Waste heat utilisation from Power-to-X in the district heating system of the Capital Region of Denmark

Master's Thesis

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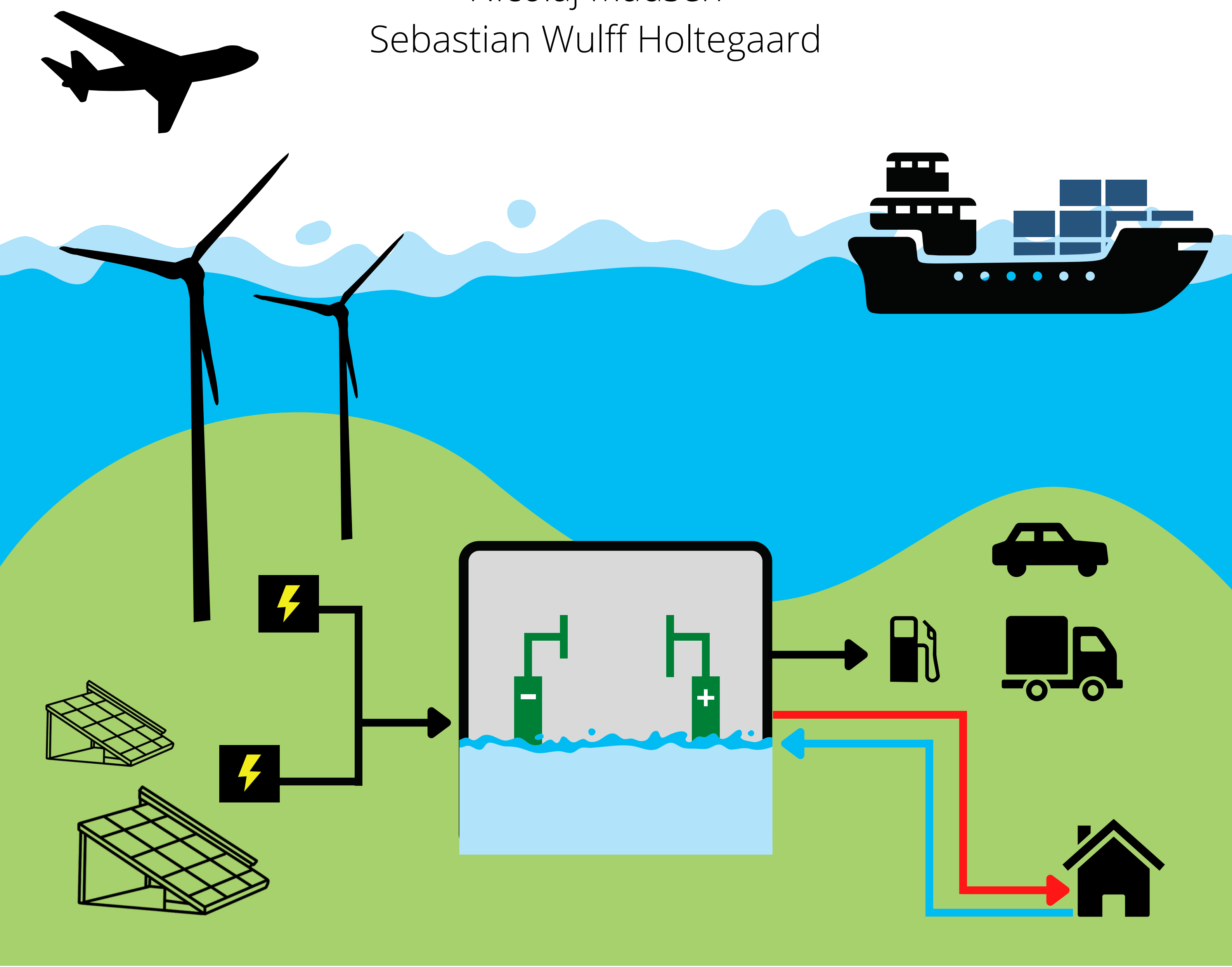

AALBORG UNIVERSITY
STUDENT REPORT

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Title:
Waste heat utilisation from Power-to-X in the district heating system of the Capital Region of Denmark

Semester:
4th semester project

Project period:
Feb. 1th 2022 - Jun. 3rd 2022

ECTS:
30

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Words: 28.842 words
Pages: 100 pages
Appendices: 15 pages

Synopsis:

As Denmark work towards achieving its 2030 and 2050 goals, increasing pressure to secure higher renewable shares in the energy sector is becoming ever more consuming in the political debate. PtX has become the umbrella concept for a series of technologies capable of producing renewable fuels from green electricity. Additionally, the processes of PtX produce heat at various stages. As such, PtX has the potential to not only influence the electricity sector by utilising variable renewable electricity when available, and the transport sector by supplying renewable fuels, but also to supply waste heat to the DH system. As such, integration of PtX have become an increasingly relevant for the green transition. This is also the case in the Capital Region of Denmark. With this, the report seek to answer the following:

"How should waste heat from PtX be integrated into the future district heating system in the Capital Region of Denmark?"

To answer this research question, a verity of methods are applied including literature study, energy system modelling and techno-economic assessment/analysis. Access to existing DH networks are essential if waste heat from PtX are to be utilised. Additionally, access to a point source of CO_2 is ideal. Two sites are selected based on GIS analysis, and PtX facilities are scaled according to the spatial requirements and available land-area in these sites. The effects of integrating waste heat into the DH system of either site is analysed using energyPRO. A techno-economic analysis is performed to determine the financial viability of the electrolyser and a potential heat pump for upgrading low temperature waste heat for use in future district heating systems, that are expected to operate at a temperature of 55°C.

Preface

This Master Thesis is written by 4th semester student form the 'Sustainable Energy Planning and Management' (SEPM4) master program at Aalborg University. The Master Thesis was written in the period from February 1st to June 3rd 2022.

The focus of the thesis have been utilisation of waste heat from PtX in the future district heating system in the Capital Region of Denmark. The thesis is therefore directed towards people with interest in these fields.

The group would like to extend thanks to Iva Ridjan Skov (Associate Professor, Department of Planning) for supervision and guidance throughout the project period. Additional thank you is extended to:

- Steffen Nielsen - Associate Professor, Department of Planning
- Peter Sorknæs - Associate Professor, Department of Planning

Reading guide

The Master Thesis is written in chronological order and it is therefore advised that it is read as such. This is to ensure that the reader has a thorough knowledge of the material read. Additionally, it is recommended that appendix is considered when referred to.

The chapters, sections, and subsections in this report are all numbered. The chapters are numbered "X", and the sections are numbered "X.X", and the subsections are numbered "X.X.X". The figures and tables are numbered according to the chapter they appear in. E.g., if a figure and a table is the first in a chapter, it is numbered "X.1". A list of figures and tables can be found after the table of contents. The applied source reference is the "Harvard-method'.

Abbreviation list

Abbreviation	Definition
4GDH	4th Generation District Heating
AEC	Alkaline Electrolysis Cell
AHP	Analytical Hierarchy Process
DEA	Danish Energy Agency
DH	District Heating
DSO	Distribution System Operator
EU	European Union
GHG	Greenhouse Gas
HFV	Hillerød-Farum-Værløse district heating system
LCoE	Levelised Cost of Energy
LCoH	Levelised Cost of Heat
NPV	Net Present Value
NØS	Nordøstsjælland district heating system
PEMEC	Polymer Electrolyte Membrane Electrolysis Cell
PtX	Power-to-X
SOEC	Solid Oxide Electrolysis Cell
SWOT	Strengths, Weaknesses, Opportunities and Threats
TEA	Techno-economic Assessment or Analysis
TRL	Technlogical Readiness Level
TSO	Transmission System Operator

Executive Summary

Global warming and its affect on the climate have forced countries in Europe to step up the transition of the energy system. As such, increasing renewability in the energy sector has been observed during the last couple of decades. However, some sectors still lack behind in the green transition. This is especially the case in the transport sector, since fluctuating renewable energy sources alone do not facilitate a sustainable transition in the short to medium term.

The emergence of new technological innovations may offer the solution. Power-to-X (PtX) have recently gained traction within the energy community as a way to utilise variable renewable electricity in times of overproduction to produce e.g. fuels such as hydrogen and methanol for use in the transport sector. Additionally, the nature of PtX allow conversion of electricity to product that are more easily stored, thereby adding flexibility to the energy system in the future.

During the process of converting renewable electricity to renewable fuels, heat is produced at various stages. This heat may vary between 70°C during reaction and 35°from the auxiliary systems, and therefore represent a potentially wasted heat source if not purposed for other uses. One such use is integration into the DH system for the benefit of the heating sector. As such, PtX may therefore act as a bridge between the electricity, heating and transport sector in the sense that electricity is used to produce fuels for use in transport while waste heat is delivered to the DH system. Additionally, the emergence of concepts such as 4. Generation District Heating (4GDH) offers further potential for utilisation of waste heat from PtX. By promoting a decrease in supply and return temperature in the DH system with 4GDH, waste heat gains additional value if utilised for DH purposes.

With this, the objective of the report have been to investigate the integration of waste heat into the future low temperature DH system with 4GDH. For this purpose, a case study of the Capital Region of Denmark is conducted to contextualise the setting within which PtX, and waste heat from PtX, is integrated. Additionally, the report is limited to investigation of PtX in the form of water electrolysis for hydrogen production. Therefore, an investigation of different types of water/steam based electrolysis is offered. The technological solutions that are investigated include: Alkaline Electrolysis Cell (AEC), Polymer Electrolyte Membrane Electrolysis Cell (PEMEC), and Solid Oxide Electrolysis Cell (SOEC). Based on assessment of the advantages and disadvantages of the individual technology, AEC is ultimately decided as the technological solution subject to further analysis.

The investigation occurred in four phases: 1) Identification of suitable locations for PtX, 2) Development of reference systems for PtX integration, 3) Integration of PtX into the reference systems, and 4) Techno-economic assessment/analysis of proposed PtX. This required extensive information gathering and data collection, and the application of a combination of abductive, deductive and inductive methods of reasoning. Additionally, to further contextualise barriers and possibilities within the setting of the report, a theoretical conceptual framework was developed based on the theory of Choice Awareness, for the purpose of promoting alternatives for the benefit of decision-making based on later findings.

Geographical information systems (GIS) analysis was conducted to identify suitable locations for PtX. This analysis was based on a series of parameters excluding locations with existing buildings, infrastructure and preserve worthy nature, and prioritising locations with access to the existing DH network. Additionally, point sources of carbon dioxide (CO_2) emissions were prioritised to allow for later expansion with e.g., methanol production, which requires carbon as a feedstock along with hydrogen. Upon more qualitative evaluation, suitable location for PtX was further limited to included areas with the possibility for delivery directly to the end-consumer by establishing business synergies. Based on this investigation, locations in Helsingør and Hillerød were identified as suitable for PtX.

To assess the affects on the energy system by establishing PtX facilities in Helsingør and Hillerød, the coherent DH systems connected to these areas were modelled. This was done using the modelling software, energyPRO. Following decisions related to operation strategy in the tool, reference models of the 'Nordøstsjælland' (NØS) and 'Hillerød-Farum-Værløse' (HFV) DH systems were developed. Based on available knowledge of the distribution networks and transmission lines between these networks, the systems were split into multiple distribution areas, each with their own set of production units and demands. The NØS DH system was divided into the distribution areas: Hornbæk Fjernvarme A.m.b.a., Forsyning Helsingør A/S, I/S Norfors, and AK Fjernvarme. The HFV DH system was divided into the distribution areas: Hillerød Forsyning Holding A/S, Farum Fjernvarme A.m.b.a, and Værløse Varmeværk A.m.b.a. Aside from production unit characteristics, transmission lines, and demands, other inputs included: electricity prices, seasonal temperatures, heat values relevant fuels, and their respective emission coefficients. Additionally, cost factors related to energy tax, emission tax, tariffs, fuel prices and variable O&M was included in the operation.

For PtX integration, a separate model for each the NØS and HFV DH systems was develop based on the reference models. Additional taxes on waste heat and upgraded heat was introduced along with hydrogen and oxygen prices. Additionally, a heat pump for each system was included to upgrade low temperature heat from the electrolysers. Waste heat from a 18 MW electrolyser was successfully integrated into the NØS DH system with the asssit of a $1,6$ MWth heat pump, while waste heat from a 33 MW electrolyser was successfully integrated into the HFV DH systems with the assist of a 3 MWth heat pump. The waste heat was successfully integrated resulting in a general decrease in fuel consumption.

To assess the techno-economic feasibility of integrating PtX in the NØS and HFV DH systems, NPV and LCoH calculations on the electrolyser and the heat pump were performed. The electrolyser in the NØS DH system had a NPV of 519 MDKK, and the heat pump - with an average heat sales price of 306 DKK/MWh - had a NPV of -4 MDKK. As a result of integrating waste heat from the electrolyser and upgraded heat from the heat pump the average heat sales price increased by 2 DKK/MWh. For the electrolyser in the HFV DH system had a NPV of 965 MDKK, and the heat pump - with an average heat sales price of 356 DKK/MWh - had a NPV of 8 MDKK. By implementing waste heat from the electrolysis process and the upgraded heat from the heat pump, the average heat sales price decreases by 1 DKK/MWh.

Due to uncertainties in gathered and generated data, sensitivity analysis is performed throughout the report. During technical assessment of system operation with PtX integration, the hydrogen and oxygen price was determined to be the most influential factors causing the electrolyser to operate as base-load regardless of electricity price. To illustrate the flexible capabilities of electrolysis, these cost factors was therefore adjusted to investigate system operation with flexible electrolysis operating in periods with low electricity prices. This resulted in intermittent production patterns, which was considered optimal renewable integration.

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Introduction 1

Global warming has been shown to be directly caused by human activities, mainly through fossil fuel burning, causing climate change. The term 'Climate change' indicates long-term changes in average weather patterns that have come to define local, regional, national, and global climates on Earth [European Commission, 2021a; United Nations, 2020]. To combat the negative effects of human activity on the climate, the need for a renewable transition of the energy sector has become more relevant than ever. As such, transition goals have been developed that move towards 2030 and 2050. These aim at a 70% reduction in CO_2-emissions compared to 1990 numbers before 2030 [State of Green, 2021, p. 4-5], and a 100% fossil-free energy system before 2050 [State of Green, 2021, p. 4].

The goals have become a central part of the Danish effort to secure the future energy supply and by promoting the integration of technologies indented to secure a renewable and stable future in Denmark. A vital part of these efforts have, and still are, the renewable transitions of the main sectors in the Danish energy mix: electricity, heating, and transport. In 2020 the renewable share in the electricity sector amounted to 73, 6% [DEA, 2020a, p. 13], and is expected to exceed 100% renewability by 2027 [DEA, 2020b], while the renewable share in district heating (DH) production amounted to 67, 7% [DEA, 2020a, p. 17]. However, the renewable share in the transport sector is still limited. As such, merely 6, 72% of the energy used for transport comes from renewable sources [DEA, 2020a, p. 27]. This is a relatively low amount compared to the collective European renewable share in the transport sector of 10, 1% as of 2020 [European Environment Agency, 2020]. A step towards increasing the renewable share in the transport sector in Denmark is the integration of Power-to-X (PtX) products such as hydrogen and/or hydrogen-derived synfuels for e.g. aviation and shipping [DDHA, 2021]. Furthermore, a new strategy for PtX in Denmark moving forward also highlights the Danish Government's vision to become an exporter of both products and technology based on PtX [Danish Ministry of Climate, Energy and Utilities, 2021, p. 45-50].

The processes associated with PtX produce waste heat [DDHA, 2021]. This therefore offers additional possibilities in the renewable transition agenda, as the integration of waste heat has become an increasingly important step in securing a sustainable transition towards a more renewable energy [Energistyrelsen, 2020]. This is evident both through the efforts of the Danish Government to stress the importance of utilising this wasted energy source and through their active implementation of recent regulatory changes to promote the use of waste heat from industrial processes in the energy mix [Danish Ministry of Climate Energy and Utilities, 2021]. As such, PtX offers a technological solution capable of acting as a link between sectors in a smart energy system approach [Lund et al., 2017b].

The use of waste heat in DH is especially relevant due to the possibility of effectively utilising centralised thermal storage facilities to integrate waste heat [Fang et al., 2013; Lund et al., 2014]. Additionally, a high heat demand density is paramount for the economic feasibility of DH [Nielsen and Grundahl, 2018, p. 3].

Power-to-X in the district heating system 2

2.1 Power-to-X

Energy - in terms of electricity, heat, etc. - is considered one of the most basic fundamental needs for human survival. Accomplishing a green transition of a country's and/or city's energy system will therefore necessitate changes to the existing system to reach their respective goals (2030 and 2050 in the Danish context) [The European Commission Directorate General for Energy, 2013; Overland, 2016]. Energy sources can, for example, be used to produce electricity and heat and are also used for transportation [Thorin, 2014].

PtX acts as an umbrella term for a series of electricity conversion, energy storage, and conversion pathways that utilise electricity. The "X" resembles the type of energy into which electricity is converted [TMI, 2021]. However, a distinction is made between PtX from renewable energy sources and fossil fuels, which determines the overall renewability of the product. As such, the product is considered renewable if inputs for the PtX process stem from renewable sources such as electricity from wind and solar and/or biogenic CO_2 as a feedstock for specific PtX processes [DDHA, 2021, p. 8]. PtX is considered an alternative option for energy storage compared to other more classical electric energy storage technologies such as mechanical storage and batteries [de Vasconcelos and Lavoie, 2019].

By using PtX, electricity from renewable sources can be converted into, e.g., hydrogen [DTU, 2021]. Furthermore, carbon-based structures can also be used in PtX technologies, making them more compatible with existing infrastructure for e.g. transportation and large-scale energy production; carbon dioxide (CO_2) is a notably abundant carbon-based feedstock that is suitable for PtX technologies [de Vasconcelos and Lavoie, 2019]. The end product would thus be hydrogen-based substances such as methanol, methane, etc. As a result, these technologies would allow for storage of renewable energy, as well as the reduction of CO_2-emissions at the source and production of renewable fuels [DTU, 2021; de Vasconcelos and Lavoie, 2019]. However, renewable electricity production from technologies such as wind turbines and photovoltaic panels pose a rather unique constraint because they fluctuate depending on the weather. This implies that the output from these systems is greater during particular periods. As such, the demand does not always match the supply, making sole reliance on these solutions a risky proposition, especially if such sustainable solutions are to be adopted on a large scale [de Vasconcelos and Lavoie, 2019].

Water electrolysis, which produces hydrogen and oxygen, is the most well-known process for producing hydrogen from renewable energy. Hydrogen produced from electrolysis processes is hailed as one of the most environmentally friendly solutions since the only biproduct is water [Carmo et al., 2013; Buttler and Spliethoff, 2018; Chi and Yu, 2018]. Electrolysis-based hydrogen production is, in many cases, still limited by cost and storage. Additionally, the process is power-intensive and as such it requires a vast amount of renewable electricity [Carmo et al., 2013; Buttler and Spliethoff, 2018; Chi and Yu, 2018].

2.1.1 Waste heat

PtX covers a wide array of technologies and processing facilities. Figure 2.1 depicts an overview of potential PtX related value chains, with hydrogen production from water electrolysis as the starting point.

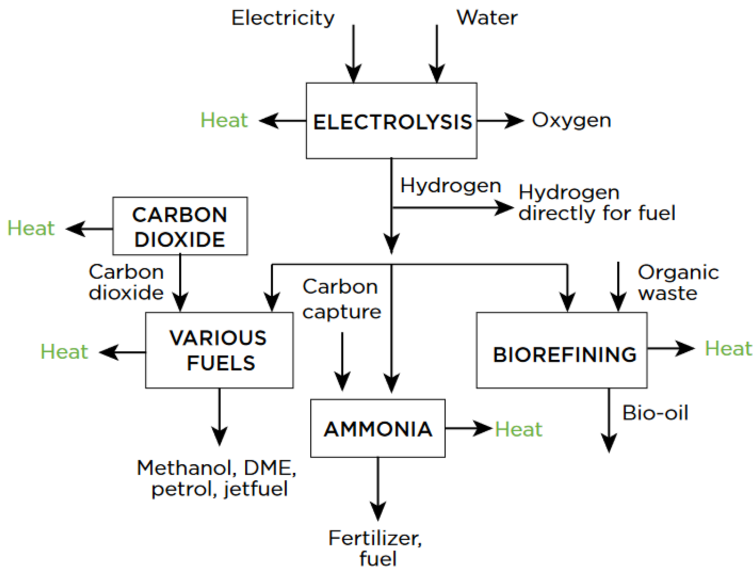

Figure 2.1. A variety of value-chains for different PtX technologies [DDHA, 2021, p. 8].

It is observed that waste heat is produced at various stages in the value chain with hydrogen as the feed stock. The share of energy that goes into the electrolysis process itself - excluding ancillary systems - that cannot be released directly by combustion of the produced hydrogen is referred to as waste heat. The amount of waste heat produced is proportional to the efficiency of the electrolysis; the less efficient the system, the more heat is generated and vice versa [DDHA, 2021, p. 52]. In that part of the PtX chain, a considerable amount of waste heat is generated. As a result of upgrading hydrogen to green fuels, more waste heat is produced due to the additional processes. As such, the proportion of potential waste heat utilisation increases [DDHA, 2021, p. 9].

The temperature (quality) of the waste heat has a considerable impact on the economic value of the heat [DDHA, 2021, p. 23]. This temperature is partly dependent on the flow from the PtX plant, and as such is an important parameter in assessing the value of the waste heat. A temperature of 60-70°C waste heat may be directly integrated depending on the supply temperature (may vary between DH distributors), while 35°C waste heat produced from the auxiliary system needs to be upgraded, e.g., via a heat pump. As such, the different temperatures have different economic value, which affects the sale of heat to benefit the economic case of the PtX plant [DDHA, 2021, pp. 12, 23 & 59]. The waste heat can be used to minimise primary energy usage and thereby indirectly contribute to CO_2 reduction and the necessity for investment in new heat supplying technologies [Broberg Viklund and Johansson, 2014]. Additionally, utilisation of waste heat may also increase the efficiency [DEA, 2021e, pp. 94-118]. The waste heat may be especially valuable if it can replace costly peak load production in the winter months [DDHA, 2021, p. 59].

The broad consensus, in the Danish context, is that waste heat from PtX can and should be used for DH. However, the concern is that, moving forward, the positive effects of sectoral integration of PtX waste heat into DH are continuously overlooked due to a lack of a clear overview and definition of the advantages of doing so [DDHA, 2021, p. 43]. The positive effects mentioned include; reduction in production cost of e.g. hydrogen, increased energy efficiency, increased green exports, etc. For further elaboration on the positive effects of integrating waste heat from PtX into the DH, it is referred to [DDHA, 2021]. However, it is evident that the potential for waste heat utilisation in the DH is present.

2.2 District waste heat utilisation

DH is expected to play a crucial role in the future energy system(s). This is also the assessment in '*IDA's Climate Response* 2045', which is the result of a research collaboration between '*Ingeniørforeningen i Danmark*' (IDA) and the Sustainable Energy Planning Research Group from Aalborg University. In the report it is described that DH is expected to cover 63% of the total heat demand by 2030 (primarily at the expense of current natural gas consumption and infrastructure), amounting to approx. 39, 5 TWh [Lund et al., 2021, p. 26]. However, it is the consensus of the scientific community that DH networks need to evolve with the times to allow for better macroeconomic energy efficiency [Böhm et al., 2021; Lund et al., 2021; Mathiesen et al., 2021]. An example hereof is a DH system that allows integration of new heat sources such as waste heat, geothermal, and solar heat to a larger extent. A possible evolution of the DH network(s) is offered by [Lund et al., 2014] with a transition to *4th generation district heating* (4GDH). The concept is intended as an integrated part of smart energy systems [Lund et al., 2017b] and introduce a definition to the concept of *smart thermal grids* in connection to concepts of *smart electricity grids* and *smart gas grids* [Lund et al., 2014, 2017b]. The idea of 4GDH is to establish distribution networks with temperatures as low as 50°C in the supply pipes and 20°C in the return pipes [Lund et al., 2014, p. 4]. A more conservative temperature level in the supply pies is 55-65°C and 25-35°C in the return pipes [Sorknæs et al., 2020, p. 2]. This would enable recycled heat from low-temperature sources and further integration of renewable heat sources. 4GDH offers better conditions for a centralised DH grid with a number of distributed heating and cooling units as grid buffers, intended to lower costs and grid losses [Lund et al., 2014, p. 4]. As such, the concept offers more opportunities to effectively utilise waste heat from both high- and low-temperature heat sources such as those originating from processes of PtX production [Böhm et al., 2021].

To utilise waste heat from PtX effectively, certain barriers/uncertainties have to be addressed. Aside from the inherent economical barriers and uncertainties that are inevitably associated with new technological advancement as PtX is established as a reliable and stable technological alternative, chances are that waste heat produced from PtX are effectively limited due to more effective processes [Böhm et al., 2021, p. 31939]. This could potentially destabilise the security of the DH supply if the system is made dependent on waste heat from PtX [Rambøll, 2021, pp. 5-6]. This is also a concern raised in '*Varmeplan Danmark* 2021' [Mathiesen et al., 2021, pp. 14-15], despite the 'Technology Readiness Level' (TRL) of PtX indicating a relatively mature technological alternative, especially for hydrogen production [Rambøll, 2021, p. 6].

Additional uncertainties regarding the temporal profiles and spatial availability of renewable electricity sources limit the number of suitable location for PtX [Burre et al., 2020; Böhm et al., 2021]. This is especially the case due to the power-intensive nature of PtX, as mentioned in section 2.1, which also raises concerns as to the overall readiness of the transmission grid. This is despite an otherwise well-developed existing energy infrastructure for both electricity and heating in Denmark [DDHA, 2021, p. 47]. Adding hereto, an important part of integrating the waste heat is to limit thermal grid losses, which may require close proximity to centralised DH plants [Lund et al., 2014, p. 4]. This further limits suitable locations for PtX, since the temperature of the waste heat needs to supplement the existing DH supply in a manner that

maintains high energy efficiency. Therefore, suitable feed-in locations for the waste heat must be identified, which consider existing DH networks and infrastructure, and possible synergies such as synergy with district cooling [DDHA, 2021, p. 47].
Additional uncertainties related to the location of PtX may include, but are not limited to, access to a clean and stable water supply, and availability of resources such as carbon (preferably from waste and biomass sources) and nitrogen (preferably from atmosphere) for certain PtX-products [DDHA, 2021; Böhm et al., 2021; Burre et al., 2020]. As such, the identification of suitable locations for PtX is not only a matter of temporal and spatial availability of renewable energy sources and access to energy infrastructure, but also a matter of the availability of raw materials with a certain quality [Burre et al., 2020, p. 78].

The integration of waste heat from PtX will ultimately be a balance between heat demand and market demand, since the demand for PtX will directly affect what type(s) of PtX product(s) that is produced and what technological solutions (state-of-the-art) that are applied to produce for this demand. Regardless of the efficiency (affected by state-of-the-art), the waste heat that is produced should be utilised for DH if possible. To maximise the utilisation of the waste heat that is produced, this may require PtX production decentralised across Danish regions, thereby imposing a limit on the amount of PtX facilities in individual areas. Additionally, waste heat produced from PtX has to compete not only with the conventional heat supply, but also with other waste heat sources [Böhm et al., 2021, pp. 31945-31946]. As such, an important part of utilising the waste heat in the DH is to determine when and where integration is the most suitable alternative, which is determined on a variety of factors. Some of these factors are described in [Böhm et al., 2021, p. 31945] and include - apart from the already mentioned - cost of recovery, short-term constancy, presence of back-up systems etc.

Additional barriers and uncertainties associated with PtX are described in [Skov et al., 2021], which is an in-depth analysis applying the analytical hierarchy process (AHP) to evaluate and compare different academic and industrial experts' perspectives on the most common strengths, weaknesses, opportunities and threats (SWOT) for PtX as an innovative new technology.

Based on the uncertainties, it is argued that either of the six largest DH systems in Denmark also represent the most attractive areas for locating PtX [DDHA, 2021, pp. 26 & 47]. Coincidentally, these six areas are located around the larger Danish cities and urban areas (Aarhus, Aalborg, Esbjerg, Odense, the Triangle Region, and the Capital Region).
According to the Danish Energy Agency (DEA), the six areas produce and distribute approx. 67 petajoules (PJ) of heat from DH per year. This is compared to approx. 400 smaller decentralised DH areas spread throughout Denmark, which produces approx. 53 PJ of heat from DH per year [DEA, 2015, p. 4]. Of the 67 PJ provided by the six largest DH systems in Denmark, approx. 28 PJ stems from the Capital Region of Denmark, thereby making it the largest DH systems in Denmark and the area with the potentially best opportunities - based on the previous - to utilise PtX to its full extent.

2.3 Capital Region of Denmark

In the Capital Region of Denmark there is a total of 29 municipalities and they are home to $1,8$ million people, about 32% of the Danish population, yet covers 6% of the total area of Denmark. At the same time, it is responsible for 40% of GDP [Region Hovedstaden, 2020, 2022]. It is expected by 2030 that the population of the Capital Region will further increase by 130.000 people, further increasing the population density and creating greater need for heating in the region. [Region Hovedstaden, 2020]. As a result of this population density, the region is naturally quite heavily urbanised and space for development is in high demand. One example of this comes in the form of a proposal for artificial islands that can provide space for the development of industry. [Vilsbøll, 2019].

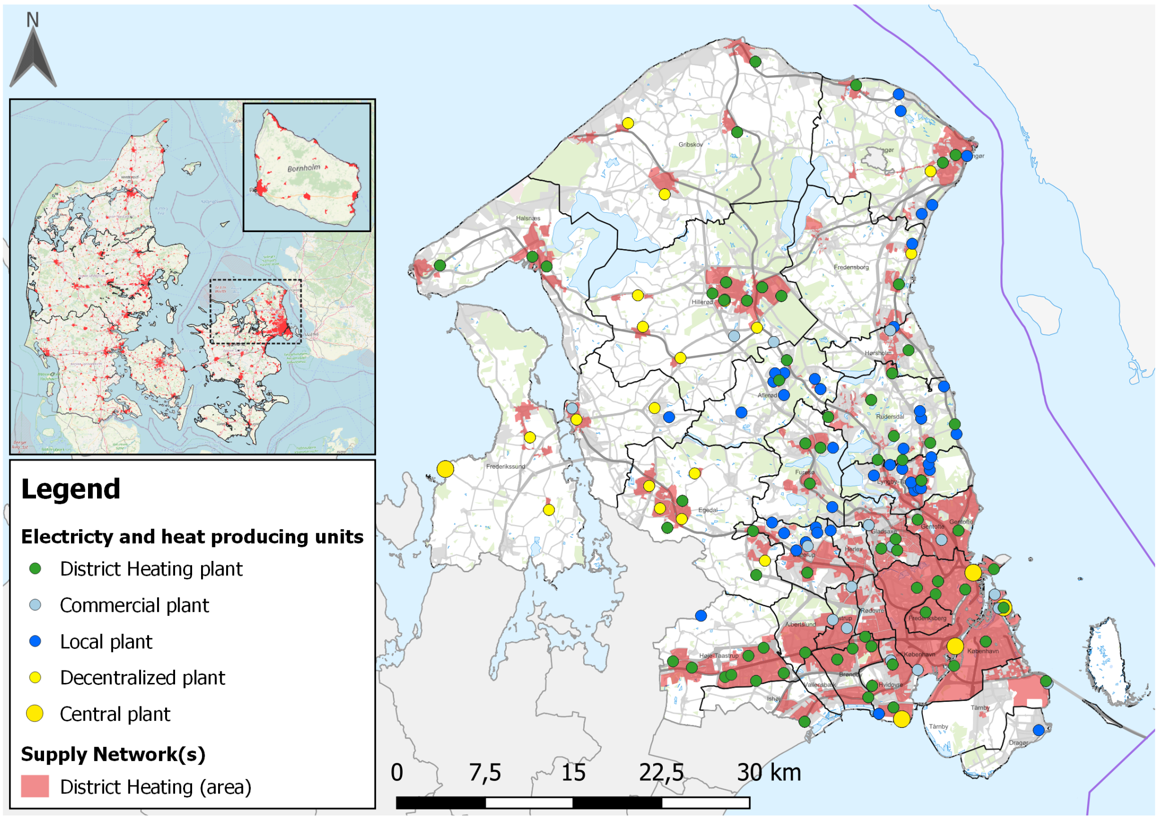

Figure 2.2. DH network(s) and electricity and heat producing units in the Capital Region of Denmark [Erhvervsstyrelsen, 2021; Open Data DK, N/A]

The DH system in the Capital Region consists of 21 separate DH grids delivering 28, 27 PJ, approx. 28% of Denmarks' national heating demand; 95% of this heat is currently produced by combined heat and power plants, utilising waste and biomass [Rambøll, 2020]. Districts and production plants located in the Capital Region of Denmark are illustrated on figure 2.2. This system will undergo changes moving forward as the system seeks to move away from reliance on biomass and waste incineration and incorporate better utilisation of wind energy in the form of heat pumps, electric boilers, and thermal storages. [Rambøll, 2020]. Given the future heating system will be setup to utilise periodically low electricity prices, introducing PtX industries that produce waste heat in a similar production pattern to the proposed heating technologies, should be possible. This is further supported by the issue of transitioning the Capital Region of Denmark, while balancing massive urban development and increased demand on the power grid, with transformation of the means of heat production. In this regard, and apart from delivering high quality waste heat from the electrolyser, PtX also offers new opportunities to utilise large heat pumps due to low-temperature heat sources in the auxiliary system(s) [DDHA, 2021, pp. 26 & 53] (see also section 2.1.1).

The municipalities of Greater Copenhagen along with the major DH companies in the area originally set an ambitious goal of reaching CO_2 neutrality by 2025 [Ea Energianalyse, 2021]. Although this goal does not appear to be feasible within the timeline, the involved parties are still striving to reach CO_2 neutrality [Danskfjernvarme, 2021]. This is supported by a relatively high share of renewable DH in most of 29 municipalities located in the Capital Region of Denmark, as illustrated in table 2.1. As such, the average share of renewable DH is approx. 57% for the entire region.

Table 2.1. Municipalities located in the 'Captial Region of Denmark' with their respective DH consumption and their share of renewable heat used. All the related data for the individual municipalities is from 2019 with the exception of Hørsholm municipality that data is from 2016 [SparEnergi, 2022].

Municipality	**DH consumption [GWh]**	**Share of renewable [GWh]**	**Share of renewable [%]**
Albertslund	158, 06	98, 50	62, 32%
Allerød	30, 28	22, 33	73, 76%
Ballerup	107, 22	66, 83	62, 33%
Bornholm	229, 72	154, 75	67, 36%
Brøndby	288, 33	179, 69	62, 32%
Dragør	0, 00	0, 00	0, 00%
Egedal	52, 50	11, 19	21, 32%
Fredensborg	110, 56	83, 06	75, 13%
Frederiksberg	741, 67	462, 19	62, 32%
Frederikssund	87, 50	36, 83	42, 10%
Furesø	139, 44	71, 64	51, 37%
Gentofte	427, 78	266, 58	62, 32%
Gladsaxe	192, 78	120, 14	62, 32%
Glostrup	2, 22	1, 39	62, 50%
Gribskov	62, 22	20, 03	32, 19%
Halsnæs	131, 67	98, 58	74, 87%
Helsingør	406, 11	305, 08	75, 12%
Herlev	133, 06	82, 92	62, 32%
Hillerød	221, 94	109, 17	49, 19%
Hvidovre	206, 11	128, 36	62, 28%
Høje-Taastrup	286, 39	178, 47	62, 32%
Hørsholm	74, 44	55, 92	75, 11%
Ishøj	71, 11	44, 31	62, 30%
København	4302, 50	2681, 31	62, 32%
Lyngby-Taarbæk	68, 33	39, 75	58, 17%
Rudersdal	123, 89	29, 86	24, 10%
Rødovre	147, 22	91, 75	62, 32%
Tårnby	183, 06	114, 08	62, 32%
Vallensbæk	58, 89	36, 69	62, 31%

While there is still significant uncertainty regarding the specific role of PtX in the future heating system, it is believed to have significant potential [Ea Energianalyse, 2021, pp. 5 & 30]. This is further supported by the renewable share of DH in the individual municipally, as illustrated in table 2.1, leaving space for the waste heat of PtX to be incorporated in the DH system(s).

2.3.1 Energy visions and strategies

The Capital Region of Denmark have in collaboration with its 29 municipalities, and likewise the affected supply companies developed goals for the future energy/heat supply in the region. It could be argued that the goals set out by the Capital Region of Denmark stem from the UN's *'Sustainable Development Goals (SDG)'* agenda that withholds actions regarding people, planet and prosperity [United Nations, 2015b] and the so-called *'Paris Agreement' (COP-21)* which was the first global, comprehensive, and legally binding climate agreement [United Nations, 2015a]. As such, the aforementioned global agreements have altered today's approach to development, which also promotes the energy sector to consist of more renewable sources. This shift in paradigm has been reinforced at several levels, most notably at the supranational level in the 'European Union' (EU), where the current energy visions and strategies reflect the goals/aim of the Paris Agreement. Denmark - as a member nation of EU - is required to develop national strategies and, moreover, visions that align with the overarching EU goals. This is stated in the the mandatory EU strategy *'Integrated National Energy and Climate Plan' (NECP)* that spans for the period 2021-2030 [Danish Ministry of Climate, Energy and Utilities, 2019]. However, the individual members state have the possibility to further adopt the EU's goals by developing more ambitious goals. An example hereof is evident from the Danish 2030 goal; the EU's goal is 55% CO_2 reduction compared to 1990, while the goal in Denmark is 70% reduction compared to 1990 [European Union, 2021; Danish Ministry of Climate, Energy and Utilities, 2020]. However, it is up to the individual municipalities as to how they will accomplish the commitments.

In table 2.2 an overview of the current Danish agreements that concerns the energy and climate sector and the energy and environmental goals for the Capital Region of Denmark are shown.

Table 2.2. Overview of the current Danish agreements in the energy and climate sector and visions and strategies for the Capital Region of Denmark.

Agreement	**Objective / Goal**	**Reference**
Energy Agreement 2018	Net zero-emission society by 2050 No coal usage in electricity production after 2030 55% renewable energy of total energy consumption by 2030	[Danish Ministry of Climate, Energy and Utilities, 2018]
Climate Law 2019	70% reduction of GHG-emissions by 2030 Climate-neutral by 2050	[Danish Ministry of Climate, Energy and Utilities, 2020]
Danish NECP 2019	70% reduction of GHG-emissions by 2030 55% renewable energy in total energy consumption by 2030 >100% of electricity from renewable energy by 2030 90% of DH is renewable by 2030	[Danish Ministry of Climate, Energy and Utilities, 2019]
Capital Region of Denmark visions and strategies	**Objective / Goal**	**Source**
FFH50	CO_2 neutral DH by 2050	[Vestforbrænding et al., N/A]
'Energi På Tværs'	Fossil-free electricity supply by 2035 Fossil-free heat supply by 2035	[Energi På Tværs, 2018a,b]

Water Electrolysis Technologies 3

Hydrogen is a crucial component of PtX production. As such, the first step in the PtX-process is often the production of hydrogen either for direct use or as a component in other PtX products such as methanol or ammonia [Dansk Energi, N/A]. In this regard and with an increasing amount of renewable electricity being introduced into the Danish energy-mix [DEA, 2020b], electrolysis offers a green solution to hydrogen production from water.

This chapter aims to explore the water electrolysis process by assessing the characteristics and specifications of different types of electrolysis technologies. As such, following a brief introduction to the principle of water electrolysis, three electrolysis technologies are subsequently presented. These technologies include: 'Alkaline Electrolysis Cells' (AECs), 'Polymer Electrolyte Membrane Electrolysis Cells' (PEMECs), and 'Solid Oxide Electrolysis Cells' (SOECs). This is followed by a summary of the advantages and disadvantages of these technological solutions for producing hydrogen through water electrolysis.

3.1 The Principle of Water Electrolysis

The working principle of water 'electrolysis' is to use electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O). The basic process of electrolysis is illustrated by the following chemical reaction [DEA, 2021e, p. 94]:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{3.1}$$

The reaction occurs in a unit called an 'electrolyser'. This unit may vary greatly in size and capacity. The splitting of water into hydrogen and oxygen, respectively, occurs in two reactions at the two electrodes (cathode (-) and anode (+)). 'Charge equalisation' occurs between the two reactions (cathode and anode) via ion conduction through an electrolyte (substance that is electrically conductive). Furthermore, a membrane/separator is also required to separate the two reactions and prevent the resultant gases from mixing with one another. Depending on the electrolysis technology, the ion charge as well as the kind of electrolyte used, varies (illustrated in figures 3.1, 3.2, and 3.3) [Hussy, 2021]. For all three aforementioned technological solutions (AEC, PEMEC, and SOEC), the main output is hydrogen, oxygen, and waste heat, however, to varying degrees [DEA, 2021e, p. 96]. In regard to the waste heat, a distinction between the heat that is produced as a result of the chemical reaction of creating hydrogen (water electrolysis), and the waste heat from the auxiliary systems (compressors, rectifiers, pumps etc.) is made. For the auxiliary systems, a temperature of 35°C is expected for all three technological solutions [DDHA, 2021, p. 53].

3.1.1 Alkaline Electrolysis Cell (AEC)

Alkaline electrolysis is a process that uses electricity and water as inputs for the ensuing reaction and operates at a temperature of 65-90°C under either atmospheric pressure or pressurised conditions (up to 35 bar). The electrodes used are either made up of steel or nickel and is separated by a micro-porous diaphragm to avoid the hydrogen and oxygen from mixing. The electrolyte used in AEC is of alkaline nature (either potassium hydroxide (KOH) or sodium hydroxide (NaOH)) [DEA, 2021e, p. 95].

Alkaline Electrolysis is the most commercially available electrolysis technology of the three and has a TRL of 9. A TRL of 9 implies that the technology is "*actual system proven in operational environment*" [European Commission, 2021b, p. 29]. The TRL of 9 was reasoned by the fact that AEC is able to have installed capacities up to 100 MW [Rambøll, 2021, p. 47].

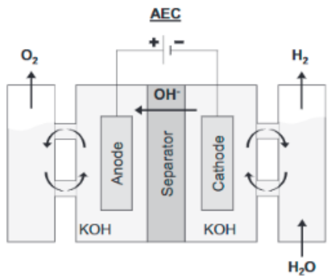

Figure 3.1. Operating principle of AEC [DEA, 2021e, p. 94].

Figure 3.1 illustrates the operating principle of AEC. First, water is introduced to the cathode and during the process of electrolysis, OH^- ions are transported across the membrane/separator to create hydrogen and oxygen [DEA, 2021e, p. 95]. The reactions at both the cathode and anode are illustrated in the following chemical reactions:

Reaction at cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{3.2}$$

Reaction at anode:

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \tag{3.3}$$

Table 3.1 list the technical specifications for hydrogen production from AEC for both a 1MW and 100MW plant for the years 2020 and 2030 respectively. For AEC, the electricity input is 100% regardless of the scale and year. The amount of hydrogen increases by $0,4$ kg/MWh input$_e$ towards 2030. By scaling the AEC, there is a general trend; the amount of unrecoverable heat decreases (2%-points) for both 2020 and 2030. Furthermore, the amount of recoverable heat increases (2%-points). For 2020 the expected temperature from AEC - that can be used in the district heating - is 50°C, however it is expected to increase to 70°C in 2024 [DEA, 2021e, pp. 96-114].

Table 3.1. Hydrogen production via AEC for both a 1MW and 100MW plant for 2020 and 2030, according to [DEA, 2021e, pp. 107-110].

	2020		2030	
	1 **MW AECs**	100 **MW AECs**	1 **MW AECs**	100 **MW AECs**
Input				
Electricity (input$_e$) [% total input (MWh/MWh)]	100%	100%	100%	100%
Water for electrolysis [kg/MWh input$_e$]	180	180	184	184
Output				
Hydrogen [kg/MWh input$_e$]	20, 0	20, 0	20, 4	20, 4
Heat loss [% total input$_e$ (MWh/MWh)]	21, 4%	21, 4%	19, 6%	19, 6%
- Hereof unrecoverable heat [%-points of heat loss]	5, 0%	3, 0%	5, 0%	3, 0%
- Hereof recoverable heat [%-points of heat loss]	16, 4%	18, 4%	14, 6%	16, 6%

3.1.2 Polymer Electrolyte Membrane Electrolysis Cell (PEMEC)

Polymer Electrolyte Membrane Electrolysis also has two electrodes and they are in direct contact with a 'proton exchange polymer electrolyte membrane' (often perfluorosulfonic acid (PFSA)), which forms a membrane electrode assembly (MEA) [DEA, 2021e, p. 95]. PEMEC operates at a temperature between 50-80°C and is furthermore able to operate at pressurised conditions up to 80 bar or more [Rambøll, 2021, p. 47].

PEMEC has a TRL of 7, due to capacity in the single digit MW scale [Rambøll, 2021, p. 47]. A TRL of 7 implies that "*system prototype demonstration in operational environment*", meaning success with large-scale demonstration is not yet achieved [European Commission, 2021b, p. 29].

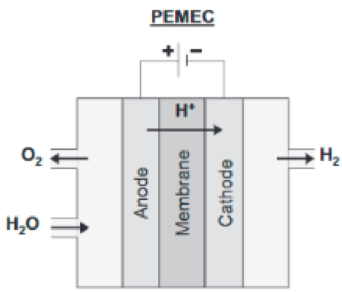

Figure 3.2. Operating principle of PEMEC [DEA, 2021e, p. 94].

Figure 3.2 shows the operating principle of PEMEC. PEMEC operates by introducing water at the anode and by adding electricity, the H^+ ions are transported across the membrane and consequently the hydrogen is separated from the oxygen [DEA, 2021e, p. 95]. The operating principle of PEMEC is illustrated below in the form of chemical reactions at both the anode and cathode:

Reaction at anode:

$$H_2O \rightarrow \frac{1}{2}O_2 + 2e^- + 2H^+ \tag{3.4}$$

Reaction at cathode:

$$2H^+ + 2e^- \rightarrow H_2 \tag{3.5}$$

Table 3.2 illustrates the technical specifications for hydrogen production from PEMEC for a 1MW and 100MW plant for both 2020 and 2030. Like AEC, PEMEC also uses 100% electricity input regardless of the scale and year. As time progresses towards 2030 the hydrogen output increases by 2, 3 kg/MWh input$_e$. As the technology is further developed towards 2030, a decrease in general heat loss (8, 8%-points) due to higher efficiency is expected, while also recoverable heat (8, 8%-points) heat is achieved, while the unrecoverable share is maintained. As such, the decrease in recoverable heat is explained by the higher efficiency in the internal processes since the unrecoverable share remains the same.

Table 3.2. Hydrogen production via PEMEC for both a 1MW and 100MW plant for 2020 and 2030, according to [DEA, 2021e, pp. 111-114].

	2020		2030	
	1 **MW PEMECs**	100 **MW PEMECs**	1 **MW PEMECs**	100 **MW PEMECs**
Input				
Electricity (input$_e$) [% total input (MWh/MWh)]	100%	100%	100%	100%
Water for electrolysis [kg/MWh input$_e$]	157	157	177	177
Output				
Hydrogen [kg/MWh input$_e$]	17, 4	17, 4	19, 7	19, 7
Heat loss [% total input$_e$ (MWh/MWh)]	31, 4%	31, 4%	22, 6%	22, 6%
- Hereof unrecoverable heat [%-points of heat loss]	5, 0%	3, 0%	5, 0%	3, 0%
- Hereof recoverable heat [%-points of heat loss]	26, 4%	28, 4%	17, 6%	19, 6%

3.1.3 Solid Oxide Electrolysis Cell (SOEC)

Solid Oxide Electrolysis is the most recently developed water electrolysis technology of the three. It differs from AEC and PEMEC due to the use of steam instead of water; and operates at a temperature between 600-1000°C [Rambøll, 2021, p. 47]. The electrolyte used for SOEC is an oxide ion conducting solid phase component (typically yttria stabilised zirconia (YSZ)). The cathode consists of a composition of nickel and YSZ to enable/ensure hydrogen production. The anode is however made up of ionic-electronic conductors, which typically is a mixture of lanthanum strontium manganate (LSM) and YSZ [DEA, 2021e, p. 95].

Solid Oxide Electrolysis has a TRL of 5, which implies the following: "*technology validated in relevant environment*" [Rambøll, 2021; European Commission, 2021b]. This TRL is reasoned by only kW size plants having been demonstrated [Rambøll, 2021, p. 47].

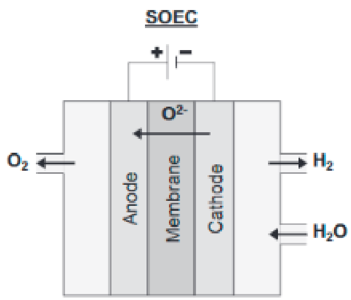

Figure 3.3. Operating principle of SOEC [DEA, 2021e, p. 94].

Figure 3.3 illustrates the operating principle for Solid Oxide Electrolysis. Under the electrolysis process - where steam and electricity is added - O^2- ions are transported across the solid electrolyte, thus separating the hydrogen and oxygen [DEA, 2021e, p. 95]. The chemical reaction of this process at both the anode and cathode is as follows:

Reaction at anode:

$$H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{3.6}$$

Reaction at cathode:

$$2O^{2-} \rightarrow O_2 + 4e^- \tag{3.7}$$

Table 3.3 illustrates the technical specifications for hydrogen production from SOEC for a 1MW plant for the years 2020 and 2030. SOEC is currently in the demonstration phase for up-scaling, meaning no large scale applications for SOEC are demonstrated to date [DEA, 2021e, p. 100]. SOEC further distinguishes itself from AEC and PEMEC in that it utilises heat as an input. As such, the electricity input only accounts for 79, 5% (2020), while the remaining input is heat. The hydrogen output increases by 0, 9 kg/MWh input towards 2030 and the heat loss decreases by 3, 6%-points. SOEC does not allow for utilisation of waste heat in the DH because it is used internally to produce steam [DEA, 2021e, p. 96].

Table 3.3. Hydrogen production via SOEC for a 1MW plant for 2020 and 2030, according to [DEA, 2021e, pp. 107-110].

	2020 1 **MW SOECs**	2030 1 **MW SOECs**
Input		
Electricity (input$_e$) [% total input (MWh/MWh)]	79, 5%	80, 5%
Heat [%total input (MWh/MWh)]	20, 5%	19, 5%
Water for electrolysis [kg/MWh input$_e$]	209	217
Output		
Hydrogen [kg/MWh input]	23, 3	24, 2
Heat loss [% total input$_e$ (MWh/MWh)]	8, 4%	4, 8%

3.2 Summary of Electrolysis Technologies

Table 3.4 summarises the advantages and disadvantages of the three technological solutions for water electrolysis: AEC, PEMEC, and SOEC. It is found that Alkaline Electrolysis has the highest TRL of the three technologies, because of already existing installed capacities of 100 MW. This is, among other things, reflected by the fact that AEC has the lowest investment cost. It is possible to utilise some amount of waste heat related to both AEC and PEMEC for district heating purposes, however the total amount varies. PEMEC has the highest degree of recoverable heat, whereas AEC lacks behind by a couple of %-points. AEC, however, has a higher efficiency of hydrogen production compared to PEMEC; SOEC has the highest efficiency of the three electrolysis technologies but lacks the possibility for up-scaling currently.

Table 3.4. Summary of the advantages and disadvantages of AEC, PEMEC, and SOEC.

Technology	Advantages	Disadvantages
AEC	TRL 9 (100 MW scale) Low investment cost Low spatial requirements	Medium efficiency Medium amount of recoverable heat (compared to PEMEC)
PEMEC	Low investment cost Highest amount of recoverable heat (compared to AEC)	TRL 7 (single-digit MW scale) Medium efficiency Medium spatial requirements
SOEC	High efficiency	TRL 5 (kW scale) High investment cost Medium spatial requirements No recoverable heat

Problem formulation 4

Transition to renewable heat production in the Capital region of Denmark is an ambitious endeavour. This is not least due to the simultaneous need to balance massive urban development, which puts increasing demand on the electricity grid, with partly conversion of current heat production, as mentioned in section 2.3. The Capital Region of Denmark must seek new and alternative ways of securing its heating supply to accommodate the green transition. The emergence of PtX to support the transition of otherwise challenging sectors, such as the transport sector, offers new opportunities for the heating sector. One such opportunity is the integration of waste heat produced from PtX in the DH network(s). The waste heat from the electrolysis process has been shown to offer sufficient quality (temperature) for both direct integration in the DH and for utilising large heat pumps, as mentioned in section 2.2. This may be especially relevant with the emergence and transition to 4GDH, which allows for lower supply and return temperatures in the DH system, as mentioned in section 2.2. However, questions of how, when, and at what scale the integration of waste heat from PtX should be integrated should be investigated.

Therefore, the report seeks to answer the following:

> *"How should waste heat from PtX be integrated into the future district heating system in the Capital Region of Denmark?"*

To answer the problem formulation, multiple factors need to be considered.

Suitable location for PtX in the Capital Region of Denmark need to be identified. This require extensive analysis of the geographical setting within the region. As such, consideration related to access, limitations and possibilities should be investigated. Based on the identification of suitable location, integration with the DH system in these areas should be investigated. This is to insure, that waste heat is integrated into the energy-mix benefit the overall renewability of the system. Finally, the investigation should include financial considerations. This is essential since the final decision to establish PtX will inevitably depend on the techno-economic implications of the proposed plants.

For these reasons, the problem formulation is supported by a multitude of subquestions, which are stated in the following:

- What are suitable locations for the establishment of PtX plants subject to existing conditions and the desire to integrate waste heat from PtX processes into the DH system?
- What are the effects of implementing waste heat from PtX into the DH systems of the identified suitable locations?
- What are the techno-economic implications of the proposed PtX plants?

4.1 Delimitation

The island of Bornholm is, for administrative purposes, a part of the Capital Region of Denmark. However, the energy system of the island is inherently isolated with higher dependency on local sources of energy, especially in the transition to 100% renewability. Several papers have been developed offering insight into the unique situation of island communities and their struggle to achieve high levels of self-sufficiency in terms of renewable utilisation. For further reference to these papers, it is referred to [Marczinkowski et al., 2019]. Some inspiration may be drawn from the experiences of the island of Samsø. The island has achieved self-sufficiency from local renewable energy sources. As such, 100% of the electricity supply on the island comes from renewable sources (primarily from wind), while the percentage of renewable energy for heat is 70% (primarily from biomass), which is compensated by export of electricity to the mainland from offshore wind turbines. However, the transportation sector still needs to be addressed before a fossil-free island can be achieved [renewables networking.eu, N/A; SMILE, 2020]. This further stresses the relevance of locating and utilising PtX technologies to produce hydrogen and synthetic e-fuels from renewable electricity, as mentioned in section 2.1, for use in the local energy system of islands.

In the case of Bornholm, this is further supported by the DEA's intentions to establish the worlds first energy islands in the North and Baltic seas. In the Baltic Sea, Bornholm is intended to serve as a hub for offshore wind farms by hosting electrotechnical facilities on the island to handle 2 GW of energy [DEA, 2021b]. Based on these plans, an investigation was carried out by researchers from the Technical University of Denmark (DTU) to identify optimal locations for PtX facilities to produce hydrogen in conjunction with the energy island [Singlitico et al., 2020]. It was determined that by placing PtX on Bornholm, it would be possible to lower the cost of production due to a lower grid connection cost. However, it would also limit the possibility of producing certain PtX-products due to limited access to CO_2 sources. On Bornholm, these sources is mostly comprised of biomass combustion in combined heat and power (CHP) plants and biogas produced on the island. Additionally, due to the relatively low heat demand compared to the Copenhagen area, the possibility of utilising waste heat from PtX is limited [Singlitico et al., 2020]. This is despite the DH network supplying $93,2\%$ of the total heat demand while also representing $63,6\%$ of the total CO_2-emissions connected to heat production [SparEnergi.dk, 2019]. Bornholm is therefore not included in the scope of the investigation. As such, the geographical area subject to investigation is limited to the mainland of the Capital Region of Denmark.

Hydrogen consumption in Europe is expected to increase significantly towards 2030 and 2050. This is also the assessment of Green Power Denmark (previously 'Dansk Energy'). In 2020, Green Power Denmark released a report projecting the consumption of hydrogen to increase five to six fold by 2050, and especially in the period from 2030 to 2050 where the demand is expected to quadruple [Dansk Energi, 2020, pp. 18-19]. The expected increase in hydrogen consumption is partly explained by the need for hydrogen as a feedstock in the production of other PtX products such as methanol and ammonia, as mentioned in chapter 3. This tendency is highlighted by an increase in the market value of companies investing into green hydrogen production of between 300-500% leading up to 2020 [Dansk Energi, 2020, p. 20].
Following this market trend, an increase in electrolysis capacity is therefore expected to produce green hydrogen utilising the increasing green electricity share in the Danish electricity grid [DEA, 2020b]. As mentioned in chapter 3 this increasing capacity for electrolysis is inevitably accompanied by waste heat production, which should be integrated into the Danish DH systems. As such, the investigation is limited to waste heat from the electrolysis process as the PtX technology subject to investigation.

Research design 5

The research design is useful to establish an overview and/or a guideline to help the researcher steer the investigation towards the intended goal. Developing a research design is therefore considered part of the planning towards how and in which order research should be conducted. More specifically, it is considered a map on how to get from the 'beginning' to the 'end' of the investigation, which is an important part of the empirical and problem-oriented study [Farthing, 2016; Yin, 2018]. Preceding any preliminary analysis, the research that is conducted in the report is offered based on the problem formulation stated in chapter 4. Therefore, the problem formulation is considered as the 'beginning' of the investigation. This also means that the subsequent 'end' of the investigation is represented by the answer or conclusion fitting the problem formulation. Getting from the 'beginning' to the 'end' of the investigation typically requires both methods of data gathering and a theoretical foundation to connect empirical data to the context or situation in question [Yin, 2018]. For this reason; methods, theories, and reasoning's are included in the research design. The research design is illustrated in Figure 5.1.

It is argued that preliminary research is dominated by an abductive method of reasoning. As such, the concept and phenomenons of PtX are observed through predominantly literature study in chapter 2. Potential for utilisation of waste heat from the processes of water electrolysis is observed and the technical specifications are explored in chapter 3. These observations are considered in the context of the green transition in Denmark and a selected case area. This leads to the inevitable hypothesis that waste heat from PtX would benefit the renewable transition of the DH system in the case area. This hypothesis is posed as a question in section 4 in accordance with the methods of abduction described in section 7.2.1.

Following this, it is argued that the second part of the investigation is dominated by a deductive method of reasoning. As such, a number of empirical predictions are produced based on the hypothesis. These empirical predictions are represented by the subquestions posed in chapter 4. These subquestions are meant to support the hypothesis by offering valuable insight into the consequences hereof. For this purpose, a necessary theoretical perspective is established. This theoretical perspective is described in section 6.2.

Lastly, it is argued that the last part of the investigation, leading to the conclusion, is dominated by an inductive method of reasoning. As such, the hypothesis and empirical prediction are tested and compared with the results of the investigation. This included evaluation/assessment of uncertainties and initially excluded considerations, and their potential impact on the result. Finally, conclusions are arrived at to answer the hypothesis.

With this, the abduction, deduction, and induction phases are illustrated in the research design in figure 5.1. Use of methods is described in chapter 8, and the application of theory is described in section 6.2.

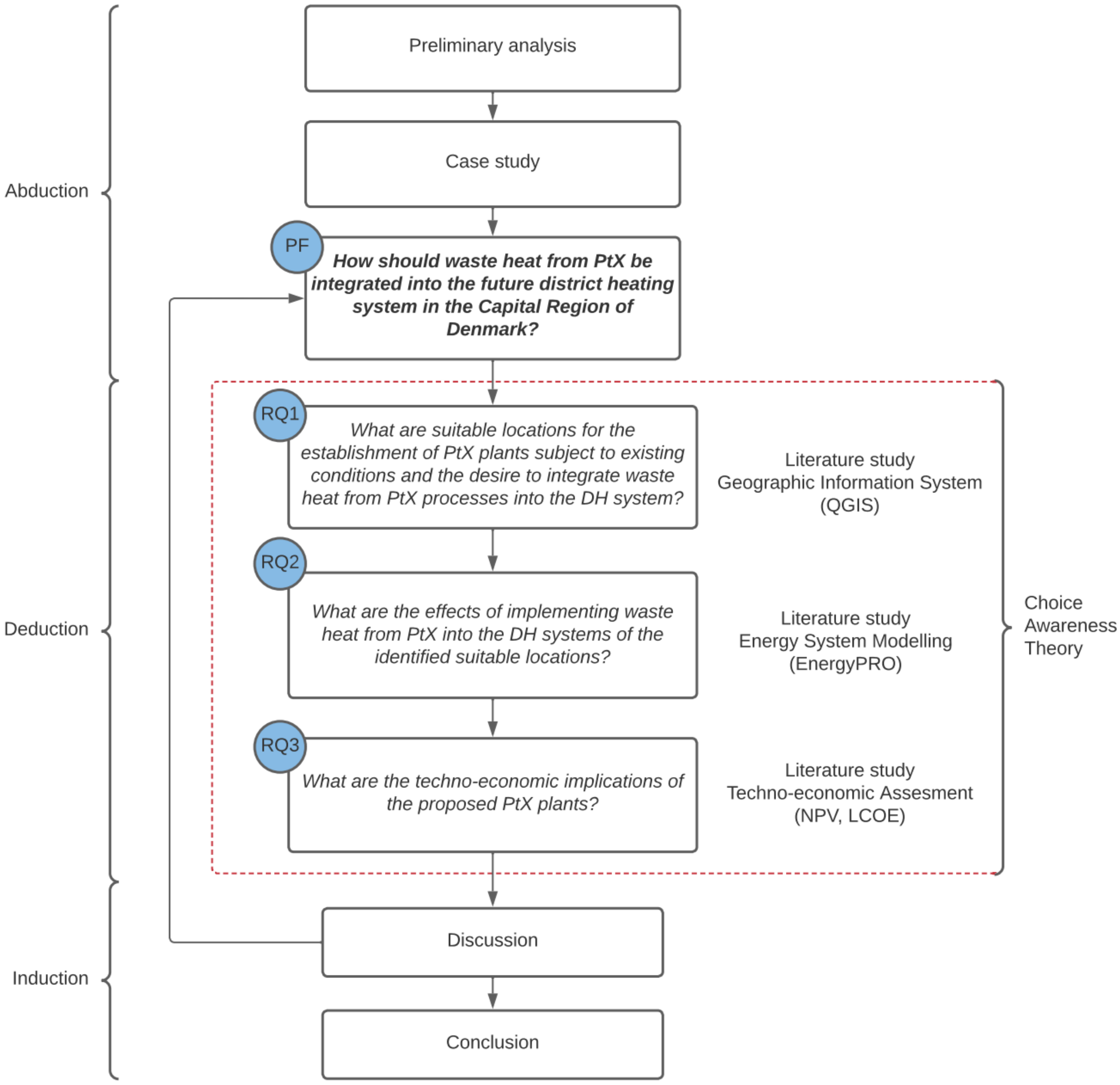

Figure 5.1. Research design of the report including subquestions, research strategy, methods and theory.

Theory 6

The purpose of this chapter is to describe the theory 'Choice Awareness' and present a 'Theoretical Conceptual Framework' for how the theory is implemented throughout the report.

6.1 Choice Awareness Theory

The theory 'Choice Awareness' is concerned with how to implement a 'radical technological change'; e.g, how a society goes from a fossil fuel energy system to a renewable energy system [Lund, 2014a, p. 15]. Radical technological change is defined as a significant shift in one or more of the five dimensions of technology: *technique*, *knowledge*, *organisation*, *products*, and *profit* [Lund, 2014a, p. 20]. Not all technological changes are equally significant in terms of affecting current organisations and institutions. As a result, certain technological changes provide a greater challenge to political decision-making than others. If one of the aforementioned dimensions are significantly changed, subsequently, at least one of the other dimensions will change. If not, the initial change will eventually be undone [Lund, 2014a, p. 20].

'Choice Awareness' is rooted within discourse and power theory, which means that one understands that different organisations vary vastly in terms of how they perceive reality and as a result, how to solve problems; thus implying that there will be a 'winner' and a 'loser' as a result of a change. It is therefore reasoned that the current organisations in 'power' will seek to keep the 'narrative' on their interests. It is thus argued that radical institutional change will not be implemented by organisations in 'power' because they want to preserve their current position and/or interests [Lund, 2014a, p. 15]. As a result, this may lead to a situation of 'no choice', meaning that society's perception of e.g., a proposal may be manipulated into a discourse of: "there is no other choice but to do X" by organisations in 'power'. However, Choice Awareness retains that this is not the case; there is always another choice and by creating awareness of the other available choices, it opens up for discussions and thus for better decision-making [Lund, 2014a, p. 15].

The theory 'Choice Awareness' uses the word 'choice', however, there is made a distinction between a *true* choice and a *false* choice. A true choice would be the ability to choose between two or more real choices ('real choices' implying that the choices are thoroughly researched) while a false choice, on the other hand, refers to a situation where there is a singular choice proposed; thus implying a for-or-against choice. In this regard, 'Choice Awareness' emphasises the necessity of providing true choices to decision-makers, in order to guarantee that a 'choice' does not become a delusion [Lund, 2014a, p. 16].

Based on the aforementioned core elements of 'Choice Awareness', the theory proposes two different theses. The first thesis makes use of the concepts '*Choice Perception*' and '*Choice-Eliminating Mechanisms*' to explain observed tendencies, while the second thesis makes use of the concept '*Raising Choice Awareness*' to present a plan to mitigate the first thesis.

6.1.1 The First Choice Awareness Thesis

The first 'Choice Awareness' thesis revolves around the concepts '*Choice Perception*' and '*Choice-Eliminating Mechanisms*'.

'Choice Perception' - as a concept - has arisen as a direct result of discourse theory and has its origin herein. It is based upon the idea that organisations perceive and articulate things differently because they exercise different discourses [Lund, 2014a, p. 23]. Thus, it could be said that the implementation of radical technological change boils down to different and even conflicting perceptions and articulations of reality between organisations [Lund, 2014a, p. 24]. An example of this could be the description and discussion surrounding climate change; some politicians and environmental organisations may share their perception of reality, whilst other politicians and environmental organisations have another perception. Moreover, unlike environmental organisations, industrial organisations do not usually assign the same expediency to climate change issues. Instead, some industrial organisations argue that a eco-friendly option has to exist in the current market [Lund, 2014a, p. 23-24]. This highlights how different perceptions of reality leads to different solutions regarding the same real problem. However, 'Choice Awareness' proposes the idea that no perception may claim to be more true/real than another perception, since reality, or the understanding of reality, is present in all articulations and discourses [Lund, 2014a, p. 24]. 'Choice Awareness' therefore posits that the collective perception of choice, as well as which alternatives to evaluate, is a critical component of decision-making. However, it is not only because of different perceptions of reality and discourses that certain choices and alternatives do not become a part of the collective perception; existing organisations makes use of 'choice-eliminating mechanisms' strategies to influence the public perception to their gain [Lund, 2014a, pp. 24-26].

Organisations' use of 'choice-eliminating mechanisms' can unfold in a wide variety of strategies. Outside the scene of formal power, one such strategy may revolve around the removal of alternatives from public discourse that does not fit the narrative existing organisations promote. Moreover, if certain alternatives are mentioned in public discussion, they are dismissed and deemed illegitimate based on a comparison to the favoured option(s) [Lund, 2014a, pp. 26-27]. Furthermore, 'Choice Awareness Theory' also employs 'Power Theory' to explain/describe the different multiple levels where 'choice-eliminating mechanisms' operate and how it affects the decision-making process. For this reason, four types of power are introduced: *direct power*, *indirect power*, *mind-controlling power*, and*structural power*. 'Direct power' is often exerted throughout the decision-making process, which could be in the form of items on the agenda in a city council. 'Indirect power', however, is more closely associated with the selection of what should not and what should be an item on the agenda. Because the removal of choice generally occurs before items (alternatives) becomes a part of the agenda, 'choice-eliminating mechanisms' are more commonly associated with 'indirect power' [Lund, 2014a, pp. 27-28]. Indirect power can also be exercised after a decision have been made, simply by not integrating the decision or implementing another decision [Lund, 2014a, p. 28]. 'Mind-controlling power' entails exerting power in such a manner that certain actors shape other actors' perception of their interest into a perception/discourse that align with themselves [Lund, 2014a, p. 28]. 'Structural power' differs from the aforementioned types of power, because it is exerted within the societal framework (constituted by habits, routines etc.). Whereas the other three types of power are exerted between actors [Lund, 2014a, pp. 28-29].

Based on the aforementioned the first thesis of Choice Awareness Theory is as follows:

> *"When society defines and seeks to implement objectives implying radical technological change,*

> *the influence and discourse of existing institutions will affect the implementation. This impact will hinder the development of new solutions and eliminate certain alternatives and will seek to create a perception indicating that society has no choice but to implement technologies that will save and constitute existing positions."* [Lund, 2014a, p. 30]

As illustrated by the first thesis, 'Choice Awareness' shows that existing organisations and institutions have an ambivalent relationship with radical technological change. This implies that disagreements between different alternatives are no longer seen as a means of determining the optimal solution, but instead as a roadblock to planning and decision-making [Mouffe, 2016]. Contrary, the second thesis of 'Choice Awareness' proposes a counter-strategy to this perception, which aims to overcome the dispositions that emerge from the first thesis.

6.1.2 The Second Choice Awareness Thesis

The second thesis of 'Choice Awareness' revolves around the concept *Raising Choice Awareness*.

'Raising choice awareness' is a concept that is meant to counteract organisations' use of 'choice-eliminating mechanisms' by elevating the choice perception, thus making it known that both technical and institutional alternatives exist. In terms of institutional alternatives, this entails the creation of both regulatory and policy measures, and the establishment of an appropriate democratic infrastructure [Lund, 2014a, p. 30].

Developing well-founded technical alternatives is the first step in improving the perception of choice and acceptance of radical technological change. In this regard 'Choice Awareness' puts forth the motion that the term "risk assessment" should be replaced with the "alternative assessment". This is to prevent the process of developing and evaluating alternatives itself becomes a 'choice-eliminating mechanism', since exclusion of certain alternatives may become a reality as a result of economic, institutional, etc. reasons [Lund, 2014a, p. 31-32]. Rather, the goal is to see if improvements in other areas, such as institutional reform, results in improved outcomes. If the alternatives ought to be considered 'real' and feasible/true alternatives, significant analysis and documentation is required. Furthermore, it is essential that alternatives that would result in a radical technological change must not become isolated, but are also not forced into the existing system [Lund, 2014a, p. 31]. As a consequence, while developing and expanding projects and programs linked to these alternatives, a balance is required.

The second thesis of 'Choice Awareness' therefore reads as follows:

> *"Society will benefit from focusing on Choice Awareness, that is, raising the awareness that alternatives do exist and that it is possible to make a choice."* [Lund, 2014a, p. 34]

The second thesis shows the necessity for a more open attitude towards alternatives, where conflict and debate are seen as beneficial to the overall development and evaluation of alternatives [Mouffe, 2016]. It is of the understanding - in terms of 'Choice Awareness' - that this would create more suitable conditions for at better decision-making process [Lund, 2014a, p. 33].

6.2 Theoretical Conceptual Framework

The purpose of the report is to examine *how* waste heat from PtX should be integrated into the future district heating network based on a case-study of the Capital Region of Denmark. In this regard, 'Choice Awareness' is implemented to create awareness of, e.g., the barriers and possibilities associated with PtX for integration with the DH system in the Capital Region of Denmark.

As mentioned in section 6.1, the purpose of 'Choice Awareness' is to examine *how* to implement radical technological change. In relation to the case-study of the Capital Region of Denmark, it is argued that by implementing PtX with the intention to utilise the waste heat that is created as a byproduct is considered a radical technological change. By implementing the PtX facility and utilising the waste heat, it would affect more than one of the five dimensions of technology mentioned in section 6.1. According to 'Choice Awareness' the existing institutions would try to stifle the emergence of new alternatives; this may be explained by the barriers explained in section 2.2. It is mentioned in section 2.2, that one of the barriers PtX has (as a technology) is related to the economic aspect (compared to other technologies). External risks - in terms of high electricity prices, a lack of available support schemes - may explain part of the lack of economic viability. Furthermore, because large scale integration of PtX is a relatively new direction, there are likewise uncertainties related hereto in terms of: market readiness of PtX-products, available carbon sources, clean and stable water supply, electricity grid, etc. This could be seen as an institutional system that is potentially halting the growth of PtX. A research method based on the theory 'Choice Awareness' is therefore introduced and illustrated on figure 6.1.

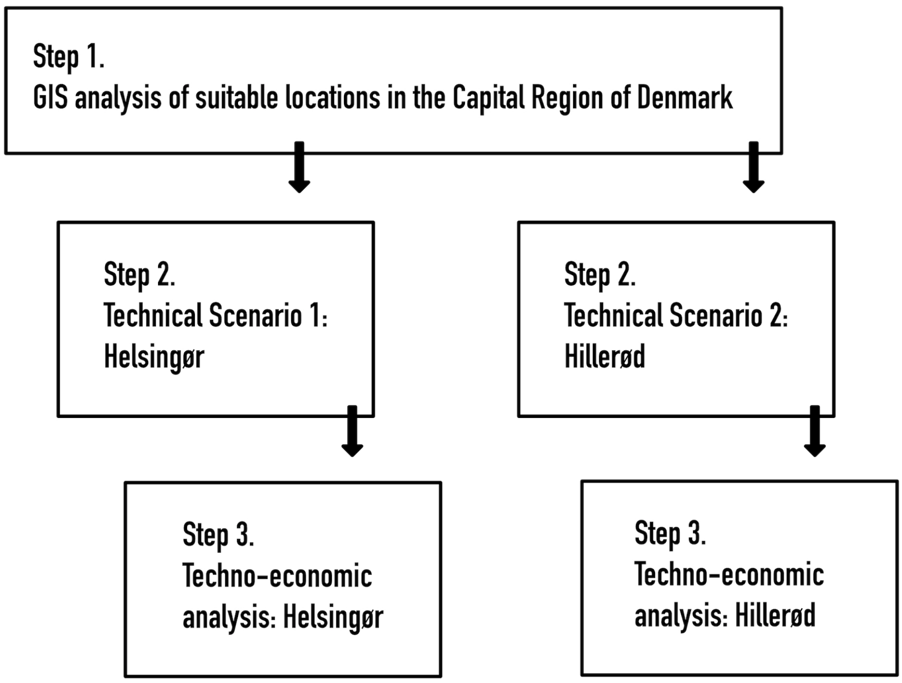

Figure 6.1. Modified research method for the report, based on the methodology of 'Choice Awareness' [Lund, 2014b].

The research method shown in figure 6.1 can theoretically be used to evaluate an endless number of alternatives; solely focusing on PtX may represent a level of 'choice-eliminating mechanisms', but since the scope of the report is limited to PtX, this is unavoidable. To avoid 'choice-eliminating mechanisms' a more comprehensive analysis with the inclusion of different types of alternatives would have to be conducted. It could thus be argued that the findings of this report could be part of a larger, more comprehensive report that evaluates a wider variety of alternatives.

With inspiration from the methodology of Choice Awareness Theory [Lund, 2014b], the first step is to identify suitable locations for PtX in the Capital Region of Denmark. In this regard, two suitable locations were identified using GIS-analysis, based on a set of criteria (see section 8.1): Helsingør and Hillerød. The second step builds upon the suitable locations found in step one. Reference models of the two locations were subsequently modelled in EnergyPRO. Because the focus of the report concerns the future district heating system, projections concerning the characteristics of the two energy systems were applied (for a more detailed description see Appendix A). A PtX facility would thus be inserted into the two EnergyPRO models, to evaluate *how* the energy systems were affected by the supply of waste heat from said PtX-facility (for a more detailed description see section 8.2). The third step revolves around assessing the techno-economic implications of establishing and operating the two PtX-facilities (see section 8.3).

A theoretical conceptual framework that uses a three-step approach, based on the 'Choice Awareness' methodological approach and the problem formulation and subquestions, is therefore shaped:

1. Analysis of suitable locations for utilising waste heat from PtX in the Capital Region of Denmark.
2. Analysis of the affects of implementing waste heat from PtX in the two suitable locations.
3. Analysis of the techno-economic implications of implementing a PtX-facility in the two suitable locations.

Methods 7

The purpose of this section is to explain the methods used throughout this report. *How* the methods are used in relation to the design of the report is explained in section 8.

7.1 Case study

The report is concentrated on a single concrete issue/problem, which is presented by the problem formulation in section 4. To investigate and answer this problem formulation, the problem is contextualised by introducing a case study. The case study is a valuable method when conducting empirical studies. This is especially the case when boundaries between the phenomenon(s), that are investigated, and context are not clearly defined. In such case, to understand the real-life phenomenon, which is subject to contextual conditions, technical characteristics such as data collection and data analysis become essential to understanding [Yin, 2018, p. 18]. The case study inquiry therefore deals with a variety of conditional variables and as such, relies on multiple sources of evidence. In this regard, the case study may benefit from prior development of theoretical frameworks to guide data collection and analysis [Yin, 2018, p. 18].

When conducting a case study, generalisation can be difficult [Yin, 2018, pp. 20-21]. However, it is argued that if the case is strategically selected, it may contribute to the generalisation of the findings of the investigation [Flyvbjerg, 2010, pp. 470 & 473]. [Yin, 2018] categorise four different case strategies, each matched with a different purpose for the case inquiry. The four identified case strategies are listed in the following:

- The critical case, where one tests a theory
- The extreme case, where one describes a rare case
- The unique case, where one analyses a phenomenon that is inaccessible to scientific investigation
- The prelude case, where one explores a case in preparation for a multiple case design
  [Yin, 2018]

Based on these strategies, it is argued that it may be beneficial, from an understanding- and action-orientated perspective, to select a more atypical case to identify and analyse causes and consequences rather than symptoms and frequency [Flyvbjerg, 2010, pp. 473-475]. As such, it may be a mistake to only consider statistical generalisation as valid, if the single/stand-alone case is able to support theoretical concepts and principles [Yin, 2018, p. 38]. In this case, findings may yet be applicable for other single-cases, which support analytical generalisation and limit the necessity of a time-consuming multiple-case study [Salkind, 2010, pp. 117-118].

When conducting an investigation related to a case however, the investigation may still constitute of more than a single unit of analysis. According to Yin [2018] the case study may as such, constitute of either a single unit of analysis (holistic) or multiple sub-units of analysis (embedded), independent of whether a single-case or a multiple-case study is applied [Salkind, 2010, pp. 117-118]. Figure 7.1 illustrates the relation between the single-case and multiple-case study and between the holistic and embedded analytical approach.

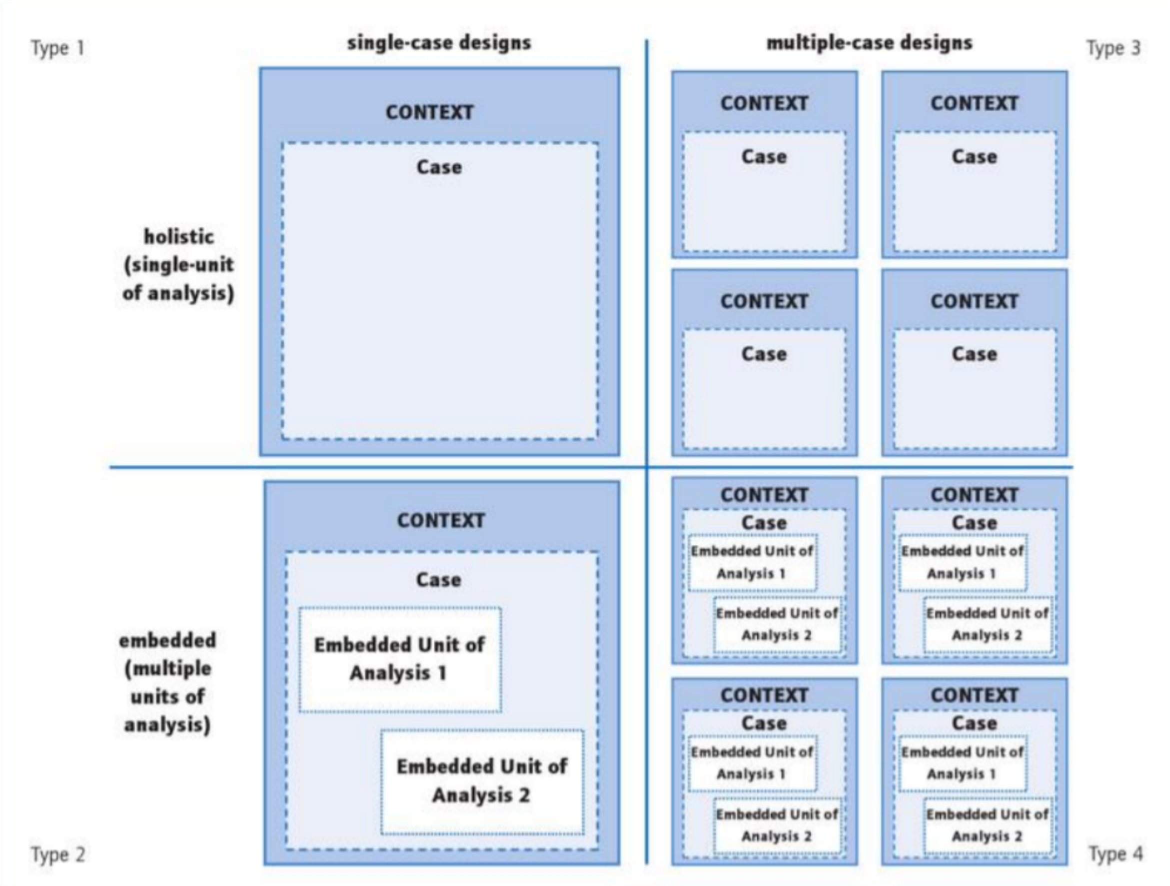

Figure 7.1. Illustration of the relationship between the single-case and multiple-case study and between the holistic and embedded analytical approach resulting in Type 1, 2, 3, and 4 case-study. [Yin, 2018, p. 48]

To strengthen the scientific argument of a case study, it may be necessary to introduce other methods to the scientific inquiry. As such, the case inquiry may benefit from mixed-method research by including a variety of different qualitative and quantitative methods [Yin, 2018, p. 63]. In this regard, especially methods of literature study are valuable for the purpose of information and data gathering

7.1.1 Literature-study / Literature Review

The following method is used to address problems that have already been answered by past iterations. This method is divided into three phases, according to Salkind [2010]:

- Asking a question
- Retrieving literature
- Interpretation

The first step in a literature review - as with any research discipline - is to identify/frame a problem. The fundamental concerns are the questions which the review seeks to answer, as well as the constructs of interest. Defining the constructs of interest might be complicated for two reasons: the current literature may use various terminologies to describe the same construct and vice versa [Salkind, 2010, pp. 726-727]. When gathering relevant literature for the review, it is helpful to think of the literature as a sample selected from a population of all conceivable works. This perspective emphasises the significance of gathering an unbiased literature sample for the review. The findings may therefore be prejudiced if the evaluated literature is not exhaustive - or at least indicative - of the existing research [Salkind, 2010, p. 727]. The second step (retrieval of literature) should therefore be done in a transparent matter by making the used search terms available to the reader. The third and final phase is interpretation. In this phase the literature is read, analysed and lastly interpreted to develop/reach a conclusion regarding the researcher's initial question (phase 1). Because of the nature of qualitative research, the researcher is subconsciously creating an internal synthesis of the outcome. As a result of the researcher's inherent biases, the conclusion is automatically "skewed" [Salkind, 2010, pp. 727-728].

7.2 Method of reasoning

Reasoning is the process of making predictions, constructing explanations and drawing conclusions based on accumulated knowledge. Traditionally, one of three methods of reasoning are applied, dependent on the goal and approach of the research. These are the *deductive*, *inductive*, and *abductive* methods of reasoning.

The deductive method of reasoning seeks to apply existing theory to formulate a hypothesis, based on which an empirical study is conducted [Plowright, 2015, pp. 30-31 & 33-34]. The understanding of deductive reasoning is thus that by asserting specific rules or principles (theory) a guaranteed outcome can be achieved. Opposite to this, the basis of the inductive method of reasoning is the empirical study itself (antecedent case), based on which new theory is developed [Plowright, 2015, pp. 31-32 & 34-35]. The understanding of inductive reasoning is thus that observations (specific and limited in scope) may proceed a generalised outcome based on accumulated evidence. Apart from the deductive and inductive reasoning, the basis of the abductive method of reasoning is the researcher's surprise or pondering over certain observations [Plowright, 2015, pp. 32-33]. The understanding of abductive reasoning is thus that an incomplete understanding has caused an unforeseen consequence to be observed which necessitate the introduction of a set of predictions or expectations to explain the most likely reason for the observed.
The inferential logic of the deductive, inductive and abductive inquiry is indicated in table 7.1.

Table 7.1. Inferential logic as progressing over time of inqury for the abductive, deductive and inductive method of reasoning. With inspiration from [Plowright, 2015].

Inferential logic		*Progress over time of inquiry*				
Abduction	:	Consequent result	→	Rule or principle	→	Antecedent case
Deduction	:	Rule or principle	→	Antecedent case	→	Consequent result
Induction	:	Antecedent case	→	Consequent result	→	Rule or principle

Despite traditionally being applied separately, Charles Sanders Peirce (first introduced the concept of abduction in 1870) stressed how all three methods of reasoning are - in principle - introduced during any giving investigation, resulting from a chronological cause-effected relationship [Plowright, 2015, pp. 38-39]. The cause-effected relationship between the deductive, inductive, and abductive reasoning is described in the following.

7.2.1 Abduction

Abductive reasoning begins with the researcher's surprise or pondering over the observation(s) of a given phenomenon, as mentioned. In this regard, the fist stage of inquiry seeks to find; why the phenomenon behaves the way that it does. Such inquiry requires a form of "reconstruction" of the events and conditions that lead to the observed to predict a likely explanation [Plowright, 2015, p. 39]. With this in mind, Peirce explained abductive reasoning as follows:

> *The surprising fact C, is observed;*
> *But if A were true, C would be a matter of course;*
> *Hence, there is reason to believe that A is true.*
> $[Plowright,\ 2015, p.39]$

The explanation/conclusion derived from the predictions is essentially nothing more than a qualified (based on general principles or theoretical ideas) guess. This is because it is assumed that there is even a connection between the antecedent (A) and the consequence (C) hereof [Plowright, 2015, p. 39]. The purpose of the exercise is to develop a well founded overarching hypothesis to explain the observed. For the propose of convenience within the field of research, this hypothesis should - according to Peirce - be posed as a question. This is to make sure that the purpose of the inquiry is maintained; meaning, the phenomenon(s) or case(s) the researcher wishes to investigate is investigated, and the question(s) that the researcher need answered is answered [Plowright, 2015, p. 40].

7.2.2 Deduction

Based on the hypothesis/question from the previous stage of inquiry, a number of observable, empirical predictions is generated during the deductive stage of inquiry. To maintain the scientific argument, this requires a process of; firstly explaining the terms and conditions of the hypothesis to eliminate ambiguity, and secondly of demonstration based on the analytic deductive argument [Plowright, 2015, p. 41], taking the form:

> *If A, then B;*
> *A; therefore B.*
> $[Plowright,\ 2015, p.30\&41]$

The purpose of demonstration based on the analytic deductive argument is to identify consequences of the hypothesis, that then become subject to inductive testing in a latter stage of inquiry. Thus, the deductive inquiry includes determining other empirically observable and testable predictions that can be inferred based on the overarching hypothesis [Plowright, 2015, p. 41]. Here, the premise is therefore; if hypothesis *A* is true, then supplementary hypothesis *B* is relevant to explore. These supplementary hypothesis' too, should be posed as questions (sub-questions) [Plowright, 2015, p. 42].

Peirce emphasises, that the deductive reasoning in this sense is not at practical exercise, but rather a creative process based in logical procedures aimed at preparing for testing/answering one's hypothesis/question by acquiring the necessary theoretical perspective [Plowright, 2015, pp. 41-42]. However, this newfound theoretical perspective or understanding needs to be tested by determining the predictive value of the hypothetical consequences [Plowright, 2015, pp. 42-43].

7.2.3 Induction

Based on newfound theoretical perspective from the previous stage of inquiry, predictions and expectations are tested and compared empirically and systematically to the findings of the inquiry [Plowright, 2015, p. 43]. In this regard, Peirce offers three stages of inductive reasoning: *classification*, *probations* and *sentential* [Plowright, 2015, pp. 44-48].

The Classification stage seeks to develop and formulate ideas of testing the hypothesis/question. This includes setting the terms and conditions of the testing [Plowright, 2015, pp. 44-45]. The classification stage is followed by Probations, which are the 'testing-arguments' (propositions or research questions) that are to be investigated [Plowright, 2015, p. 45]. Peirce offers three orders of Probations:

- *First order: crude induction;*
- *Second order: qualitative gradual induction;*
- *Third order: quantitative gradual induction*
  [Plowright, 2015, p. 45]

For more information on the first, second, and third order of induction is referred to [Plowright, 2015]. The third stage of inductive reasoning, according to Peirce, is the Sentenial stage. The purpose of this stage is to evaluate the findings of the inductive testing and pass final judgement on whether these support the predictions and expectations derived from the initial hypothesis/question [Plowright, 2015, p. 48]. The Sentential stage is considered as the conclusion of the inquiry.

7.3 Geographic Information System (GIS)

A geographic information system (GIS), is a computer system that stores, manages, analyses, and displays geospatial data [Esri, 2021; Chang, 2019]; geospatial data refers to data that describes both the locations and qualities of spatial features [Chang, 2019, p. 1]. This could, e.g., be data regarding population, protected areas (e.g. Nature-2000 areas), district heating areas, different types of zoning, and other similar data. GIS allows for all of these various forms of data to be superimposed on top of one another on a single map [National Geographic, 2017]. GIS thus links data to a map by combining location data (where objects are) with various sorts of descriptive data (what things are like there) [Esri, 2021]. To connect these seemingly unrelated variables, GIS uses 'location' as the fundamental index variable. By utilising GIS it allows for comparison of geospatial data, to see how they interact/relate with each other. Depending on the data used, it can be merged to create a range of different individual maps [National Geographic, 2017]. An advantage of utilising GIS is that it allows for better decision making [Esri, 2021].

In GIS, there are two fundamental types of data that remain separate: vector and raster data [Chang, 2019, p. 86]. Vector data models constructs spatial features by points, lines, and polygons by projecting them in a x-, and y-coordinate system (see figure 7.2). The points, lines, and polygons can then be used as inputs in a vector data analysis [Chang, 2019, p. 229]. An example of a vector data analysis could be "buffer zones". These buffer zone could then be considered as a sort of protective zone; this could, e.g., be critical habitats, wetlands, etc. [Chang, 2019, p. 232]. In contrary, a regular grid covers the space in raster data models (see figure 7.3) and the value of the specific grid cell represents the features of a spatial phenomenon at the cell position [Chang, 2019, p. 71]. An example of a raster data analysis could be an elevation map.

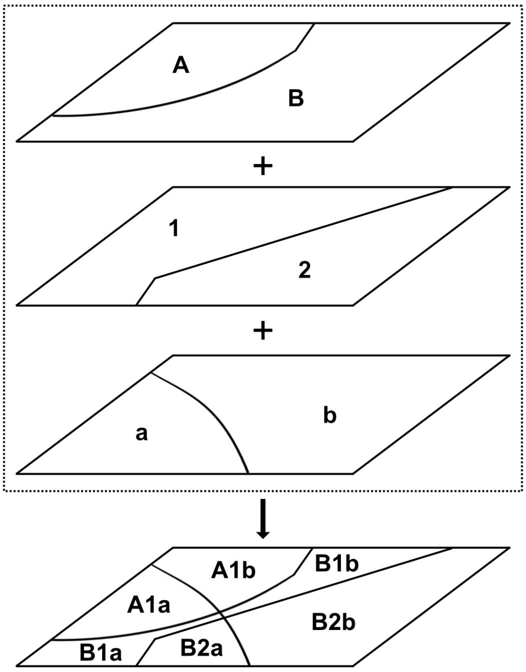

Figure 7.2. Own illustration of a vector-based overlay operation that merges both geometries and attributes from a several layers to create an output (final map). The figure is based upon [Chang, 2019, p. 9].

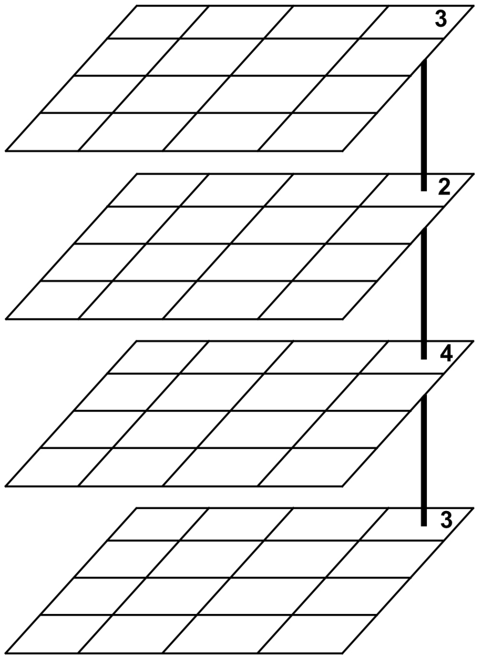

Figure 7.3. Own illustration of a raster data operation with several rasters that utilises fixed cell locations. E.g., a local mean value for the output can be calculated by dividing the top three layers (3, 2, and 4) by the amount of active layers (3). The figure is based upon [Chang, 2019, p. 9].

When making GIS-analysis' it is important to be aware of which type of data is used. An example of this could be 'buffering' that applies to both vector and raster data models. A vector-based buffering operation and a raster based physical distance both measures distances from between selected features. Because the vector-based operation is between points, lines, and polygons, it would make for a more accurate analysis, since the raster based operation is between cells. Therefore, by utilising the strengths of vector based buffering it allows for more accurate analysis – comparatively [Chang, 2019, p. 272].

7.4 Energy system modelling

'Energy systems modelling' is used to aid in the design, planning, and implementation of future energy systems. In order to construct an energy system model, it inevitably implies the need to identify and highlight certain characteristics/elements of reality in a computer model. Thus, implying that changes made in the model would be reflected in the real world energy system subject to investigation. Depending on the goal/scope of the energy system model, choices about which technologies, industries, sectors, etc. to include and exclude are necessary [Lund et al., 2017a, pp. 1-2]. Constructing the model itself is only one element of

the process; some decisions prior to the modelling work are necessary. Firstly, the goal of the model has to be defined, since different goals necessitate different model designs, data, etc. Data - both relating to the current energy system and the changes that seeks to be implemented - must be collected, findings analysed, and conclusions derived. Based on the findings it is further possible to design implementation strategies and/or policy changes [Lund et al., 2017a, p. 2]. Different models differ in scale; some employ a national approach whereas others focus on a regional scale. Furthermore, some models are broad in scope (e.g, conversion of renewable heat production), while others focus on specific areas (e.g, integration of excess heat from PtX) [Lund et al., 2017a, p. 2].
When making energy system models, two different approaches exists: *optimisation* and *simulation*. The approaches are esplained and compared in the following.

7.4.1 Simulation vs. Optimisation

The phrase 'optimisation' is regularly used interchangeably with a modelling approach where a variety of decision variables are either computed to maximise or minimise an objective function to a set of decided constraints. The decision variables often relate to the characteristics of an energy system [Lund et al., 2017a, p. 3]. The overarching goal of an optimisation approach is to find one singular optimal solution subject to constrains. Depending on the proposed objective function (the goal of the energy system analysis), this could e.g., relate to energy consumption, CO_2-emissions, economics, etc. As a result, the optimal solution is usually either the least expensive means to achieve the goal of the proposed objective function (cost-effectiveness approach) or the optimum combination of economic costs and benefits (cost-benefit approach) [Lund et al., 2017a, p. 3]. In an optimisation approach, the description of the existing system becomes necessary in order to ascertain the least expensive path from the existing system to the optimal future system. This approach often encompasses the current system as a starting point for the algorithms (inter-dependencies between the objective function and the constraints) to find the optimal path moving forward [Lund et al., 2017a, p. 3].

In contrast to optimisation is the simulation approach. This approach is used to simulate and envisage a specific energy system's behaviour under a set of conditions [Lund et al., 2017a, p. 3]. The objective/purpose of a simulation model is to analyse and evaluate the effect of different key parameters (such as costs, emissions, energy supply, etc.), thus - typically - resulting in different scenarios. As a result, simulation models can be classified as a form of scenario model. The premise is that instead of constructing an optimal strategy based only on quantitative analysis based on a single criterion (optimisation approach/model), the different scenarios are evaluated based on multiple criteria. Several crucial factors must be considered, and their perceived significance cannot always be evaluated by a single common denominator [Lund et al., 2017a, pp 3-4]. As a result of using a simulation approach, the specifics of the existing system become less relevant, while the intricacies of the various future energy system become a key factor [Lund et al., 2017a, pp. 4-5].

The most fundamental distinction between the optimisation and simulation model is whether the model itself can find the single best/optimal solution or not. The optimisation models are designed as such, that they can compute the optimal solution based on a set of restrictions, rules, and presumptions by amalgamating before-mentioned with e.g., economic values [Lund et al., 2017a, p. 5]. However, for simulation models the users themselves are in control of all the crucial decisions based on a range of criteria that cannot necessarily be valued using a single common denominator. As a result, the considerations regarding the more than one simulation models - that the users have made beforehand - are able to being compared, but not directly commensurable [Lund et al., 2017a, p. 5]. It could therefore be summarised that in the optimisation model, one (the modeller) provides data, an objective function, and constraints to the model, and then the model is able to find the single most optimal solution within the specified framework one has given the model. In the simulation model, however, one focuses on parts of the energy system and then uses the model to compute the effects of various combinations to provide grounds for decision-making [Lund et al., 2017a, p. 5].

7.5 Techno-economic assessment/analysis

Techno-economic assessment or analysis (TEA) is a method of determining the economic performance of alternative technologies (process, product and service). TEA may be used for, but are not limited to, evaluating economic feasibility, guiding research and development and quantifying uncertainties and risks, by systematically identifying and assessing relevant economic factors/parameters. This often includes comparative analysis with other alternatives and externalises to facilitate better decision-making [Burk, 2017].

Some of the most common metrics for conducting TEA is 'Net Present Value' (NPV) and 'Levelised Cost of Energy' (LCoE). The key indicators of these two metrics are described in the following.

7.5.1 Net Present Value

NPV is a metric used in financial assessment strategy to analyse and evaluate potential investment opportunities. NPV aim to project the value of a potential investment by including all future cash inflows and outflows, discounted to the present day, and reduce this data into a single numerical value [Zweifel et al., 2017; Bhattacharyya, 2019]. NPV can be expressed as:

$$NPV = \sum_{t=1}^{n} \frac{(R_t + C_t)}{(1+i)^t} - I_0 \tag{7.1}$$

Where:

R_t	Revenue in year t
C_t	expenditures in year t
r	Discount rate
n	Lifetime of investment
I_0	Initial investment

The resulting NPV from equation 7.1 indicates the profitability of the given investment opportunity. As such, a positive NPV indicates that the investment opportunity will turn a profit within *n* years amounting to the value of the NPV [Zweifel et al., 2017; Bhattacharyya, 2019].

7.5.2 Levelised Cost of Energy

LCoE or Levelised Cost of Electricity is a metric used to determine the unit energy cost in a given technologies' lifetime. LCoE is widely used as a comparative measure, typically to compare alternative electricity generating technologies, and considers capital, operating and financing costs. LCoE sums the lifetime costs of the system in consideration (NPV), and divides it by the total energy production delivered by the systems in its lifetime to arrive at a cost per unit of energy [Aldersey-Williams and Rubert, 2019, pp. 169-170]. LCoE can be expressed as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{7.2}$$

Where:

I_t	The cost of investment expenditures in year t
M_t	Operations and maintenance expenditures in year t
F_t	Fuel expenditures in year t
E_t	Energy generation in year t
r	Discount rate
n	Lifespan of investment

The LCoE is understood to be the average minimum price at which a unit of energy that is generated by the system should be sold to offset the total cost of the system in its lifetime [CFI, 2021]. Hence, LCoE is also a valuable metric to compare against relevant market price of energy to determine economic competitiveness.

To indicate the desire to find the minimum price at which waste heat produced from PtX has to be sold, the equation is modified slightly. As such, the equation is modified to indicate the 'Levelised Cost of Heat' (LCoH):

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}} \tag{7.3}$$

where H_t indicates heat generation in year t. This modification is justified based on previous scientific works [Li et al., 2019; Nian et al., 2016]. In the case of more than one method of heat production (variations in waste heat produced from the process of different PtX products), the overall LCoH could be calculated by combining the LCoH of each production method respective of their heat production [Li et al., 2019, p. 18].

Methodology 8

The purpose of this chapter is to provide a contextual framework for the investigative approach using the methods described in chapter 7. This is done by systematically describing and explaining data, assumptions, and decisions leading to the result of the investigations of the report.

The analysis is based upon a single-embedded case-study (type 2 - see figure 7.1) of the Capital Region of Denmark. The embedded nature of the case-study subsequently entails multiple subsets of analysis. These subsets of analysis are represented by the subquestions in chapter 4. As such, the investigative approach is described in chronological order to illustrate the cause-and-effect interactions between the different subsets of analysis as defined by the subquestions. Based on the problem formulation (see chapter 4) and the theoretical framework (see section 6.2), each step of the chronological order is enumerated:

- **Step 1:** Identifying suitable location(s) for PtX
- **Step 2:** Developing reference system(s) for PtX integration
- **Step 3:** Integration of PtX into developed reference system(s)
- **Step 4:** Techno-economic assessment/analysis of integrated PtX facilities

8.1 Procedure for identification of suitable location(s) for PtX

To find suitable locations for utilising waste heat from PtX, in the Capital Region of Denmark, a geographical information system (GIS) analysis is conducted. The general outline of the process is described in the following steps: determine requirements for the project, collect data based on the requirements, treatment of the collected data, perform analysis to highlight potential suitable locations, and qualitative analysis of potential locations. These sub-steps are described in the following.

8.1.1 Requirements for placement of PtX plant and collection of data

To find suitable location(s) for placement of a PtX plant(s), assumptions relating to the suitability of the potential location(s) are made. Proximity to a CO_2 source is prioritised to allow for the possibility of expanding the products (hydrogen) with carbon-based structures to allow for, e.g., methanol production (see also section 2.1). This would secure availability of CO_2 and limit the necessity for transport of the resource to the PtX site. To account for this, in the GIS-analysis, data for CO_2 point sources and their emission amounts are identified and introduced as an input. The aforementioned data is gathered from 'The European Pollutant Release and Transfer Register Regulation' (EPRTR) and is from 2021 [EEA, 2021]. The data from EPRTR concern companies with significant emissions to air, water, and soil, as well as companies that produce a significant amount of waste [EPA, 2021]. Another requirement that is prioritised highly is the distance to the existing DH grid. This is done to limit, or possibly remove, the need for expansion of the current DH network. Data for the 2021 DH network is gathered from 'plandata' [Erhvervsstyrelsen, 2021].

Moreover, off-limit areas are included to limit the impact on established infrastructure and buildings. As such, protection areas, roads, rail roads, burial sites, levees, streams, valuable raw material sites, existing low- and high-level construction, as well as city centers are categorised as a 'no-build-zone'. Data related to these parameters are acquired from 'Dataforsyningen' (part of the Agency for Data Supply and Efficiency) based on the newest data for 2021 [Dataforsyningen, 2021].

8.1.2 Treatment of data and identification of suitable locations

The aforementioned GIS data have been treated in a variety of ways. The areas of interest - those near CO_2 point sources and the DH supply area - are given a point value based on proximity. The CO_2 and DH area data is firstly limited to the Capital Region of Denmark by using the 'clip tool' in QGIS, after which the 'multi ring buffer' tool is applied to both in order to make five increments of 500 meters, up to 2.500 meters. The increments of the DH network are visualised in figure 8.1 and the increments for the CO_2 point sources are visualised in figure 8.2.

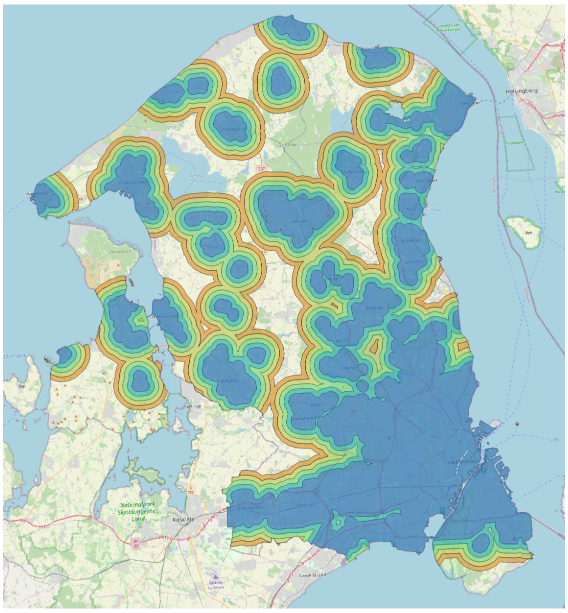

Figure 8.1. DH grid in the Capital Region of Denmark with five increments of 500 meters. Data is from [Erhvervsstyrelsen, 2021].

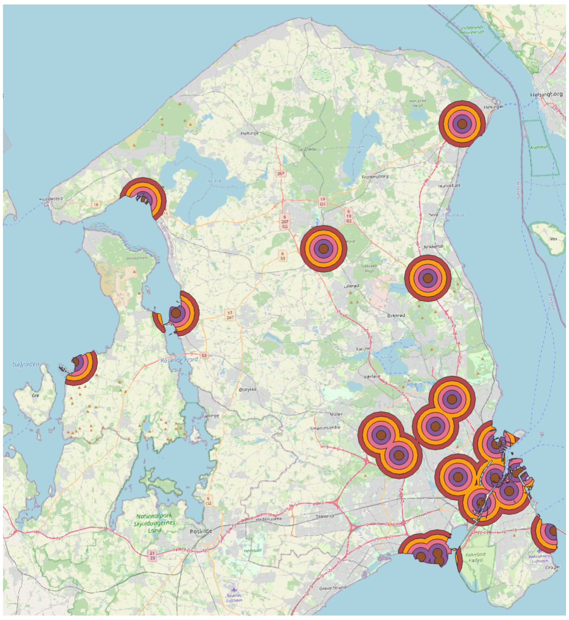

Figure 8.2. CO_2 point sources according to [EEA, 2021] in the Capital Region of Denmark with five increments of 500 meters.

To determine which sites are most suitable for PtX, point values are assigned to each of the five increments of 500 meters (each ring segment), closer being better, decreasing linearly every step from the middle. The inner most increment has a point value of 25 and the outer most circle has a point value of 5. Next, the overlap between the CO_2 and DH data are determined and given a new score based on the sum of the overlapping segments. Where overlaps between the two data sets occurs, the value of each overlapping layer is added together and a new value range is thus created: 50 to 5 points (e.g. if a location is in the inner most increment of e.g. the CO_2 point source and the location furthermore is in the outer most increment of the DH data it would result in a score of 30). 50 points would imply that the location is within 500 meters of both the DH network as well as the CO_2 point source; whereas e.g. 5 points would mean the location is either within the DH network or CO_2 point source's proximity and no overlap between the two. Figure 8.3 illustrates three CO_2 point sources with overlapping DH data.

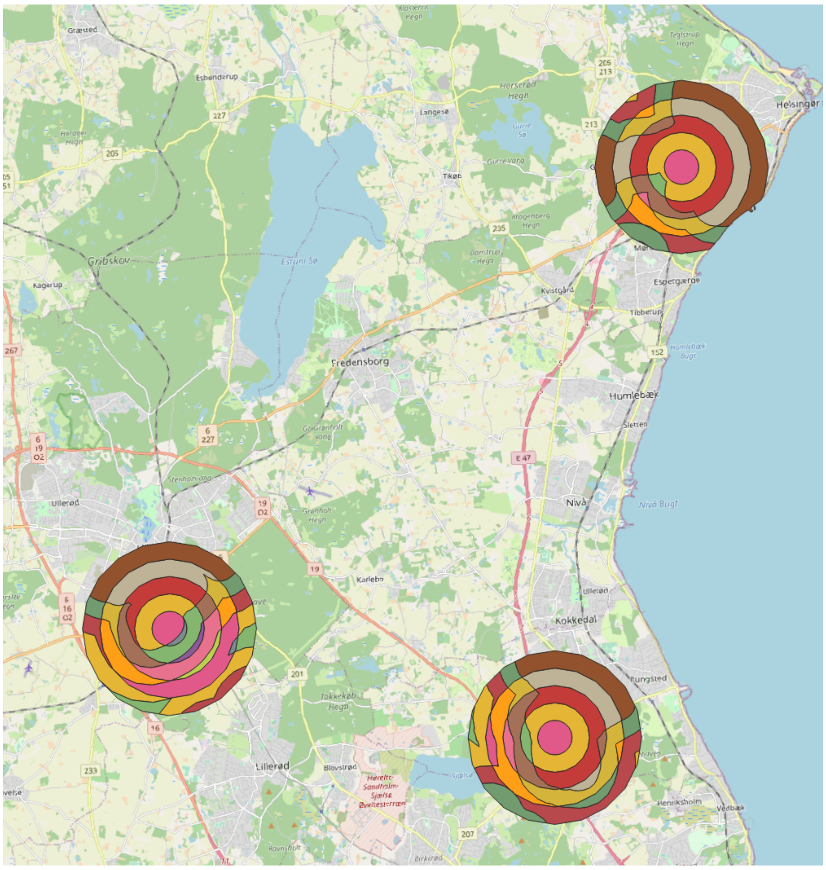

Figure 8.3. Zoomed in area of CO_2 point sources according to [EEA, 2021] in the Capital Region of Denmark with five increments of 500 meters, showing overlay with DH ring buffers.

To limit interference with existing local plans, a decision to avoid areas with existing planning interest, is made. These are split into three main categories: 'buildings', 'infrastructure', and 'nature'. The buildings included are all existing buildings; commercial, housing, etc. Infrastructure includes roads, railways, as well as installations such as wastewater treatment facilities, airports, etc. Roads and railways had a buffer added to them as the data was a line and as such did not encompass the actual area of the road. Finally, areas with preserve worthy nature, included bodies of water, any installations around the same such as dikes and dams, and protected nature were included. Also included are cultural sites such as historic burial sites, current burial sites, statues, etc. The final consideration included the exclusion of natural resource areas such as limestone deposits. All of these areas are determined to be non-permissive for the construction of any potential PtX plant, and for the purpose of the analysis, their areas are merged in QGIS and dissolved into a single shape for the next step of the analysis. The non-permissive area used in the analysis is visualised in figure 8.4.

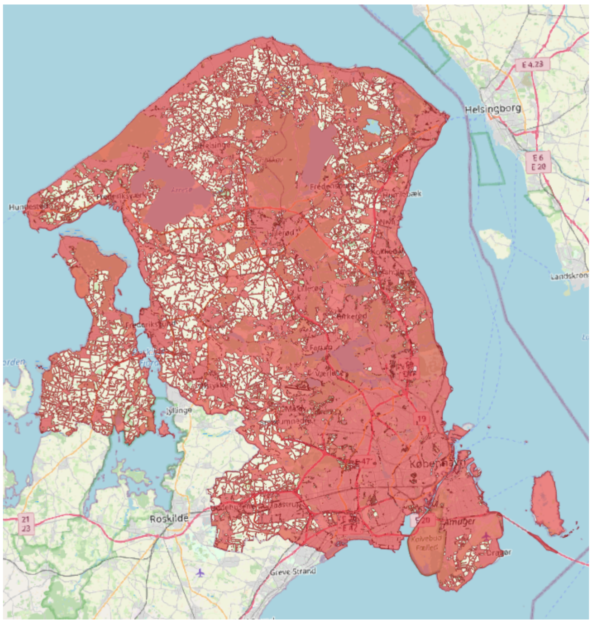

Figure 8.4. Non-permissive area consisting of three main categories: 'buildings', 'infrastructure', and 'nature', merged into a single layer in the Capital Region of Denmark. Based on data from [Dataforsyningen, 2021].

With the non-permissive areas and area proximity-based suitable locations (based on proximity to CO_2 point sources and DH area) determined, it is possible to determine areas suitable for further investigation by subtracting the non-permissive area from the area proximity based suitable locations. The resulting shapefile, as illustrated in figure 8.5, is rasterised, meaning burning in the point values assigned earlier. Thus, the map visually presented in figure 8.6 highlights suitable locations to undergo further and more qualitative evaluation.

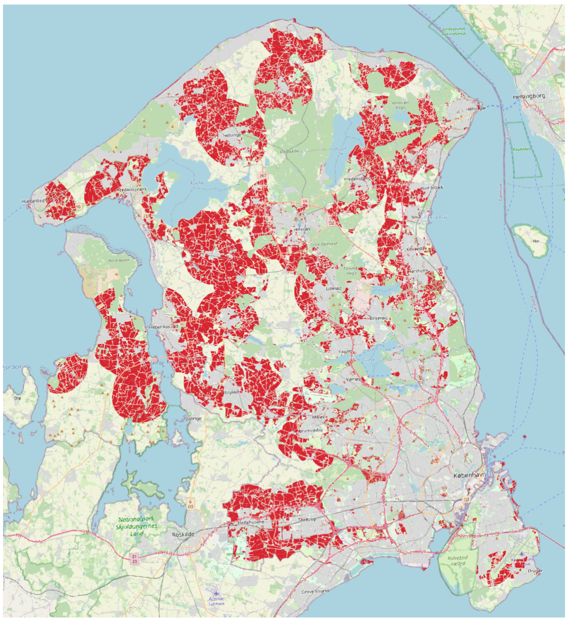

Figure 8.5. Suitable areas for placement of PtX plant in the Capital Region of Denmark, before rasterising and highlighting point values.

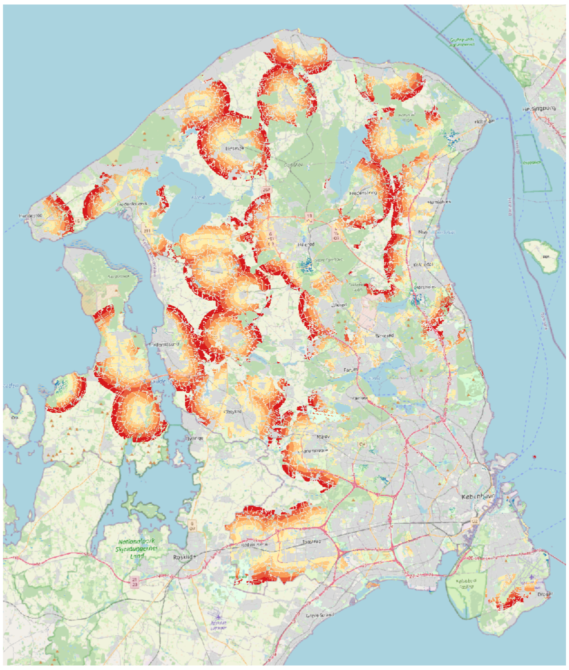

Figure 8.6. Suitable areas for placement of PtX plant in the Capital Region of Denmark.

8.1.3 Qualitative evaluation of the suitable locations

Due to limitations of the collected data, a subsequent qualitative evaluation of the suitable locations on figure 8.5 must be performed to determine their suitability. This includes verifying that the areas are in fact suitable, according to the parameters listed in section 8.1.2, as well as surveying nearby areas for incompatibility and any further opportunities.

The areas are inspected using orthographic photos (from 2021) to ensure there are no unexpected features that would exclude the area from consideration. In figures 8.7 & 8.8, an area highlighted by the GIS analysis is shown on the left. Upon further inspection, the area is found to be a recreational park area, thus not suited for demolition and subsequent construction of a PtX plant. In this specific case, it appears that the data supplied from 'Dataforsyningen' does not contain this feature, despite being present upon further inspection.

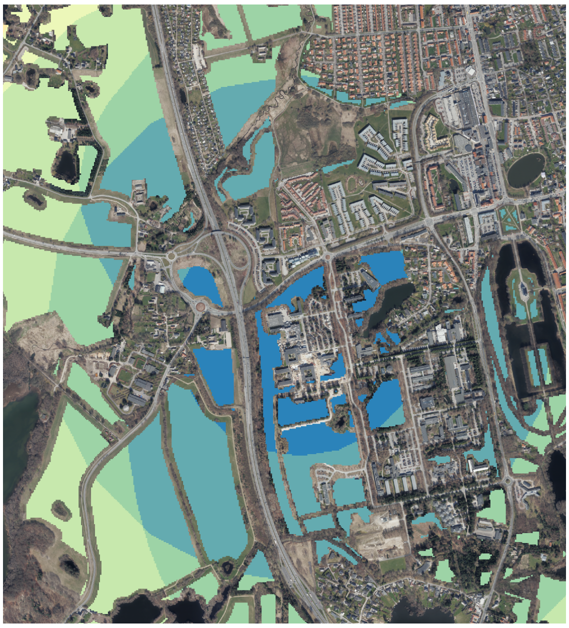

Figure 8.7. A potential suitable location in 'Hørsholm'. The dark blue color indicates the most suitable locations.

Figure 8.8. Ortographic photo of 'Hørsholm'.

When identifying nearby opportunities for business collaboration with the PtX plant, certain types of industries are well-suited, as they can use the oxygen caused by water electrolysis in their processes. Among the businesses of interest are fish farming, metal industry, medical care, and paper production, as well as many more according to DEA [2021e, p. 96]. The ability to off-load the O_2 - caused by electrolysis - to nearby businesses/companies is therefore included in the consideration when identifying suitable location(s).

8.2 Procedure for developing reference systems

To investigate the impact of integrating waste heat - from PtX - into the future DH system in the Capital Region of Denmark, energy system modelling is applied. This is done for the purpose of developing an - as accurate as possible - illustration of the current DH system(s) subject to integration with PtX. This section aims to describe the decisions and assumptions made in the development of the models.

The general outline of the process is described in the following steps: identifying work area, identifying suitable modelling tool, selecting operation strategy, techno-economic considerations, developing reference model(s), introducing PtX into the reference model(s), and limitations of the model(s). These steps are described in the following.

8.2.1 Identifying work area

Having established suitable and selected specific locations for PtX in section 8.1, the extent of the DH system connected to these locations are identified. This is to make sure that the areas that are potentially affected by the integration of waste heat from PtX, is included in the investigation. The locations selected for PtX to be established are located in Helsingør and Hillerød, respectively. As such, the DH systems connected to these areas are subject to modelling. The DH systems in question include the 'Nordøstsjælland' DH system and the 'Hillerød-Farum-Værløse' DH system.

First step is to establish relevant distribution areas within the DH systems. To identify these areas, some assumptions are made. A reasonable assumption is that the distribution areas are connected by a series of main lines (distribution network) which are further interconnected by a heat transmission grid running from one central distribution plant to another DEA [2017]. However, to simplify the system, the many smaller, distribution areas are accumulated based on the distribution network, they are connected to, and available knowledge of established transmission lines in the DH system. Based on these assumptions, the NØS DH system includes the distribution areas of 'Hornbæk Fjernvarme A.m.b.a', 'Forsyning Helsingør A/S', 'I/S Norfors' and 'AK Fjernvarme'. The HFV DH system includes the distribution areas of 'Hillerød Forsyning A/S', 'Farum Fjernvarme A.m.b.a' and 'Værløse Varmeværk A.m.b.a'. The geographical location and relative distance between these distribution areas are illustrated in Figure 8.9.

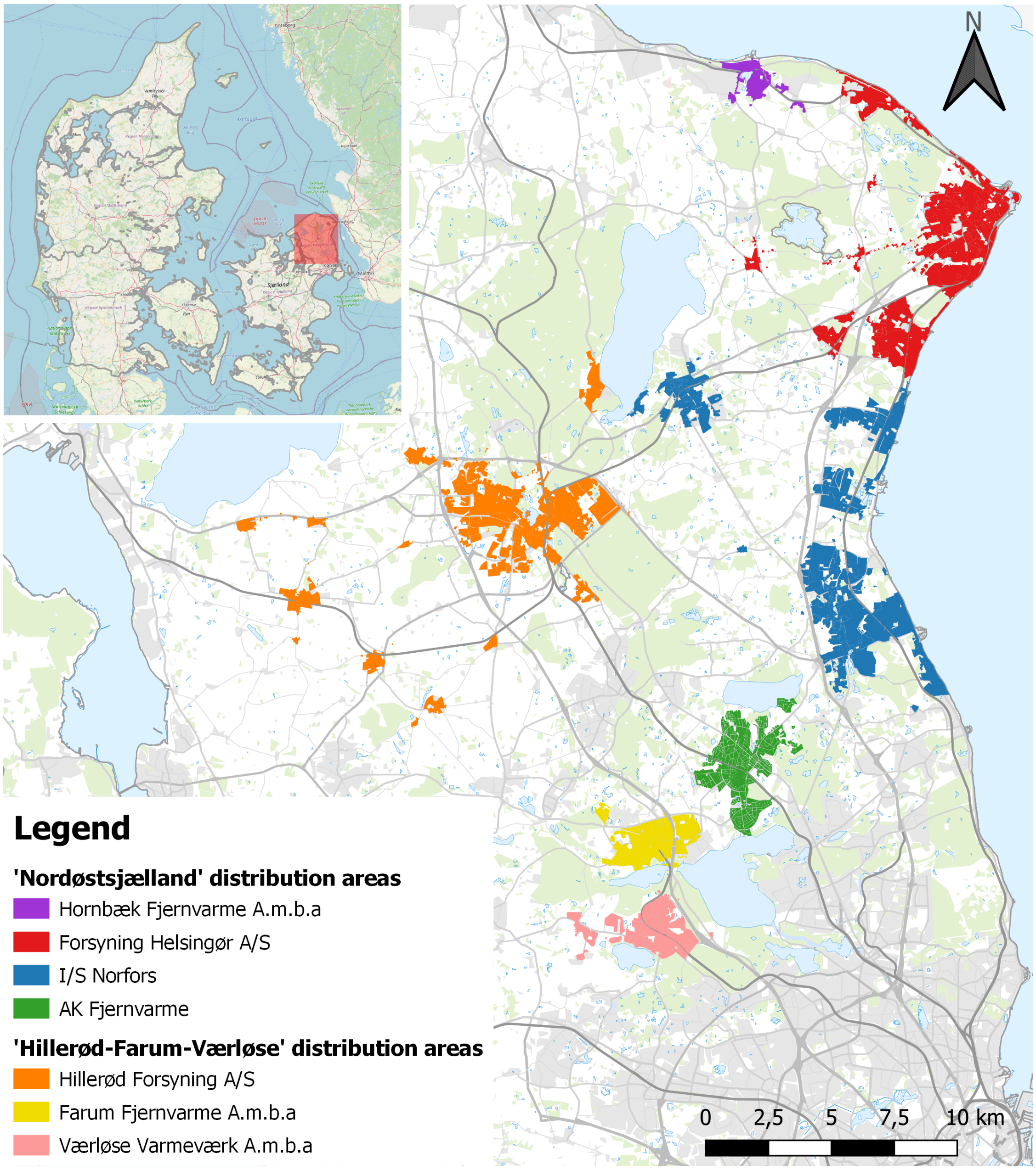

Figure 8.9. Identified distribution areas for in the NØS and HFV DH systems based on data from [EnergyMaps, 2020] representing the DH system in 2030.

The identified distribution areas effectively represent the work area of the models, meaning all input data is relevant to these areas.

8.2.2 Identifying suitable modelling tool

Based on the identified work area and the intention to integrate waste heat from PtX, a suitable energy system modelling tool is selected. [Connolly et al., 2010; Allegrini et al., 2015; Ringkjøb et al., 2018] are reviews of different modelling tools.

Based on the reviews, energyPRO (version 4.8.139) is selected as the modelling software to complete the

task. EnergyPRO is selected due to its capability of combined techno-economic analysis and optimisation of complex energy systems with multiple different energy producing units, including PtX [EMD International A/S, 2021a]. As such, the tool is capable of energy system analyses as well as single-plant analysis. This is advantageous when integrating PtX with fuel production and waste heat from processes at different temperatures, some of which could be upgraded. Compared to other tools such as EnergyPLAN, energyPRO provides more freedom to model the complexities of PtX. Additionally, the tool excels at modelling system at the local to regional scale thereby fitting the work area established in Figure 8.9.
A limitation of the software is that it only partly includes the heating sector. As such, only the DH sector is included in the program and not individual heating. However, since the analysis focus on waste heat for DH purposes, this is determined to no effect on the integrity of the intended models and the subsequent analysis.

8.2.3 Selecting operation strategy

The energyPRO modelling software applies a 'least-cost' approach to cover the demands. Based on operation costs (fuel cost, taxation, revenue etc.) for the individual production unit, a priority number is calculated for each unit in every time step (hourly) with the unit with the lowest marginal cost of production being awarded the highest priority. As such, the unit with the highest priority (lowest number) is scheduled for production first. This implies that CHP units are generally higher prioritised since e.g. sale of electricity is also included in the calculation. Some units are manually assigned a higher priority to insure that these units deliver in every hour they are available. Based on the calculated and assigned priority numbers, units are then dispatched in the model to cover the demands in every time step [EMD International A/S, 2021a].

To allow fuel producing energy units in the model, the build-in open source mixed-integer-linear-programming (MILP) CBC, is used as the calculation method [EMD International A/S, 2021b]. This is necessary when PtX is included in the model since fuels, such as hydrogen, is produced through electrolysis. To ensure that the models are developed on the same premise, MILP is therefore set as the calculation method for every model. The advantages hereof is the accuracy of the solutions that is delivered, and that optimal dispatch of the units is found without having to adjust operation strategy of the individual units [EMD International A/S, 2021b, p. 7]. However, using the MILP solver also presents some potential disadvantages. One disadvantage is that if a production unit is allowed to transmit energy between sites, but is not allowed to production to storage, then the solver does not prevent the transmitted energy from being stored in other sites [EMD International A/S, 2021b, p. 12]. A possible solution to this issue is by moving storage to the same site as the production unit [EMD International A/S, 2021b, p. 13]. For this reason, a suitable size storage is added to each site, thereby limiting this issue. For further elaboration on specifications of the implemented storage's is referred to Appendix A.

8.2.4 Techno-economic considerations

Investment costs are not included in the model(s) since the reference model(s) represent business-as-usual scenarios, meaning investments are assumed to be accounted for already. When introducing PtX, any potential investment costs are calculated and processed in a separate spread-sheet analysis during the techno-economic analysis. The techno-economic analysis is elaborated in section 8.3.

Fixed O&M do not influence the operation of the system, since this cost has to be paid regardless of operation. Therefore, fixed O&M of the production units are not included in the models. However, variable

O&M is depended on the operation of the system and is therefore included in the model. The variable O&M cost of the reference models are listed in Table A.8 and A.9 in Appendix A.

Heat sales, and import and export prices for transmission of heat between sites are not included in the model(s). This is because energyPRO considers the economy of the system in its entirety, but does not consider bilateral sales between producers in the system. Demonstration of the heat sales price of the individual production units are calculated in a separate spread-sheet analysis in Appendix A. This analysis assumes bilateral contract by calculating the heat sales price of the individual production unit based on fuel cost, O&M, taxation, tariffs, and investments for the heat production for the entire year.
The price of imported and exported heat between the different distribution areas (transmissions) is determined based on the heat sales price of the marginal producer. A reasonable assumption is that the transmission of heat from site A to site B would entail a contractual heat price in a real world scenario. In this case, the heat production cost is different from the heat sales price. As such, the marginal producer in site A sets the price of exporting (transmitting) heat to site B. This assumption is considered reasonable since it can be difficult to determine from which production unit heat is exported, if more than one production unit is exporting at the same time. The marginal producer, and thereby the export price, is determined in Appendix A.

8.2.5 Developing reference model(s)

Having established the general setup of the model(s), this section aims to describe the setup of the reference systems for the NØS and the HFV DH system(s), respectively. Assumptions and considerations about input-data for the reference models are described in Appendix A.

For the purpose of the modelling conducted, the "DESIGN" module is selected due to an interest in analysing energy conversion and operation payments when running the model. For more information regarding the calculation modules and detailed description of all folders is referred to [EMD International A/S, 2021a].

'Nordøstsjælland' reference model

In the reference model for the NØS DH system, the entire system is modelled including all distribution areas with their heat transmissions, heat demands, production plants with capacities and consumption, variable O&M, fuels with heat values and costs, emissions and taxation, and estimated storage capacities. These data inputs are described in Appendix A. However, to limit computational time and data handling, some aggregation is applied. As such, if one site has more than, e.g., one boiler with the same characteristics, then these boilers are grouped to represent the collective capacity and consumption of all boilers in the individual site. In this way, there are never more than one unit of a specific technology per site. Additionally, all demands are aggregated for each site.

The energyPRO interface and sites for the NØS reference model are presented in figure 8.10.

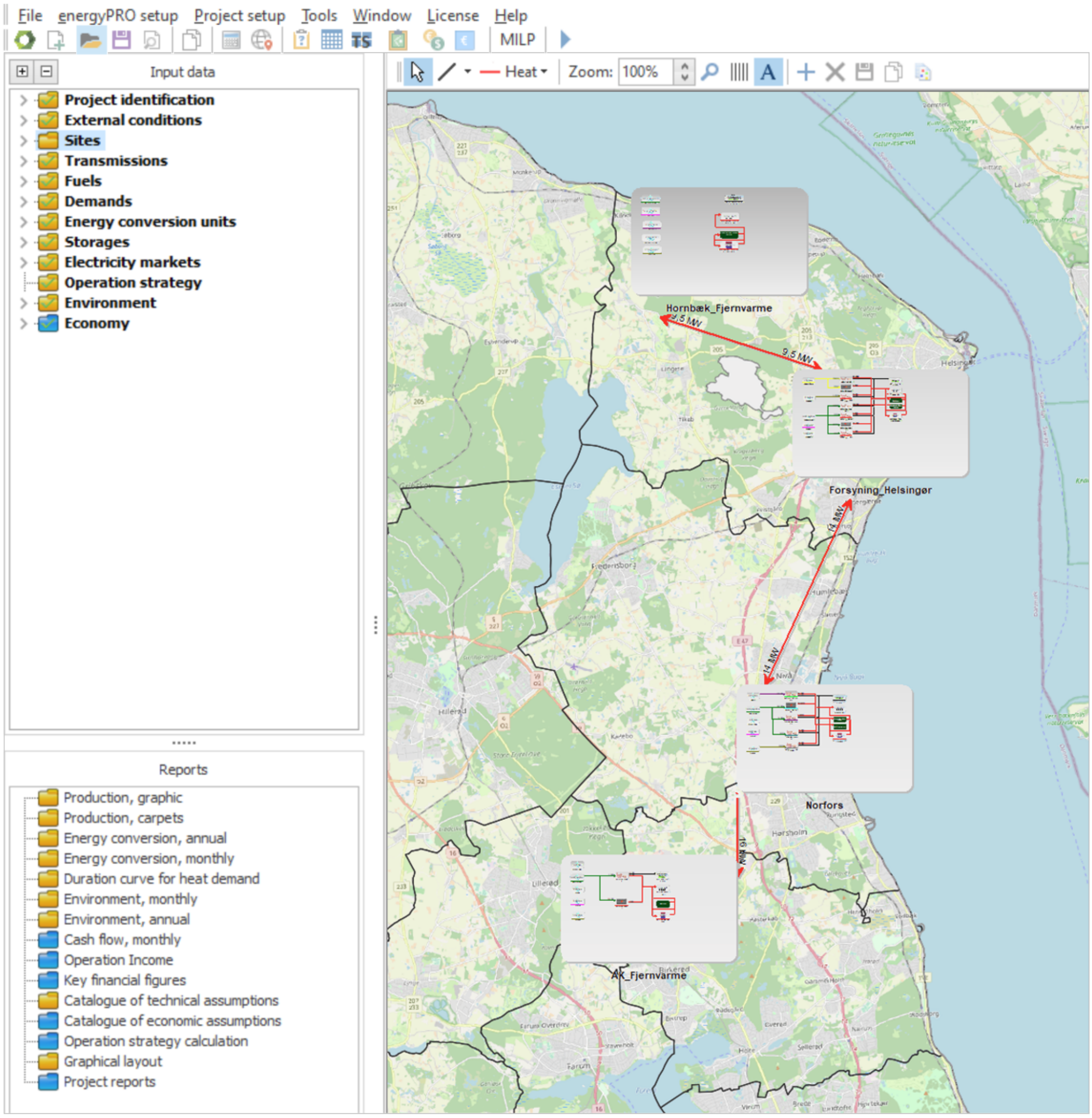

Figure 8.10. Screenshot of the energyPRO interface including modelled sites in the reference model for the NØS DH system forecasted to 2030. Liberties are taken to include a background map to illustrate the general location of the modelled sites.

'Hillerød-Farum-Værløse' reference model

Like in the reference model for the NØS DH system, the reference model for the HFV DH system is modelled including all the same types of data inputs. These data input are described in appendix A. Aggregation of production units is also applied in this model. However, in the model for the HFV DH system, some units are set to have high priority manually. These include the waste heat from Nordisk Perlite ApS and solar heat. The waste heat from Nordisk Perlite ApS is included as base-load in every hour it is available, and solar heat is set to be prioritised when available.

The energyPRO interface and sites for the HFV reference model are presented in Figure 8.10.

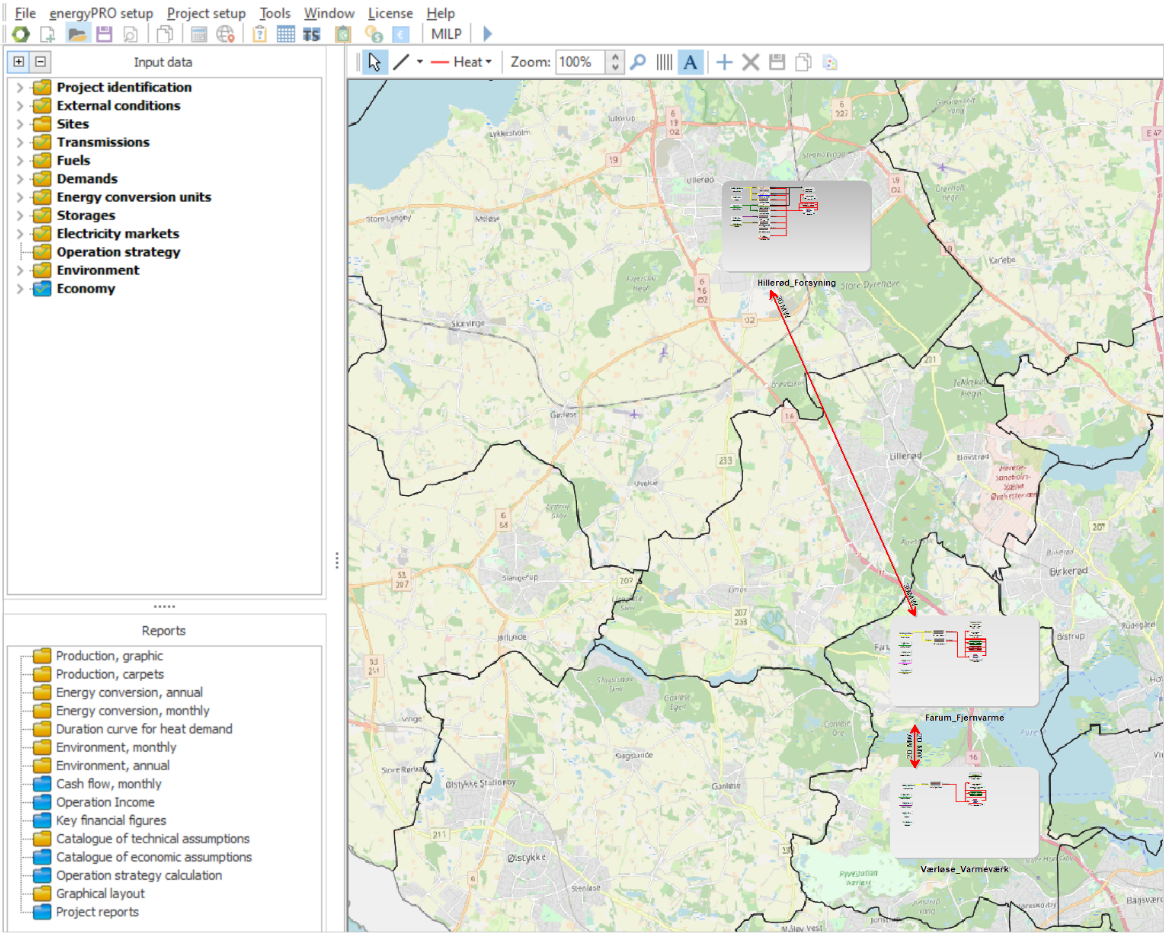

Figure 8.11. Screenshot of the energyPRO interface including modelled sites in the reference model for the HFV DH network forecasted to 2030. Liberties are taken to include a background map to illustrate the general location of the modelled sites.

8.2.6 Introducing PtX into the reference systems

Based on the developed reference models, PtX is introduced to the systems in the form of electrolysis. This is done separately for both the NØS and the HFV DH systems. PtX is integrated as individual sites to allow the intricacies of the PtX plant to be modelled without influence from other production units. Waste heat from the processes of the PtX plant is however set to be delivered to the distribution area (site) within which the plant is located. This implies that in the NØS DH system, the PtX site is set to deliver waste heat to the distribution area of 'Forsyning Helsingør A/S', while in the HFV DH system, the PtX site is set to deliver waste heat to the distribution area of 'Hillerød Forsyning A/S'. The transmission line between the PtX site(s) and the connected distribution areas are assumed to have unlimited capacity. This is to make sure that all waste heat that is produced from the processes of the PtX plant(s) can be integrated into the DH system. This assumption is considered reasonable since the PtX plant(s) in reality would be considered part of the distribution areas to which the heat is transmitted.

The priority number of the electrolysers are set to be calculated using the MILP solver mentioned in the previous. This is to simulate a situation where the electrolyser acts as a flexible production depending on the electricity market. The heat pumps are set to have high priority, but are limited to production only when production from the electrolyser is present. This is to simulate a situation where low temperature waste heat

- from the auxiliary systems of the electrolyser - is upgraded and utilised by the heat pumps before being fed to the DH system.

The setup of the electrolysis plants, including the heat pump and sale of products, is illustrated in Figure 8.12.

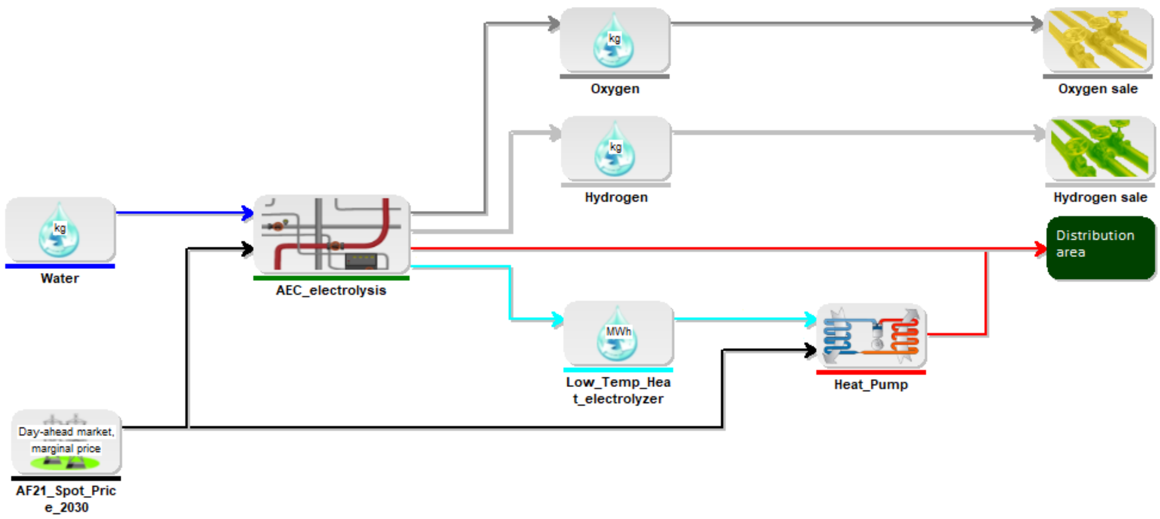

Figure 8.12. Setup of the electrolysis plants including heat pump for upgrading low temperature heat.

Having established the setup of the electrolysis plant, the following aims to describe the technical and financial assumptions of the data-inputs for integrating PtX into the reference models of the NØS and HFV DH systems respectively.

Technical assumptions

The type of electrolysis that is modelled is AEC. This type of electrolysis is chosen due to the in section 3.2 mentioned advantages of high TRL allowing for scaling with low investment cost compared to PEMEC and SOEC.

The capacities of the electrolysis plant(s) are determined based on the spatial requirements (MW/m^2) for alkaline electrolysis (AEC), compared to the available space at the two selected areas (the green hatched area on Figure 9.4 and 9.6). The spatial requirement for electrolysis is assumed to be 1000 m^2 per MW of electrolysis, based on e-email correspondence with a representative from European Energy. This spatial requirement includes reserved space for expansion with methanisation processes for methanol production. The estimated capacities of the electrolysis are listed in Table 8.1.
Using these capacities, the water usage and hydrogen production of the electrolysis processes are determined based on the characteristics of AEC in Table 3.1 in section 3.1.1. The resulting oxygen production is determined based on the ratio between the atomic weight of hydrogen and oxygen. The reaction of the electrolysis production is illustrated by equations 3.2 and 3.3. From this, it is evident that for every hydrogen (gas) molecule (H_2) produced in the electrolyser, a half oxygen (gas) molecule (O_2) is also produced. Thus, for every two hydrogen molecules, a single oxygen molecule is produced. Using their respective atomic weights and this ratio, the mass of the oxygen gas produced is determined. The amount of oxygen produced in the electrolysis process, based on the capacities, is listed in Table 8.1.

The AEC delivers high quality heat at 70°C from the electrolysis process, as mentioned in section 3.1.1, and low quality heat at 35°C from the auxiliary systems, as mentioned in section 3.1. A 40/60 split is assumed between high and low quality heat delivery, respectively. This is based on assumptions in [DDHA, 2021], a case study of a 20 MW_e electrolysis plant.
To determine the amount of heat subject to the 40/60 split, linear interpolation is applied based on the amount of recoverable heat per capacity of electrolysis. The amount of recoverable heat from AEC is listed in Table 3.1 in section 3.1.1. As such, linear interpolation is performed between the amount of recoverable heat from a 1 MW AEC (14, 6%) and a 100 MW AEC (16, 6%). For Helsingør, this amounts to a recoverable heat percentage of 14, 96% of the total electricity input. For Hillerød, this amounts to a recoverable heat percentage of 15, 26% of the total electricity input.

The characteristics of the electrolysis integrated in the NØS and HFV DH systems, respectively, are listed in Table 8.1.

Table 8.1. Characteristics of the electrolysers (AEC) for Helsingør and Hillerød

	Helsingør AEC	**Hillerød AEC**	**Unit**
Electric capacity	18, 0	33, 0	MW
Water usage	3312, 0	6072, 0	kg/h
Hydrogen prod.	367, 2	673, 2	kg/h
Oxygen prod.	2914, 1	5342, 5	kg/h
High temp. waste heat	1, 1	2, 0	MWh
Low temp. waste heat	1, 6	3, 0	MWh

To utilise the amount of low quality heat (low temp. waste heat in Table 8.1), this heat is upgraded to be sold along with the high quality heat using a heat pump. Assuming 4GDH to be implemented in the future DH system (2030), the capacity of the heat pump is determined based on a calculated theoretical COP value (explained in Appendix B). The characteristics of the heat pumps are listed in Table 8.2.

Table 8.2. Characteristics of the heat pumps for Helsingør and Hillerød.

	Electric capacity [kW]	**Heat Source [MWh]**	**COP value**
Helsingør			
Heat pump	85, 00	1, 60	19, 38
Hillerød			
Heat pump	156, 00	3, 00	19, 38

Financial assumptions

Electrolysis requires large amounts of water and electricity for the production of hydrogen with oxygen as a by-product, as mentioned in section 3.1. In the PtX model(s), a price on water, hydrogen, and oxygen is therefore introduced. The electricity price is represented by the hourly price forecast for 2030 described in Appendix A. The price of water, hydrogen, and oxygen is listed in Table 8.3.

Table 8.3. Oxygen, hydrogen, and water prices used in the model.

	Price	Unit	Reference
Oxygen	$1,12$	DKK/kg	[Bellotti et al., 2019, p. 4724]
Hydrogen	$20,00$	DKK/kg	[Meza, 2022]
Water (Helsingør)	$16,37$	DKK/m^3	[DANVA, 2022]
Water (Hillerød)	$21,19$	DKK/m^3	[DANVA, 2022]

The oxygen price represents a typical market value for oxygen [Bellotti et al., 2019, p. 4724]. The hydrogen price is determined based on estimates by the IEA on a theoretical competitive price for hydrogen in the future [IEA, 2019, p. 149], IRENA's exploration of strategies and policies to drive down the cost on electrolysis and green hydrogen [Irena, 2019], and assumptions in 'Power-to-X and DH' in which a case study of a 20 MW$_e$ and 400 MW$_e$ electrolysis is conducted [DDHA, 2021, p. 17]. Additionally, the price is determined based on the assumption that the hydrogen that is produced during electrolysis in the model, represents green hydrogen. This assumption is considered reasonable since the renewable share of electricity is expected to exceed 100% in 2027 [DEA, 2020b]. The water price for Helsingør is based on the average commercial water price from 'Hillerød Vand A/S' ($18,31$ DKK/m^3) and 'Nyhuse Vandværk' ($14,42$ DKK/m^3). The water price for Hillerød is likewise based on the commercial water price from 'Forsyning Helsingør Vand A/S' [DANVA, 2022].

Consumption of electricity is subject to tariffs. These tariffs include a transmission tariff, a system tariff, and a balance tariff [Energinet, 2022]. The transmission tariff covers Energinet's costs related to operation and maintenance of the overall electricity grid and maintenance of international connections. The system tariff covers the cost to ensure security of supply and the overall quality of the electricity supply. This includes reserve capacity, system operation, etc. Finally, the balance tariff covers part of Energinet's total costs for system services and management of the balancing market [Energinet, 2022]. The tariff scheme for the electrolyser and the heat pump is listed in Table 8.4.

Table 8.4. Tariff scheme for the electricity consuming units.

	Tariff	Unit	Reference
Transmission	$49,0$	DKK/MWh	[Energinet, 2022]
System	$61,0$	DKK/MWh	[Energinet, 2022]
Balance (consumer)	$2,29$	DKK/MWh	[Energinet, 2022]

Fixed O&M is not included in the model, since this cost have no affect on the operation of the system. However, the variable cost of the electrolysis and the heat pump is included since the cost depends on the number of operation hours. As mentioned in the previous, Helsingør has a heat pump (utilising industrial waste heat) with a heat capacity of $1,6$ MW and Hillerød 3 MW. The variable O&M for Helsingør's heat pump is based on a linear interpolation of the variable O&M for a heat pump (that utilises industrial waste heat) with a heat capacity of 1 MW and 3 MW. The variable O&M for electrolysis and heat pumps are listed in Table 8.5.

Table 8.5. Variable O&M for AEC and heat pumps used in Helsingør and Hillerød.

	Variable O&M	Unit	Reference
Helsingør			
18MW AEC	-	-	-
1,6MW heat pump	19,64	DKK/MWh	[DEA, 2021d, p. 308-310]
Hillerød			
33MW AEC	-	-	-
3MW heat pump	18,60	DKK/MWh	[DEA, 2021d, p. 310]

The electrolyser and the heat pump are taxed differently from the other technologies in the system. If the electricity is used for process, then the producer is reimbursed for the entire electricity tax except for a fixed tax rate on the electricity that is used for process purposes [PwC, 2022a]. The tax on the waste heat that is produced in the electrolysis processes is set at a fixed cost. However, this tax is currently pending decision in the Danish parliament to be removed [Parliament of Denmark, 2021; DEA, 2021c], if an agreement with the waste heat producer can be established [PwC, 2022c].
For upgraded heat in the heat pump where the original heat source comes from the soil, air, or other renewable sources, a tax on electricity consumption and heat production is paid. Additionally, a tax reduction amounting to the difference between the electricity tax and the heat tax is included [Skat, 2022]. The taxation scheme for electrolysis and the heat pump, respectively, are listed in Table 8.6.

Table 8.6. Taxation scheme for electrolysis and heat pumps in the model.

	Tax	Unit	Reference
Electrolysis			
Electricity	4,00	DKK/MWh	[PwC, 2022a]
Waste heat	7,17	DKK/MWh	[PwC, 2022c]
Heat pump			
Electricity	885,00	DKK/MWh	[Skat, 2022]
Upgraded heat	214,00	DKK/MWh	[Skat, 2022]
Tax reduction	671,00	DKK/MWh	[Skat, 2022]

The tax reduction of the heat pump is included in the models as a revenue to offset parts of the electricity and heat tax on the heat pump (tax on the upgraded heat in the heat pump).

8.2.7 Limitations of the model(s)

A general limitation of the models, is that they illustrate "perfect" world cases in the sense that no unforeseen malfunction or errors occurs in the system. As such, no unforeseen influences on the system occurs which may affect the theoretical optimal operation of the system determined by the set parameters.
Additionally, the system has perfect knowledge of external conditions such as the weather, electricity price and heating demand. Thus, the software is able to plan optimal dispatch of units without having to react to sudden extreme weather events, electricity outages or malfunctions in the production units, which could cause sub-optimal operation. Such events would therefore change the operation of the system and may require higher reliance on back-up generation capacity.

Bidding strategies in the electricity market and regulation markets are not considered in the models, despite possibly affecting the operation strategy of the system. As such, some production units may potentially gain revenue by offering services to balance the electricity grid. However, the electricity prices in the model are not effected by changes to supply and demands in the grid. As such, grid management is not considered.

Due to limitations of the software, all CHP units are modelled as back-pressure units, meaning a fixed ratio between electricity and heat output is achieved with no variations. Additionally, ramp-up and ramp-down times are not considered due to extended computational time in the energyPRO software. In reality, however, one would expect a time delay and increased usage of resources on start-up. The resulting operation of the systems in the models therefore reflects an optimistic operation.

Transmission costs are not included in the models. This means that there are no negative effects of transmitting heat between distribution areas. As a result, the models tend to prioritise transmitting heat from distribution areas with low marginal cost of production to distribution areas with high marginal cost of production. In reality, the transmission of heat between distribution areas would be accompanied by a price on the transmitted heat. This may affect the operation of the system. If e.g., the marginal producer in site A sells heat at a certain price point, and an additional cost on transmission of the heat is added, then the total cost may exceed the marginal production achieved in site B. In this case, no transmission of heat would occur, and the demand in site B would instead be covered by the production unit(s) within the distribution area.

8.3 Performing techno-economic assessment of PtX

As part of the efforts of conducting a techno-economic assessment/analysis of implementing PtX at the two suitable locations - Helsingør and Hillerød - a NPV of the two PtX plants is conducted to asses the financial feasibility. Furthermore, a LCoH is calculated to illustrate the price at which the waste heat and the upgraded heat have to be sold at, for the investment to remain neutral (NPV=0). This is compared to the heat sale price of the other producing units in the DH systems.

The financial data of the electrolysers are linearly interpolated between data for electrolysers with a capacity of 1 MW and 100 MW. Furthermore, the 1, 6 MWth heat pump is similarly linearly interpolated between a 1 MWth and 3 MWth heat pump; it was not necessary to make an interpolation for the 3 MW heat pump since data for this capacity was already listed in the literature. The values used in the techno-economic analysis are listed in Table 8.7.

In calculating the heat sale price for each plant, fuel costs, variable O&M, environmental taxes (Energy tax, CO_2, SO_2, CH_4, and NO_2), refunded taxes and electricity tariffs are calculated using the energyPRO software. Investment cost and fixed O&M are listed in table 8.7.

Table 8.7. Input values used in the techno-economic analysis [DEA, 2021d,e].

Hillerød	**Value**	**Helsingør**	**Value**	**Unit**
33 **MW AEC**		18 **MW AEC**		
Specific investment	3.952.218	Specific investment	4.087.490	DKK/MW of total input$_e$
Fixed O&M	4, 03	Fixed O&M	4, 48	% of specific investment/year
Technical lifetime	30	Technical lifetime	30	Years
3 **MW HP**		1, 6 **MW HP**		
Specific investment	5.654.400	Specific investment	7.633.440	DKK/MW
Fixed O&M	14.880	Fixed O&M	14.880	DKK/MWh/year
Variable O&M	18, 6	Variable O&M	19, 64	DKK/MWh
Technical lifetime	25	Technical lifetime	25	Years

For CHP units, it is taken into account that part of the cost of production should be carried by the electricity price. This is done by calculating a ratio between the amount of electrical energy and thermal energy produced, applying this ratio to the expenses; e.g., if a unit produces 20% electricity and 80% heat, the heat sales price is based on 80% of the expenses. In calculating the heat sales price, it is assumed that the investment cost is divided over the lifetime of the unit in equal instalments, thus resulting in a yearly cost with no interest applied. This assumption is made due to varying commissioning dates of the many smaller production units, which have been aggregated into larger units for the purpose of the analysis.

Waste heat sales is assigned a fixed price dependent on if the heat is sold in the winter or summer months; in the summer months, the price is set at 150 DKK/MWh, while the price in the winter months is set at 200 DKK/MWh [DDHA, 2021, p. 16]. As such the yearly cost to the consumer is calculated based on production in each the summer and winter period. The summer period is assumed to start the 15th of April and ending the 15th of October, while the remaining period is considered as the winter period. With this, the heat sales price is calculated using equation 8.1.

$$\text{Heat sales price} = \frac{\text{Expenses} \cdot \text{Heat ratio}}{\text{Thermal energy}} \tag{8.1}$$

In addition, a weighted mean heat sales price is calculated for each of the distribution areas visualised in Figure 8.9, considering total heat production in these areas. In calculating the weighted mean, the units with only expenses and no production have their expenses added to the total, thus taking into account their cost to the consumer.

8.3.1 Net Present Value

To evaluate the financial viability of the PtX plants and their respective heat pumps, NPV calculations are conducted.

A discount rate of 4% is used due to the recommendation by Danish Ministry of Finances regarding investments with a lifetime of $0 - 35$ years [The Ministry of Finance of Denmark, 2018]. Due to the lifetime of the electrolyser (30 years) the span of the NPV is calculated according to this lifetime, with potential for reinvesting in the heat pump after 25 years (lifetime of the heat pump). This is included as an investment in that year and a refund at the end of the full period for the remainder of the value, decreased linearly over time.

The construction time of the electrolyser is four months, while the construction time of the heat pump is six months [DEA, 2021d,e]. As such, it is assumed that in the year following investment in the electrolyser, revenue amounting to 2/3 of the rate for the year is included, and for the NPV of the heat pump a revenue amounting to 1/2 of the rate for the year is included - compared to those of succeeding years [DEA, 2021d,e].

The electrolyser includes profits from oxygen and hydrogen gasses. The heat pump has two calculations made, one using the average heat sale price for the system and one with no revenue for calculation of a 'Levelised Cost of Heat'. The NPV is calculated using equation 7.1 mentioned in section 7.5.1. The LCoH is calculated using equation 7.3 mentioned in section 7.5.2.

8.3.2 Sensitivity analysis

Due to uncertainties in the data gathered using literature-study and literature review, a sensitivity analysis is conducted. The sensitivity analysis is applied based on NPV calculations on the electrolysis plant and the heat pump utilising the average heat price of the NØS and the HFV DH system with increments of $\pm$ 5%, $\pm$ 10%, $\pm$ 15%, and $\pm$ 20% on selected input factors. The input factors - subject to the sensitivity analysis - are listed in Table 8.8.

Table 8.8. Input factors subject to sensitivity analysis.

Electrolyser	Heat pump
Investment cost	Investment cost
Operation and Maintenance	Operation and Maintenance
Fuel cost (electricity)	Fuel cost (electricity)
Water cost	Revenue
Hydrogen revenue	Taxes
Oxygen revenue	
Waste heat revenue	
Taxes	

Results 9

The purpose of this chapter is to investigate the problem formulation and subsequently the subquestions mentioned in chapter 4. This is done by using the methodological approach and theoretical framework mentioned in chapter 8 and section 6.2.

The first step of action is thus to identify suitable locations for utilising waste heat from PtX in the Capital Region of Denmark. The second investigation concerns the effect of implementing waste heat from PtX into the suitable locations found in step one. The third investigation revolves around the techno-economic aspects of implementing the waste heat from the PtX-facility at the suitable locations.

The purpose of the findings (and the report in general) is to create awareness around the topic of utilising waste heat from PtX as a renewable and suitable heat supply in the future district heating networks.

9.1 Identification of suitable location(s)

By using the methodological approach for finding the suitable locations for waste heat utilisation from PtX in the Capital Region of Denmark, as described in section 8.1, the ensuing results are shown in figure 9.1.

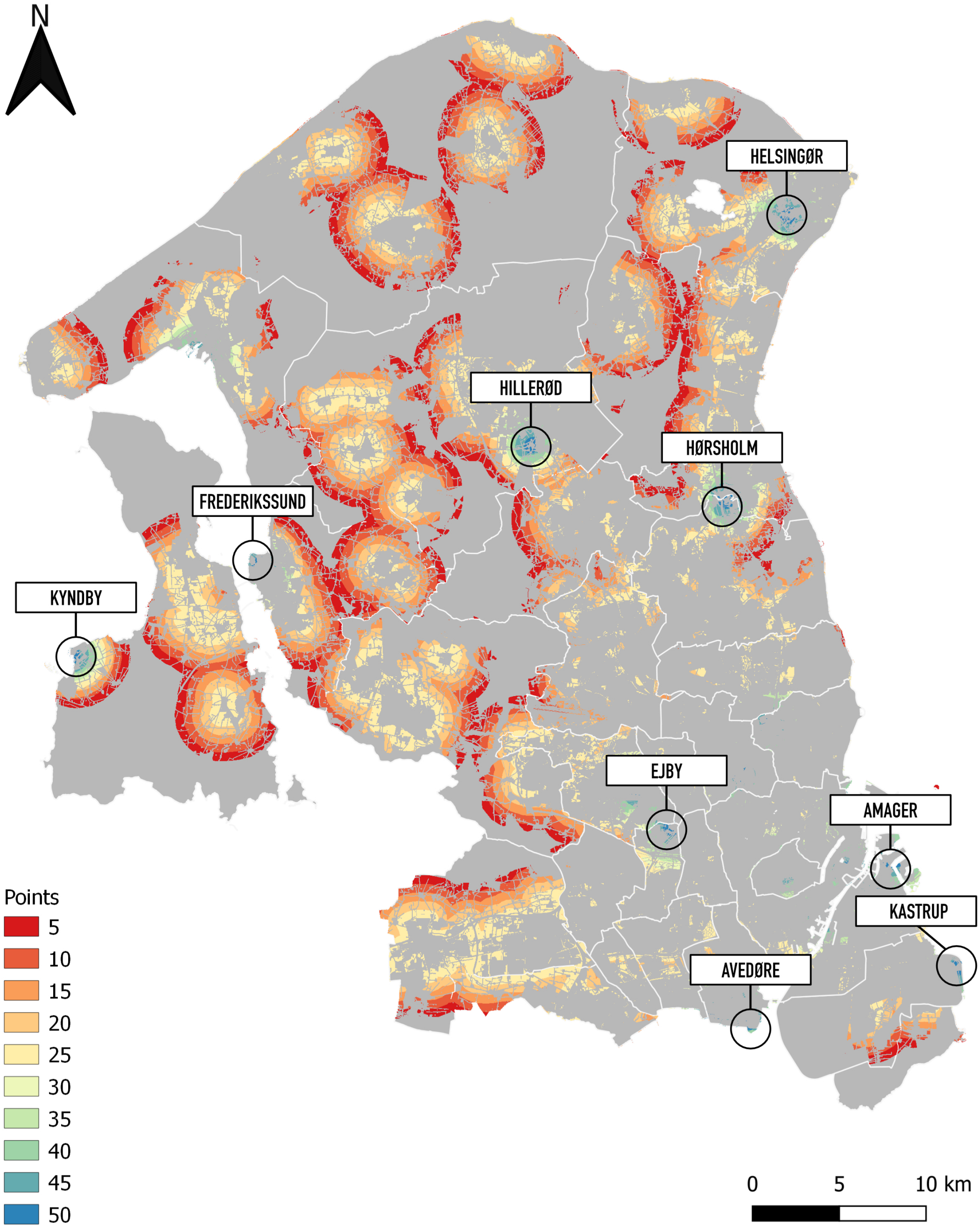

Figure 9.1. Suitable locations for implementing PtX in the Capital Region of Denmark, based on a GIS-analysis.

Figure 9.1 has a point score system that indicates the best suitable locations. The blue areas have a point score of 50 and indicate the best suitable locations and the red areas have a point score of 5, which would indicate the worst suitable locations (within the constraints of the GIS-analysis). The initial analysis thus determined nine locations (Kyndby, Frederikssund, Hillerød, Helsingør, Hørsholm, Ejby, Avedøre, Amager, and Kastrup) that *may* be suitable for a PtX facility; these locations are illustrated in figure 9.1.

Regardless of the end-product (hydrogen, methanol, ammonia, etc.) one desires from PtX, electrolysis is a part of the process. As mentioned in section 3.1, the chemical output of electrolysis is hydrogen (H_2) and oxygen (O_2); and as mentioned in section 8.1, oxygen can be used in a variety of industries such as:

medical care, glass manufacturing, steel and metal industry and many more. A further aspect/evaluation in the selection of a suitable location(s) is therefore the allocation of O_2. In this regard, two suitable locations were chosen: Helsingør and Hillerød. They were chosen on the further basis of being in close proximity to one or more industries that could utilise oxygen.

9.1.1 Helsingør ('Nordøstsjælland' DH system)

As illustrated by figure 9.1, Helsingør is a town located on the east coast of 'Nordsjælland'. The suitable locations found in Helsingør - as a result of the GIS-analysis mentioned in section 8.1 - are depicted on figure 9.2.

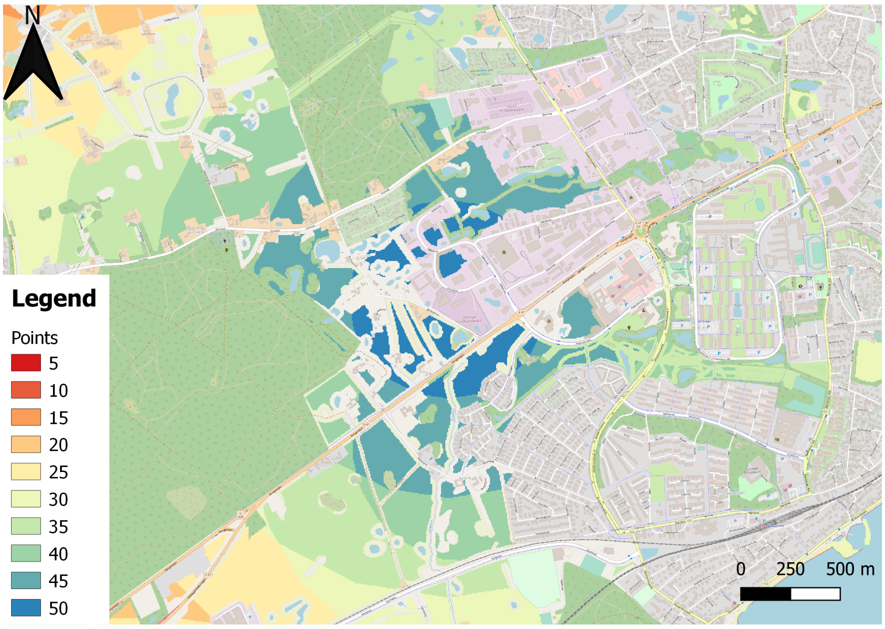

Figure 9.2. Suitable locations for placement of PtX-facility in Helsingør.

The Helsingør location is found suitable (in addition to the parameters of the GIS-analysis) on the basis of close proximity to three industries that can allocate the oxygen from the electrolysis process, which can be seen on figure 9.3.

Figure 9.3. Suitable locations for placement of PtX-facility in Helsingør. 'Selected area' (green hatched area) is the chosen location for placement of PtX-facility (for further analysis) and the purple hatched areas is a potential O_2 consumer and the red hatched area is a CO_2 source.

There are currently located two medical facilities in the Helsingør area. The closest one is 'Nyt Sundhedshus Helsingør' that is located within 900 meters of the suitable location (the purple hatched area southeast of the selected area). The other medical facility is 'Sundhedshuset Helsingør' that is located approx. 3, 7km from the suitable location (the purple hatched area northeast of the selected area). Another company that could allocate the O_2 is 'Semi-Staal A/S', which specialises in manufacturing of machinery and equipment, and is located approx. 200 meters from the suitable location (the purple hatched area directly north of the selected area). Furthermore, 'Helsingør Kraftvarmeværk' (Helsingør CHP-plant) is located approx. 200 meters - which could act as a potential CO_2 source - from the suitable location, which can be seen on figure 9.3.

It can be observed by Figure 9.3, that there is a potential suitable location (50 point score) south of the potential CO_2 source (red hatched area), that is considerable larger than the selected area (green hatched area). The reason for not building a PtX facility here is that the PtX facility would be in close proximity of a residential area (approx. 20 meters), and the selected area is located within an industrial area.

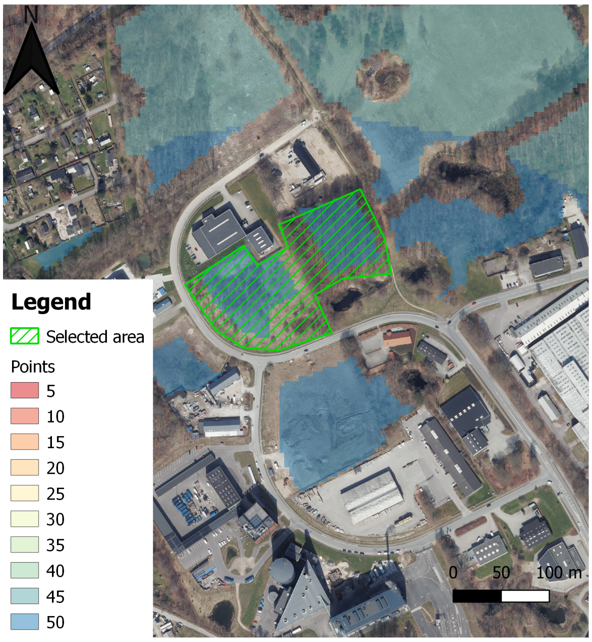

Figure 9.4. Close-up of the selected area for placement of PtX-facility in Helsingør.

Figure 9.4 presents a zoomed in picture of the selected area, which is the location for placement of the PtX facility for further analysis.

9.1.2 Hillerød ('Hillerød-Farum-Værløse' DH system)

Hillerød is a town located centrally in 'Nordsjælland', which can be seen on figure 9.1. The suitable locations for a Power-to-X facility are illustrated on figure 9.5.

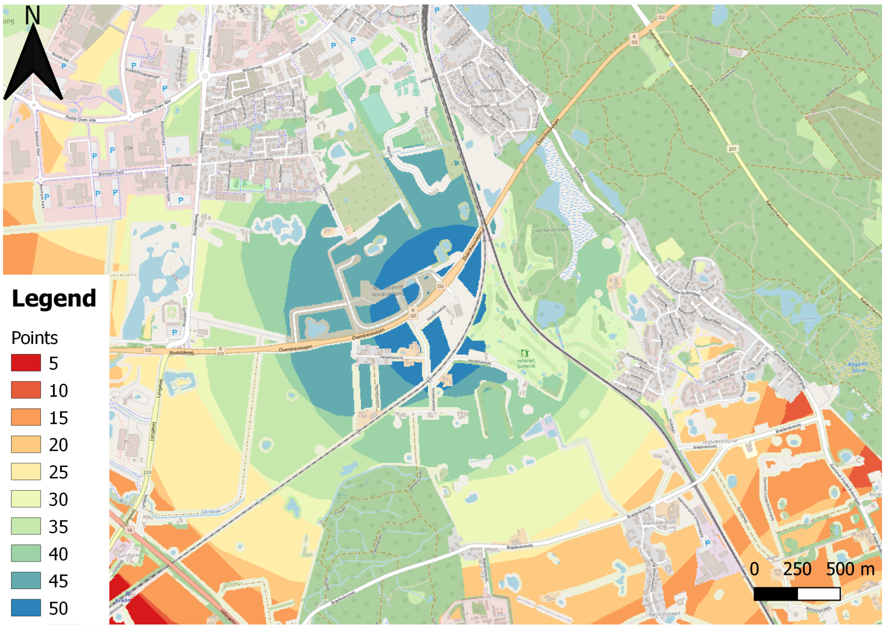

Figure 9.5. Suitable locations for placement of PtX-facility in Hillerød.

The Hillerød location is selected (in addition to the parameters of the GIS-analysis) due to its close proximity to an industry that can allocate the O_2 from the electrolysis process.

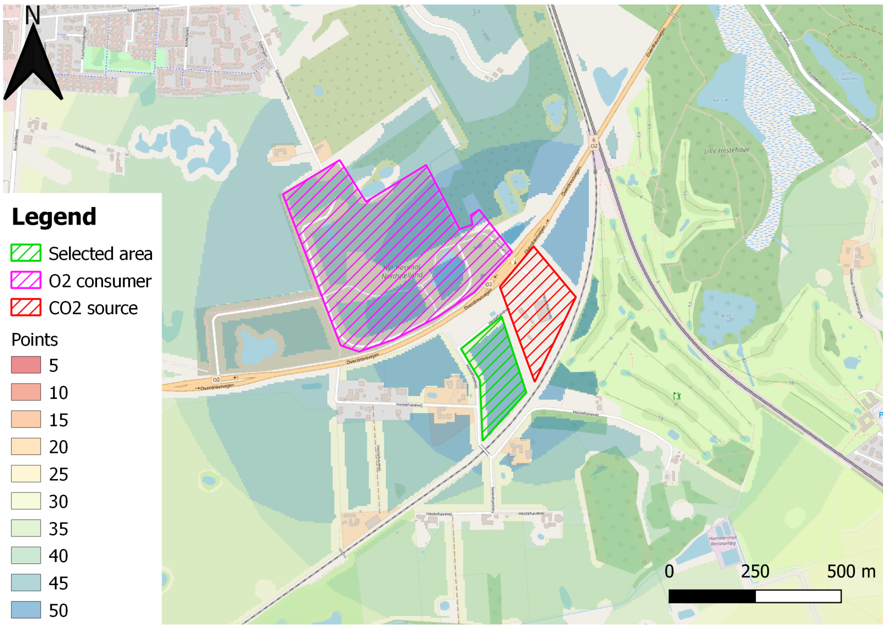

Figure 9.6. Suitable locations for placement of PtX-facility in Hillerød. 'Selected area' (green hatched area) is the chosen location for placement of PtX-facility (for further analysis) and the purple hatched area is a potential O_2 consumer and the red hatched area is a CO_2 source.

That industry is a future medical facility called 'Ny hospital Nordsjælland' and it is expected to be build by 2025 [Godtsygehusbyggeri, 2022]. It is located approx. 300 m from the suitable location, illustrated on figure 9.6. Moreover, 'Hillerød Kraftvarmeværk' (Hillerød CHP-plant) - which could act as a potential CO_2 source - is located approx. 200 m from the suitable location, which is illustrated on figure 9.6. The selected area (the green hatched area on figure 9.6) illustrates the specific area that a PtX-facility is going to be placed for further analysis.

9.2 Reference systems for PtX integration

The following section serves to present the results of the reference models, based on a 'business-as-usual scenario forecasted to 2030 (see Appendix A for an explanation of the 'business-as-usual scenario (reference model/system)). The reference system for the NØS DH system is presented first, followed by the reference system for the HFV DH system.

9.2.1 'Nordøstsjælland' DH system

In the reference model for NØS a variety of different technologies are used to cover the heat demand utilising a variety of different types of fuel. An overview of the types and shares of fuel is presented in 9.7, and an overview of the different types and share of technologies used for heat production is presented in figure 9.8.

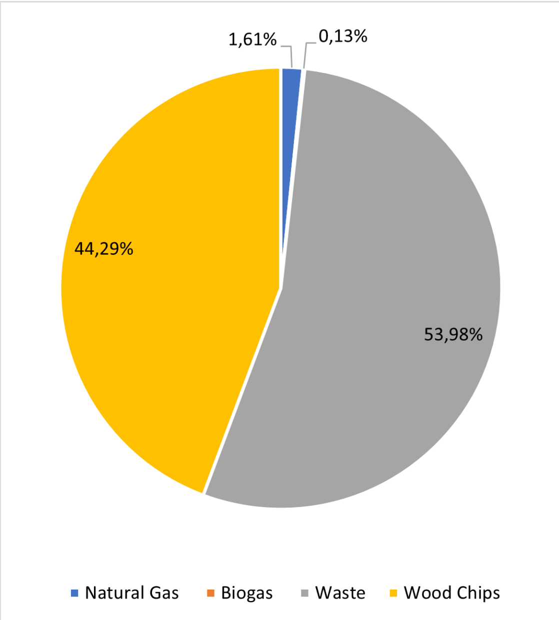

Figure 9.7. Heat produced from fuel in the NØS DH system.

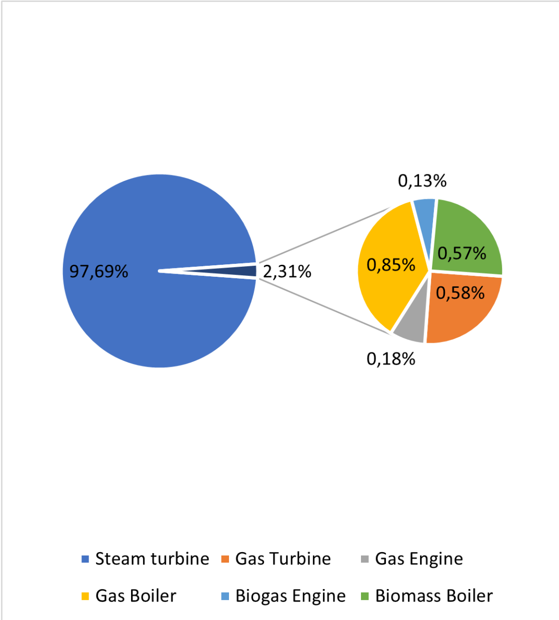

Figure 9.8. Heat produced based on technology in the NØS DH system.

It can be observed by figure 9.7, that both waste and wood chips account for the vast majority of the total heat produced from fuels (98, 3%); waste accounts for approx. 54% (361.774 MWh) and wood chips approx. 44% (296.831 MWh). The last two types of fuel in the NØS DH system are, respectively, natural gas that accounts for approx. 2% (10, 794 MWh) and biogas 0, 1% (857 MWh).
Regarding the heat produced from technologies - see figure 9.8 - approx. 98% (654.787 MWh) originates from the steam turbine (CHP plant). The remaining part comes from gas turbines (3.867 MWh), gas engines (1.207 MWh), gas boilers (5.719 MWh), biogas engines (857 MWh), and biomass boilers (3.818 MWh).

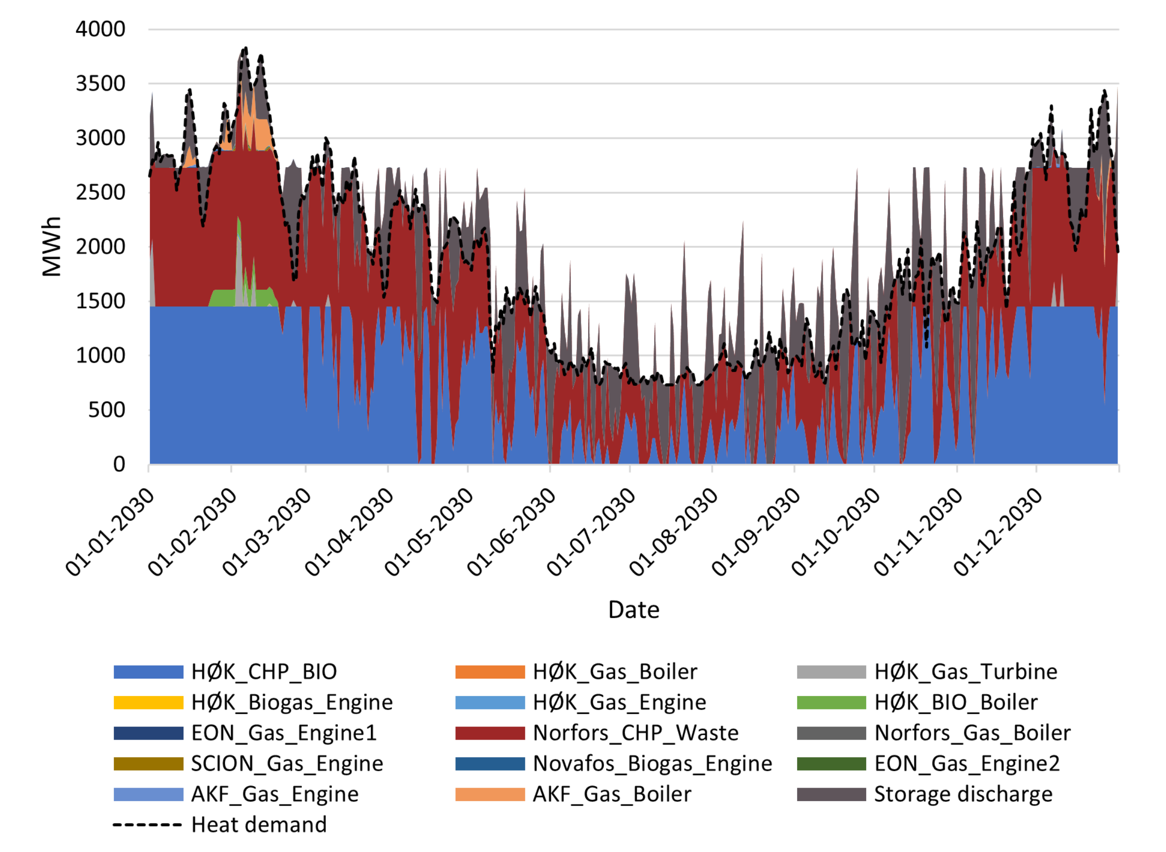

Figure 9.9. Daily heat demand, daily heat production from units, and daily storage discharge in the reference scenario for the NØS DH system.

Figure 9.9 illustrates the daily heat demand, daily heat production, and daily storage discharge based on the individual heat producing units in the reference scenario for NØS. HØK CHP BIO and Norfors CHP Waste produces heat throughout the entire year with some exceptions. Because the operating strategy for the CHP-plants are based on electricity demand (and because the vast majority of the heat produced stems from the CHP plants), there are certain hours throughout the year where there is a surplus of heat. The surplus of heat - which is illustrated on figure 9.9 by the grey area above the heat demand - is thus stored in the available thermal storages. During the summer period, the production of heat is limited to production from the CHP units utilising wood chips and waste as fuel. The sudden ramp-ups and ramp-downs of the CHP units are explained by the system to utilising the electricity market by producing heat in times with increasing electricity prices, while utilising the storages in times of decreasing electricity prices. As such, surplus heat is fed into the thermal storages in times with increased electricity prices.

9.2.2 'Hillerød-Farum-Værløse' DH system

The second suitable location found is the HFV DH system. In this DH system, there are also a variety of different technologies present and as a result different fuel types are used to meet the heat demand. The share of heat produced from fuels can be seen on figure 9.10 and an overview of the share of heat produced from technology is illustrated on figure 9.11.

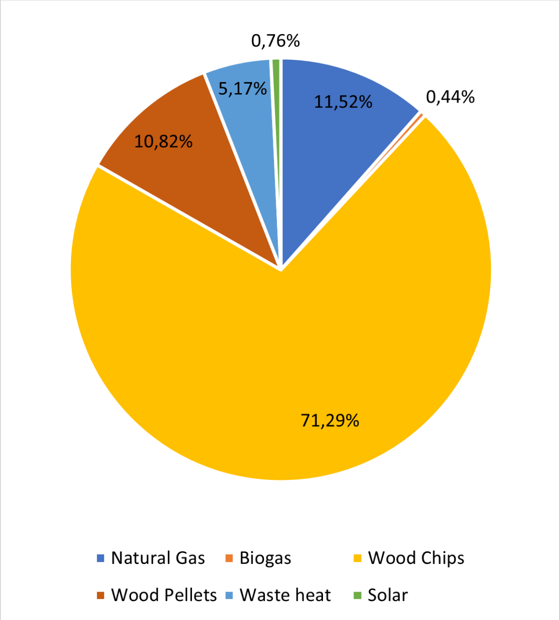

Figure 9.10. Heat produced from fuel in the HFV DH system.

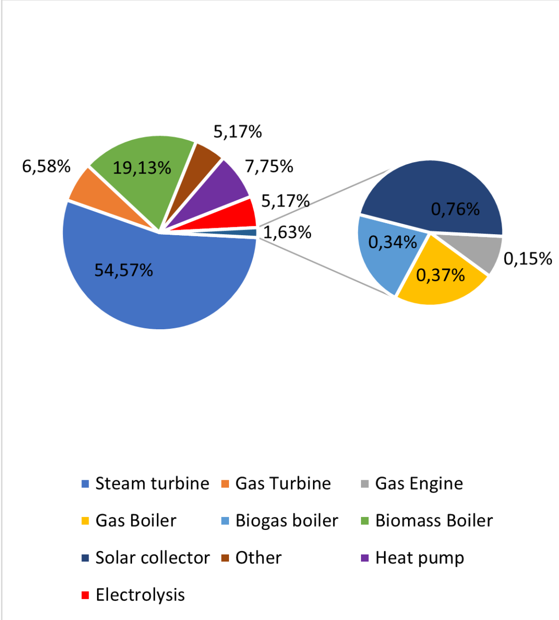

Figure 9.11. Heat produced based on technology in the HFV DH system.

As illustrated by figure 9.10, the largest amount of produced heat comes from the fuel type wood chips, which account for approx. 71% (241.639 MWh) of the total fuel usage. Next is natural gas and wood pellets that combined accounts for approx. 22%; natural gas 11, 5% (39.052 MWh) and wood pellets 10, 8% (36.671 MWh). The remaining heat is produced from the following fuels: biogas (1.498 MWh), waste heat (17.520 MWh), and solar (2.588 MWh).

Regarding the heat produced from technology - see figure 9.11 - approx. 82% (278.310 MWh) stems from the steam turbine (200.137 MWh) and biomass boiler (78.172 MWh). The gas turbines (34.448 MWh) and "other" (17.520 MWh) - which is waste heat from existing business in the HFV area - accounts for approx. 15% of the total heat produced. The remaining technologies such as biogas boilers, gas boiler, gas engine, and solar collector accounts for approx. 3% (8.691 MWh) of the total heat produced.

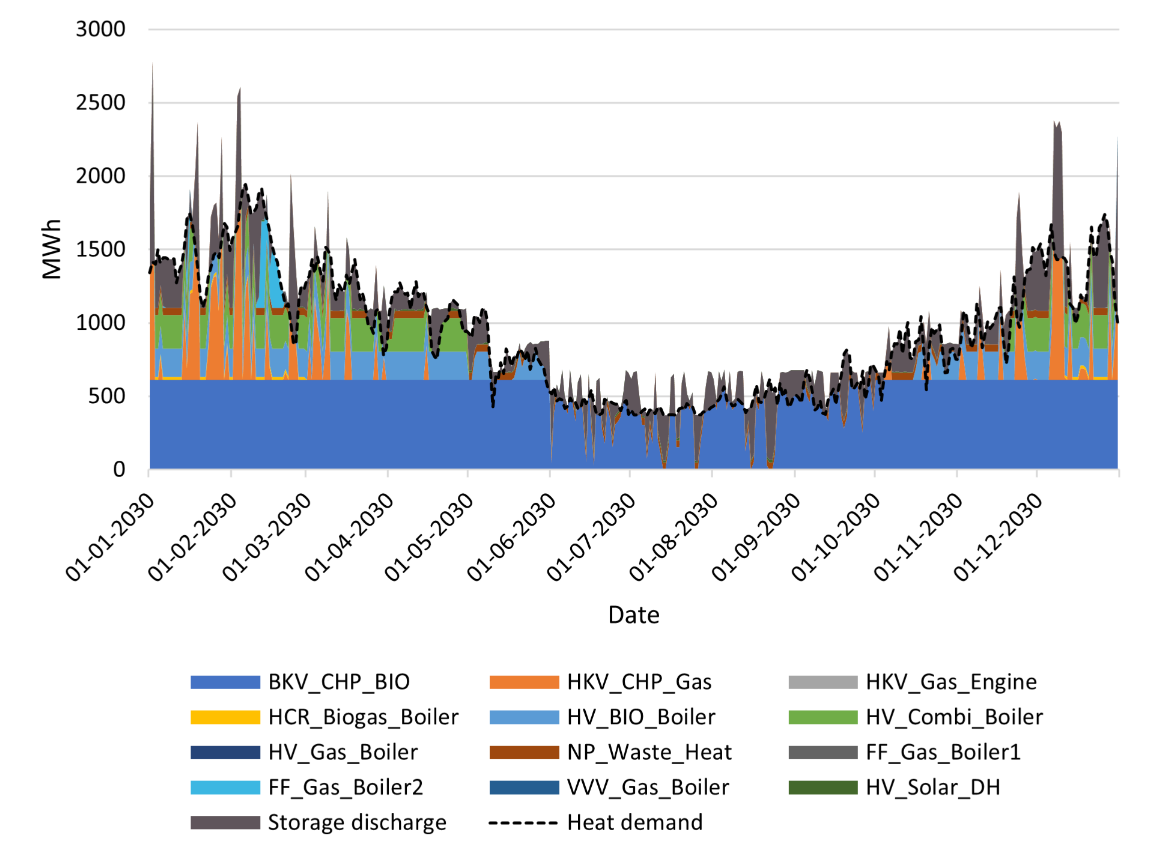

Figure 9.12. Heat producing units, heat demand, and storage discharge in the HFV DH system.

Figure 9.12 shows the daily heat demand, daily heat production, and daily storage discharge in the HFV DH system. The waste heat from the heat producing unit "NP Waste Heat" is used throughout the entire year. BKV CHP BIO is that main heat producing unit and produces throughout the entire year, with some exceptions in the summer months. The summer months (01-06-2030 to 01-10-2030) is supplied by BKV CHP BIO, waste heat and the thermal storage. Like the reference model for the NØS DH system, the operation of the HFV DH system attempts to utilise the electricity market by increasing heat productions in times with decreasing electricity prices, and feeding surplus heat to the storage. This is again evident from the discharge of the storages during hours with decreasing electricity prices.

9.3 Integration of PtX in the reference systems

The following section presents the results of implementing the suitable capacity of PtX (electrolysis) into the reference models for the NØS and HFV DH systems, based on the methodological approach mentioned in section 8.2.6. The results of implementing PtX into the reference model for the NØS DH system are presented first and followed by HFV DH system.

9.3.1 'Nordøstsjælland' DH system

In the NØS DH system, an 18 MW electrolyser and a heat pump with a heat capacity of $1,6$ MW is implemented. Utilising waste heat from the electrolyser and the heat pump in conjunction with already installed heat capacity, the new fuel composition is illustrated in Figure 9.13, and the subsequent technology use is illustrated in Figure 9.14.

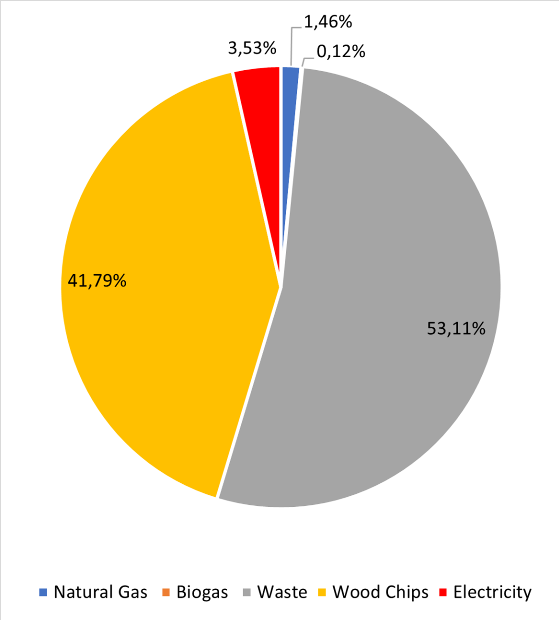

Figure 9.13. Heat produced from fuel with integration of waste heat from PtX in the NØS DH system.

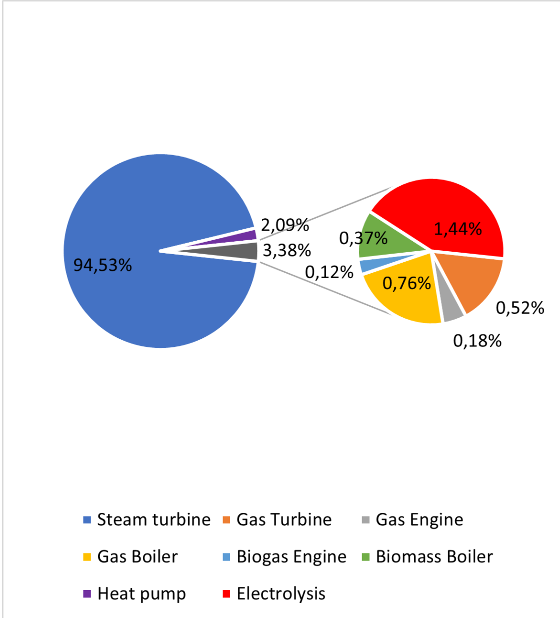

Figure 9.14. Heat produced from technology with integration of waste heat from PtX in the NØS DH system.

It is observed that heat produced from waste and wood chips amounts to a combined $94,9\%$ of the total heat produced. The remaining heat production stems from a combination of natural gas ($1,46\%$), biogas ($0,12\%$) and electricity ($3,53\%$). The majority of the heat is produced from steam turbine ($94,53\%$), while the remaining heat is produced from a combination of gas turbines ($0,52\%$), gas engines ($0,18\%$), gas boilers ($0,76\%$), biogas engines ($0,12\%$), biomass boilers ($0,37\%$), heat pump ($2,09\%$), and electrolysis ($1,44\%$).

The amount of heat produced based on fuel type and technology use in the reference system compared to the system with PtX integration is listed in Table 9.1.

Table 9.1. Heat produced from fuel and technology in MWh for the reference model and by implementing waste heat from PtX in the NØS DH system.

[MWh]	Reference model	Integration of PtX	Change
Heat from fuel			
Natural gas	10.795	9.756	−1.039
Biogas	858	771	−87
Waste	361.775	355.997	−5.778
Wood chips	296.831	280.082	−16.749
Electricity	0	23.652	23.652
Heat from technology			
Steam turbine	654.787	633.618	−21.169
Gas Turbine	3.868	3.506	−362
Gas Engine	1.207	1.187	−20
Gas Boiler	5.719	5.062	−657
Biogas Engine	858	771	−87
Biomass Boiler	3.819	2.461	−1.358
Heat pump	0	14.016	14.016
Electrolysis	0	9.636	9.636

It is observed from table 9.1, that the largest decrease in heat production from fuels is wood chips followed by waste. Moreover, a decrease in heat production from natural gas and biogas is observed. It is further observed that there is an increase in heat produced from electricity. This is due to electricity consumption by the electrolyser and the heat pump. By implementing the PtX into the NØS DH system there is also a change in how much heat each technology produces. The biggest decrease in heat production from technology stem from the steam turbine. Furthermore, a decrease in heat produced from the gas turbine, gas engine, gas boiler, biogas engine, biomass boiler is observed. Compared to the reference system, integration of the waste heat from the electrolyser account for the decreased production of the remaining production units.

Figure 9.15 illustrates heat producing units, heat demand, and storage discharge in the NØS DH system when integration of waste heat from PtX.

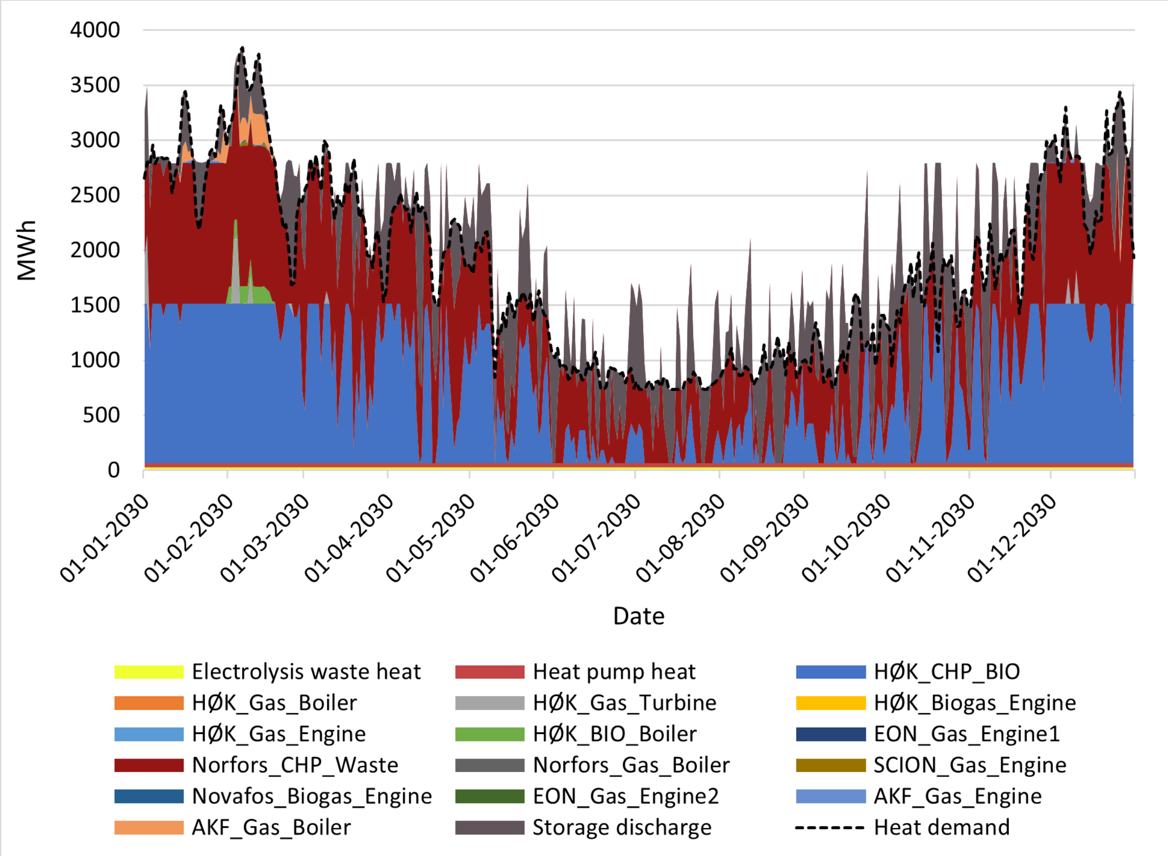

Figure 9.15. Heat producing units, heat demand, and storage discharge in the NØS DH system with integration of waste heat from PtX.

It is observed that the waste heat from the electrolyser and the upgraded heat from the heat pump appear to operate as base-load. This is explained by the hydrogen price (20 DKK/kg) and sales of oxygen resulting in a willingness to produce, even in hours of increasing electricity prices. As such, the resulting waste heat production is constant since hydrogen and oxygen sales are continuously taking place during every hour of the year. Additionally, the integration of the specific capacity waste heat from the electrolysis results in lesser reliance on storage capacity, which is especially the case in the summer months.

The yearly inputs and outputs resulting from the integration of the 18 MW electrolyser and 1, 6 MWth heat pump is listed in Table 9.2.

Table 9.2. Annually inputs for operation of heat pump and electrolysis and outputs as a result of operating heat pump and electrolysis in the NØS DH system.

	Amount	Unit
Input		
Electricity for heat pump	744	MWh
Electricity for electrolysis	157.680	MWh
Water	29.013	m^3
Output		
Heat pump heat	14.016	MWh
Electrolysis waste heat	9.636	MWh
Oxygen	25.528	tonne
Hydrogen	3.217	tonne

9.3.2 'Hillerød-Farum-Værløse' DH system

In the HFV DH system a 33 MW electrolyser and with a 3 MWth connected heat pump is implemented. Utilising waste heat from the electrolyser and the heat pump in conjunction with already installed heat capacity, the new fuel composition is illustrated in Figure 9.16, and the subsequent technology use is illustrated in Figure 9.14.

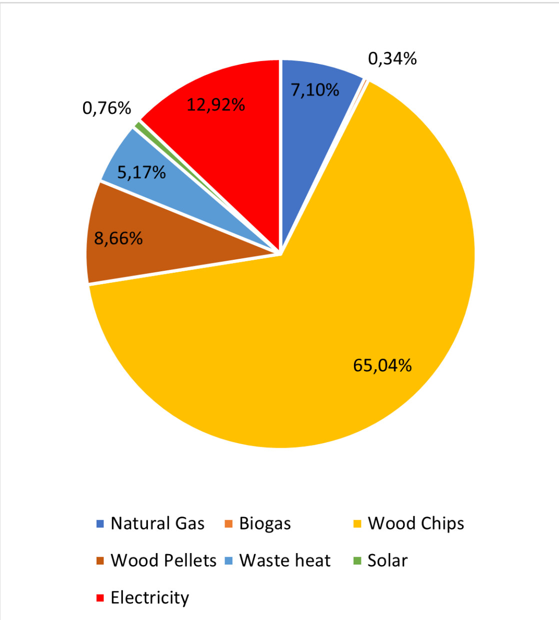

Figure 9.16. Heat produced from fuel with integration of waste heat from PtX in the HFV DH system.

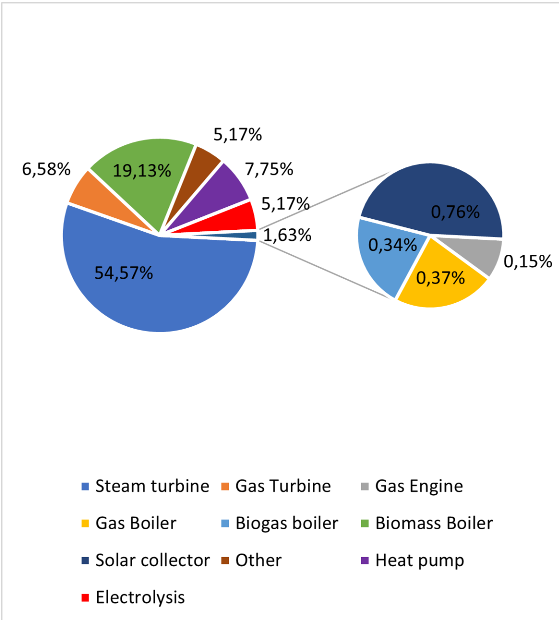

Figure 9.17. Heat produced from technology with integration of waste heat from PtX in the HFV DH system.

It is observed that the vast majority (65, 04%) of heat comes from wood chips, followed by electricity (12, 92%) and wood pellets (8, 66%). The remaining heat production stems from the combination of natural gas (7, 10%), waste (5, 17%), solar (0, 76%), and biogas (0, 34%). Majority of the heat is produced from steam turbine (54, 57%), followed by the biomass boilers (19, 13%) and the heat pump (7, 75%). The remaining heat is produced by a combination of gas turbine (6, 58%), electrolysis (5, 17%), other (5, 17%), solar (0, 76%), gas boiler (0, 37%), biogas boiler (0, 34%), and gas engine (0, 15%).

The amount of heat produced based on fuel type and technology use in the reference system compared to the system with PtX integration is listed in Table 9.1.

Table 9.3. Heat produced from fuel and technology in MWh for the reference model and by implementing waste heat from PtX in the HFV DH system.

[MWh]	Reference model	Integration of PtX	Change
Heat from fuel			
Natural Gas	39.053	24.076	$-14,977$
Biogas	1.498	1.168	-330
Wood Chips	241.639	220.471	-21.168
Wood Pellets	36.671	29.346	-7.325
Waste heat	17.520	17.520	0
Solar	2.589	2.589	0
Electricity	0	43.800	43.800
Heat from technology			
Steam turbine	200.139	184.969	-15.170
Gas Turbine	34.448	22.305	-12.143
Gas Engine	741	511	-230
Gas Boiler	3.864	1.259	-2.605
Biogas boiler	1.498	1.168	-330
Biomass Boiler	78.172	64.848	-13.324
Solar collector	2.589	2.589	0
Other	17.520	17.520	0
Heat pump	0	26.280	26.280
Electrolysis	0	17.520	17.520

It is observed from table 9.3 that when implementing the waste heat from the 33 MW electrolyser and the 3 MWth heat pump, there is a notable decrease in the heat production from wood chips, natural gas, and wood pellets. Furthermore, there is a decrease in the heat produced from biogas. The amount of heat from both waste and solar remains the same. It can further be observed that there is an increase in heat production from electricity, due to electricity consumption in the electrolyser and heat pump.
Upon further inspection of table 9.3, there is a substantial decrease in the heat produced from the steam turbine, biomass boiler, and gas turbine. Moreover, there is a decrease in heat stemming from the gas engine and biogas boiler. The amount of heat stemming from solar collector and "others" (waste heat) remains the same. As a result of implementing PtX into the HFV DH system a vast amount of the heat production now comes from both the heat pump and electrolyser.

Figure 9.18 illustrates heat producing units, heat demand, and storage discharge in the HFV DH system when integrating waste heat from PtX.

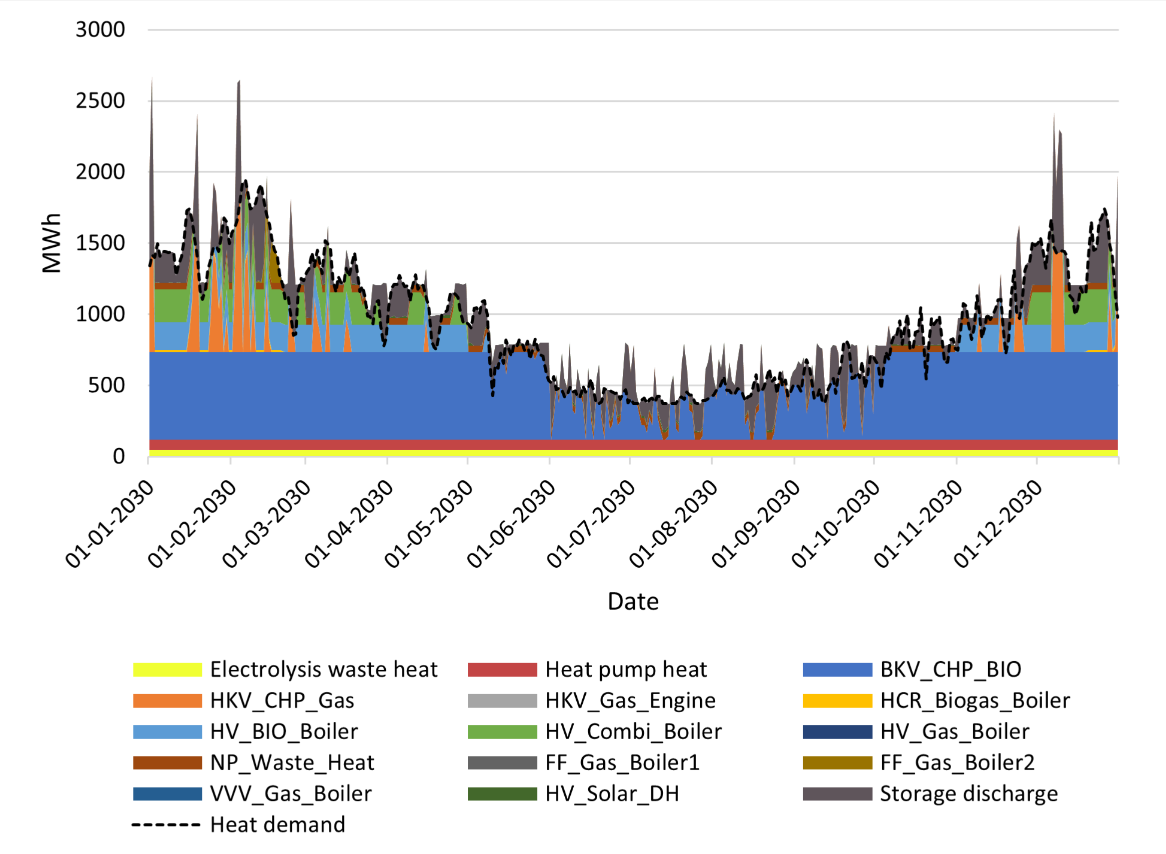

Figure 9.18. Heat producing units, heat demand, and storage discharge in the HFV DH system with integration of waste heat from PtX.

Like in the NØS DH system, it is observed that the waste heat from the electrolyser and the upgraded heat from the heat pump appear to operate as base-load. This is due to the same reasons as when PtX is integrated in the NØS DH system since the same assumptions about hydrogen and oxygen prices are made. Additionally, it is observed that a lesser reliance on the CHP units is achieved. This is especially the case of the gas turbine for peak loads, and the steam turbine which is utilised less in the summer months due to the integration of the waste heat. Furthermore, less reliance on discharge from the storage is observed.

The yearly inputs and outputs resulting from the integration of the 33 MW electrolyser and 3 MWth heat pump is listed in Table 9.4.

Table 9.4. Annually inputs for operation of heat pump and electrolysis and outputs as a result of operating heat pump and electrolysis in the HFV DH system.

	Amount	**Unit**
Input		
Electricity for heat pump	1.367	MWh
Electricity for electrolysis	289.080	MWh
Water	53.191	m^3
Output		
Heat pump heat	26.280	MWh
Electrolysis waste heat	17.520	MWh
Oxygen	46.800	tonne
Hydrogen	5.897	tonne

9.3.3 Sensitivity analysis of models

In the previous section it was shown that the electrolyser and heat pumps will run constantly if allowed, due to its' profitability. Due to the inaccuracy of price forecasts, some scenarios of lower revenue are tested to investigate the effect on the system. The scenarios tested are first a 50% reduction in hydrogen price to $10DKK/kg$, the second being a 75% in oxygen price to $0,28DKK/kg$ and the third a combination of the previous two.

'Nordøstsjælland' DH system

In the base scenario of PtX implementation in the NØS DH system (see section 9.3.1), the electrolyser and heat pump operates the entire year (8760 hours). When introducing a 50% reduction of the hydrogen price, the number of operating hours decreases significantly to just 3195 hours for the entire year. This is due to the decreased profitability of the units compared to their running costs.

When decreasing the revenue from oxygen sales by 75%, assumed to be either due to a decrease in price or insufficient demand, a similar effect is shown, reducing the number of operation hours to 3958 hours per year. This illustrates that the revenue from selling oxygen has a significant impact on the profitability of the system. However, the effect is not quite as severe as with the hydrogen revenue reduction, allowing 763 additional hours.

From the third scenario of combining the two cases, with 50% reduced hydrogen revenue and 75% reduced oxygen revenue, the number of operating hours is down 2749 hours per year.

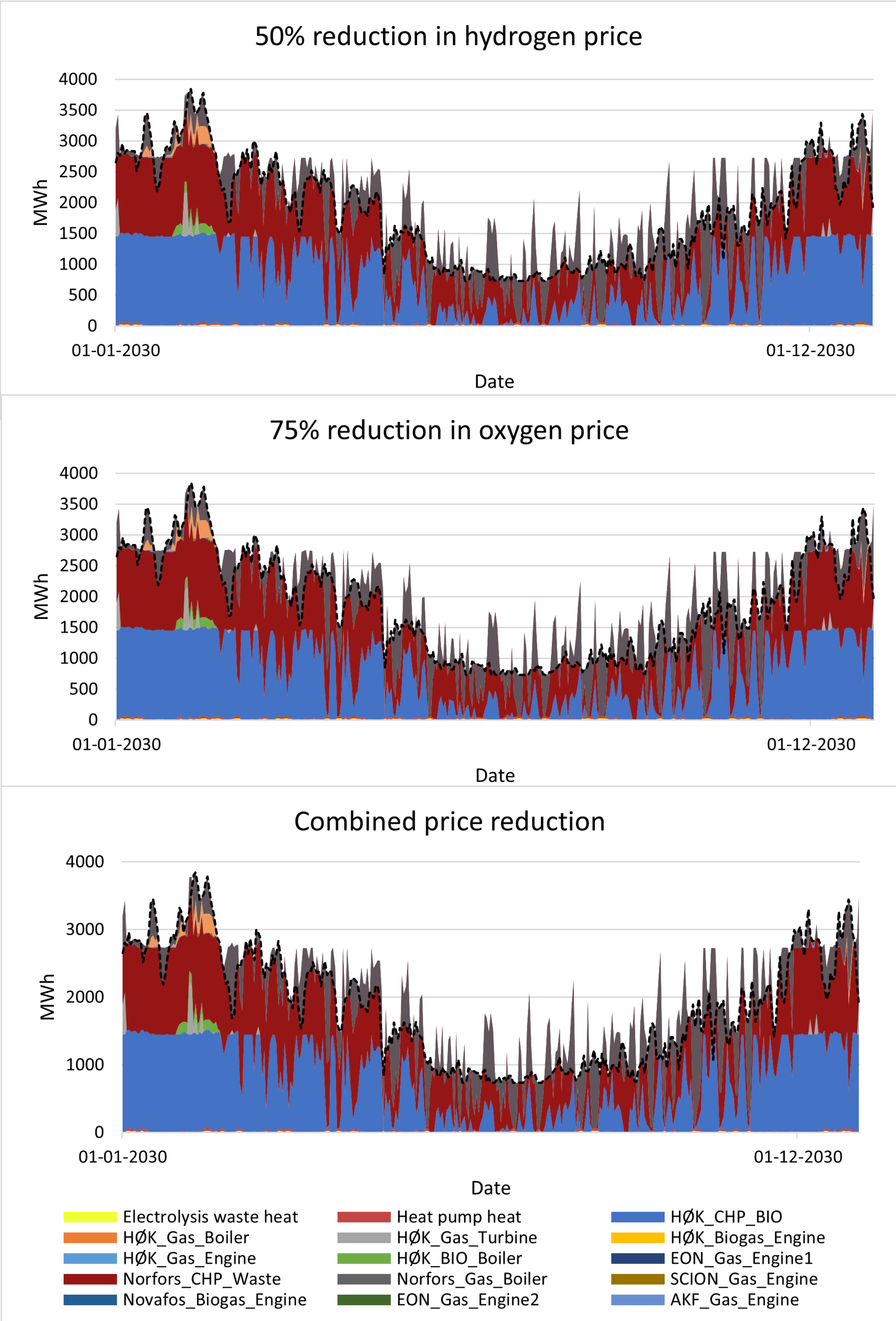

Figure 9.19. Showing the effects on three different sensitivity scenarios on the operation of the NØS system, per day.

'Hillerød-Farum-Værløse' DH system

In the HFV DH system, the base scenario (see section 9.3.2) is like the NØS DH system; the electrolyser and heat pump operate 8760 hours a year if allowed. As with the NØS system, when decreasing the hydrogen price by 50% there will be significantly fewer operating hours at just 3378 hours.

Again, similarly to the NØS system when reducing the revenue from oxygen by 75% a steep decline in the number of operating hours is observed, but similarly not quite as significant an effect compared to the effect of the hydrogen revenue reduction, at 4162 hours, a difference of 784 hours.

As with the NØS DH system, it is observed when combining the two reductions, the total effect is greater than the individual effects at 2773 hours of operation. Notably the effects are not directly additive, but appears to have a diminishing effect.

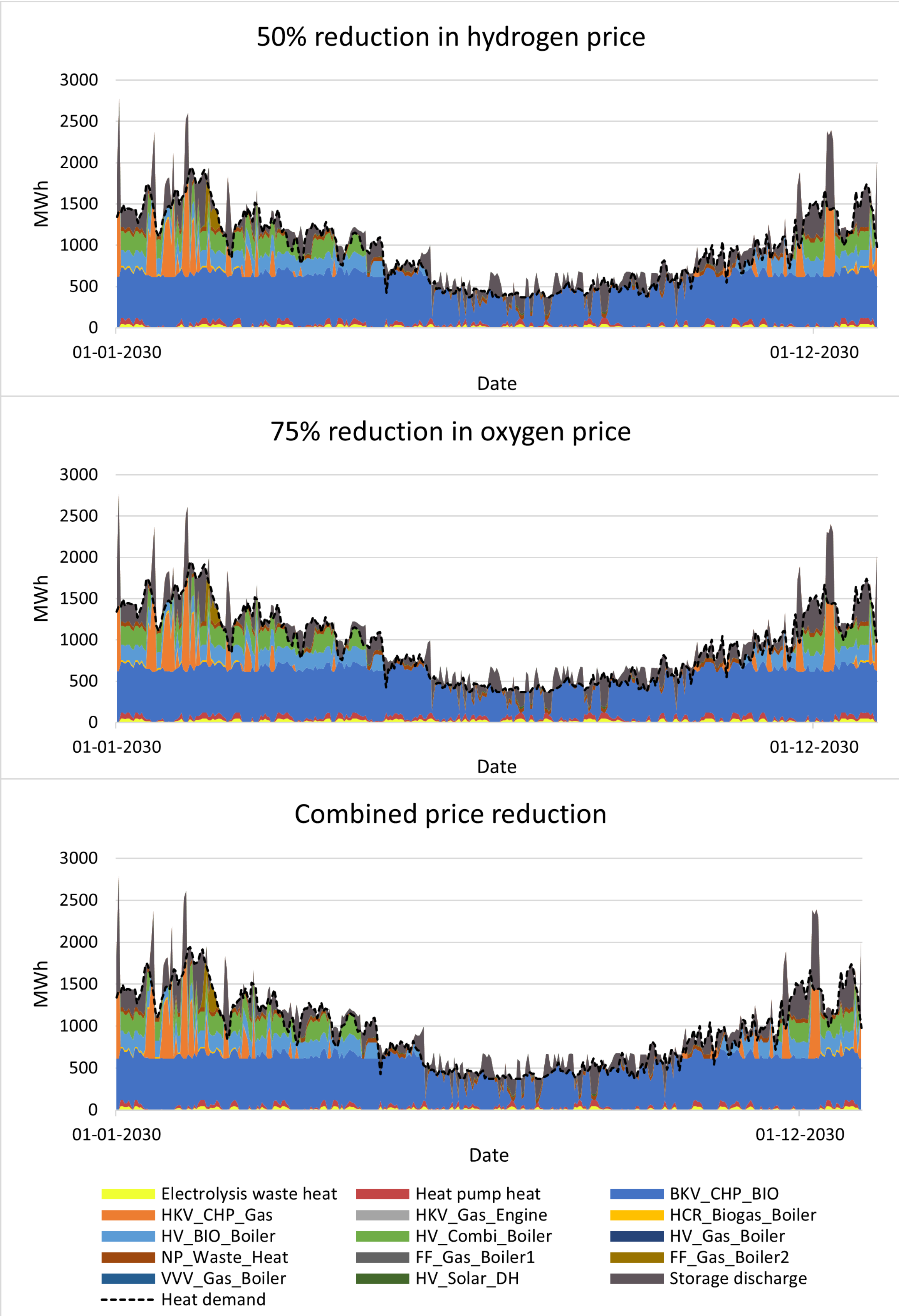

Figure 9.20. Showing the effects on three different sensitivity scenarios on the operation of the HFV system, per day.

9.4 Techno-economic assessment of PtX plant

The following section presents a techno-economic assessment of integrating waste heat from the PtX plant(s) in the district heating system(s). This includes an assessment of the heat sale price for the units available in the respective energy systems (see section 8.3 for methodological approach). Furthermore, an assessment of the NPV for both the heat pump and electrolyser (see section 8.3.1 for methodological approach).

9.4.1 'Nordøstsjælland' DH system

Table 9.5 presents a 'Net Present Value' calculation for the electrolysis, heat pump with average heat sale price of 306 DKK/MWh and with no revenue. Furthermore, a 'Levelised Cost of Heat' for the heat pump with average heat sale price of 306 DKK/MWh and with no revenue.

Table 9.5. Net Present Value and Levelised Cost of Heat for the electrolyser, heat pump with average heat sale price, and heat pump with no revenue in the NØS DH system.

	Net Present Value [MDKK]	**Levelised Cost of Heat [DKK/MWh]**
Electrolyser	519	–
HP with Avg. heat price	−4	+15
HP with no revenue	−80	322

Upon inspection of table 9.5, it is observed that the electrolysis has an NPV of 519 MDKK. Regarding the heat pump with a heat sale price of 306 DKK/MWh (avg. heat sale price) it shows a NPV of -4 MDKK, and the heat pump with no revenue -80 MDKK. For the heat pump that sells the upgraded heat for 306 DKK/MWh to break even, the heat sales prices has to be be increased by 15 DKK/MWh. Moreover, the heat pump with no revenue, has to sell the heat for 322 DKK/MWh to have a NPV=0.

Figure 9.21 illustrates the implications - on the heat sale price - of implementing electrolysis and a heat pump in the NØS DH .

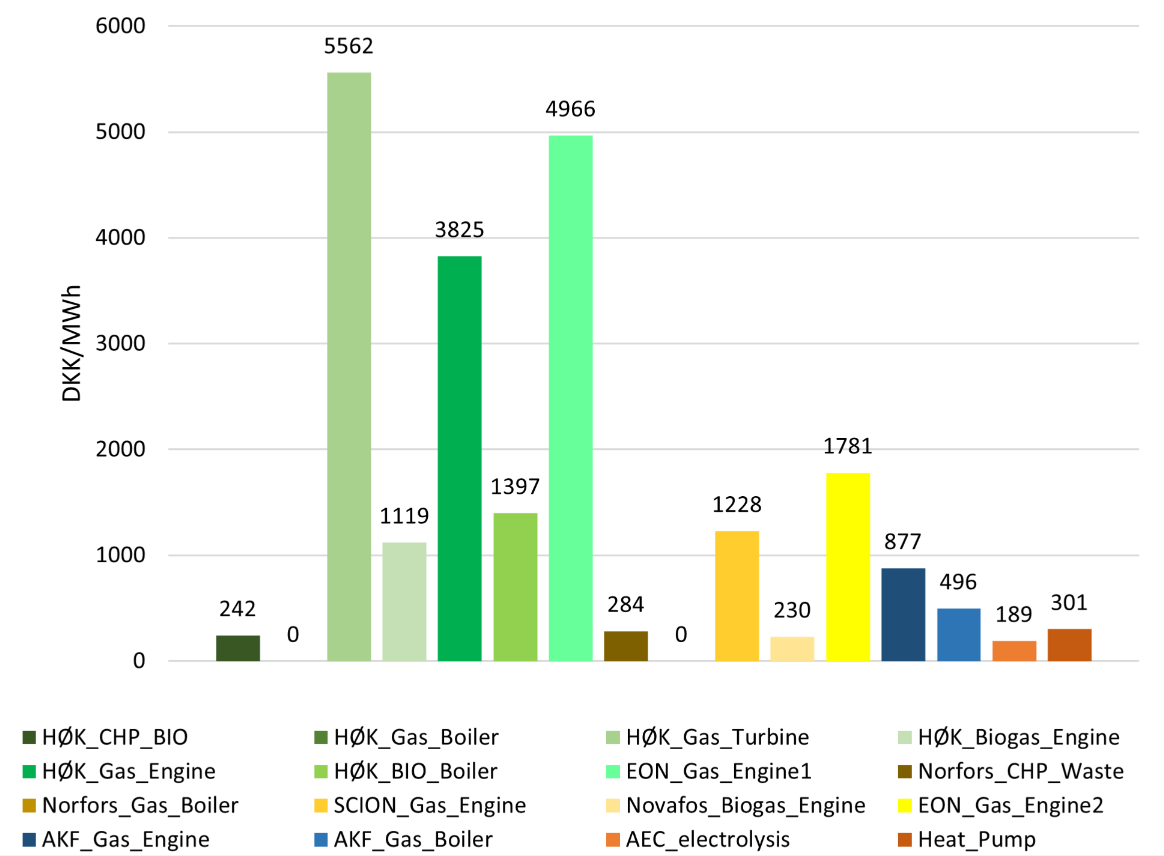

Figure 9.21. Heat sale price of the heat producing units in the NØS DH system with integration of PtX. The green columns represent the heat producing units in Forsyning Helsingør A/S. The yellow columns represent the heat producing units in I/S Norfors. The blue columns represent the heat producing units in AK Fjernvarme. The orange columns represent the heat producing units in the PtX site.

The heat sale prices in figure 9.21 somewhat reflects the amount of heat sold; a unit with a low amount of heat produced would thus have a relatively high heat sale price, since the total cost for one year is divided by the amount of heat sold. This is illustrated by e.g. observing HØK Gas Turbine, which has a heat sale price of 5.562 DKK/MWh, but the share of production stemming from this unit is 1% of the total.

Figure 9.22 presents the combined heat sale price for the three distribution areas (Forsyning Helsingør A/S, I/S Norfors, and AK Fjernvarme) and the PtX site that is placed within Forsyning Helsingør A/S' distribution area.

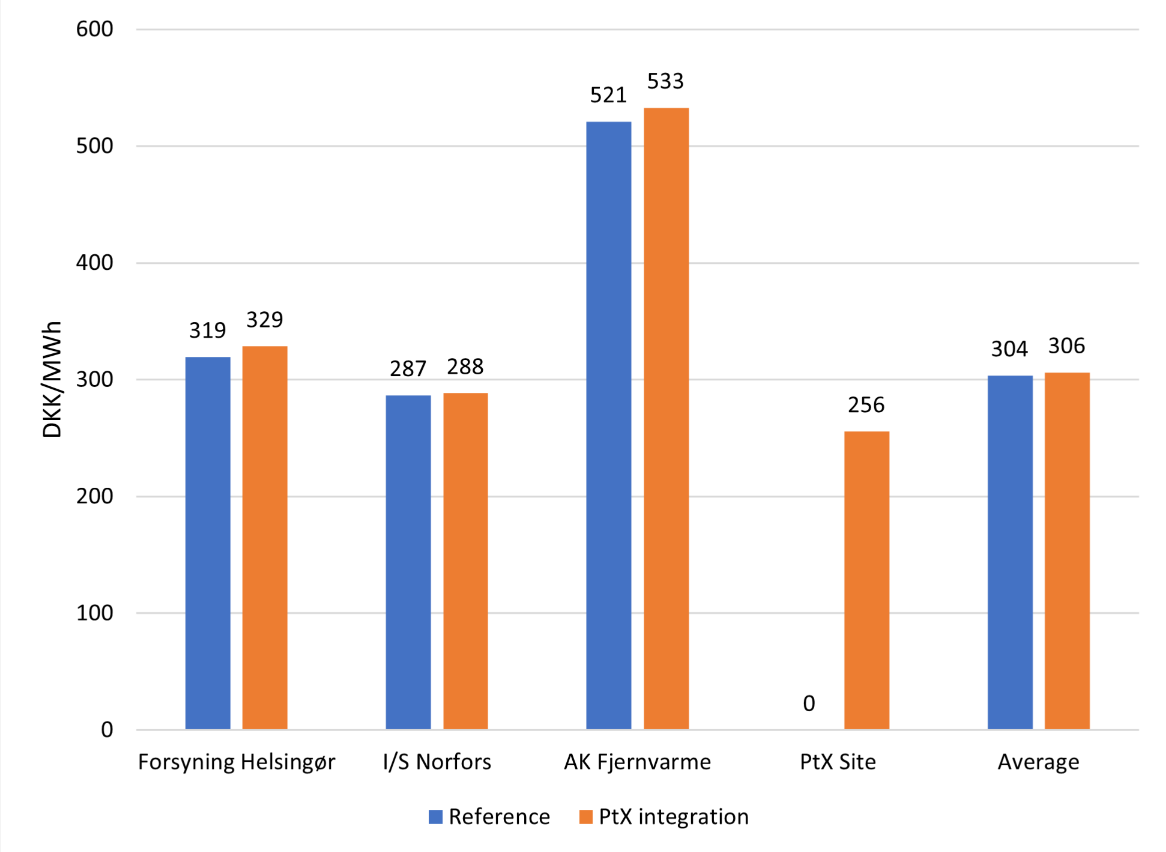

Figure 9.22. Combined heat sale prices divided into the three distribution areas in NØS DH system.

It is observed from figure 9.22, that by implementing PtX in the NØS DH system, an increase in the heat sale prices at the three distribution areas occur. At Forsyning Helsingør A/S, there is an increase of 10 DKK/MWh and for I/S Norfors 1 DKK/MWh in the heat sale price. The heat sale price for AK Fjernvarme increases with 12 DKK/MWh and the heat sale price from the PtX site (electrolysis and heat pump) is 256 DKK/MWh. This results in an average heat sale price of 306 DKK/MWh, which is an increase of 2 DKK/MWh - compared to the reference model.

9.4.2 'Hillerød-Farum-Værløse' DH system

Table 9.6 presents the 'Net Present Value' calculation for the electrolyser, heat pump with an average heat sale price of 356 DKK/MWh, and the heat pump with no revenue. Furthermore, a 'Levelised Cost of Heat' for the heat pump with no revenue.

Table 9.6. Net Present Value and Levelised Cost of Heat for the electrolyser, heat pump with average heat sale price, and heat pump with no revenue in the HFV DH system.

	Net Present Value [MDKK]	**Levelised Cost of Heat [DKK/MWh]**
Electrolyser	965	-
HP with Avg. heat price	8	-
HP with no revenue	-158	338

It is observed by table 9.6, that the electrolyser has a NPV of 965 MDKK. The heat pump that sells the upgraded heat for 356 DKK/MWh, has a NPV of 8 MDKK and the heat pump with no revenue -158 MDKK. Moreover, the heat pump with no revenue has a Levelised Cost of Heat of 338 MWh/DKK, which implies a NPV of 0.

Figure 9.23 illustrates the heat sale price for the three distribution areas in HFV DH system and the heat sale price from the PtX site.

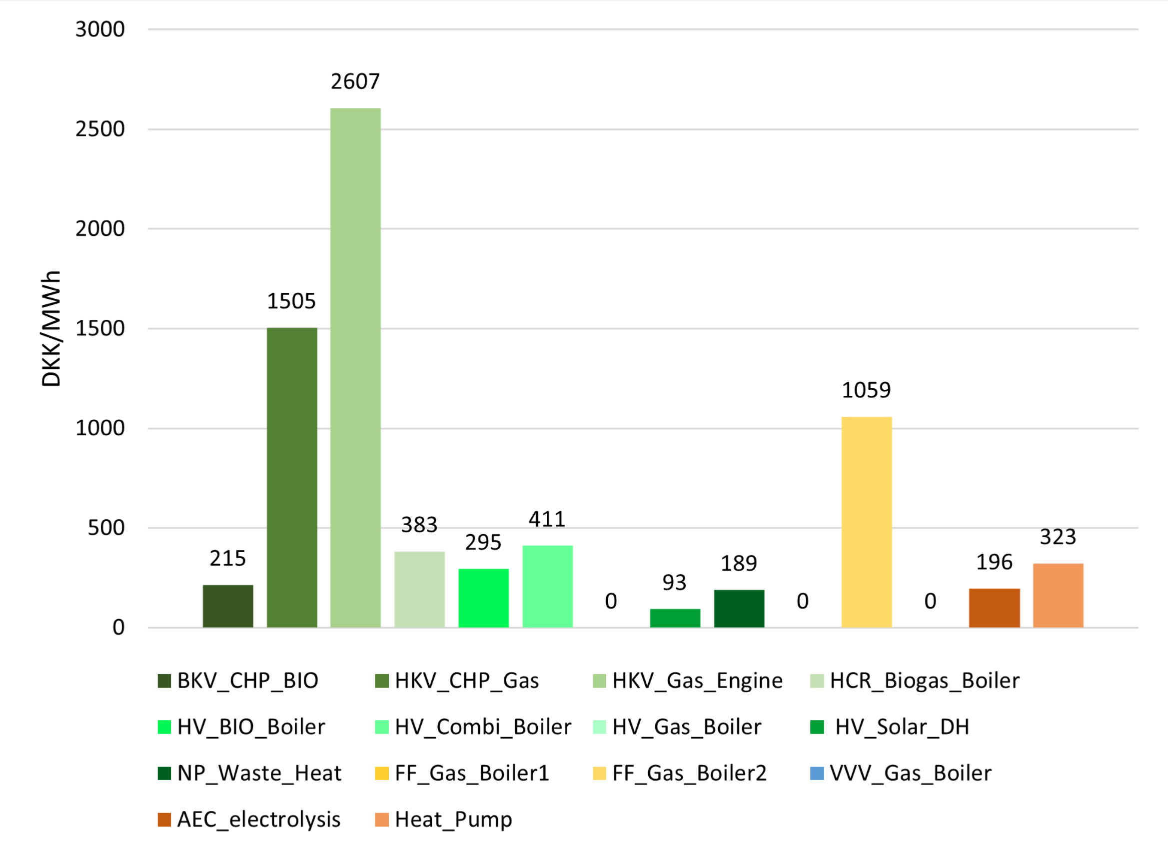

Figure 9.23. Heat sale price of the heat producing units in the HFV DH system with integration of PtX. The green columns represent the heat producing units in Hillerød Forsyning A/S. The yellow columns represent the heat producing units in Farum Fjernvarme A.m.b.a.. The blue columns represent the heat producing units in Værløse Varmeværk A.m.b.a. The orange columns represent the heat producing units in the PtX site.

Again, the heat sale prices illustrated on figure 9.23 - to a certain degree - reflects the amount of heat sold per unit. Take HKV Gas Engine as an example, the heat sale price is 2.607 DKK/MWh, but that specific unit only produces 0, 15% of the total heat.

Figure 9.24 illustrates the combined heat sale price for the three distribution areas (Hillerød Forsyning A/S, Farum Fjernvarme A.m.b.a., and Værløse Varmeværk A.m.b.a.) and the PtX site that is located within Hillerød Forsyning A/S' distribution area.

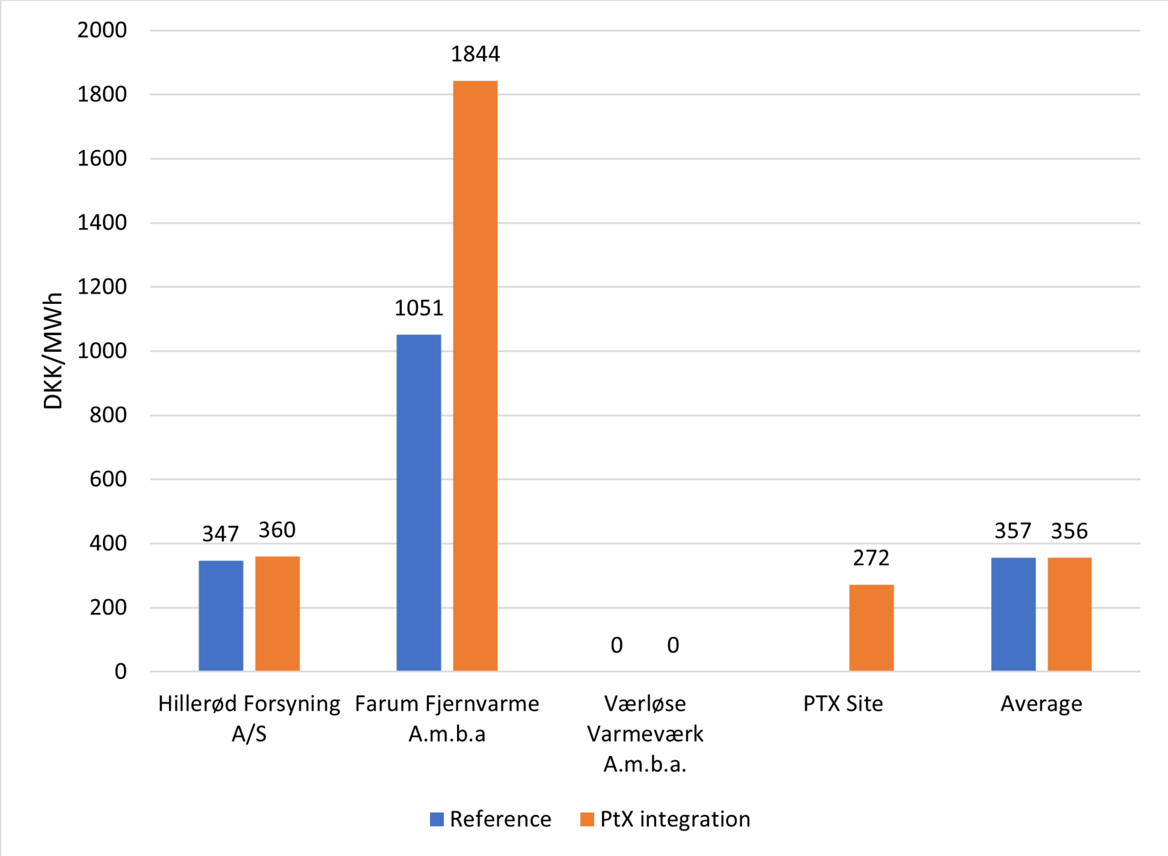

Figure 9.24. Combined heat sale prices divided into the three distribution areas in HFV DH system.

Upon inspection of figure 9.24 it is noted that by implementing PtX in the HFV DH system, an increase in the heat sale prices at two of the distribution areas increases. For Hillerød Forsyning A/S the heat sale prices increases with 13 DKK/MWh and for Farum Fjernvarme A.m.b.a. the price increases with 793 DKK/MWh. The PtX sites heat sale price is 272 DKK/MWh. The average heat sale price for the reference model is 357 DKK/MWh and by integration PtX it results in a price of 356 DKK/MWh.

9.4.3 Sensitivity-analysis

The following section presents a sensitivity analysis of the input factors mentioned in section 8.3.2. The methodological approach for this section is described in section 8.3.2.

Electrolysis (electrolysers)

Figures 9.25 and 9.26 illustrates the effect the input factors (investment, O&M, fuel, etc.) has on the NPV for the electrolysers in both the NØS (left) and HFV DH system (right). The 'base case' represents the techno-economic findings in section 9.4.

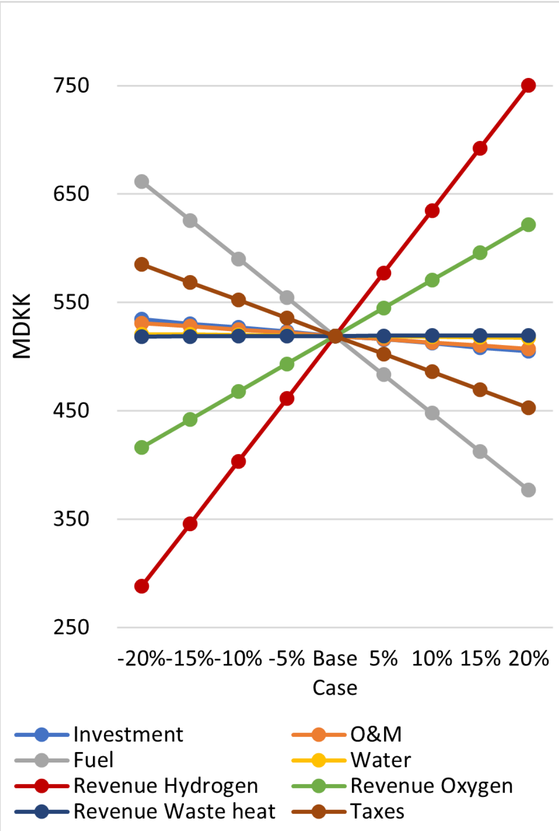

Figure 9.25. Sensitivity of the NPV calculation of the NØS electrolyser, plotted in increments of 5% and displayed in MDKK.

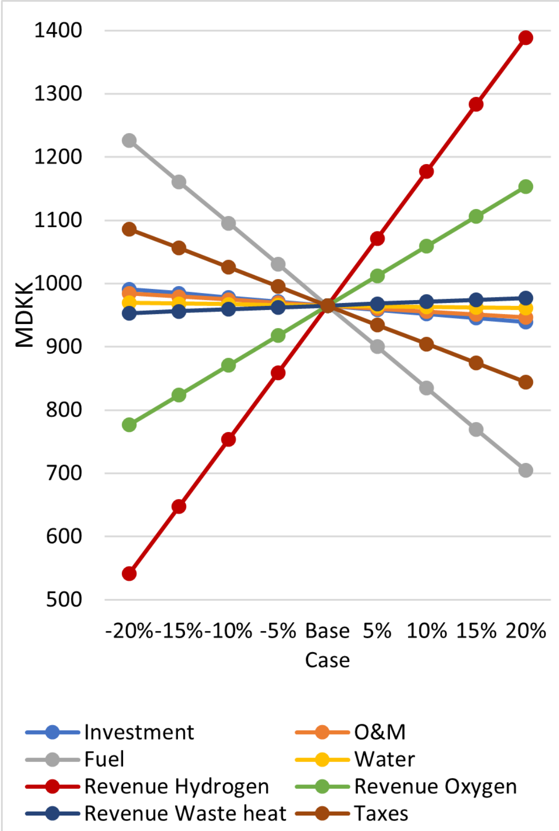

Figure 9.26. Sensitivity of the NPV calculation of the HFV electrolyser, plotted in increments of 5% and displayed in MDKK.

Upon inspection of figures 9.25 and 9.26 it is observed that a change in the revenue from hydrogen has the greatest effect on the NPV of the electrolyser (steepest slope). If the revenue from hydrogen decreases, the NPV would subsequently decrease and vice versa. The price of fuel - electricity for the electrolysis process - has the second greatest effect on the NPV, as this represents the greatest expense incurred in the operation of the electrolyser. A decrease in fuel price would make the feasibility of the electrolyser increase and vice versa. The revenue of oxygen and the effects of taxation are also significant, thus to a lesser degree. If the revenue from oxygen would decrease, the NPV would decrease as a result, and if the taxes were to be increased, the financial feasibility of the electrolyser would increase. The remaining input factors (investment, O&M, water price, and revenue from waste heat) are less critical input factors of the financial viability of the electrolyser - comparatively.

With the significant input factors (hydrogen revenue, price of fuel, oxygen revenue, and taxation) in mind for the electrolyser, they are elaborated further upon below Table 9.7 and 9.8.

Table 9.7. Input factors effect on the NPV for the electrolyser in the NØS DH system.

[MDKK]	−20%	−15%	−10%	−5%	**Base Case**	5%	10%	15%	20%
Investment	534	530	527	523	519	516	512	508	505
O&M	531	528	525	522	519	516	513	510	507
Fuel	661	626	590	555	519	483	448	412	377
Water	521	520	520	519	519	519	518	518	517
Revenue Hydrogen	288	346	403	461	519	577	635	692	750
Revenue Oxygen	416	442	468	493	519	545	570	596	622
Revenue Waste heat	518	519	519	519	519	519	519	519	520
Taxes	585	569	552	536	519	503	486	469	453

For the electrolyser in the NØS DH system, a decrease of 20% in hydrogen revenue result in a NPV of 288 MDKK, while an increase of 20% result in a NPV of 750 MDKK. This is evident from Table 9.7. As such, a difference in the extreme scenario of 424 MDKK is observed. This is explained by the relative capacity (18 MW) of the electrolysis capable of producing 367, 2 kg/h (see table 8.1), and the favourable price of hydrogen (see table 8.3). Other critical cost factors include the oxygen costs, electricty costs, and taxes. The impact of the oxygen is explained by the amounts produced (25.528 tonne), which is assumed able to be sold in its entirety. The electricity cost is explained by the power-intensive nature of the electrolysis resulting to large amounts of electricity consumption (157.680 MWh). Finally, the impact of the taxes is explained by the large amounts of electricity consumption, since drawing from the electricity grid is subject to tariffs, and that there is additional taxes on consumption. The impact on the NPV of these variables are listed in table 9.7.

Table 9.8. Input factors effect on the NPV for the electrolyser in the HFV DH system.

[MDKK]	−20%	−15%	−10%	−5%	**Base Case**	5%	10%	15%	20%
Investment	991	985	978	972	965	959	952	946	939
O&M	984	979	975	970	965	960	956	951	946
Fuel	1226	1.161	1.096	1.030	965	900	835	770	704
Water	969	968	967	966	965	964	963	962	961
Revenue Hydrogen	541	647	753	859	965	1.071	1.177	1.283	1.389
Revenue Oxygen	777	824	871	918	965	1.012	1.059	1.106	1.153
Revenue Waste heat	953	956	959	962	965	968	971	974	977
Taxes	1.086	1.056	1.026	995	965	935	905	874	844

For the electrolyser in the HFV DH system, a decrease of 20% in hydrogen revenue result in a NPV of 541 MDKK, while an increase of 20% result in a NPV of 1.389 MDKK. This is evident from Table 9.8. As such, a difference in the extreme scenario of 848 MDKK is observed. This is explained by the relative capacity of the electrolysis (33 MW) capable of producing 673, 2 kg/h (see table 8.1) at a favourable price of hydrogen (see table 8.3). Like the electrolyser in the NØS DH system, other critical cost factors include the oxygen costs, electricty costs, and taxes. Again, impact of the oxygen is explained by the amounts produced (46.800 tonne), which is assumed able to be sold in its entirety. The electricity cost is again explained by the power-intensive nature of the electrolysis resulting to large amounts of electricity consumption (289.080 MWh). Finally, the impact of the taxes is also explained by the large amounts of electricity consumption subject to tariffs and taxes. The impact on the NPV of these variables are listed in table 9.7.

Heat pumps

Figures 9.27 and 9.28 presents the input factors effect on the NPV for the heat pumps paying the average heat sales price in the NØS (left) and HFV DH system (right). The 'base case' represents the techno-economic findings in section 9.4.

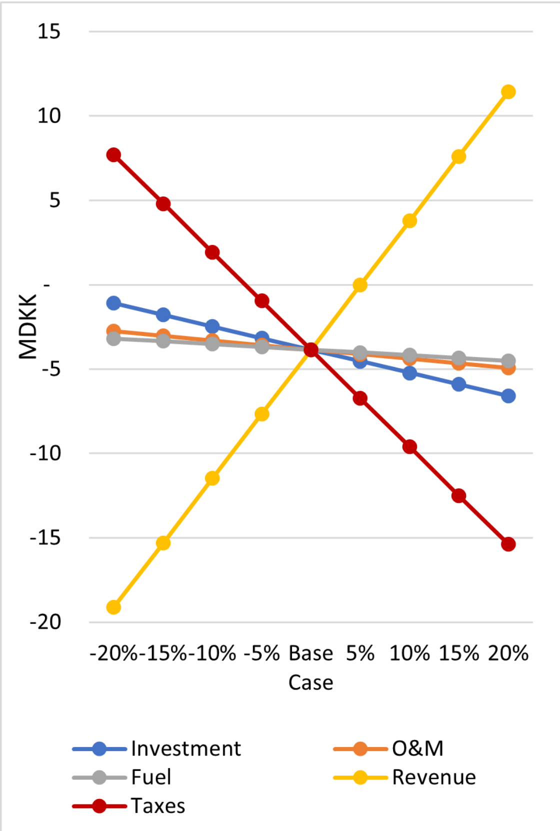

Figure 9.27. Sensitivity of the NPV calculation of the NØS heat pump, plotted in increments of 5% and displayed in MDKK.

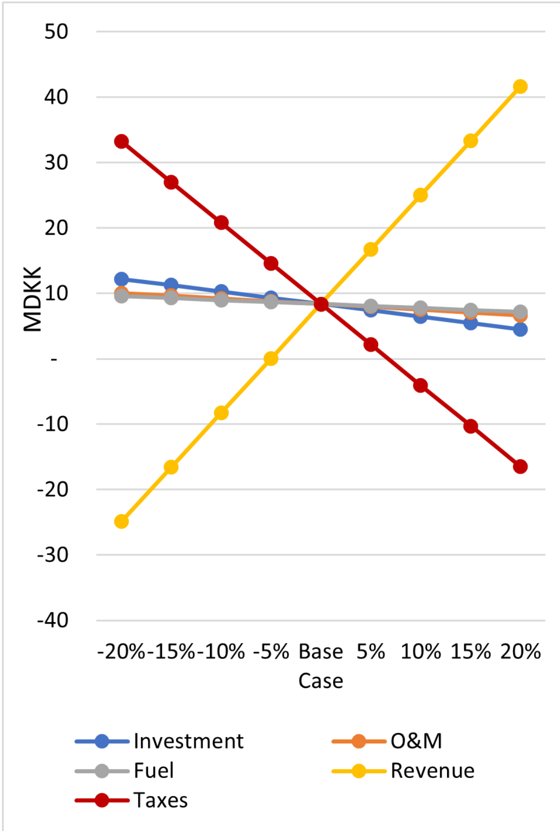

Figure 9.28. Sensitivity of the NPV calculation of the HFV heat pump, plotted in increments of 5% and displayed in MDKK.

It is observed in Figures 9.27 and 9.28 that revenue (sales of the upgraded heat) has the single greatest effect on the financial feasibility of the heat pumps. A decrease in the revenue would thus have a negative impact on the NPV and vice versa. Taxes have the second largest effect on the NPV and if a decrease occurs, it would have a positive effect on the financial feasibility of the heat pumps. Regarding the last remaining input factors (investment, fuel (electricity), and O&M), they have a less significant impact on the NPV for the heat pumps - comparatively.

The significant input factors (revenue and taxes) will be elaborated further upon - for their respective DH systems - below Table 9.9 and 9.10.

Table 9.9. Input factors effect on the NPV for the heat pump in the NØS DH system.

[MDKK]	−20%	−15%	−10%	−5%	**Base Case**	5%	10%	15%	20%
Investment	−1,09	−1,78	−2,47	−3,16	−3,85	−4,53	−5,22	−5,91	−6,60
O&M	−2,76	−3,03	−3,30	−3,57	−3,85	−4,12	−4,39	−4,66	−4,93
Fuel	−3,18	−3,35	−3,51	−3,68	−3,85	−4,01	−4,18	−4,34	−4,51
Revenue	−19,12	−15,30	−11,48	−7,66	−3,85	−0,03	3,79	7,61	11,43
Taxes	7,69	4,81	1,92	−0,96	−3,85	−6,73	−9,61	−12,50	−15,38

For the heat pump in the NØS DH system, a 20% decrease in taxes result in a NPV of 7, 69 MDKK, while a 20% increase in taxes result in a NPV of -15, 38 MDKK. This is evident from Table 9.9. As such, a difference in the extreme scenario for taxes of -7, 69 MDKK is observed. This is explained by the relatively high electricity tax on electricity consumption and tax on upgraded heat used for the heat pump compared to the electricity tax and waste heat used for the electrolyser (listed in Table 8.6).

Table 9.10. Input factors effect on the NPV for the heat pump in the HFV DH system.

[MDKK]	−20%	−15%	−10%	−5%	**Base Case**	5%	10%	15%	20%
Investment	12,21	11,26	10,30	9,34	8,38	7,43	6,47	5,51	4,56
O&M	10,07	9,65	9,23	8,81	8,38	7,96	7,54	7,12	6,69
Fuel	9,61	9,30	8,99	8,69	8,38	8,08	7,77	7,47	7,16
Revenue	−24,89	−16,57	−8,26	0,06	8,38	16,70	25,02	33,34	41,66
Taxes	33,25	27,03	20,81	14,60	8,38	2,17	−4,05	−10,26	−16,48

For the heat pump in the HFV DH system, a 20% decrease in taxes result in a NPV of 33, 35 MDKK, while a 20% increase in taxes result in a NPV of -16, 48 MDKK. This is evident from Table 9.9. As such, a difference in the extreme scenario for taxes of -16, 77 MDKK is observed. Like in the NØS DH system, this is explained by relatively high taxes on electricity consumption and upgraded heat, compared to the electricity tax and waste heat used for the electrolyser (listed in table 8.6).

9.5 Summary

The analysis finds the integration of PtX waste heat leads to an overall reduction in primary fuel usage, while increasing electricity usage. Per the assumptions of the methodology regarding the renewability of the electricity by 2030, this is determined to be a positive effect in the system. However, this is even without considering the effects of the produced PtX products in their intended energy sector.

It is determined through the techno-economic analysis that while an electrolyser in itself is a feasible investment, the addition of a heat pump for the purpose of upgrading waste heat (from auxiliary systems) is not always financially feasible. In the case of the NØS system with lower average heat sale price, the heat pump was not able to compete as it was too expensive, while in the NFV system it was barely feasible. In the sensitivity analysis of the heat pump it was found that taxation plays a major role in the feasibility of the heat pump and that any reduction in this saw a major benefit to the NPV of this investment.

It was likewise found that the reduction in load across existing production units resulted in an increased heat sale price, as the investment then had to be carried by fewer units of energy sold. Thus, introducing the PtX waste heat without reducing existing heat production capacity risks leading to overall increased consumer prices, under these analysis parameters.

Discussion 10

This chapter serves as an opportunity to address aspect relevant for the investigation(s), which may have initially been excluded. First the limitations of the methods applied and the mythological approach is addressed. This is followed by a discussion of the limitation of the electricity grid when introducing PtX, and the possibilities within future hydrogen infrastructure, which may require further considerations to be included in the investigation.

10.1 Limitations of the methodological approach

The methodological approach of the study is based on a conceptual theoretical framework influenced by Choice Awareness Theory. This is described in section 6.2. However, the conceptual theoretical framework is heavily modified compared to the original methodology of Choice Awareness to fit the scope of the report. As such, it may be argued that the full yield of applying the theory is not achieved, and that further work should include more attention to socio-economic factors and policy measures to promote the implementing waste heat from PtX into the DH system. However, it is also determined that the modification and application of the concepts of Choice Awareness Theory benefit the result of the report by assessing multiple alternatives.

Uncertainties related to information and data generation is a general limitation of the investigations that is conducted in the report. This is primarily due to reliance on second-hand knowledge via literature-study and literature review. While easily retractable, relating it to the specific case study for investigation in the report has at times required interpretations and assumptions. While not ideal, this is accepted as a general uncertainty of the investigations. Additionally, by documenting the process of interpretation and application of this data in Chapter 8, a certain level of validity is achieved. Further validity may have been achieved by introducing other information and data generating methods in the investigation. As such, the presence of e.g. interviews with respect to relevant actors may have helped limit uncertainties regarding the specific situation of the case study. As such, communication with relevant district heating suppliers was attempted established. However, interviews was never completed. Due to the timeline of the project, some data therefore had to be generated. This process too is documented in Chapter 8 and appendix A and B.

The study aims to project scenarios with PtX integration in 2030. As such, especially cost factors are subject to uncertainties. Moreover, question of consistency is raised due to some data, e.g. prices on water and oxygen, representing current prices and not necessarily the prices in 2030. As such, the result may not represent accurate scenarios for 2030. However, the prices are used since the represent available data. In acknowledgement hereof, sensitivity analysis is applied in section 9.4.3 to asses the impact of the individual cost factors on the overall economics, thereby limiting uncertainties related to the impact of gaps in knowledge.

As seen in figures 9.24 & 9.22 of section 9.4, when the PtX site is added the average prices of the other sites tend to increase, due to the way the heat sale price is calculated. As the calculation includes investment cost, this investment is to be paid by fewer units of energy, resulting in a higher price per unit when the total number of units decrease. While in the case of the NØS system the average price increases, this opposite is the case of the NFV system in which the producing units are significantly more expensive.

10.2 Heat pump considerations

As highlighted in section 9.4.3, the heat pump is subject to heavy taxation which significantly hinders its potential for use in upgrading waste heat to the point of making the addition of a heat pump in the NØS system infeasible. The tax paid to upgrade waste heat for use in district heating could be viewed as detrimental to the utilisation of waste heat in district heating grids, as it adds unnecessary expenses to the production. A reduction or removal of this taxation, would make the use of a heat pump in both systems a cheap source of heat for consumers. From the perspective of the entity wishing to make use of their waste heat, they are being taxed for this heat in two turns, firstly by the energy tax they pay for the fuel (electricity, natural gas, etc.) and secondly when upgrading the waste heat to a usable state. This has a disincentivising effect as seen in the case of server farms and results in the wasting of energy [Villadsen and Madsen, 2017].

The heat pumps modelled for NØS and HFV are both set to run at the same time as their respective electrolysers, upgrading the waste heat as it is produced. It is possible a better heat price could be found if a temporary storage tank was added for the waste heat and a higher capacity heat pump was installed, being able to utilise lower electricity prices when available. The savings obtained by lower electricity prices would need to be weighed against the added expense of a storage tank and greater heat pump capacity. Further by utilising the larger heat pumps, some costs such as O&M as listed in the Danish Energy Agency's technology catalogue, would be reduced per capacity size as some efficiency of scale has an effect. These further savings also may have a small impact, as seen in section 9.4.3.

10.3 Need for expansion of the electricity grid

Introducing PtX into the current energy mix without first expanding the capacity of the electricity grid may cause issues in terms of stable supply with an increasing share of renewable electricity. This is not least due to the power intensive nature of PtX, as mentioned in section 2.1. As such, the successful integration of waste heat from PtX in the future energy system largely depend on the interaction with the electricity grid [Danish Ministry of Climate Energy and Utilities, 2021]. In this regard, expanding the electricity grid is becoming increasingly necessary due to changes in generation structure with increasing amount of renewable electricity coming from distributed generation technologies such as wind and solar. However, the process of expanding the transmission capacity goes beyond international boarders, meaning the challenges of expanding the electricity grid is not simply technical, but also political and regulatory. [Battaglini et al., 2012] is an overview of perceived barriers and possibilities for expanding the electricity grid in the European Union.

Electrolysis may yet offer an opportunity to reduce or postpone necessary expansion or reinforcement of the electricity grid, by utilising the flexible production capabilities of the technology. In this case, production from the electrolysis would be intermittent dependant on e.g. times with increased electricity rates, such as when the wind is blowing and wind turbine capacity is utilised, or when the sun is shinning and solar collector capacity is utilised. Moreover, operating the electrolysis in this manner may contribute to increase the settlement price for renewable energy facilities during hours of overproduction. This could potentially help limit financial risk of renewable energy facilities, thereby indirectly promoting further investment into intermittent renewable technologies for the benefit of the green transition. However, if the electricity grid is not extended or reinforced, then this would require the electrolysis to be located in close proximity to green electricity production and in areas dominated by electricity production and not electricity consumption. This may therefore further limit suitable locations for PtX. According to an analysis by the DEA and Energinet [Danish Ministry of Climate Energy and Utilities, 2021, p. 46], the areas within which suitable locations for PtX was identified during GIS-analysis (in section 9.1), is dominated by electricity consumption. This may therefore ultimately disrupt any plans to establish PtX in these locations pending expansion or reinforcement of the electricity grid, and/or connection to new renewable energy facilities with suitable capacity to supply the electrolysis with green electricity.

A possible solution to this issue may be direct (link) connection to renewable energy facilities. This could be either a direct link to own electricity production or to an external electricity producer. If such a connection is established this may negate electricity tariffs - depending on regulation in 2030 - since the connection between the PtX plant and the electricity producer circumvent the public electricity grid. This may further promote distributed PtX [Energinet, 2019] and co-location of PtX and renewable energy facilities [Danish Ministry of Climate Energy and Utilities, 2021, p. 47]. However, it may also limit suitable capacity of the PtX plants if large amounts of green electricity is needed and the connected renewable energy facilities have limited capacity. In this case, a suitable capacity of the electrolysis would be determined based on communication with the electricity producer. Additionally, if the distance between the PtX plant and the renewable energy facilities is too great, then this may ultimately de-value the business-case due to investments in transmission lines, since this cost would be paid by the constructor [Danish Ministry of Climate Energy and Utilities, 2021, p. 47].
Irregardless, the socio-economic value of placing PtX appropriately to the electricity-grid outweigh the socio-economic value of utilising the waste heat resulting from the processes of the PtX plants. Therefore, more attention towards identifying suitable locations based on the future electricity grid should be paid.

10.4 Possibilities in the future hydrogen infrastructure

The infrastructure required to distribute the hydrogen that is produced from the electrolysis is not addressed in the report. In this regard, an essential element to the general hydrogen economy is to secure a cost effective distribution infrastructure. [Markert et al., 2017, p. 7703] gives an overview of the functional supply and distribution chain for hydrogen. Three primary transportation options are identified: truck, ship, and pipelines. The choice of transportation depend on a variety of factors such as for what application the hydrogen is purposed, the quantity that is produced, the distance the hydrogen has to be transported, and the density of the hydrogen demand (locally and on the market). Additionally, implementation of hydrogen storage capacity is considered a crucial part in establishing a viable hydrogen infrastructure for the benefit of the green transition. For further elaboration on the factors related to the transport of hydrogen, and the role of hydrogen storage in a future hydrogen infrastructure, is refereed to [Dagdougui et al., 2018].

It is argued that the most cost effective method of transporting the quantities of hydrogen produced by the electrolysis plants presented in section 9.3, is via pipelines if not for the potentially large investment required dependent on aforementioned factors. However, due to the timeline of the proposed electrolysis (2030) investment of the producer may be limited to connection to established hydrogen transmission and networks by 2030. As such, a broad political agreement was reached on March 15, 2022, to promote development of PtX and green fuels such as hydrogen in Denmark. As part of the agreement, Energinet and Evida is offered the opportunity to establish and operate future hydrogen infrastructure in Denmark due to their roles as transmission system operator (TSO), and distribution system operator (DSO), respectivly [Energinet, N/A]. As such, both Energinet and Evida is currently part of initiatives to explore the possibility of future hydrogen infrastructure in denmark.

Energinet is part of the European Hydrogen Backbone (EHB) initiative. EHB present a vision for how the hydrogen infrastructure could evolve towards 2030 and 2040. [Wang et al., 2020]. If such a supranational transmission is established, this may potentially offer producers of green hydrogen from electrolysis and opportunity to off-load large quantities of hydrogen to an international market. This is made possible by an expected 6.800 km of dedicated hydrogen pipeline in 2030 extended extended to approx. 23.000 km pipeline by 2040. Most of these pipelines (70%) are expected to consist of repurposed natural gas pipelines, meaning the establishing of the network will largely depend on future market conditions for both hydrogen and natural gas. Additionally, this transmission network is expected to offer opportunities for optimising production from PtX by securing near-guarantees that the hydrogen that is produced can be directly feed to the network if operated flexibly according to the renewable share in the electricity grid [Energinet, N/A]. EHB do not offer any specifics in regards to the distribution networks, but mainly concern hydrogen transmission lines across most of Europe with an estimated capacity of between 3-13 GW transport capacity per pipeline at varies points [Wang et al., 2020, p. 11].

Evida is part of Ready4H2, which is an alliance between 91 local gas network operators spread accross 18 countries in Europe. The alliance aim to combine the collective knowledge and experiences of gas distributors in the EU to contribute to the transition of the European energy infrastructure and stimulating the growing hydrogen market [Ready4H2, 2022a,b,c]. Like EHB, Ready4H2 consider the potential in repurposing existing natural gas infrastructure for hydrogen application. The difference is, that while EHB offer the potential for transmission across boarders, the Ready4H2 alliance focus on bringing the hydrogen to the end-user via the local distribution networks [Ready4H2, 2022c]. This is especially favourable since they estimate that 99% of industrial and commercial gas users are already connected to the distribution networks [Ready4H2, 2022b]. Additionally, they estimate that over one million km of distribution pipeline are currently ready for hydrogen repurposing [Ready4H2, 2022a]. This include distribution networks connected to the identified location for PtX in section 9.1.

With this, the locations identified for PtX in the form of electrolysis, may yet prove to offer viable locations for connection to future hydrogen transmission depending on development in distribution networks of the distribution areas identified in figure 8.9 in section 8.2.1. As such, the incentive for PtX is expected to increase in these areas if security with a stable supply of renewable electricity can be established.

Conclusion 11

The investigation of this report aimed to answer the following problem formulation:

> *"How should waste heat from PtX be integrated into the future district heating system in the Capital Region of Denmark?"*

To answer this problem formulation, a variety of methods were applied. These included both qualitative and quantitative methods. Qualitative methods included literature study and literature review, while quantitative methods included TEA with use of the financial metrics NPV and LCoH to analyse numerical data. Additionally, GIS-analysis was conducted using the QGIS tool, and energy system models were developed using the energyPRO software. To contextualise observed phenomenons, a theoretical conceptual framework was developed based on the theory of Choice Awareness. Observed phenomenons were based on a real-world case study of the Capital Region of Denmark.

Following preliminary analysis, investigation of different types of water electrolysis technologies was conducted. This analysis included the investigation technologies: AEC, PEMEC, and SOEC. It was found that AEC currently offers the highest TRL with low investment cost and minimum spatial requirements compared to other technological solutions. AEC was therefore chosen as the subject for further investigation.

Based on requirements and characteristics of AEC, a GIS-analysis was performed to identify suitable locations for this type of electrolysis. This analysis include additional parameters such as e.g., access to local DH networks due to interest in utilising waste heat from the processes of the electrolysis. From the analysis, two suitable locations for PtX was identified. One located in Helsingør and another in Hillerød.

To investigate the integration of waste heat from PtX into the DH system of the identified areas, energy system modelling was applied. First, reference models of the identified NØS and HFV DH systems were developed, followed by integration of AEC with suitable capacities. As such, an AECs with capacities of 18 MW and 33 MW was introduced to the NØS and HFV DH systems, respectively. Additionally, heat pumps with capacities 1,6 MWth and 3,0 MWth, respectively, were introduced to offer the possibility of upgrading low temperature heat from auxiliary systems in the AECs. Following integration of waste heat from PtX, the performance of the systems indicated a decrease in overall fuel consumption with increased reliance on electricity consumption.

To evaluate the economic feasibility of the PtX plants, TEA was performed. From the perspective of operating a PtX plant, it was found that earnings from high temperature waste heat has a relatively small impact on the overall economy of the plant, while being a cheap source of heat for the district heating consumers. The use of a heat pump to upgrade the low temperature waste heat was found to be beneficial in one of the two cases but not the other. This is primarily due to the current expenses associated with the upgrading of waste heat that creates an artificially high LCoH. Therefore, under these conditions, it was found that it was only beneficial to use a heat pump for upgrading waste heat in district heating systems with higher heating costs. Due to the LCoH of the heat pump varying with scale, a blanket recommendation of heat pump usage for upgrading waste heat cannot be concluded. However, it is recommended that it be determined on a case by case basis and will also depend greatly upon the operation of the connected PtX plant.

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Appendix A: Model Setup A

Appendix A aim to present data and describe assumption used to develop the reference model(s) for the NØS and HFV DH system. The reference model(s) seek to represent the future energy systems assuming a business-as-usual development. As such, data is foretasted to 2030 when possible, based on newest available data. The model(s) are developed in EnergyPRO, hence all data presented in the appendix has relevance as input-data in the EnergyPRO tool.

A.1 Heat Demand

The heat demands used in the models are based on scenarios in [Mathiesen et al., 2021] with data from 'The Danish Heat Atlas' [EnergyMaps, 2020]. The estimates are calculated based on construction year, renovation information, size, heating technology etc. and consider both recommendations towards expanding the DH network(s) and implementing energy savings. The data-set is however limited by self-reporting to BBR (the Danish Building and Housing Register) and accuracy, since the estimates are based on data from 2020. Additionally, a 20% grid loss in the main lines is included in the final heat demands. The data is clipped to include only relevant distribution areas, disregarding the heat demand of buildings that falls outside these areas.

To enable import and export of heat between the distribution areas, a transmission grid is included consisting of a number of connected transmission lines. In the NØS DH system these transmission lines consist of a $9,5$ MW connection between 'Hornbæk Fjernvarme A.m.b.a' and the 'Forsyning Helsingør A/S', a $14-16$ MW connection between 'Forsyning Helsingør A/S' and 'I/S Norfors', and a 16 MW connection between 'I/S Norfors' and 'AK Fjernvarme' [COWI , 2015, p. 2].
In the HFV DH system the DH transmission lines consist of a 30 MW connection between 'Hillerød Forsyning A/S' and 'Farum Fjernvarme A.m.b.a' and a 20 MW connection between 'Farum Fjernvarme A.m.b.a' and 'Værløse Varmeværk A.m.b.a' [COWI , 2015, p. 2].

The heat demands of the identified distribution areas in the NØS DH system are listed in Table A.1, and the heat demands of the identified distribution areas in the HFV DH system are listed in Table A.2.

Table A.1. Yearly heat demand of the identified distribution areas in the coherent NØS DH system.

Distribution area	**Heat demand** 2030 **[MWh]**	**Share of total heat demand** 2030 **[%]**
Hornbæk Fjernvarme A.m.b.a.	$19.351,6$	3%
Forsyning Helsingør A/S	$268.719,7$	40%
I/S Norfors	$278.870,1$	42%
AK Fjernvarme	$103.283,6$	15%

'Hornbæk fjernvarme A.m.b.a.' include the DH demand of Hornbæk area. 'Forsyning Helsingør A/S' include the DH demand of Helsingør stretching towards Tikøb, and the Ålsgårde and Espergærde areas. 'I/S Norfors' include the DH demand of the Hørsholm, Kokkedal, Nivå, Humlebæk and Fredensborg areas. Finally, AK Fjernvarme include the DH demand of the Birkerød area.

Table A.2. Yearly heat demand of the identified distribution areas in the coherent HFV DH system.

Distribution area	**Heat demand** 2030 **[MWh]**	**Share of total heat demand** 2030 **[%]**
Hillerød Forsyning A/S	$244.532,4$	72%
Farum Fjernvarme A.m.b.a.	$86.098,4$	25%
Værløse Varmeværk A.m.b.a.	$8.322,2$	3%

'Hillerød Forsyning Holding A/S' include the DH demands of the Hillerød, Skævinge, Gørløse, Meløse and St. Lyngby areas. 'Farum Fjernvarme A.m.b.a' include the DH demand of the Farum area. The DH demand for 'Værløse Varmeværk A.m.b.a' only make up 13% of the total demand in the distribution area. This is based on accounts from 2020 expressing an agreement with 'Vestforbrænding' to deliver heat from waste incineration [VVV, 2020]. In 2020 approx. 93% of the heat produced came from 'Vestforbrændingen' incineration of waste, while 13% of the heat delivered to 'Værløse Varmeværk A.m.b.a' customers came from their own gas fired boilers [VVV, 2020, p. 6].

The hourly heat demands are calculated using a simple degree-day method. The temperature dependent share is set at 60% and the reference grade is set a 17°C. For every hour in a common year, the heat demand is calculated using the following equation:

$$\text{Hourly heat demand} = \left(\frac{HD_{year} * T_{dep}}{D_{year}}\right) \cdot D_{hour} + \left(\frac{HD_{year} \cdot T_{nondep}}{8760}\right) \quad \text{(A.1)}$$

HD_{year}	Heat demand per year
T_{dep}	Temperature dependent share
T_{nondep}	Temperature non-dependent share
D_{year}	Degree-days per year
D_{hour}	Degree-days per hour

The heat profile for the NØS DH system is illustrated in Figure A.1, and the heat profile for the HFV DH system is illustrated in Figure A.2

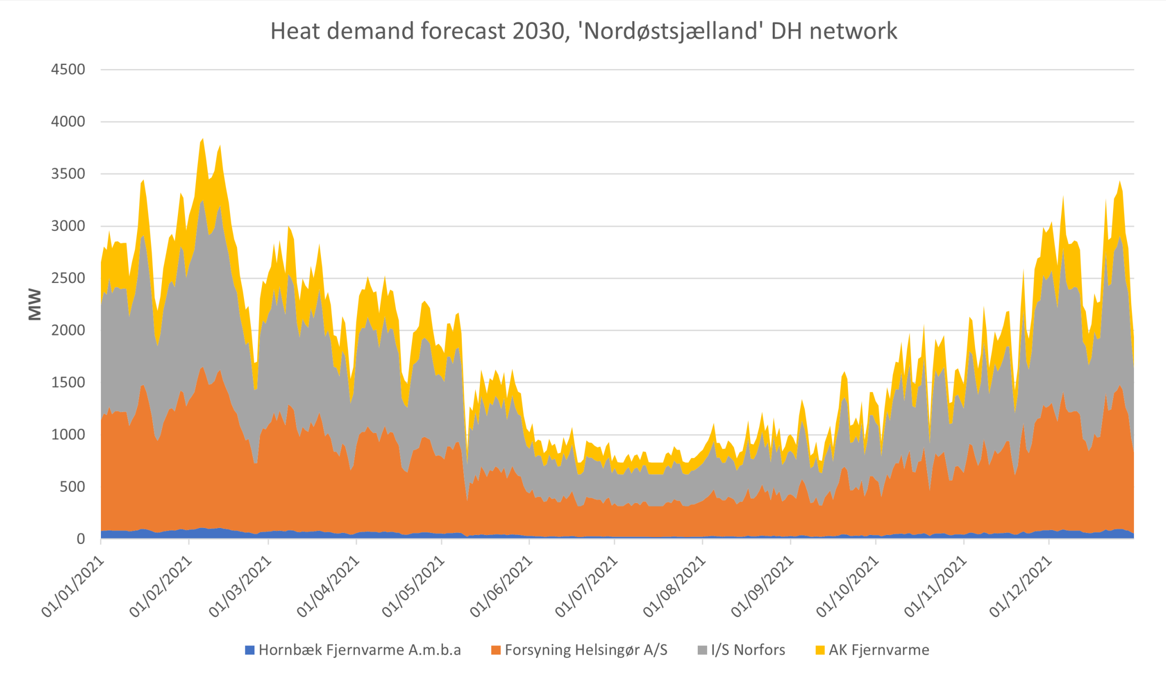

Figure A.1. Total heat demand forecast 2030 for the coherent NØS DH network.

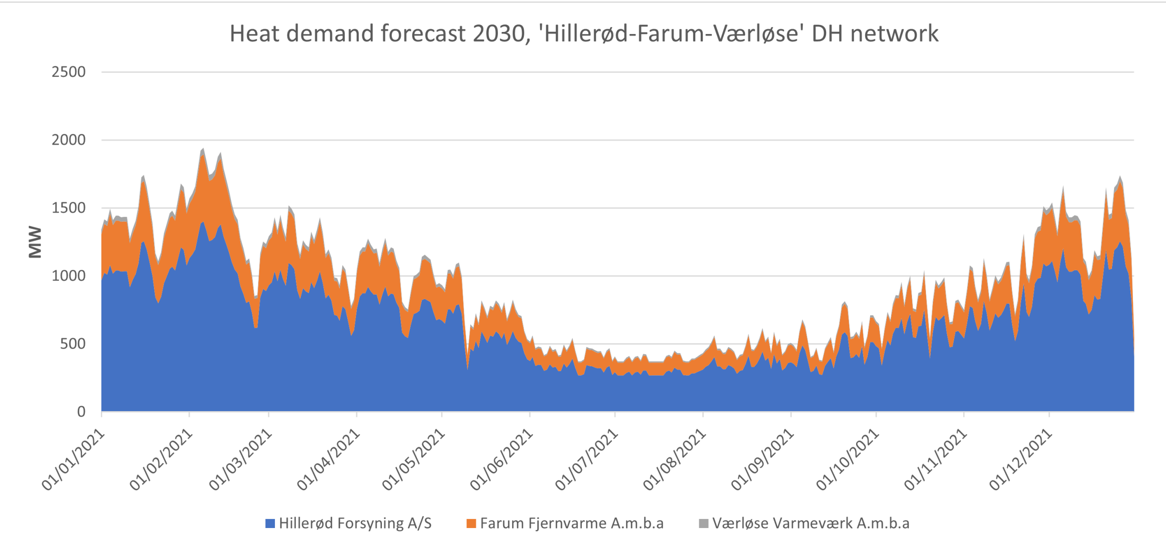

Figure A.2. Total heat demand forecast 2030 for the coherent HFV DH system.

A.2 Electricity price forecast

The electricity spot price used in the model(s) are based on the DEA's forecast towards 2040 (AF21). The hourly values for 2030 presented in the dataset are a result of simulations in the DEA's electricity market model, RAMSES. These simulations is based on assumption and use 2014 as basis year to make sure hourly profiles for consumption and production of electricity from technologies dependend on the weather are consistent [DEA, 2021a]. Table A.3 indicate the price range between 2021 electricity prices and 2030 electricity prices.

Table A.3. Overview of the price range between the 2021 and the 2030 forecasted electricity price .

	Min	0.25 **quantile**	**Average**	0.75 **quantile**	**Max**
AF21 **[DKK/MWh]**	60	420	421	440	1.360
AF30 **[DKK/MWh]**	20	110	332	480	2.250

From Table A.3 higher variations in electricity price is observed towards 2030. These variations are explained by uncertainties in forecasting several years into the future.

A.3 Unit characteristics

The modelled reference systems are assumed to follow a business-as-usual scenario. As such, the current system is assumed to be the functioning system in 2030. 'Energiproducenttælling' [Open Data DK, N/A] is used as the main source for unit characteristics, while energy consumption is estimated based on electric and heating efficiencies from the Danish energy catalog [DEA, 2021d], according to the following formulas:

Combined heat and power (CHP):

$$Energy_{consumption} = \frac{1}{Electric_{efficiency}} \cdot Electric_{capacity} \tag{A.2}$$

Heat only plants (HOP):

$$Energy_{consumption} = \frac{1}{Heating_{efficiency}} \cdot Heating_{capacity} \tag{A.3}$$

Most plants are modelled as single units assuming identical characteristics dependent on technology and type of fuel consumption, despite being independent units. This is done to limit computational time. The unit characteristics of the reference models for the NØS and HFV DH systems are listed in Table A.4 and A.5 respectively. The oil boilers listed in table A.4 are meant as part of the backup system and are not intended to run. These boilers are therefore not included in the reference model.

Table A.4. Unit characteristics of the heat producing units included in the reference model for the NØS DH system.

Distribution area	**Production plant**	**Electric capacity [MW]**	**Heat capacity [MW]**	**Energy consumption [MW]**	**Fuel**
Hornbæk Fjernvarme A.m.b.a.	Boiler	0, 00	12	14, 29	Fueloil
Forsyning Helsingør A/S	HØK CHP BIO	15, 7	60, 4	52, 86	Wood Chips
	HØK Gas Engine	1, 72	2, 60	3, 74	Natural Gas
	HØK Biogas Engine	0, 19	0, 26	0, 45	Biogas
	HØK Gas turbine (CC)	59	58, 5	118, 00	Natural Gas
	HØK Gas Boiler(s)	0	72, 1	68, 67	Natural Gas
	HØK BIO Boiler	0	6, 5	5, 70	Wood Chips
	HØK oil boiler	0	7, 3	8, 69	Fueloil
	E.ON Gas Engine (1)	0, 72	1, 1	1, 57	Natural Gas
I/S Norfors	I/S Norfors CHP	15, 4	53, 1	66, 09	Waste
	I/S Norfors Gas Boiler	0	35, 95	38, 52	Natural Gas
	SCION DTU Gas Engine	0, 97	1, 6	2, 11	Natural Gas
	Novafos BioGas Engine	0, 09	0, 27	0, 21	Biogas
	E.ON Gas Engine (2)	1, 36	2, 09	2, 96	Natural Gas
AK Fjernvarme	AKF Gas Engine	1, 05	1, 5	2, 28	Natural Gas
	AKF Gas Boiler	0	12	11, 43	Natural Gas

'Forsyning Helsingør A/S' include companies 'Helsingør Kraftvarme A/S', 'Helsingør Varme A/S' and 'Helsingør Spildevand A/S'. However, the companies are all subsidiaries of 'Forsyning Helsingør A/S' [Forsyning Helsingør A/S, 2022] and are therefore collected under acronym (HØK) for simplification.

Table A.5. Unit characteristics of the heat producing units included in the reference model for the HFV DH system.

Distribution area	Production plant	Electric capacity [MW]	Heat capacity [MW]	Energy consumption [MW]	Fuel
Hillerød Forsyning A/S	BKV CHP BIO	5, 12	25, 46	17, 24	Wood Chips
	HKV CHP Gas	77	78	154, 00	Natural Gas
	HKV Gas Engine	5	7, 2	10, 87	Natural Gas
	HCR Biogas Boiler	0	0, 8	0, 76	Biogas
	HV BIO Boiler	0	8, 14	7, 14	Wood Chips
	HV Combi Boiler	0	9, 5	9, 37	Wood Pellets
	HV Gas Boiler(s)	0	137	130, 48	Natural Gas
	HV Solar DH	0	2, 88	0, 00	Fuel-free
	Nordisk Perlite Aps	0	2	0, 00	Fuel-free
Farum Fjernvarme A.m.b.a	FF Gas Boiler1	0	30, 2	28, 76	Natural gas
	FF Gas Boiler2	0	24, 6	23, 43	Natural Gas
Værløse Varmeværk A.m.b.a	VV Gas Boiler	0	19, 8	18, 86	Natural Gas

'Hillerød Forsyning A/S' include companies 'Hillerød Kraftvarme Aps', 'Hillerød Varme A/S' and 'Hillerød Spildevand A/S'. However, the companies are all subsidiaries of 'Hillerød Forsyning Holdings A/S' [Hillerød Forsyning Holding A/S, 2022], and are therefore, to some extent, collected under the (HV) for simplification.

A.4 Heat values and emission coefficients

Heat values and emission coefficients used in the models are primarily based on the DEA's standardised values [DEA, 2022, p. 7]. Additionally, the heat value of biogas is assumed based on danish energy statistic data from 2020 [DEA, 2020a]. The heat values are listed in Table A.6, and represent lower calorific values.

Table A.6. Heat values used in the model(s).

	Natural gas [GJ/1000Nm^3]	Fueloil [GJ/ton]	Wood chips [GJ/ton]	Wood pellets [GJ/ton]	Waste [GJ/ton]	Biogas [GJ/1000m^3]
Heat value	39, 59	40, 65	9, 30	17, 50	10, 60	23, 00

While CO_2-emissions are exclusively depended on the type of fuel that is consumed, SO_2 (sulfurdioxide), CH_4 (methane), NO_x (nitrogenoxide), and N_2O (nitrousoxide) are also depended on the technology that is used. To simplify, the emission coefficients is listed according to typical combinations of fuel type and technologies based on data from 2019 [DEA, 2022, p. 28-29]. The emission coefficients used in the models are listed in Table A.7.

Table A.7. Emission coefficients based on typical combinations of fuel and technology use [DEA, 2022, p. 28-29].

Fuel	**Plant type**	**CO_2 [kg/GJ]**	**SO_2 [g/GJ]**	**CH_4 [G/GJ]**	**NO_x [g/GJ]**
Central cogeneration plants					
Natural Gas	Steam turbine	56, 5	0, 4	1, 0	28, 0
Fueloil	Steam turbine	79, 3	100, 0	0, 8	138, 0
Wood Chips	Steam turbine	0, 0	1, 9	3, 1	33, 0
Wood Pellets	Steam turbine	0, 0	1, 9	3, 1	33, 0
Decentralized cogeneration plants					
Natural Gas	Gas turbine	56, 5	0, 4	1, 7	48, 0
Natural Gas	Gas engine	56, 5	0, 5	481, 0	135, 0
Biogas	Gas engine	0, 0	19, 2	434, 0	202, 0
Wood Chips	Steam turbine	0, 0	1, 9	3, 1	81, 0
Wood Pellets	Steam turbine	0, 0	1, 9	3, 1	81, 0
Waste	Steam turbine	42, 5	8, 3	0, 3	79, 0
Heat only production (HOP)					
Natural Gas	Boiler	56, 5	0, 4	1, 0	31, 7
Wood Chips	Boiler	0, 0	11, 0	11, 0	90, 0
Wood Pellets	Boiler	0, 0	11, 0	3, 0	90, 0
Biogas	Boiler	0, 0	25, 0	1, 0	28, 0

Emissions from biomass (wood chips and wood pellets) and biogas are assumed to be carbon neutral due to the possibility of re-planting. According to the IEA, biomass combustion is considered a carbon-neutral process since the CO_2 that is released to the atmosphere during the process was previously absorbed by plant-life [IEA, 2007]. Therefore, an emission-factor of zero is applied for all biomass and biogas combustion. Additionally, the the emission coefficients for wood chips and wood pellets are assumed to be the same based on assumption in [DEA, 2022].

A.5 Operation and Maintenance

Operation and Maintenance (O&M) cost used in the model(s) are primarily based on the Danish technology data catalogue for centralised and decentralised production of electricity and district heat DEA [2021d]. Fixed O&M is not included in the model, since this cost is not affected by the operation of the system.

However, variable O&M costs is included since this cost depend on the operation of the technologies in the system. The variable O&M cost are listed in Table A.8 and A.9.

Table A.8. Variable O&M cost of the heat producing units included in the reference model for the NØS DH system.

Distribution area	**Plant**	**Variable O&M**	**Unit**
Hornbæk Fjernvarme A.m.b.a.	Boiler	-	
Forsyning Helsingør A/S	HØK CHP BIO	33, 48	[DKK/MWh$_e$]
	HØK Gas Engine	40, 18	[DKK/MWh$_e$]
	HØK Biogas Engine	59, 52	[DKK/MWh$_e$]
	HØK Gas turbine (CC)	33, 48	[DKK/MWh$_e$]
	HØK Gas Boiler(s)	8, 18	[DKK/MWh]
	HØK BIO Boiler	19, 27	[DKK/MWh]
	HØK oil boiler	-	
	E.ON Gas Engine (1)	40, 18	[DKK/MWh$_e$]
I/S Norfors	I/S Norfors CHP	188, 23	[DKK/MWh$_e$]
	I/S Norfors Gas Boiler	8, 18	[DKK/MWh]
	SCION DTU Gas Engine	40, 18	[DKK/MWh$_e$]
	Novafos BioGas Engine	59, 52	[DKK/MWh$_e$]
	E.ON Gas Engine (2)	40, 18	[DKK/MWh$_e$]
AK Fjernvarme	AKF Gas Engine	40, 18	[DKK/MWh$_e$]
	AKF Gas Boiler	8, 18	[DKK/MWh]

Table A.9. Variable O&M cost of the heat producing units included in the reference model for the HFV DH system.

Distribution area	Plant	Variable O&M	Unit
Hillerød Forsyning A/S	BKV CHP BIO	69, 19	[DKK/MWh$_e$]
	HKV CHP Gas	33, 48	[DKK/MWh$_e$]
	HKV Gas Engine	40, 18	[DKK/MWh$_e$]
	HCR Biogas Boiler	8, 18	[DKK/MWh]
	HV BIO Boiler	19, 27	[DKK/MWh]
	HV Combi Boiler	13, 84	[DKK/MWh]
	HV Gas Boiler(s)	8, 18	[DKK/MWh]
	HV Solar DH	1, 41	[DKK/MWh$_{out}$]
	Nordisk Perlite Aps	-	
Farum Fjernvarme A.m.b.a	FF Gas Boiler1	8, 18	[DKK/MWh]
	FF Gas Boiler2	8, 18	[DKK/MWh]
Værløse Varmeværk A.m.b.a	VV Gas Boiler	8, 18	[DKK/MWh]

A.6 Fuel Price

Fuel prices are based on the DEA's price projections towards 2040 for use in Energinet's work with developing the infrastructure of the future energy system [DEA, 2021a]. The fuel prices projections for 2030 are listed in Table A.10.

Table A.10. Fuel prices used in the model(s) [DEA, 2021a].

	Natural gas [DKK/GJ]	**Fueloil [DKK/GJ]**	**Wood chips [DKK/GJ]**	**Wood pellets [DKK/GJ]**	**Waste [DKK/GJ]**	**Biogas [DKK/GJ]**
Fuel price 2030	46, 6	57, 4	53, 8	68, 3	0	93, 4

Waste used as fuel is assumed collected and incinerated at no additional expense of the energy producing unit. As such, no inherent price is associated with the waste and the price is set at 0 DKK for the purpose of the analysis.

The biogas price is determined based on typical production cost [HINRICHSEN, 2021] and subsidies awarded as per energy agreement from 2018 [Energistyrelsen, 2021]. In the agreement it is stated that biogas production is subsidies for all plant build before 2020 until 2032. For heating purposes, the subsidy amount to 58, 8 DKK/GJ as of 2021 [Energistyrelsen, 2021]. According to the trade association 'Biogas Denmark' biogas is produced at a minimum cost of 3, 5 DKK/m^3 (152, 17 DKK/GJ). The price of biogas is assumed to be represented by the subsidies subtracted from the production cost.

A.7 Taxation and tariffs

Plants pay tax dependent on type of fuel consumption, while being reimbursed for the share of electricity that is produced, since only fuel consumption for heat production is taxed. For CHP production it is not possible to definitively determine the amount of fuel that is used for electricity production and heat production respectively. For this reason, the Danish taxation law stipulated two formulas (E and V formula) to determine the amount of fuel subject to taxation. Plants must choose one of the formulas. [Skat, 2022].

$$Eformula : 1 - EP/0,67$$
$$Vformula : HP/1,20; minimumEP/0,35$$

The V formula is beneficial for plant with high heat production. Therefore, all plants/production units are assumed to follow the V formula.

Tax rates are based on pwc's overview of current energy taxation [PwC, 2022b]. Future changes in tax rates can be difficult to predict, and the model(s) therefore assume a policy-freeze on the listed tax rates for 2022 towards 2030. Taxation are listed according to typical combinations of technology and fuels in Table A.11.

Table A.11. Tax rates based on typical combinations of fuel type and technology use in 2022. [PwC, 2022b]

Fuel	Plant type	Energy tax [DKK/GJ]	CO_2 tax [DKK/GJ]	SO_2 tax [DKK/GJ]	CH_4 tax [DKK/GJ]	NO_x tax [DKK/GJ]
Central cogenetation plants						
Natural Gas	Steam turbine	63,05	10,23	0,01	0,00	0,20
Fueloil	Steam turbine	62,78	13,90	5,01	0,00	0,74
Wood Chips	Steam turbine	0,00	0,00	0,00	0,00	0,50
Wood Pellets	Steam turbine	0,00	0,00	0,00	0,00	0,50
Decentralized cogeneration plants						
Natural Gas	Gas turbine	63,05	10,23	0,01	0,00	0,20
Natural Gas	Gas engine	78,66	10,23	0,02	1,77	0,76
Biogas	Gas engine	4,26	0,00	0,00	1,30	1,10
Wood Chips	Steam turbine	0,00	0,00	0,00	0,00	0,50
Wood Pellets	Steam turbine	0,00	0,00	0,00	0,00	0,50
Waste	Steam turbine	2,45	16,91	1,04	0,00	0,50
Heat only production (HOP)						
Natural Gas	Boiler	63,05	10,23	0,01	0,00	0,20
Wood Chips	Boiler	0,00	0,00	0,00	0,00	0,50
Wood Pellets	Boiler	0,00	0,00	0,00	0,00	0,50
Biogas	Boiler	4,26	0,00	0,00	0,00	0,30

For CHP units, tariffs on electricity production delivered to the grid are included in the calculations. These tariffs include a 'feed-in tariff' for operation and maintenance of the overall electricity grid and maintenance of international connections by Energinet. Additionally, a 'balance tariff' is included for system services and management of the balance market by Energinet [Energinet, 2022]. The tariffs are listed in Table A.12.

Table A.12. Tariff scheme for the electricity producing units. [Energinet, 2022]

Electricity grid	**DKK/MWh**
Feed-in tariff	3
Balance tariff (Producer)	1, 16

A.8 Marginal heat price

All production units are assumed to be owned and operated by district heating companies for the purpose of simplification. This implies that the heat price is determined based on the marginal cost of production. As such, based on the "Hvile-i-sig-selv" principle [Erhvervsstyrelsen, 2011], a theoretical heat price is determined based variable costs for one unit of heat following equation A.4:

$$HeatPrice = \frac{FC_{year} + OM_{year} + T_{year}}{R} \tag{A.4}$$

FC_{year}	Fuel costs for the year
OM_{year}	Operation and maintenance costs for the year
T_{year}	Taxation for the year (Energy, CO_2, SO_2, CH_4 and NO_x tax)
R	Ratio between heat and electricity production

The marginal heat cost is determined for each system's individual units as seen in figures A.3 & A.4. These include fuel cost, variable O&M, energy tax, CO_2 tax, SO_2 tax, CH_4 tax and NO_x tax.

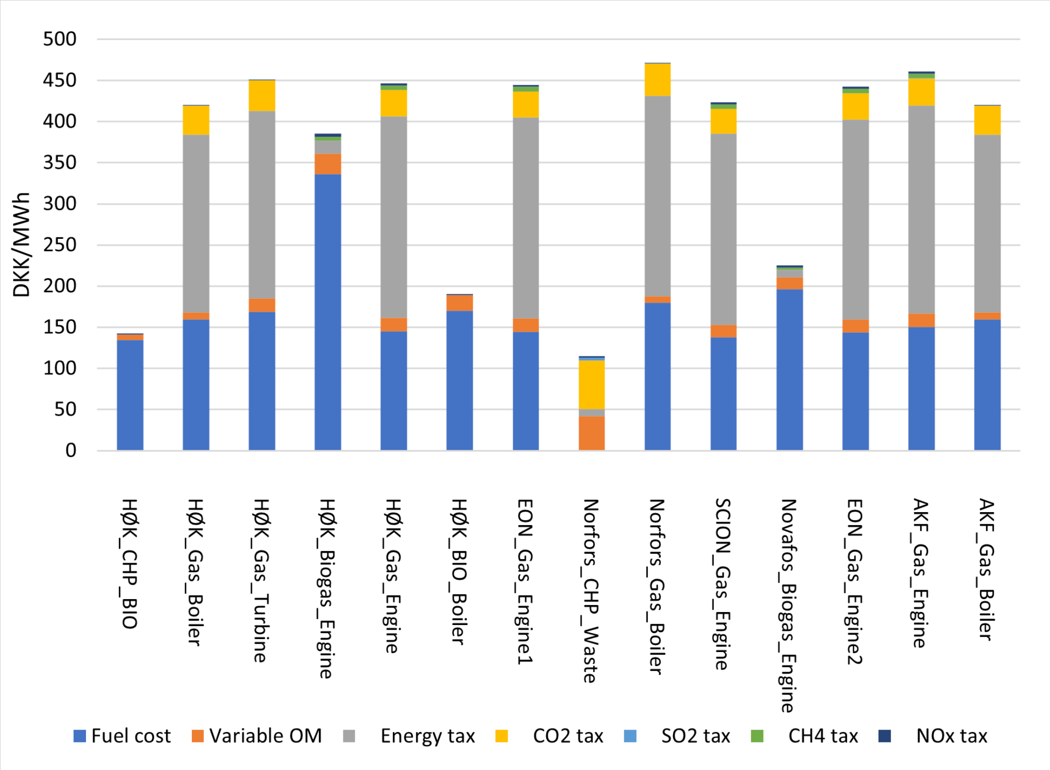

Figure A.3. Marginal price of heat production for each unit in the NØS system.

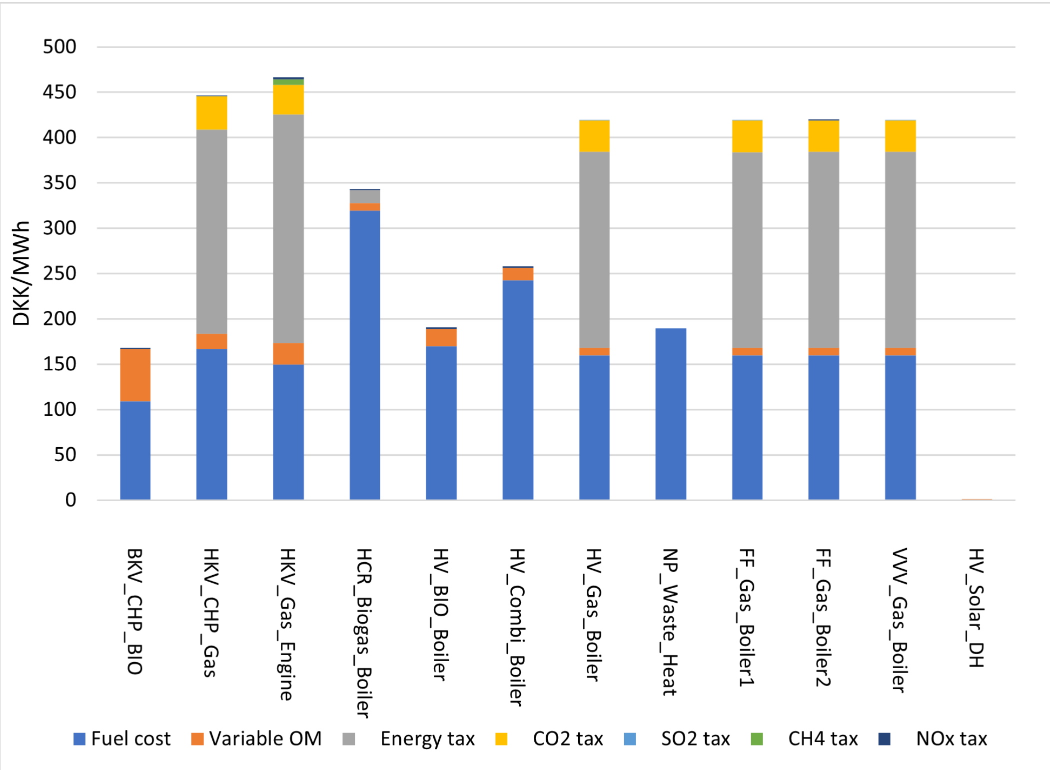

Figure A.4. Marginal price of heat production for each unit in the HFV system

A.9 Thermal energy storage

To balance peak demands without increasing the capacities of the production units, a suitable size thermal storage for each of the identified distribution areas are implemented in the model.

The size of the individual thermal storage is determined by the highest demand for two continuous days in a year. This is done based on hourly demands provided by EnergyPro for each site. The hourly data are summed by date, thus providing daily heating demands. The daily heating demands are added together two by two, e.g. 1/1 + 2/1, 2/1 + 3/1, 3/1 + 4/1, etc. thus the two continuous days with the highest demand can be found using a MAX function in Excel. It is assumed that the storage is at half capacity at the beginning and the end of the year to avoid complications and maintain security of supply in the first and last hours/days of system. The estimated storage capacities for each of the identified distribution areas are listed in Table A.13 for the NØS DH system and Table A.14 for the HFV DH system.

Table A.13. Estimated storage capacities for the distribution areas in the NØS DH system.

Distribution area	**Storage capacity [MWh]**
Hornbæk Fjernvarme A.m.b.a.	215
Forsyning Helsingør A/S	3.000
I/S Norfors	3.100
AK Fjernvarme	1.150

Table A.14. Estimated storage capacities for the distribution areas in the HFV DH system.

District heating area	**Storage capacity [MWh]**
Hillerød Forsyning A/S	2.700
Fjernvarme A.m.b.a.	950
Værløse A.m.b.a.	95

Appendix B: Heat Pump B

Assuming 4GDH with a supply temperature in the pipes of 55°C and a return temperature of 25°C a theoretical COP value is calculated using a simple Lorentz model. The heat source of the heat pump is the low temperature heat from the auxiliary system of the electrolysis process (35°C), as explained in chapter 3. This heat source is cooled to 30 °C in the heat pump resulting in a relatively high COP value compared to what is found in heat pumps for space heating purposes [Rambøll et al., 2019, p. 4]. The is due to the small difference in mean temperatures from the heat source and the heated medium.

$$HP_{COP} = \eta \cdot \frac{T_{DH}}{T_{DH} - T_{HS}} \tag{B.1}$$

$$T_{DH} = \frac{T_{DH,1} - T_{DH,0}}{ln\left(\frac{T_{DH,1} + 273,15}{T_{DH,0} + 273,15}\right)} \tag{B.2}$$

$$T_{HS} = \frac{T_{HS,0} - T_{HS,1}}{ln\left(\frac{T_{HS,0} + 273,15}{T_{HS,1} + 273,15}\right)} \tag{B.3}$$

Where:

HP_{COP}	Heat pump coefficient of performance
η	Lorentz efficiency
T_{DH}	Lorentz mean temperature of district heating
$T_{DH,1}$	District heating temperature delivered
$T_{DH,0}$	District heating return temperature
T_{HS}	Lorentz mean of the heat source
$T_{HS,1}$	Temperature of return flow to heat source
$T_{HS,0}$	Heat source temperature

In most cases of calculating a heat pump the amount of available heat to draw from is considered infinite such as when drawing from outdoor air; in this case however the amount of available thermal energy is determined by the capacity and operation of the electrolyser. As such it is necessary to calculate the scale of the heat pump in a different way. Assuming there is no heat loss between the heat input and output, it is possible to determine the capacity of the heat pump by reversing the formula:

$$P \cdot COP = Q_h \tag{B.4}$$

$$Q_h = Q_c, \tag{B.5}$$

$$\frac{Q_c}{COP} = P \tag{B.6}$$

Where:

P	Power [MW]
COP	Coefficient of performance
Q_H	Thermal energy output [MW]
Q_C	Thermal energy from heat source [MW]