanol. On the other hand, it could reduce export of electricity since the PtX plant potentially would achieve a higher net income from utilising the local RES compared to selling it to the market. However, the purpose of this thesis is to investigate the waste heat and not find an optimal operation of the PtX plant based on potential income. This means that our approach has been to analyse how fluctuating waste heat could be implemented and for the district heating companies, the prices and economy of the PtX plant are considered an externality that does not influence the district heating system directly. In addition to this, the availability and disposal of the waste heat are directly related to the district heating companies since the waste heat might add more value to the system if available during the heating season rather than the summer period. This also means that the model is sensitive towards changes in full load hours due to the fluctuations as illustrated in Figure 20 as well as the sensitivity proven in Figure 33.

The availability of CO2 for methanol production has not been included in the modelling of the PtX plant and it is assumed an unlimited source. However, interviews and section Analysis 1: PtX Technology in a Local Context of District Heating have shown that the local biogas plants and the waste CHP potentially could provide the PtX plant with CO2 if CC was implemented. The results of the modelling show a greater economic benefit for utilising the waste heat from PtX if the waste CHP is decommissioned, cf. Figure 36. In addition to this, a CC technology could according to (Danish Energy Agency, 2021b) provide additional waste heat from the amine washing of the flue gas as well as the compression of the CO2 from the waste CHP's combustion. It is stated that 80% of the potential waste heat output would require heat pumps to utilise the waste heat whereas 20% could be available at 80°C. (Danish Energy Agency, 2021b) Additionally, CC on the waste CHP could increase both the shares of waste heat for the system in general but it would also entail a certain lock-in effect where the system including both the district heating and the PtX plant is dependent on the operation of the waste CHP. Moreover, the results show that the system is saturated, and that the utilisation of waste heat generated from both CC and PtX would potentially cannibalise each other meaning that the system runs a surplus of waste heat production, which would induce cooling of the waste heat either by seawater or by cooling towers, which could increase the investments required to utilise the waste heat.

This thesis did not analyse the availability of the CO2 for the PtX plant, and it is considered a delimitation which could presumably change the operation of the PtX plant to not only operate based on an equilibrium of the local RES and import/export on the electricity market. This operation would either require storage for the CO2 to reflect the identified optimum of the plant based on the electricity production/consumption and the available full load hours. This means that the PtX plant could change the operation to hours when the CO2, in reality, is available due to the need for CO2 for methanol production. In addition to this, the price of CO2 has not been assessed. This could further make the identified optimal operation of the PtX plant uncertain due to extra costs for producing the methanol, which could potentially mean that the plant would incentivise the utilisation of local RES due to costs included for the CO2.

Another delimitation of the modelling is the utilisation of heat storage in the district heating systems. In the energy modelling, all units are computed to utilise heat storage no matter the geographical placement of the units. This means that the only constraint for the heat production units to utilise the heat storage is the transmission capacity of areas. E.g., storages in Sønderborg are potentially available for the waste heat from PtX. According to (EMD International, 2023) there is a *workaround* method to correct for the delimitation which requires further computation than conducted in the model. However, the workaround suggests moving heat storage to the sites of the units that are prohibited from utilising heat storage. This means that if the workaround has been implemented, the heat storage that is located next to the waste CHP should be moved to the PtX location, which is assumed to be a greater delimitation than what has been chosen for the model. In addition to this, the delimitation of heat storages has been considered by adding isolated sites for the heat storage and heat production units where the transmission is prohibited to only transmit heat from the sites, meaning that heat cannot be transmitted from the additional system to the storage. i.e., the heat storage unit located at the waste CHP can only be utilised by the waste CHP and not for either waste heat from PtX or any other heat production unit. On the other hand, the same approach has not been applied to the heat storages in Nordborg meaning that the waste heat potentially can utilise the heat storages in Nordborg but not in Sønderborg. This is a delimitation because the geographical placement of the heat storage is different from the waste heat and the storage in Nordborg. To quantify, the total heat storage capacity of the system is 82,500m3 which corresponds to approximately 1460MWh. When taking the constraints of heat storage for waste heat into account, the available heat storage capacity of waste heat from PtX is approximately 600MWh, which corresponds to 0.1% of the annual heat demand. On the other hand, the actual heat storage available for the waste heat would likely be the heat storages in Nordborg, which correspondsto 355MWh. Moreover, all heat storages are assumed to be available at the transmission level.

Part of the scenarios is that the waste CHP is included throughout the investigation period. There are, however, some uncertainties to this. In Denmark, there is currently a surplus of waste incineration capacity compared to the amount of waste generated (Kommunernes Landsforening, 2020). In an analysis of which plants should close to lower the capacity, the waste incineration plant in Sønderborg was pointed out as a candidate for decommissioning (Kommunernes Landsforening, 2020). The plan was not carried out and because of that, the surplus of waste incineration capacity is likely to be reduced through increased competition in the sector (Ministry of Food, Agriculture and Fisheries of Denmark, 2020). There is some debate on the effect of increased competition. In an interview with Sønderborg Varme, they stated that they believe they will benefit from increased competition. This is echoed by the newer waste incineration plant or plants that have reinvested in existing plants recently, as they fear being closed down due to the larger debt obligation of newer plants (Svendsen & Christensen, 2023). As the analysis showed, the waste incineration plant has a large effect on the integration of waste heat from PtX in the system. Therefore, the political development that influences the waste incineration plant will influence the ability of the system to integrate large amounts of waste heat from PtX.

Modelling of District Heating Grids

Modelling of district heating expansion showed that district heating would be more expensive than individual heat pumps for the areas collectively. However, there are some delimitations in the analysis. Firstly, an actual project by a district heating company might include different assumptions than those applied in the current analysis, which could give a different business economic result. The sensitivity analysis showed that the result is influenced by several assumptions in the model. Secondly, the modelling conducted in this analysis is done using a generic GIS model that takes location of houses, capacity requirements and capacity factors in specific district heating pipes into account. As Figure 17 shows, the model is not perfect and does not optimise for the shortest overall grid, but for the shortest grid for each house individually. This results in a few houses that are supplied by one long distribution line. A district heating company would optimise the grid to fit the local area, which this model does not accurately do. This would likely result in a cheaper distribution grid. Furthermore, district heating companies must calculate the socioeconomic impact of the expansion, which could yield a different result than the business economic result.

The cost for district heating installations used in the analysis is based on (Mathiesen, et al., 2021) and adjusted to the local context based on interviews with Sønderborg Forsyning. Generally, the cost applied in the analysis is lower compared to other district heating plans. Costs applied in this thesis are compared to costs used in (Norfors, 2022).

Table 11: Comparison of district heating installation costs

DN	Internal Pipe Dimension [mm]	Applied investment cost [Kr./m]	Norfors Investment cost [Kr./m] (Norfors, 2022)
DN25	33.7	2,500	2,703
DN32	42.4	2,500	2,830
DN40	48.3	2,500	2,934
DN50	60.3	2,559	3,138
DN65	76.1	3,064	3,426
DN80	88.9	3,624	3,825
DN100	114.3	4,351	4,413
DN125	139.7	5,152	5,190
DN150	168.3	5,694	5,997
DN200	219.1	6,504	7,494
DN250	273	7,789	9,778
DN300	323.9	9,429	11,765
DN400	406.4	11,240	N/A
DN500	508	13,312	N/A

As can be seen in Table 11 the costs applied in this thesis are lower compared to the costs from (Norfors, 2022). If data from (Norfors, 2022) were applied, the feasibility of district heating would be worse. However, given the local context and interviews with the local district heating companies, costs in Sønderborg are likely lower than in Norfors' area. A reason for this could be that Norfors is expanding district heating in impermeable areas and more areas of Sønderborg Municipality are non-impermeable areas.

The cost of individual heat pumps is based on (Danish Energy Agency, 2022b) and for single-family houses based on a cost of 75,220 kr./unit. This is substantially lower than current assumptions in district heating proposals. The district heating company Norfors states a cost of 96,642 kr./unit in a recent analysis of district heating expansions (Norfors, 2022). If this cost is implemented in this thesis, the feasibility of district heating would improve significantly compared to individual heat pumps. Whether the district heating expansions are feasible and carried out could have an effect on the amount of waste heat from PtX that can be integrated. Figure 43 shows the hourly heat demand without the expansions. It shows that the difference between the waste heat potential and the demand would increase even further, worsening the integration of waste heat from PtX.

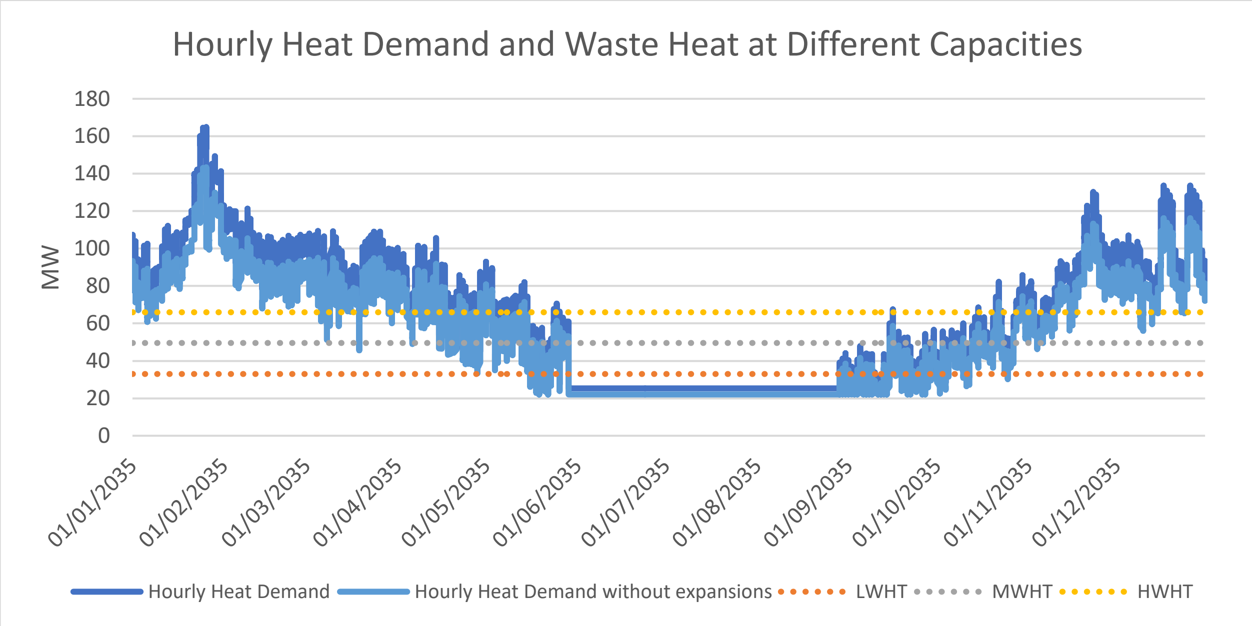

Figure 43: District heating demand with expansion and without expansions and the waste heat potential of the different scenarios.

Willingness to pay for waste heat

An assumption of this thesis is that the cost of waste heat is a result of the cost of recovery and utilisation in the district heating system (transmission costs). No actual payment for the waste heat to the PtX plant is included in the analysis and the assumption is that the PtX plant would give the waste heat away for free. This section will discuss the willingness to pay for waste heat. The discussion is based on two separate assumptions: 1) willingness to pay based on the total business economic saving between the reference scenario and low waste heat scenario and 2) willingness to pay based on the cost of a relevant alternative to waste heat from PtX. An air source heat pump is chosen as a relevant alternative.

Based on the total savings in the system from integrating PtX waste heat, a willingness to pay for the waste heat stream can be calculated. The savings in MWHT are used for the calculation and the costs of integrating the waste heat are also included. The total cost savings are 531 million kr. in the investigation period, which equates to 125kr./MWh of heat delivered from the PtX plant. However, the system would likely also be able to save costs using alternatives to the current heat units. Therefore, a willingness to pay compared to the cost of an air source heat pump is calculated. The cost of an air source heat pump is calculated at 240-288kr./MWh depending on the utilisation in the system, while the cost of waste heat from PtX incl. transmission was calculated at 219 kr./MWh in MWHT. Based on this a willingness to pay for heat can be calculated at 21-69 kr./MWh before the cost would exceed the cost of a relevant alternative.

Waste Heat from PtX in a Local and National Context

From a national perspective, the expectation is that waste heat from PtX can provide the district heating systems with a great amount of waste heat (Danish Ministry of Climate, Energy, and Utilities, 2021a). When observing other PtX plants in the southern part of Jutland like the planned plant in Kassø (54MW electrolysis and methanol production) (COWI, 2021) and the *Høst* project (1GW electrolysis and ammonia production) in Esbjerg (Høst PtX Esbjerg, n.d.) both plants are expected to provide the local district heating systems with waste heat. For the Kassø project, the estimation is that the plant will provide 50GWh/yr. of waste heat and the Høst project is expected to provide *emission-free district heating for approximately 15,000 households* (271GWh/yr.)[1]. When comparing the estimations of waste heat generated by the two PtX plants with the municipalities' district heating demands from the Danish Heat Atlas by Aalborg University (Aalborg University, n.d.) it becomes clear that the plants will provide respectively 16% and 27%, respectively, of the annual district heating demands in the municipalities of Aabenraa and Esbjerg. From a national perspective, the ambition is for the total capacity of electrolysers to reach 4-6GW in 2030 according to (Danish Ministry of Climate, Energy, and Utilities, 2021a), so both the Høst and Kassø projects are presumed to provide a significant amount (18-26%) of capacity to fulfil the expectations. When including the PtX plant I Nordborg, the three PtX plants in the southern part of Jutland could potentially be 1.25GW, which would provide 21-31% of the expected 4-6GW. Moreover, the waste heat generated from the modelled PtX plant could provide Sønderborg Municipality with 15-56% of the heat production depending on the scenario.

The local context and the analysis of the PtX case in Nordborg have shown that a greater share of the waste heat does not inevitably equal better utilisation. From a business economic perspective, the utilisation of a large amount of waste heat, i.e. HWHT, also implies increasing expenditures and investments, which for the present case reduces the economic feasibility in terms of both business and socioeconomics. A reason for this is due to a large investment in transmission lines due to the geographical location of the PtX plant in Nordborg and the distance to the city of Sønderborg where the largest heat demand is found in the municipality. In addition to this, the utilisation of waste heat is found to depend on the location of the PtX

[1] (18.1MWh/yr. * 15,000 households)/1,000

plant and especially the distance from the plant to the grid as well as the investments for utilising the waste heat. These conclusions are similar to the study (Böhm, et al., 2021) where the low cost of recovery and low costs of transmission pipes are found important when utilising waste heat from hydrogen production. The current district heating systems in Sønderborg Municipality are primarily based on dominant technologies, like biomass boilers and waste incineration. The first analysis of this thesis pointed out that waste heat as a fluctuating source is different from the primary supply of heat. A conclusion from the study by (Böhm, et al., 2021) states that seasonality is important for the utilisation of waste heat due to the heating season. On the one hand, the analyses show a high utilisation and full load hours of the waste heat and especially when utilising the waste heat in a system without waste CHP. On the other hand, the PtX plant in Nordborg is likely to be supplied with electricity from solar PV, which could incentivise the operation of the plant during the summer period. However, solar only supplies a small share of electricity consumption in the analysis. If the plant is to operate more during the summer one could argue that the value of the waste heat product for the district heating companies would be lower. A reason for this could be related to the security of supply, which is also found important (Böhm, et al., 2021). Additionally, the security of supply is of importance since the investments to utilise the waste heat from PtX are large. According to (Böhm, et al., 2021) no risk of bankruptcy is considered important when utilising waste heat. One could argue that before investing in the technique required for the utilisation, the PtX owner could provide a certain parent company guarantee to ensure that the district heating companies are not left alone with the payback of the investment in the transmission line if the PtX plant goes bankrupt or if the plant is to be decommissioned before ended lifetime. A guarantee could also be required if the PtX plant determines the availability of the waste in 6,400 hours during the year, but the waste heat is not available due to sudden outages. Moreover, the investigated case of PtX only showed a business economic feasibility when utilising the waste heat in an interconnected grid due to a surplus of heat capacity when only analysing Sønderborg Forsyning and Nordborg. One could argue that the utilisation of the waste heat in an interconnected grid would not only change the system by adding fluctuating heat production but the organisation and management of the two companies should change to let the utilisation occur. Even though the fluctuating waste heat would penetrate an interconnected system and cause baseload units to operate fewer full load hours, there are experiences with fluctuating heat production since Sønderborg Varme already has solar. The management of the organisation of the two companies, however, would have to change since a utilisation would require a transmission line and an exchange of heat. From an energy system perspective, there are benefits to doing so, but since the organisations do not directly cooperate, they are part of working groups managed by ProjectZero. An approach to ensure the management could be to define the cooperation in several agreements. E.g., an agreement where the exchange of heat is defined, meaning that the companies should negotiate costs for transmitting heat to the other company and the costs could reflect the variable costs of the heat production. The cost could also include fixed costs if the companies are certain to produce heat whenever needed.

The first analysis of this thesis identified barriers to utilising the waste heat from the PtX plant since the technology is different compared to the existing one. The technique and product differ from being a reliable heating source that can be produced and controlled when needed to a fluctuating heat source with no direct control of the district heating companies. The organisation and knowledge should change from two independent companies without formalised cooperation to a reorganisation of the companies based on an agreement of exchange of heat. The reorganisation would require knowledge of optimising heat production from a system perspective based on marginal costs as well as knowledge of managing an interconnected system to supply the entire system. The analysis showed that Sønderborg Varme currently has knowledge of managing a fluctuating heating source in terms of solar and there are plans to utilise waste heat from local tileworks. However, one could argue that the major challenges are the reorganisation of the companies that would both require new formalised cooperation and a change from dominant techniques to fluctuating heating sources like waste heat from PtX. According to (Lund, H., 2014) the utilisation of waste heat could cause a radical technological change since especially organisation would require a substantial change but also technique and product requires changes. To change the organisation of the district heating companies, knowledge is considered a substantial factor since it requires the companies to formalise their cooperation. Additionally, the technique would change substantially due to the shift from techniques that are controlled and managed by the companies to a fluctuating heating product managed by third parties that are heavily reliant on the electricity market and local RES electricity production. Since both technique, knowledge, and organisation change substantially, one could argue that an implementation of waste heat from PtX would cause a radical technological change. However, if the waste heat is to be utilised in an interconnected system that only includes an agreement of exchange of heat and where the cooperation between the district heating companies does not care for lowering the marginal costs of the system but only cares for delivering heat, one could argue that the implementation of waste heat does not provoke a radical technological change since the companies would continue to operate the existing dominant techniques of the system and only utilise the waste heat as a supplement to existing dominant techniques. To maintain the radical technological change existing techniques must adapt to the fluctuating waste heat product meaning that the management of existing techniques should operate in accordance with the availability of waste heat.

Conclusion

This thesis investigated the integration of waste heat from a PtX plant in the district heating systems of Sønderborg Municipality. In general, fluctuating waste heat from PtX is different from the existing heat production units because the current district heating systems in Sønderborg Municipality are mainly supplied by boilers and waste incineration. The utilisation of waste heat from PtX depends on whether the two district heating systems in Nordborg and Sønderborg are interconnected by a transmission line and on the capacity of the PtX plant. The utilisation of waste heat varies from 15% of the annual average heat production when only utilising the waste heat in the grid of Nordborg and 34-56% of the annual average heat production when utilising the waste heat in an interconnected system depending on the capacity of the PtX plant. The integration of waste heat would decrease the amount of heat production from peak load in the system. The results showed increased utilisation of waste heat when decommissioning the waste incineration plant. The results showed that integration of waste heat could be an economically feasible solution both in terms of business and socioeconomics when the system is interconnected. Additionally, the utilisation and feasibility of waste heat are sensitive to changes in full load hours on the PtX plant.

An expansion of the district heating system would increase the heat demand by 15% and presumably allow an increase in the utilisation of the waste heat but the analysis showed that district heating is 16% more costly than individual heat pumps on average in the areas included in the expansion. The results are shown to be sensitive to changes in assumptions like the costs of individual heat pumps, interest rate and heat production costs in the district heating, which could improve or decrease the feasibility of the expansion. However, since the expansions do not show a clear feasibility there is some uncertainty in the expansion of all areas, which could influence total heat demand and integration of waste heat.

Waste heat from PtX is a different heat source compared to the existing heat production units and the analyses showed that it could cause barriers for the utilisation. The analysis showed that the waste heat is different since the companies cannot directly control the availability of waste, and that the generation of waste heat depends on external factors like local RES electricity production and external factors like the electricity market. The utilisation of waste heat is proved to be feasible in an interconnected system but currently the district heating companies do not directly cooperate, which could be a barrier for utilising the waste heat.

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