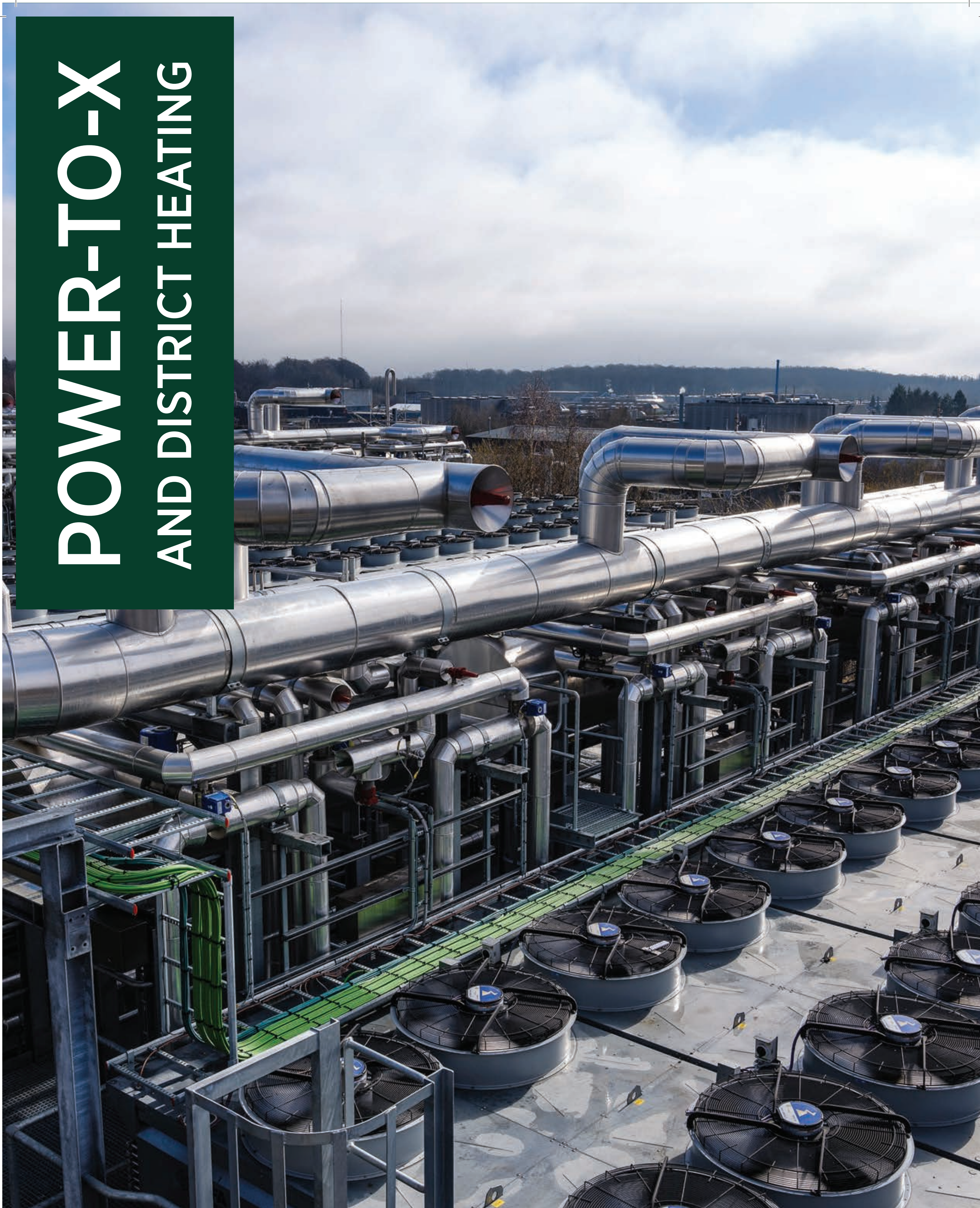
POWER-TO-X
AND DISTRICT HEATING



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Thanks to everyone who has provided input to this report.

The preparation of this report is supported by the Danish District Heating Association's R&D account.

CONTENTS

SUMMARY

There is a broad consensus that the heat from power-to-X (PtX) can be used in district heating, but there has been no overview or concrete definition of the advantages of integrating PtX and district heating. This report focuses on the role of district heating in relation to PtX, and why integrating PtX and district heating is important. It focuses on the production of hydrogen (electrolysis), as electrolysis is part of all PtX chains and much waste heat is generated at this stage.

It is uncertain where and when PtX plants will be constructed in Denmark and how large their capacity will be. Hydrogen is absolutely central, and total capacity estimates for 2030 are from 1 to 6 GW electrolysis. Waste heat is generated both from the electrolysis itself and by the auxiliary systems in the PtX plant, such as compressors. Waste heat makes up around 10-25 % of the energy and could potentially cover up to around 20 % of current district heating production at a capacity of 6 GW.

The report concludes:

- District heating can contribute to the success of PtX. The production costs of green hydrogen can be reduced if electrolysis and district heating are linked together. The financial improvements for hydrogen producers can help to accelerate the construction of larger PtX plants in Denmark.
- Heat from PtX is well suited for integration into district heating as part of a carbon-neutral district heating supply.
- The use of PtX heat for district heating promotes integration across sectors such as power, heating, transport, waste, industry and agriculture. Integration with district heating means increased energy efficiency and sectoral integration.
- It could also mean increased green exports, if the Danish PtX strategy is designed in conjunction with Danish strengths such as wind power and district heating.

CHALLENGE #1: THE VALUE OF INTEGRATION WITH DISTRICT HEATING NEEDS TO BE MADE CLEAR

District heating will improve the economy, increase energy efficiency, and accelerate the establishment of PtX in Denmark. These advantages form part of the foundation of a successful Danish PtX strategy.

Recommendations:

- A well thought Danish PtX strategy focusing on sectoral integration, energy efficiency, and speed. District heating is an important part of a Danish PtX strategy.
- The value created by integrating PtX and district heating should form part of the technical foundation of a Danish PtX strategy and the planning of specific projects.
- Build district heating into the PtX export strategy

CHALLENGE #2: INVESTMENTS IN ENERGY INFRASTRUCTURES

There are many unknowns in the development of PtX technologies and the energy infrastructures for power, heating, gas, and hydrogen. No matter which path the development takes in the end, heating infrastructure is the foundation of sectoral integration and of the ability to recycle and create value out of the heat from PtX.

Recommendations:

- The PtX strategy needs to support the efficient planning and placement of PtX plants, and integration with district heating should always be considered.
- Prioritise funds for infrastructure, including heat transmission, heat storage and improved integration of PtX into existing district heating systems.
- Learn from the experience of reusing waste heat from large data centres.
- Focus on necessary power grid reinforcements in order to prevent slow expansion, particularly expansion of the transmission grid, becoming a barrier to the establishment of PtX sites with access to district heating systems or electrification of district heating.

CHALLENGE #3: IT NEEDS TO BE TESTED IN PRACTICE

PtX technologies are essentially in place, but there are challenges in terms of implementing projects on large scale and demonstrating integration with district heating.

Recommendations:

- Prioritise funds for the demonstration of plants with integration for the production of green electricity, district heating, and the sale of green products on both a medium and a large scale.
- More funds for research, development, and demonstration with a focus on the integration of PtX and district heating.

CHALLENGE #4: TIMING AND FRAMEWORK CONDITIONS

Timing is one of the biggest challenges in making sure that PtX plants, the expansion of the power grid and the green transition of district heating all fit together seamlessly.

Frameworks, regulations, support schemes and bureaucracy will have a significant effect on the speed and direction of PtX development in Denmark and on the ability of district heating to form part of the sectoral integration of PtX.

Recommendations:

- Planning in order to ensure the necessary timing between the development of PtX plants, the power grid, district heating and buyers of green products. This includes co-operation regarding the placement of PtX plants.
- Frameworks and regulation of district heating to support the green transition and synergy with PtX.
- Prioritise CO_2 sources from waste and biomass as part of the Danish PtX strategy.
- Clear CO_2 frameworks that support the climate targets, e.g. the handling of negative CO_2 emissions and certificates.
- Secure and develop the heat base for district heating so that heat from PtX can be used to the greatest extent possible.
- New approach to power tariffs so that they do not undermine the integration of PtX and district heating and the electrification of district heating.
- Possibility of guarantees for innovative projects that could have a high-risk profile.

INTRODUCTION

The green transition in heating and power systems is well under way. With carbon neutrality targets for 2030, the heating and power industries have the responsibility and the opportunity to support the green transition in those sectors where it is more difficult to carry out.

Power-to-X (PtX) is closely tied to the green transition in the transport of goods by road, sea and air, as well as the production of carbon-neutral fertiliser for agriculture and carbon-neutral forms of products such as steel, plastic and chemical products.

The term power-to-X, or PtX, refers to the use of green power to produce a product (X), which could be green hydrogen, green basic chemicals, e-methane, e-methanol, green ammonia or green aviation fuel. All PtX processes require hydrogen, and electrolysis is therefore an important element in the green transition because it converts water into hydrogen and oxygen using green power. PtX processes involve energy loss in the form of heat, and infrastructure is needed in order to collect and make use of that heat. That is where district heating systems come in (Figure 1).

In the approaching expansion of PtX, it is an open question how much of this waste heat will end up being recycled into Denmark's district heating systems, both big and small. Part of the answer will be written by businesses, investors, municipalities as well as district heating companies, and other parts will be written in political agreements and in Denmark's future PtX strategy.

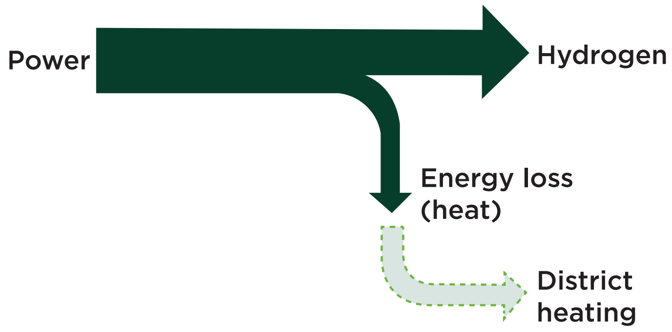


Figure 1: Power-to-X (PtX) converts power into X's such as hydrogen, methanol or aviation fuel. The waste heat can potentially be used for district heating.

There is no doubt that district heating has an important part to play in a Danish PtX strategy. Recycling heat from PtX can help to supply the Danish people with cheaper green heating, but there are also significant advantages to society in terms of the value that PtX and district heating can generate in other sectors. Selling waste heat from PtX processes for district heating could improve the competitiveness of PtX plants in Denmark. This can allow Denmark to take the lead in the PtX race and lead to a faster green transition. The same could happen if green CO_2 is captured directly from district heating production plants and used in the production of green fuels.

Expansion with full-scale PtX means significant quantities of waste heat, and the question of how much waste heat from PtX can be integrated into the district heating systems is therefore a relevant one. PtX is still a costly technology, and there is a lot of uncertainty around how much PtX capacity is coming and when, and how much waste heat will be generated by the production. It is therefore difficult to give an exact estimate. The estimate in Table 1 is from the Danish Energy Agency's Analytical Assumptions for 2020 to Energinet (AF20). The forecast for waste heat in 2040

according to AF20 corresponds to approximately 4-10 % of current district heating production. This is based on waste heat being generated both from the electrolysis itself and by the auxiliary systems in the PtX plant, such as compressors. Waste heat makes up around 10-25 % of the energy, where the 25 % level is an estimate corresponding to usage of both types of waste heat from PtX[1].

It illustrates that it is reasonable to expect district heating to be able to use the heat from many future PtX projects, including large-scale projects. The quality of the waste heat from PtX is high (high temperature and energy density) and forms an attractive source of green heat for district heating companies.

Year	Ptx, electricity capacity [GW] (AF20)	Ptx, electricity energy [TWh] (AF20)	Potential district heating energy [TWh]	Proportion of Danish district heating production
2030	1	5	0,5-1,25	1-3%
2040	3	15	1,5-3,75	4-10%

Table 1: Forecast for PtX in Denmark in 2030 and 2040 in the Danish Energy Agency's Analytical Assumptions for 2020 (AF20) to Energinet [2]. The district heating figures are based on being able to recycle 10-25 % [3] of the energy into district heating, where 25 % is an estimate corresponding to usage of both types of waste heat from PtX. District heating produced in Denmark in 2020 was 36 TWh.

There are concept studies of more than 1 GW of capacity in 2030. For example, Ingeniøren (a Danish technical newspaper) has summed the five largest plans to 4.6 GW in 2030[4]. Hydrogen Denmark's Hydrogen and PtX Strategy mentions a target of 6 GW of installed electrolysis capacity in 2030, corresponding to 6-12 TWh of heat available for use in the district heating grid[5].

At the same time, it is important to emphasise that waste heat should be used with overall energy efficiency in mind and in a way that ensures the best possible socioeconomic results and the most cost-effective operation of the PtX plant. Even at these quantities, the district heating systems will continue to be relevant buyers of waste heat, but it increases the need for planning and cooperation.

ABOUT THIS REPORT

This report has been written to provide insight and inspiration, allowing a wider audience to discover the potential value of a closer partnership between PtX and district heating.

The report is in four parts:

1. Technological overview with a focus on the waste heat from electrolysis. Electrolysis has been chosen as a focal point because green hydrogen is the foundation of PtX, and because the processes generate large quantities of heat.

2. Economics of coordinating PtX and district heating. This chapter contains economic estimates for PtX production and the value of heat if it is integrated into district heating systems.

3. The common thread in Chapter 2 is sectoral integration. An overview of the status of the largest district heating systems in Denmark, together with a description of why the existing power plant sites play a key part in the expansion of PtX in Denmark. The integration of PtX and

district heating is significant for other sectors and for the potential for green export.

4. District heating plays an important part in an effective Danish PtX strategy. The report concludes with descriptions of four challenges and associated recommendations.

1 POWER-TO-X TECHNOLOGY

Power-to-X (PtX) is defined as the conversion of green power from renewable sources, such as wind and solar, into various chemical compounds (represented by the X), such as hydrogen, green basic chemicals, ammonia, methanol and other green fuels. This produces sustainable green alternatives to supplement and eventually replace fossil fuels. At the same time, it addresses the challenges of storing energy from fluctuating power generation.

PtX covers a range of combinations of technologies and processing facilities. Figure 2 shows an overview of possible value chains, with the simplest being hydrogen production from water electrolysis. The various electrolysis technologies are described and compared in Appendix A. In longer PtX chains, heat will be generated at multiple stages of the process. Figure 3 shows an example of how heat production can be distributed across an overall process of electrolysis, carbon capture and methanol production.

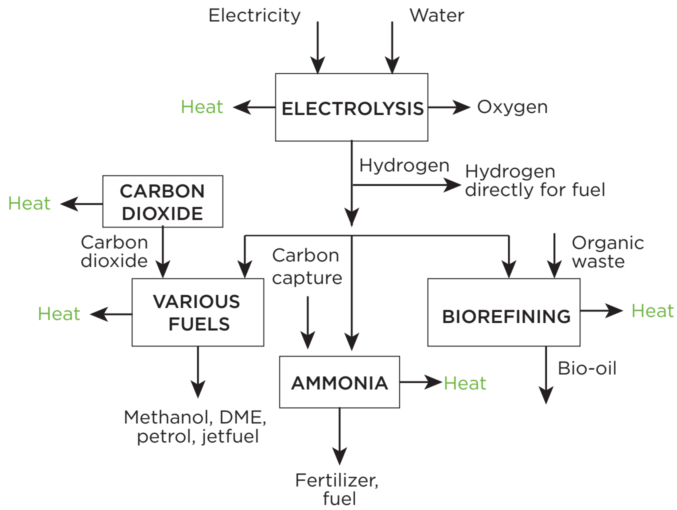


Figure 2. A series of value chains for power-to-X (PtX). All the processes involve energy loss in the form of heat. The quantity and temperature of the waste heat depends on the individual process and on how optimised the heat integration is.

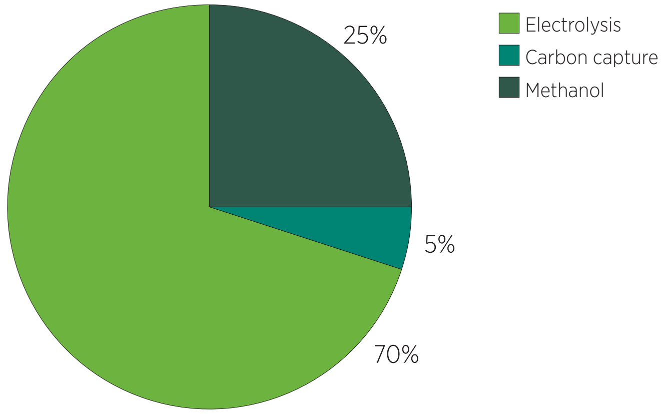


Figure 3. Estimated distribution of heat production from a PtX chain of electrolysis, carbon capture and methanol production. It is assumed that all of the hydrogen and CO_2 is converted into methanol. Parts of the heat from the methanol and electrolysis process will require a heat pump. The figures do not include heat integration and optimisation in the PtX chain.

Hydrogen can be combined with nitrogen (N_2) to form ammonia (NH_3), which is used as fertilizer, but also as a potential fuel for ships, for example. Similarly, when combined with carbon dioxide (CO_2), hydrogen can be converted into green fuels including methanol, DME, petrol, and jet fuel. While the nitrogen is obtained directly from the atmosphere, the carbon can come from a number of different sources, such as CO_2 from a biogas plant or a capture facility at a biomass or waste-fired combined heat and power (CHP) unit. Alternatively, bio-oil can be formed from more complex carbon compounds in organic waste such as wood or food waste. In that instance, hydrogen from electrolysis is used to hydrogenate the bio-oil.

A distinction also needs to be drawn between fossil and biogenic CO_2, as this has political, regulatory, and economic significance. While fossil CO_2 is emitted by burning coal, oil, gas and other fossil fuels, biogenic CO_2 is formed by burning organic materials, such as wood and food waste, which have absorbed CO_2 from the atmosphere. The actual differences therefore lie in the carbon's cycle time and isotopic composition (proportion of carbon-14).

From a waste-fired plant, 40-45 % of the total amount of CO_2 emitted typically comes from fossil sources such as plastic, while the rest is from renewable sources such as food waste. From a biomass-fired plant or a biogas plant, on the other hand, 100 % of the CO_2 is biogenic. The fossil portion has to be reported and counts towards the calculation of taxes. When using PtX to produce green fuels, however, there is an incentive to use the biogenic portion in order to make use of renewable energy sources.

Figure 4 (in Danish) shows an overview of current and upcoming Danish projects and illustrates the variety of PtX projects in Denmark. In general terms, PtX is in its early stages in the form of pilots, real small-scale projects, and concept studies of large-scale projects.

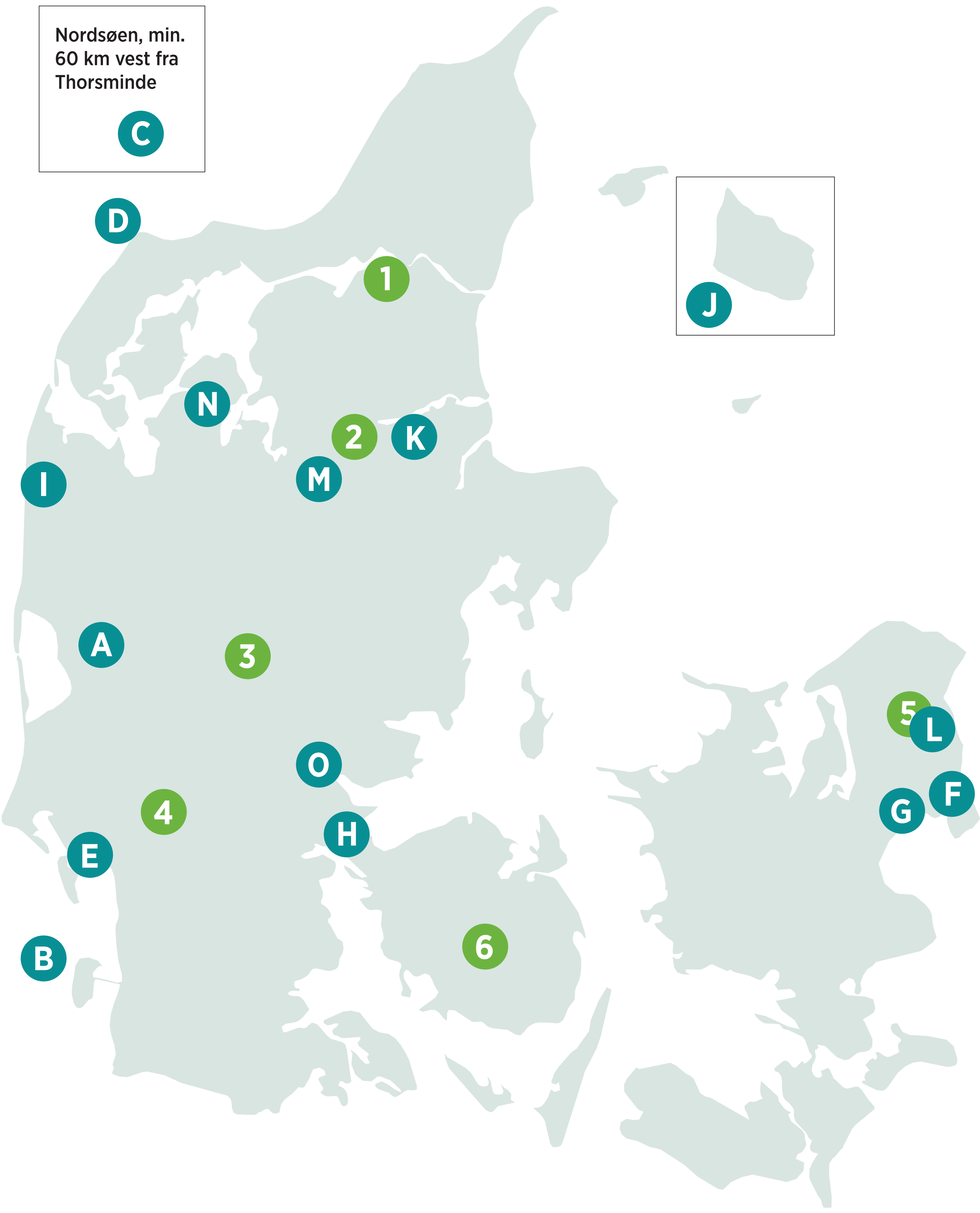
The optimal location for PtX depends on the physical conditions, including a series of factors such as:

- Access to a transmission and distribution infrastructure for power, water, heating and logistics/transport.
- Space requirements, distance requirements, as well as environmental and safety conditions.

This analysis is limited to electrolysis and therefore to hydrogen as a product, as electrolysis is a part of all PtX chains and a large quantity of waste heat is generated at this stage. The proportion of possible district heating can therefore be expected to increase by further upgrading the hydrogen to green fuels. This is largely dependent on how much effort is made to ensure heat integration and efficiency between and within the plants.

The sections below present case studies of electrolysis facilities based on commercially available technology, analysing the potential operational and financial effect of a connection to the district heating system. Electrolysis technologies and potentially available waste heat are described further in Appendix A..

POWER-TO-X PROJECTS IN DENMARK – REALISED AND PLANNED



REALISED PROJECTS		
#	**Plant name, production purpose, place and company**	**In operation**
1	Power2Met, Metanol, Aalborg · *Green Hydrogen Systems, Re:Integrate, AAU, E.ON, Nature Energy, Rockwool* *Fase I: 0,3 mio. L, Fase II: 10 mio. L, CO_2 fra biogas, H_2 fra 0,5 MW AEL*	Fase I: okt. '20, på AAU, Fase II: '22 ved Greenlab
2	HyBalance, Brint, Hobro · *Air Liquide, Hydrogenics, Centrica, Energinet, Hydrogen Valley* *Elnetstabilisering gennem brintproduktion i 1,2 MW PEM-celler, der fyldes i mobile lagre til brug til transport eller via et brintgasnet i industri*	'18
3	Integreret vindmølle/elektrolyse, Brande · *Siemens Gamesa, Green Hydrogen Systems* *Brintproduktion i en 0,4 GW AEL-celle, el direkte fra en 3 MW onshore-vindmølle. Ingen elnettilslutning.*	I starten af '21
4	Energilagring - Brintinjektion i gasnettet, Agerbæk · *Energinet, DGC, Evida, IRD Fuel Cells* *Fase I: Iblanding af op til 15% brint i et lukket højtryks-testsystem. Fase II: iblanding af op til 25% brint*	Fase I: '17-'20 Fase II: '20-
5	eSMR-MeOH, Kgs. Lyngby · *Topsøe, AU, SINTEX, Blueworld, DTU* *Demonstration af eSMR-MeOH-teknologi i industriel relevant størrelse og muliggørelsen af kommercialisering efter projektet.*	'19, komm. efter '23
6	eFuel, Broby, Fyn · *Nature Energy, DTU, SDU* *Metanisering af CO_2 i biogassen i en reaktor via en rislefilterreaktion. Mikroorganismer omdanner CO_2 og brint til metan. Fjernvarmelevering muligt. Planlagt brintforbrug til metanisering på 16 Nm^3/h*	'20
PLANNED PROJECTS		
#	**Plant name, production purpose, place and company**	**Planned**
A	Injection technology for H2-meditated production of methane (InjectMe) · *Landia A/S, AU, University of Queensland* *Projektets eksperimentelle arbejde: 1. metanproduktionskapacitet, 2. fleksibilitet; 3. priseffektivitet. Undersøgelse af teknisk og kommercielt potentiale mht. kemisk, biologisk metanisering og kemisk power-to-etanol.*	'21-'23
B	OYSTER-Project, Offshore brintproduktion på Nordsøen · *ITM Power, Ørsted, Siemens Gamesa, m.fl.* *Offshore-brintproduktion i MW-skala. Udvikling af kompakt og pålideligt design. Undersøge omkostnings- og performanceniveau for at sikre en billig brintproduktion*	'21-'24
C	Kunstig energiø i Nordsøen, i direkte omgivelse af 3-10 GW havvindparker; udlandsforbindelser ·*Den danske stat* *Ifølge klimaaftalen besluttede et bredt flertal af Folketinget i klimaaftalen bygning af energiøen, som består i fase I af 200 og i face II af 600 vindmøller*	3 GW i '30 10 GW på sigt
D	Exowave, vand, elektricitet og PtX · *Exowave ApS, AAU, MDT A/S, DanWEC* *Bestemmelse af den optimale skalerbare konfiguration og enhedsomkostning (LCOE) for elektrolyse ved kombination af vind- og bølgekraft*	'21-'22
E	Vindstrøm til CO_2-fri gødning og brændstof · *Copenhagen Infrastructure Partners, Arla, Danish Crown, DLG, Mærsk, DFDS* · *CO_2-fri prodktion af ammoniak til gødning eller brændsel. Produktion af brint via 1 GW elektrolyse. Reduktion af op til 1,5 mio. tons CO_2-varme til Esbjerg*	Beslutning: '22/'23 I drift: 2026
F	Storskala-P2X i Københavns Kommune · *Ørsted, CPH Lufthavne, Mærsk, DSV, SAS* *Fase I: 10 MW demonstrationsanlæg, Fase II: 250 MW, Fase III: 1,3 GW*	Fase I: '23, Fase II: '27, Fase III: '30
G	H2RES, Brintprod. til transport, Avedøre · *Ørsted, Everfuel, Nel, Green Hydrogen, DSV, Energinet* *2 MW brintelektrolyse til prod. af 600 kg. H_2/dag. Strømmen kommer fra 2 havvindsanlæg ved Avedøre på hver 3,6 MW*	Ca. '22
H	HySynergy, grøn brintfabrik til at erstatte sort brint i raffinaderiet, Fredericia · *Shell, Everfuel* · *Fase I: 20 MW-elektrolyse, 10 tons lagerkapacitet (500 MWh), Fase II: 1 GW fleksibel grøn brintproduktion, overskudsvarme til fjernvarme*	Fase I: '22 Fase II: '30
I	Grøn P2-ammoniakfabrik, Ramme · *Skovgaard Invest, Haldor Topsøe, Vestas* · *Produktion af 5.000 ton grøn ammoniak. Brintelektrolyseanlæg med en kapacitet på 10 MW og efterfølgende ammoniakproduktion. Derudover opføres et 50 MW solcelleanlæg*	'22
J	Energiø Bornholm *Havvindpark i størrelsesorden på 3-5 GW, overskudsel bruges til brint- og e-fuel prodution*	'28
K	LH2 Vessel, Hobro · *Ballard, DGC, AAU, MAN, OMT, FMT* *Flydende brint til opskalerede brændselscellesystemer til fremdrift af skibe - batteri/brændselscelle-hybridløsninger*	Efter '23
L	DREAME, Kgs. Lyngby · *DTU, GHS, Danish Power Systems* *Udvikling af ny elektrolytmembran for at øge effektiviteten af alkalisk elektrolyse til et niveau sammenligneligt med PEM-teknologien*	Ca. '22
M	Green Hydrogen Hub, Hobro/Viborg · *Eurowind, Corre Energy, Energinet* *Etablering af 350 MW elektrolyseanlæg og 0,2 MWh brintlager som langtidslager. Derudover kombineres det med et højtryks luftlager, kapacitet 320 MW*	Ca. '25
N	GreenLab Skive P2X, brint- og e-brændsel *Greenlab, EuroWind, Everfuel, Eniig, E.ON, Energinet, GHS, DGC, Re:Integrate* *12 MW elektrolyseanlæg; 1,6 MWh batterilager, 75 MW el fra vindmøller og solceller, CO_2 fra Greenlab Skive Biogas.*	'22
O	P2X-partnerskab i Trekantsområdet	Ca. '26

Figure 4. Overview of executed and planned PtX projects in Denmark from March 2021. With permission based on a map from the Danish Gas Technology Centre (see https://www.gasfakta.dk/p2x-kort)

2 ECONOMICS OF INTEGRATING PTX AND DISTRICT HEATING

An initial estimate has been made of the potential effect on the business economics of the electrolysis plant when factoring in revenue from selling waste heat to the district heating grid. This has been done for two different case studies; a small district heating system with a 20 MW_E electrolysis plant, as well as a larger system with a 400 MW_E plant.

It is noted that, in general, there are many uncertainties and variables when calculating the economics of a PtX plant. Estimates have therefore been drawn up as case studies to illustrate general effects and cannot be transferred directly to a specific system. To do this, more detailed calculations are required.

The assumptions made with regard to costs and revenues are described in Appendix B. Operating profiles are drawn up on the basis of these costs and revenues for the electrolysis plant per hour over the course of a year – both with and without revenue from district heating. In calculations of operating profiles, the plant investment itself and any fixed costs have not been taken into account because the plant is assumed to be operational when there is a positive contribution margin.

Case studies of a 20 MW_E electrolysis plant in a small district heating system and a 400 MW_E plant in a large district heating system are examined below.

2.1 Case study: 20 MW_E electrolysis plant with a small district heating system

This case study examines an electrolysis plant with power consumption of 20 MW_E, including a compressor, pumps, electronics etc. The electricity prices used result in a cost spread of DKK 1600-10 000 per hour, with an average of DKK 6883 per hour.

District heating prices in this case study are evaluated using the calculation software energyPRO, taking into account the electrolysis plant operating profile and delivery of waste heat at 35 °C and 70 °C, respectively. Degradation is considered as an average in the model by assuming that the plant produces 2 MW of heat at 70 °C. In addition to this, heat from auxiliary systems such as compressors is fixed at 3 MW at 35 °C; this requires heat from an electrically powered heat pump, which is included on the district heating side in energyPRO.

The electrolysis plant produces just under 0.4 tonnes of hydrogen per hour. The hydrogen price level that can be achieved has a significant effect on the number of annual operating hours. An illustration of this can be seen below in Table 2.

Price DKK/kg of hydrogen	Operating hours/year	Contribution margin DKK millions per year
11 (grey)	300	0.5
15 (blue)	1050	1.0
20 (used in case)	4150	6.0
26 break-even	8650	20.5

Table 2. Illustration of sensitivity of hydrogen price level. Revenue from the sale of district heating has not been taken into account at this point.

Whether buyers (B2B) are willing to buy hydrogen from electrolysis at a higher price than grey hydrogen has not been evaluated. This analysis assumes a price of DKK 20 per kg, which is a conservative assumption at the low end of the IEA's price estimates for green hydrogen.

The CAPEX for an electrolysis plant is estimated at around DKK 10 million per MW_E, which for 20 MW_E gives DKK 200 million. With a lifetime of 20 years and an interest rate of 3.5%, the annual CAPEX will be approximately DKK 14 million per year. Moreover, fixed costs for operation and maintenance are anticipated at 3% of CAPEX, corresponding to DKK 6 million per year. Without revenue from district heating, the hydrogen price needs to be at least around DKK 26 per kg to ensure that the fixed costs are also covered in this overall estimate for the business case.

In addition to various tariffs and connections to the power and district heating grids, there may be a number of preparatory costs, such as land prices, that affect a relevant business case and the optimum location for the electrolysis plant. This level of detail, however, is outside the scope of this report.

2.1.1 Value of waste heat

District heating must supply the cheapest heating possible and always select the heat production that gives the lowest heating prices for the customers. In order to evaluate how much the waste heat from PtX will be worth to a district heating company, calculations of the annual operating costs for the district heating system have been done in energy-PRO.

Three different types of district heating systems have been examined:

1. Natural gas only
2. Biomass and biogas for peak loads
3. A combination of biomass and an electric heat pump, and biogas for peak loads

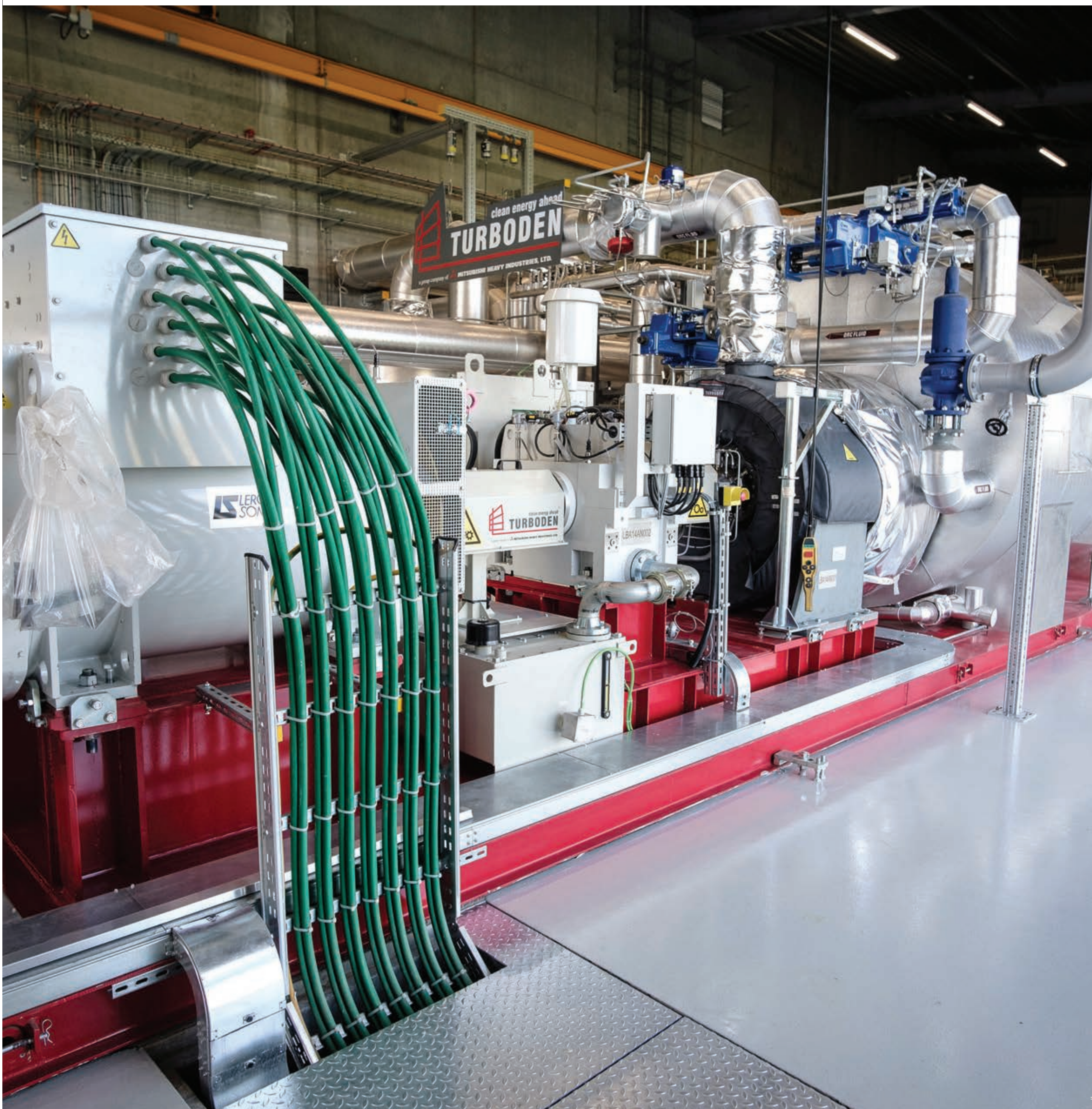


Figure 5 shows an example of how the composition of the heat production changes when firstly the heat from the electrolysis process (70 °C) and secondly the heat from the auxiliary systems (35 °C) are integrated into the district heating system. The value of the heat is highly dependent on the temperature of the heat, it is different for each of the three selected systems and finally, it also varies over the course of the year. This is illustrated in the figures and tables in Appendix C, and the methods and assumptions are also described there.

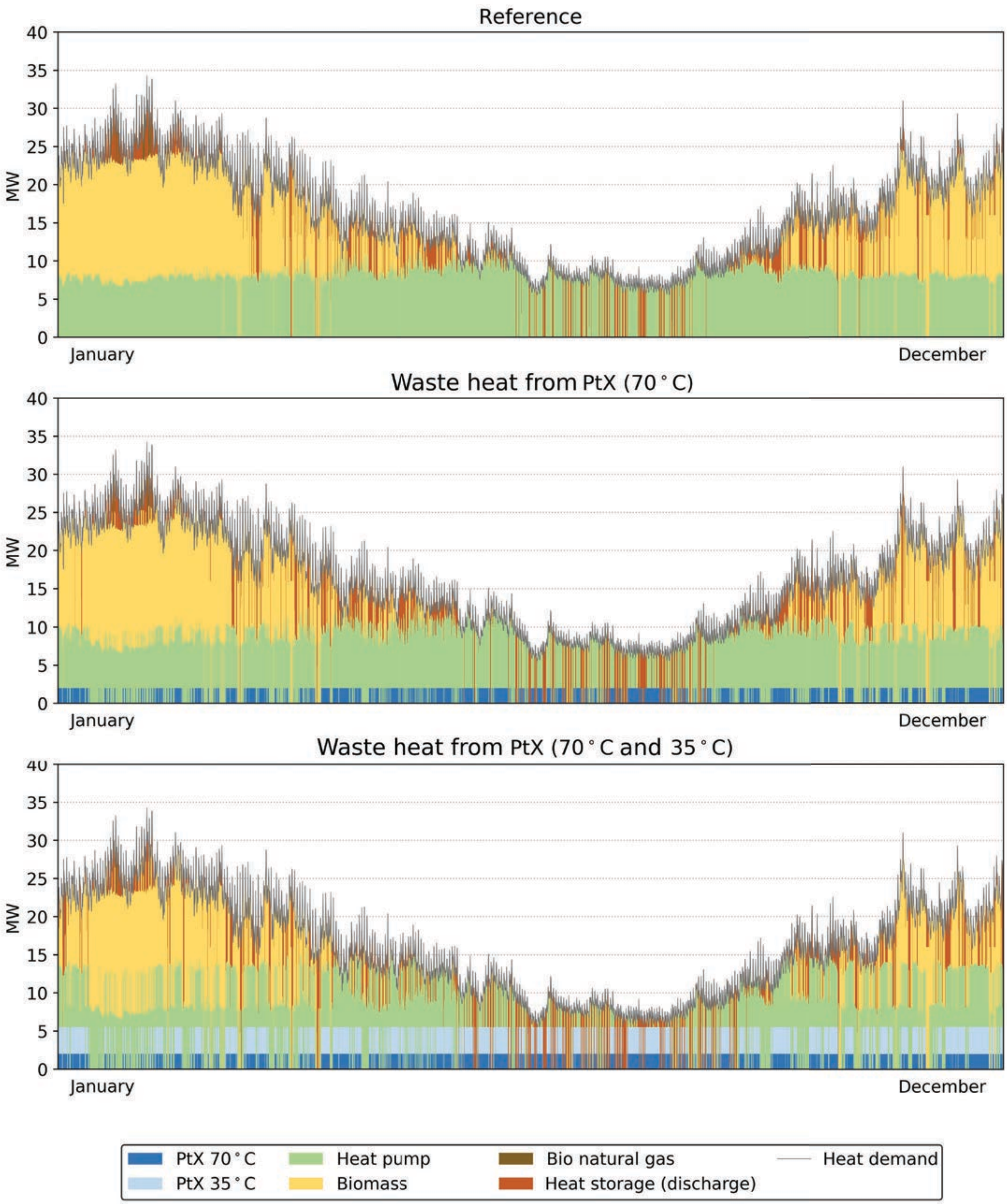


Figure 5: The composition of heat production over the course of the year for scenario 3, in which the heat is primarily produced on a biomass boiler and an electric heat pump using ambient air as the heat source. At the top is the operating profile of the district heating system over the course of a year without waste heat from PtX. In the middle, the waste heat at 70 °C is used, which displaces production on the biomass boiler and electric heat pump. At the bottom, the waste heat at both 70 °C and 35 °C is used, making up just under 20 % of annual heat production.

2.1.2 The effect of district heating on operation and economy

Based on the energyPRO scenarios in Appendix C, the following heat prices have been established for 35 °C and 70 °C:

- For 70 °C waste heat, DKK 150 per MWh is applied in the summer months and DKK 200 per MWh in the winter for the scenarios with biomass and a combination of heat pump and biomass.

- For 35 °C, a single fixed price is set for the entire year, which is DKK 35 per MWh in the biomass scenario and DKK 15 per MWh in the scenario with a combination of heat pump and biomass.

The power consumption of the heat pump needed to bring the 35 °C share up in temperature is included in the analysis of the district heating systems and has therefore been omitted from the electrolysis costs side of the case study.

The additional contribution margin due to the sale of district heating increases the number of operating hours for the electrolysis plant, resulting in a new operating profile and an increased supply of heat to the district heating system. This will once again affect the maximum willingness to pay and possibly also the district heating price levels chosen. In order to check whether this significantly changes the basis for the calculations, an additional iteration has been carried out in energyPRO with the new operating profile. The results confirm that the price levels can be kept as they are.

The effect of the sale of district heating on the operation and contribution margin of the electrolysis plant can be seen in Table 3 below. The number of operating hours during which the variable costs can be covered is increased by approximately 800 hours. Moreover, Figure 6 shows that the revenue from district heating will make up approximately 5 % of the total revenue, and that the resulting additional operating hours lead to an increase in hydrogen revenue due to greater annual production.

	Without district heating	With district heating
Operating hours per year	4150	4950
Contribution margin, DKK millions per year	6.0	8.0
Revenue from hydrogen, DKK millions per year	30	36
Revenue from district heating, DKK millions per year	0	2.0

Table 3. Effect of revenue from district heating on the operation of an electrolysis plant.

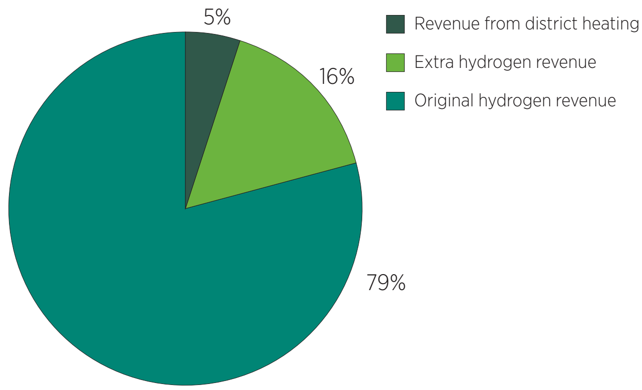


Figure 6. Distribution of revenue for 20 MW_E electrolysis plant with a district heating connection.

The effect of the sale of district heating can also be evaluated based on the number of vehicles for which fuel (hydrogen) can be produced and the number of households that can be heated. In round figures, the results are as follows:

- The waste heat from the entire electrolysis plant can supply around 1350 standard houses. This means that around 20 % of the houses in the district heating system analysed can be heated with the waste heat from the PtX plant.

- The number of hydrogen-fuelled passenger cars (0.8 kg/100 km; 20 000 km per year) that can be supplied changes from around 9300 to around 11 100 as a result of the increase in hydrogen production.

- Similarly, the number of hydrogen buses (7.5 kg/100 km; 80 000 km per year) that can be supplied with hydrogen increases from around 250 to around 300.

2.2 Case study: 400 MW_E electrolysis plant with a large district heating system

In the case study for the large district heating areas, energyPRO has not been used. Instead, a generic heat curve has been created, inspired by actual demand estimates. Because heating prices will vary between the individual systems, the following heating prices have been assumed, in line with the previous small scenarios:

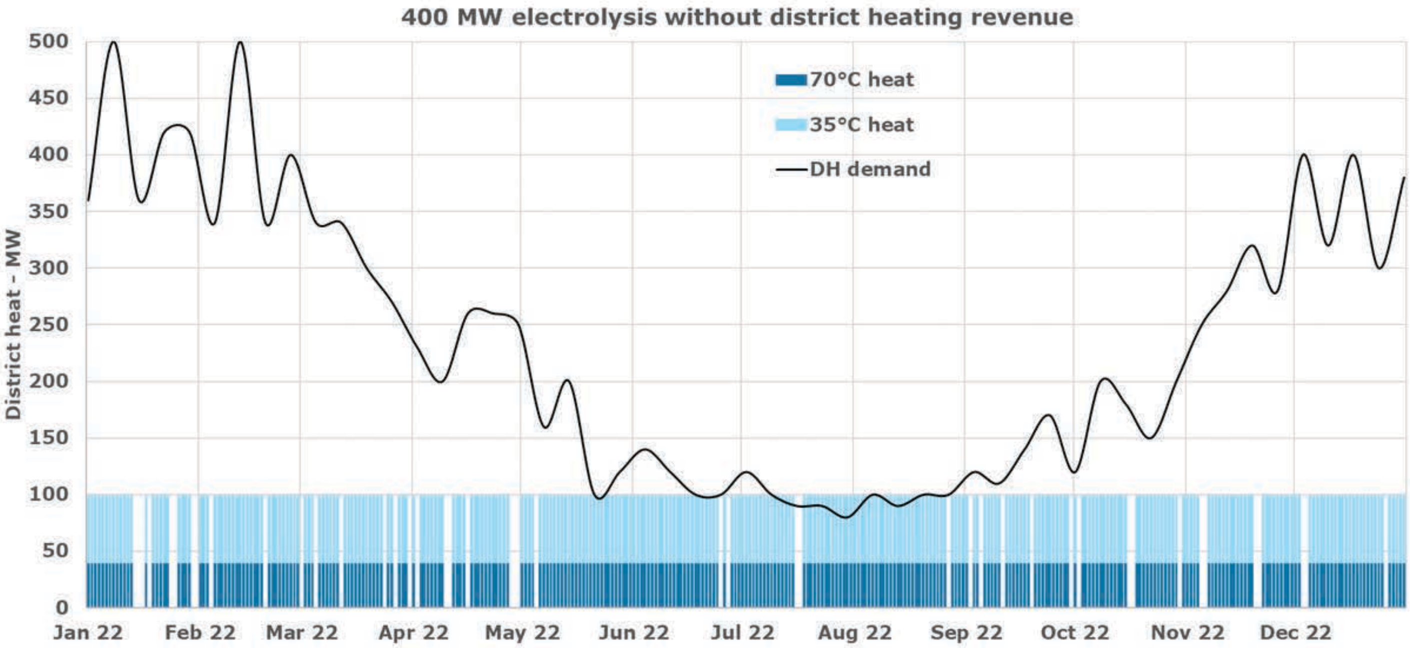
- Summer price of DKK 150 per MWh and winter price of DKK 200 per MWh for 70 °C waste heat

- DKK 15 per MWh for 35 °C waste heat

For hydrogen, the price has been maintained at DKK 20 per kg and the cost of power for the heat pump to bring the 35 °C waste heat up in temperature has been included.

The system has been calculated in terms of the operation of a 400 MW_E electrolysis plant in a large district heating system[6] which produces the operating curves below with and without revenue from district heating (see Figure 7). The black curve shows the estimated heat profile for the district heating system, while the operating profiles for waste heat at 35 °C and 70 °C are shown as light blue and dark blue bars respectively. The combined height of the bars gives the total waste heat for the electrolysis plant. The top graph shows the operating profile without revenue from district heating, while the bottom graph shows the profile with revenue from district heating. The additional operating hours resulting from the revenue are evident from the smaller number of gaps in the operating profile.

It can be seen that, depending on the size of the electrolysis plant, heat production relative to demand may be too high during the summer period. In such cases, the heat may be chilled if there are no other options, such as heat storage. However, this issue does not fall within the scope of this analysis.



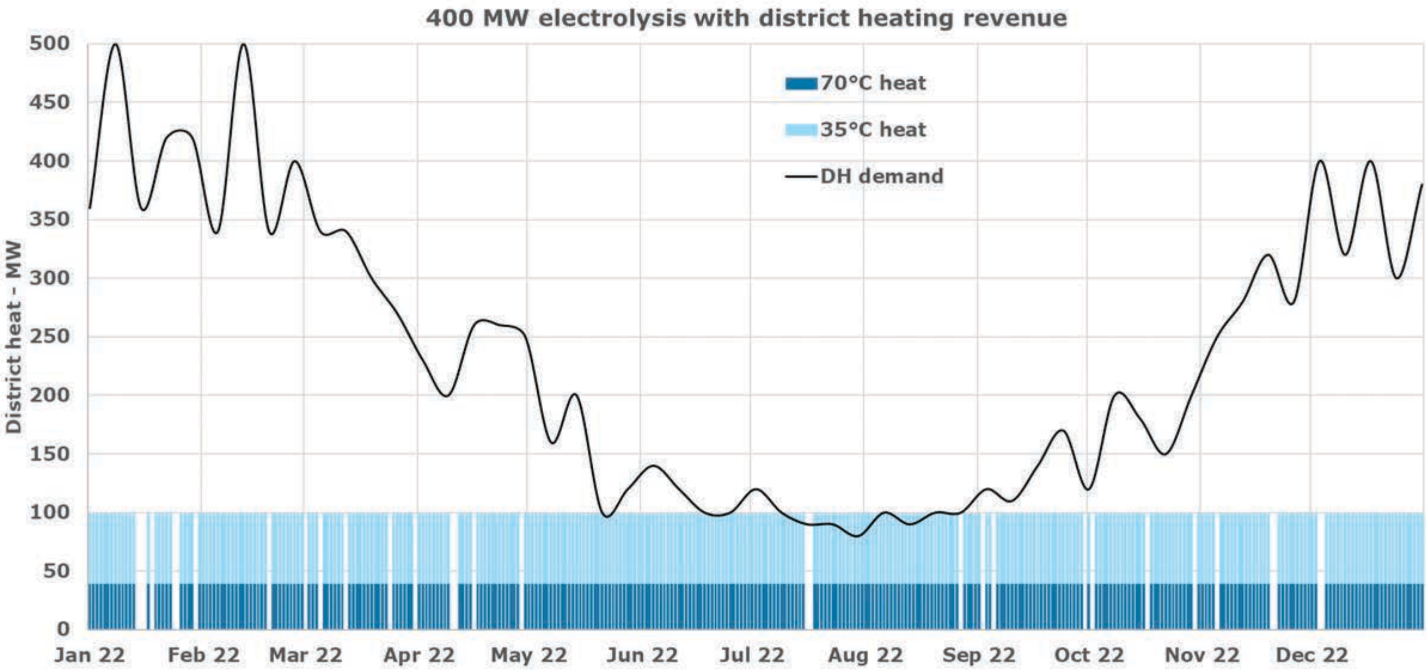


Figure 7. District heating production in a large system with waste heat from electrolysis. Top: operating profile without revenue from district heating. Bottom: operating profile with revenue from district heating. The additional operating hours due to district heating are evident from the smaller number of white gaps in the bottom profile.

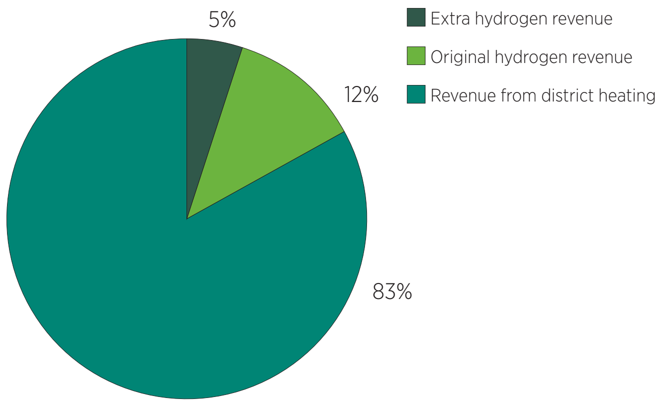


Figure 8. Distribution of estimated revenue for hydrogen and district heating. The 70 °C waste heat is purchased for DKK 150 per MWh during the summer months and DKK 200 MWh during the winter months, while the 35 °C is purchased for DKK 15 per MWh throughout the year. The additional hydrogen revenue results from additional operating hours due to the revenue from district heating.

The distribution of the estimated revenue is shown in Figure 8. The sale of district heating will make up 5 % of total revenue, leading to a significant difference in operating hours from around 4150 hours to around 4750 hours with the possibility of achieving a contribution margin. The original hydrogen revenue without sale of district heating constitutes 83 % and is now supplemented by additional revenue due to the increased operating hours.

Initially, without district heating, the produced hydrogen is enough to fuel the equivalent of 5000 hydrogen buses. The additional revenue from district heating raises this figure to 5700 buses. The corresponding increase in the number of hydrogen-fuelled passenger cars is from 186 000 to 212 000. The district heating will also cover the needs of approximately 26 000 standard houses year-round with 400 MW_E electrolysis.

It can be seen that the district heating will form a key part of the business case for the electrolysis plant. However, it is uncertain whether it will be possible to sell the waste heat at the specified prices. This depends to a large extent on the heat production that already exists in the area and on whether the geographical area in question has a shortage or a surplus of heat.

In a different situation in which the value of the heat is lower (respectively DKK 110 and DKK 180 per MWh for 70 °C, with 35 °C purchased at DKK 0 per MWh), the effect of district heating will be correspondingly less. At these prices, the number of operating hours will only rise by just over 400 per year, and the revenue from district heating will make up roughly 4 % of the total revenue (see Figure 9).

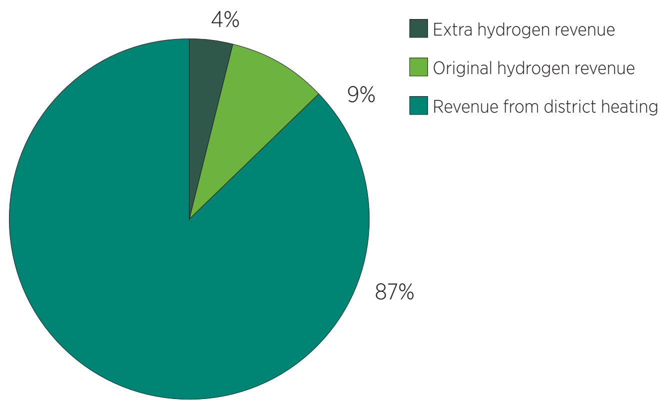


Figure 9. Sensitivity analysis: Distribution of estimated revenue for hydrogen and district heating with a heat value of DKK 110 per MWh in the summer and DKK 180 per MWh in the winter for 70 °C. Heat at 35 °C is purchased at DKK 0 per MWh.

2.3 Summary and conclusions

These overall case studies of the integration of district heating in terms of PtX have been composed with the intention of illustrating the potential advantages that can be achieved by taking district heating into account at an early stage. Specifically, it can be seen that:

- The sale of waste heat to the district heating grid will generate revenue for the electrolysis plant, making it possible to achieve more operating hours with a positive contribution margin.
- The additional operating hours increase the total annual production of hydrogen, which also helps to increase total revenue.

It should however also be noted that:

- The revenue side is only part of the overall economic picture to be considered.
- These case studies should not be used as a basis for drawing conclusions about the overall economy for a PtX plant and the improvements resulting from integration with district heating. This requires a specific analysis of the individual projects, as some of the made assumptions carries high uncertainty.

3 PTX AND DISTRICT HEATING – PART OF A LARGER GREEN SECTORAL INTEGRATION

The previous chapter illustrated how integration with district heating supports the economics and operations of the PtX plant itself. The focus of this chapter is on the connections to the transition for society in general, based on the coupling of district heating and PtX. This chapter can be seen as a long presentation of the case for why sectoral integration and district heating are crucial to a Danish PtX strategy.

3.1 The significance of district heating for PtX

District heating is undergoing an ambitious green transition – away from coal, away from natural gas and, gradually, away from biomass. At the same time, district heating is growing as more and more homes, public buildings and businesses are connecting to district heating systems. This requires new technologies and collaborations to replace traditional types of heat production.

The district heating companies are already in the process of establishing and developing new, green heat sources that obtain energy from green power, air, wastewater, seawater, industrial waste heat, solar heat, and geothermal heat. To ensure low heating prices, flexibility and security of supply, the new plant types are also being combined with different types of heat storage.

The waste heat from PtX is of interest to district heating companies for several reasons:

- It is a carbon-neutral heat source that is not based on incineration.
- It is expected to be available in large quantities, even close to big cities. There is potential to supply existing district heating areas as well as to coordinate the locations of PtX plants with new district heating areas, e.g. as part of converting natural gas areas.
- PtX plants are expected to have many operating hours and therefore to provide a stable source of heat.
- The waste heat is of high quality (high temperature and high energy density).
- It produces synergies with carbon capture in existing district heating and CHP plants.

This interest can also be seen from the fact that many district heating companies are actively seeking to join partnerships to develop PtX. There is a belief that PtX has a place in the green district heating of the future.

Power plant sites have infrastructure already in addition to other advantages that make them highly suitable locations for some of the first large PtX plants in Denmark

3.1.1 Carbon capture with existing district heating plants

The use of waste heat from electrolysis in district heating systems is not the only relevant link between PtX and district heating. The waste and biomass plants that supply heat to the district heating systems are also suitable for carbon capture (CC). Plants that produce district heating therefore have the potential to become carbon-negative, and are able to harvest the waste heat from the carbon capture process, transferring it to the district heating grid.

According to the C4 (Carbon Capture Cluster Copenhagen) partnership, there is potential to capture around 3 million tonnes of CO_2 each year in the Capital Region alone. This is equivalent to around 15 % of the reductions that Denmark needs to implement by 2030 [7].

The first step on this path is to build experience with efficient carbon capture, and then to make good use of it. One option is to store CO_2, thereby removing it from the atmosphere entirely. Another option is to recycle the green (biogenic) carbon in the PtX production of green fuels. This is likely to involve both the storage (CCS) and use (CCU) of CO_2 from a number of the plants that already exist and are supplying district heating in Denmark.

As mentioned above, in the Capital Region, C4 anticipates a potential of 3 million tonnes of CO_2 per year. For comparison, calculations [8] show that 8 million tonnes of green CO_2 per year will be needed in order to turn Denmark's anticipated aviation fuel needs (50 PJ) green by 2030. With 36 TWh of green power and 8 million tonnes of green CO_2, it will be possible to produce 85 PJ of green Fischer-Tropsch products, of which 50 PJ will be green aviation fuel.

One concern – which seems almost illogical – is that Denmark could see a shortage of CO_2. The idea is that easy sources of CO_2 could end up in short supply, which would limit how much CCU (PtX) could be generated in Denmark.

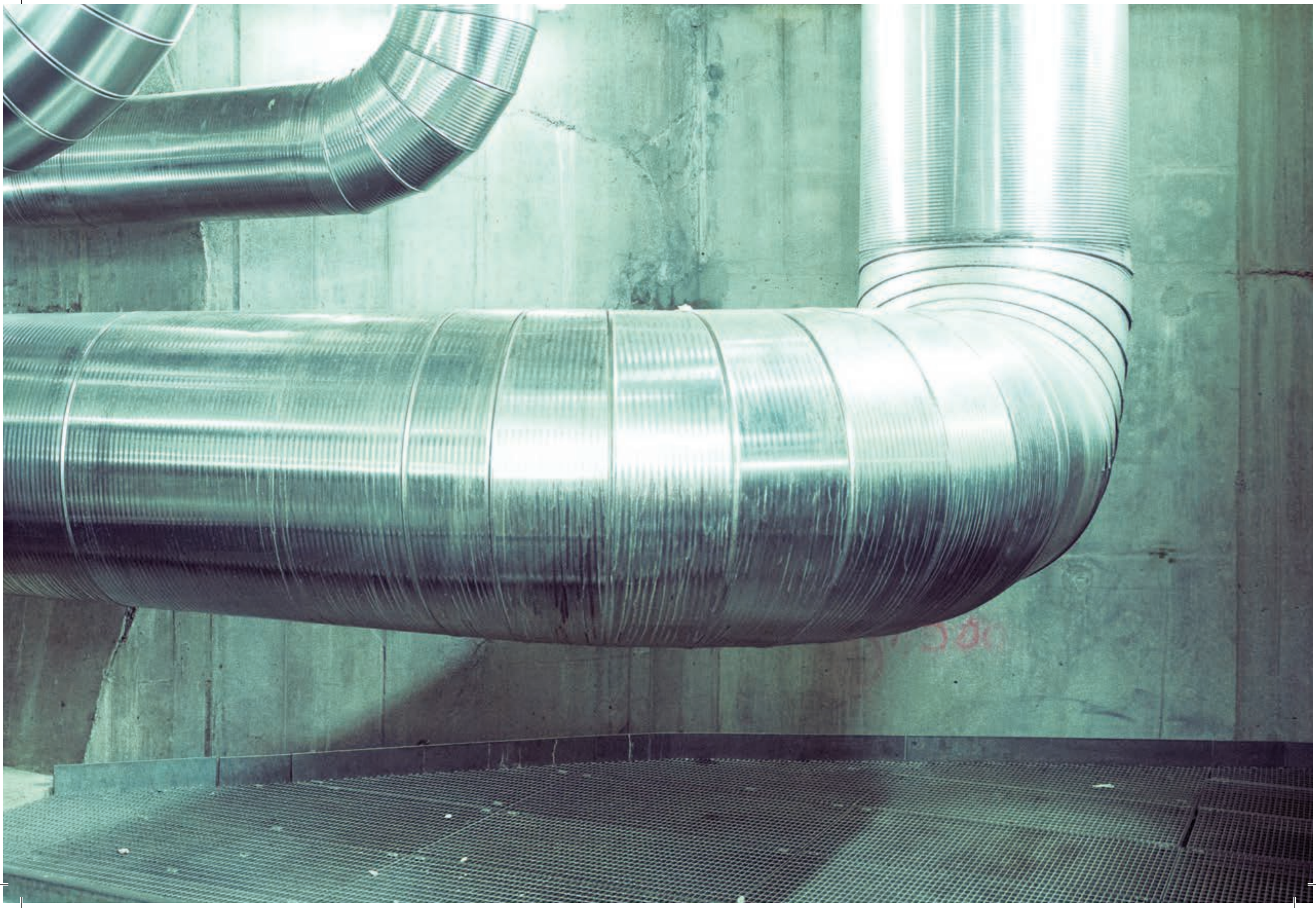
3.1.2 The role of waste and biomass plants in the green transition

Political discussions concerning the role of biomass and waste in the green transition are ongoing. For example, a number of existing district heating plants are based on various types of biomass and district heating. In technical and economical terms, it makes sense to continue operating the plants, but there is uncertainty surrounding the political will.

Bringing in waste heat from electrolysis adds yet another dimension to analysis of the future role of waste and biomass plants. Figure 10 illustrates the differences with and without a forced phasing-out of existing biomass and waste plants.

Without forced phasing-out, the old plants are replaced as they reach the end of their lifetime and are being replaced by the best technologies available. If a plant has reached the end of its lifetime at this point in time, for example, this means replacing it with large, electric heat pumps with ambient air as a heat source, while replacing it later could mean that waste heat from PtX is an option. It is not necessarily an option for all locations to obtain PtX plants close to the district heating systems, but the option to switch to electric heat pumps will still exist. There could be situations where a district heating company has invested in new plants and the option of PtX then comes to the area later on. It will not necessarily make sense from a economic and risk assessment perspective to switch technologies immediately. The likely scenario in such cases is that the next technological switch might not take place until many years later.

With forced phasing-out, new technologies may not be suitably mature or widespread to be a real alternative to the solutions we are familiar with today. Again, it is likely that district heating will continue with the new plants for a number of years, and that a technological switch will not take place immediately. In concrete terms, this could mean that the economics of a potential electrolysis plant will be worse because it will be unable to sell the heat to the district heating company. Moreover, the carbon capture options for either storage or synergy with PtX plants have disappeared from the scenario with a forced phasing-out of existing district heating plants.



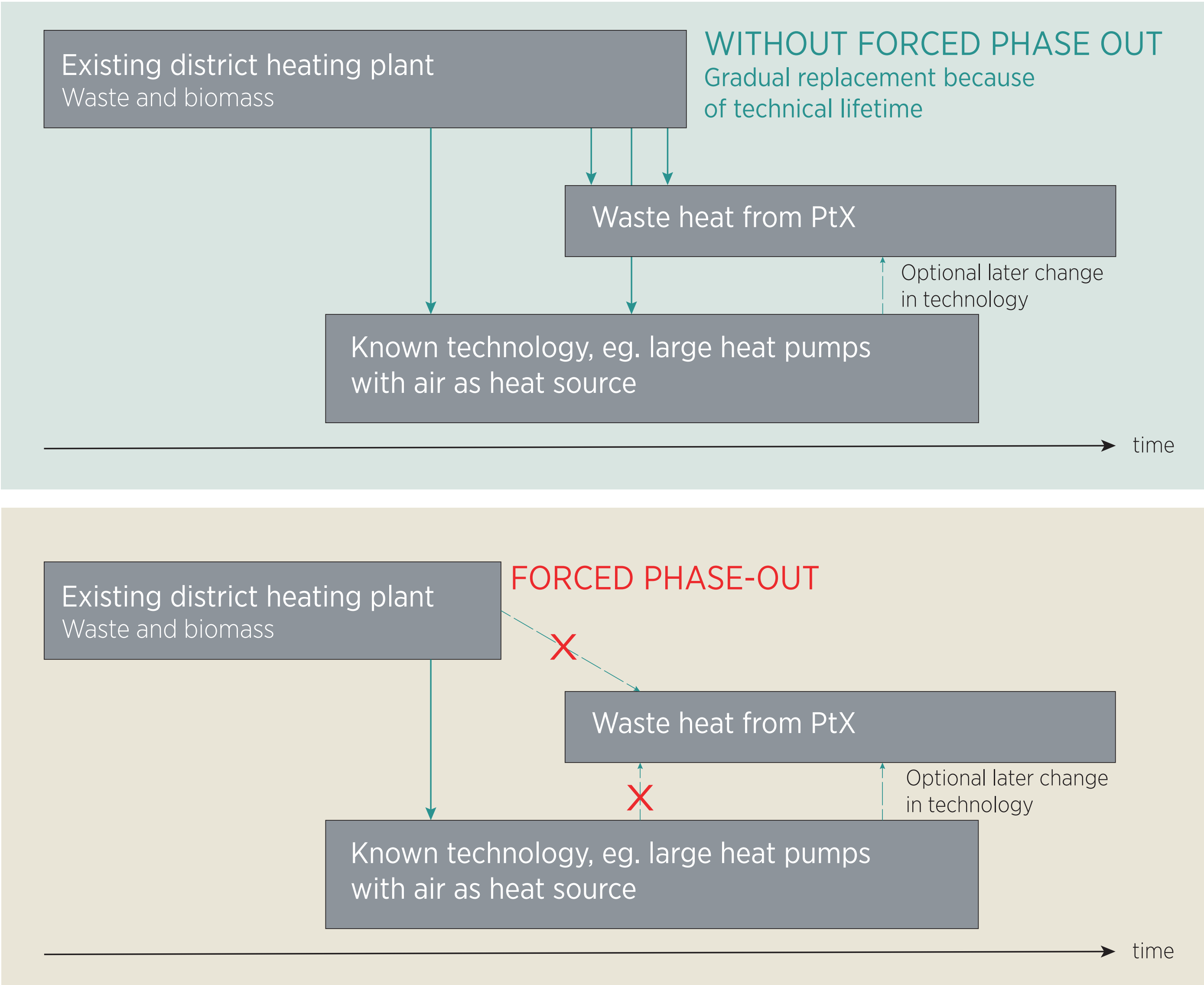


Figure 10: Without forced phasing-out (top), a direct transition to the use of PtX heat is possible, as existing biomass and waste plants can supply heat until a PtX plant is established and integrated with the district heating. With forced phasing-out (bottom), there is a risk of closing off the opportunities for integration between PtX and district heating.

Timing and strategy are important, and acting too quickly and with too narrow a focus in the short run could be expensive in the long run. In fact, the forced phasing-out of existing district heating plants based on waste and sustainable biomass could be triply expensive:

1. Investments in new plants to replace the plants being closed down.

2. Technological switch before PtX and other highly efficient heat sources are ready to take over completely. This means lower energy efficiency for many years.

3. Fewer effective CO_2 sources for carbon capture and storage (CCS) and PtX in Denmark.

3.2 Planning and location for PtX plants

As described above, for a PtX plant, an appropriate location and good sectoral integration depend on a series of physical conditions. This means that the intersections between different infrastructures and good transport conditions are particularly interesting. With the desire for a rapid green transition, it is of course worth looking first at the intersections that already exist and that could potentially be developed into PtX sites.

3.2.1 Collaboration and planning are a necessity

The district heating industry is used to seeing value generated through collaboration. This includes collaboration on power generation, the balancing of the electricity system, waste incineration, straw from agriculture, waste wood from forests, waste heat from industry, new heat sources for large heat pumps from treatment plants and water supply, the development of technologies with universities and businesses, energy planning with municipalities and, last but not least, collaboration with district heating customers. With PtX, collaboration is even more important, and the projects are even larger. District heating is not the most important element, however, and many decisions can be made without taking district heating into account.

Big decisions require us to change the way we think and to be willing not just to collaborate, but also to plan. Without planning, it is extremely difficult to achieve success with energy efficiency and synergies across sectors. This will place demands not only on the district heating companies, but on all those with a part to play in an efficient PtX breakthrough. This is because the complexity and risks are challenging, but also because timing is important. On the plus side are experience and a willingness to enter into public-private partnerships, strong local collaborations, and using heating and other infrastructures to create value in society on a broad scale.

3.2.2 Experiences from large data centres

Like PtX, data centres are new and major consumers of electricity that generate waste heat. Much has been said about recycling heat from data centres instead of chilling energy into the environment. This section compares data centres and PtX with a focus on integration with district heating. This could give rise to interesting considerations regarding the location of plants, planning and collaboration.

Is the waste heat used?

In the majority of data centres, the waste heat is not used. Figure 11 shows the situation for four hyperscale data centre sites.

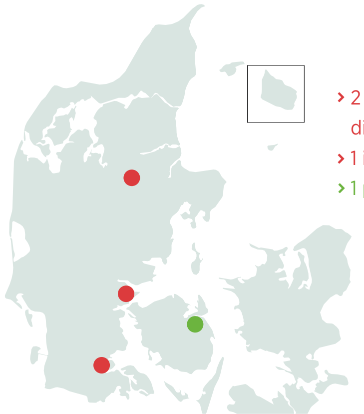


Figure 11. Waste heat from data centres will not necessarily be reused for district heating.

In two of the situations the use of waste heat from data centres is made more difficult by the distance from where there is a demand for district heating, and in a third situation the connection to the district heating grid is too expensive even though the distance is short (see Figure 12).

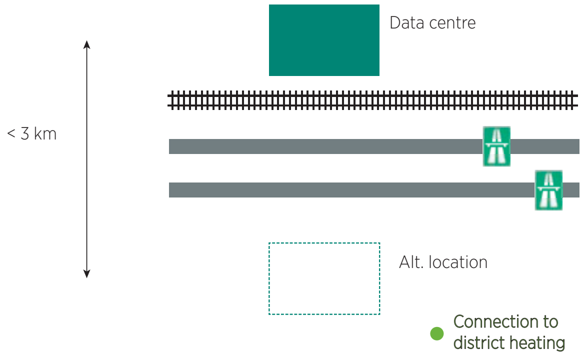


Figure 12. In the example shown, district heating was not included from the beginning. With the chosen site, a connection to the district heating grid would require costly crossings of a railway and two freeways.

What is the heat worth?

Heat from PtX is worth more than heat from air-cooled data centres, which is often built today. Waste heat from air-cooled data centres has temperatures of around 25-30 °C, while waste heat from liquid-cooled data centres has temperatures of around 60-70 °C, which is why the waste heat from liquid-cooled data centres often can be used directly in the district heating grid, while the waste heat from air-cooled data centres will need a heat pump. The waste heat from alkaline electrolysis is liquid-borne and has a temperature of 60-70 °C, and can therefore be compared to waste heat from liquid-cooled data centres.

The temperature makes a significant difference to the value of the heat, and the sale of waste heat can contribute to the economy of a PtX plant. Even if a district heating company does not pay money for the heat from a data centre, there are always costs, for example for heat exchangers, pipelines and large heat pumps that can raise the temperature of the water so that it is suitable for district heating.

Operating pattern

There is no doubt that PtX needs to use a great deal of power but, unlike data centres, PtX plants can take breaks in their power consumption. This makes it easier for the electricity system to handle PtX.

Can the design of the plant be optimised for integration with district heating?

Yes, this can be done for both PtX plants and data centres, but data centres have less of an incentive to do it. The value of the heat is not high, and data centres may be wary of making changes to designs and processes because they need to operate continuously. For PtX plants, there are both technical means and economic incentives to streamline integration with district heating systems.

Is there any interest in collaborating with district heating at an early stage?

There has been greater focus on recycling heat from data centres, and there is both internal and external pressure to improve the energy efficiency of data centres. As data centres see it work in practice, district heating is now becoming one of the parameters to be considered before selecting the site of a new data centre (see Figure 13). For PtX, there is also a growing interest in building district heating integrati-

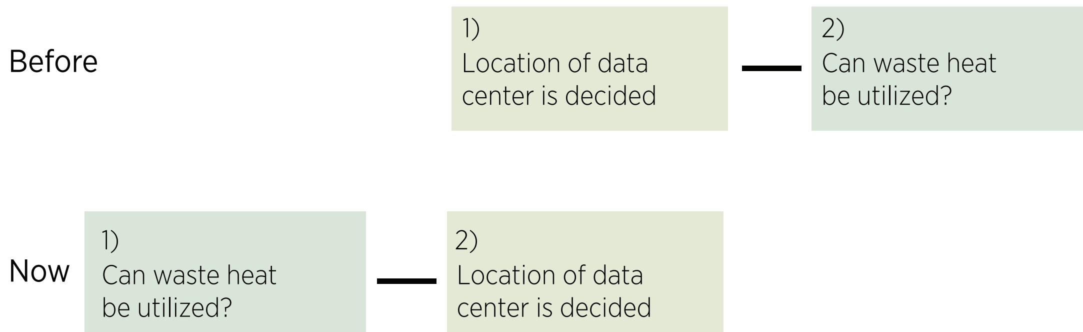


Figure 13. Development in the focus of data centres on district heating. Interest has grown with the increasingly high expectations for energy efficiency.

on into the plan from the beginning. However, district heating is just one of a large number of parameters, in that way data centres resembles PtX.

Who pays?

There are advantages for both the climate and society in recycling waste heat for district heating, but in investment terms it is seen as being a matter for the district heating company. For data centres, it has meant that the waste heat can only be used if the business case for the district heating company alone produces a positive outcome. The script for PtX has not been written yet, and it is unclear whether a broader societal perspective will be chosen for the recycling of PtX heat for district heating.

What have we learned?

There is certainly no doubt that the data centres have given us a chance to practise, and that there is more to be gained from collaboration in the case of PtX and district heating. There is also more at stake for society this time around. A key takeaway has been that district heating needs to be planned in from the start.

3.2.2 Power plant sites and refineries

There are many power plant sites in Denmark, and a lot of them are located close to the big cities, where the heat from CHP plants is an important part of the district heating supply. As the green transition continues the role of the plants are reduced, opening new opportunities at the power plant sites.

Power plant sites have good links to infrastructure and a series of advantages that make them highly suitable locations for some of the first large PtX plants in Denmark:

- **Strong connections to the power system:** The CHP plants have covered a large share of Denmark's power consumption and have strong direct connections to the power transmission grid. However, a sufficiently large supply of electricity is a general problem for large-scale PtX plants and, although the power plant sites have strong connections, their capacity is limited, though high.

- **Strong connections to heating infrastructure:** The CHP plants have made up a large share of Denmark's heat production, and the associated district heating grids can already take large quantities of heat from the power plant sites.

- **Transport:** Good port facilities with access for heavy goods transport.

- **Plenty of space:** PtX plants take up large areas, which most power plant sites have readily available.

- **Sources of CO_2:** Concentrated sources of CO_2 from waste, straw, and woodchip plants. They can be used either to store CO_2 or to produce green fuels based on green hydrogen and carbon.

- **Connections to the gas grid:** Some sites are close to the natural gas grid, which increasingly also transports biogas, and may also play a part as a future hydrogen infrastructure [9].

- **Many permits are already in place:** PtX plants require a series of safety and environmental permits, which limit the potential locations. With the requirements already met by the power plant sites, those could be an easier place to start.

- **Proximity to large energy storage sites:** Multiple large heat storage facilities linked to the power plant sites are on the way.

- **Synergies with other plants at the power plant sites:** Opportunities for sharing workshops, specialised personnel, supervision and integrated management.

Figure 14 shows an example of how closely integrated the elements at a power plant site are.

A key takeaway has been that district heating needs to be considered from the start.

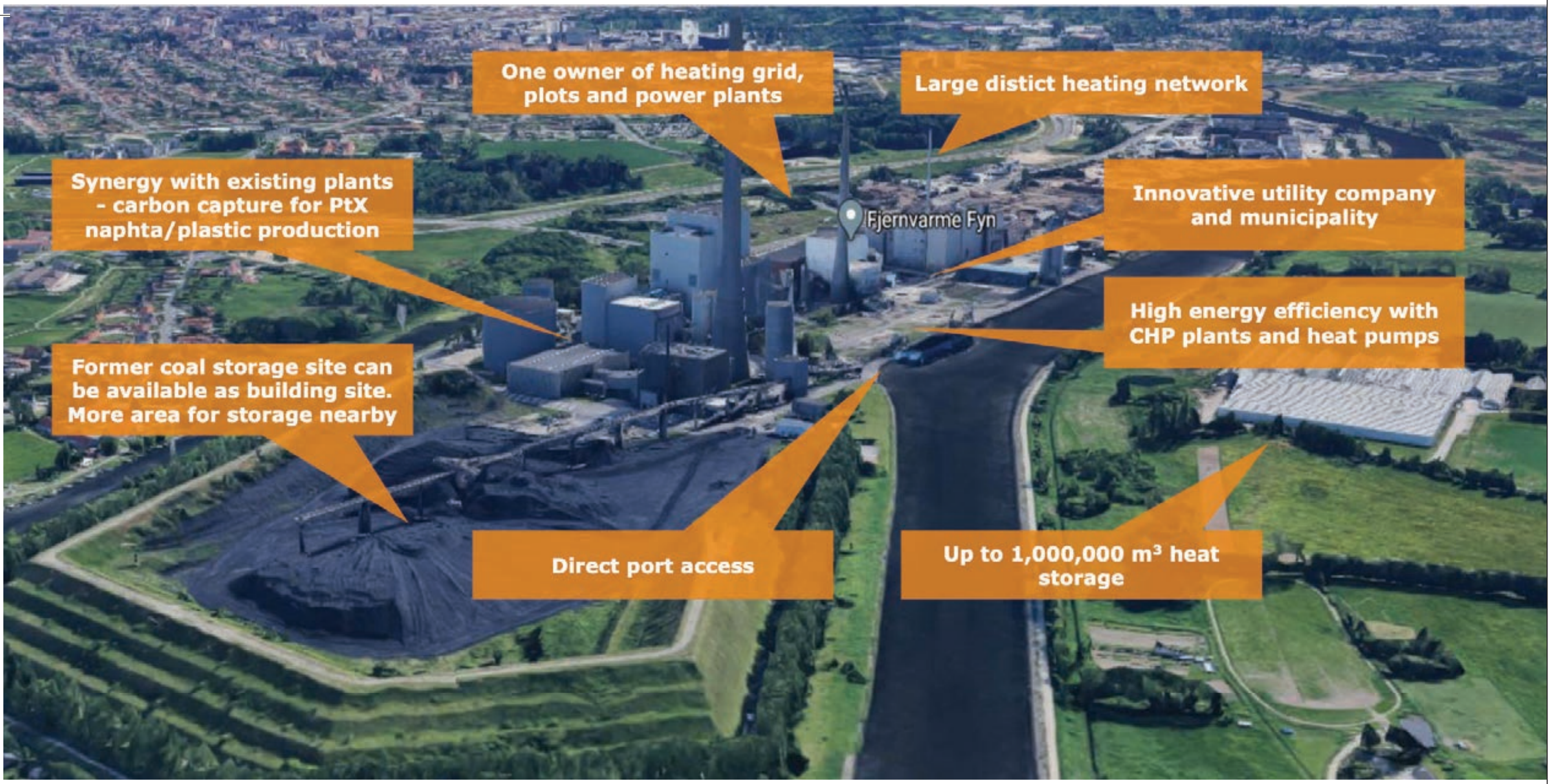


Figure 14. The power plant site in Odense is one of the possible locations for a PtX plant. The aerial photo illustrates how close to each other PtX and district heating can be located on the existing power plant sites. Source: Fjernvarme Fyn

Refineries have many of the same advantages as power plant sites, particularly in terms of safety and environmental permits. There are two oil refineries in Denmark. One is in Fredericia and is already connected to TVIS's heat transmission grid. This refinery is a crucial part of the HySynergy PtX project in the Triangle Region. The second is in Kalundborg, where PtX is currently under consideration.

3.3 PtX integration in the largest district heating systems in Denmark

The use of heat from large-scale PtX plants is particularly interesting in the larger Danish cities, and the following sections describe the situation in the six largest Danish district heating systems. There are differences between the cities and between their district heating systems. This variety is the strength that makes it possible to develop different types of PtX projects and different ways of integrating waste heat from PtX.

3.3.1 The Capital Region

Green transition and integration of waste heat from PtX

Both planning and green transition of energy systems are likely more difficult in the Capital Region than anywhere else in Denmark. Massive urban development, high demands on the power grid, an ambitious conversion of heat production and limited heat sources for large heat pumps are just some of the factors at play.

The potential for PtX in the Capital Region is currently being investigated. This is happening at individual companies, in district heating partnerships and in broader collaborations across sectors and municipalities. One example is the strategic planning partnership "The Future of District Heating in the Capital Region 2050" (FFH50)[10], in which VEKS, CTR, Vestforbrænding and HOFOR are designing a shared vision for the future of district heating in the Capital Region up to 2050. Here, PtX is part of drawing up scenarios, and the opportunities for PtX are being analysed.

Sources of CO_2

There are a number of plants where carbon capture could be of interest in the Capital Region. These plants share geography, opportunities and challenges and have therefore entered into the C4 – Carbon Capture Cluster Copenhagen partnership[11]. Its members are ARC, ARGO, BIOFOS, Copenhagen Malmö Port, CTR, HOFOR, Vestforbrænding, VEKS and Ørsted (see Figure 15). In total, they see the potential to capture approximately 3 million tonnes of CO_2 per year. The partnership's first task is to share and develop knowledge about carbon capture and to map the opportunities to establish shared transport and storage solutions.

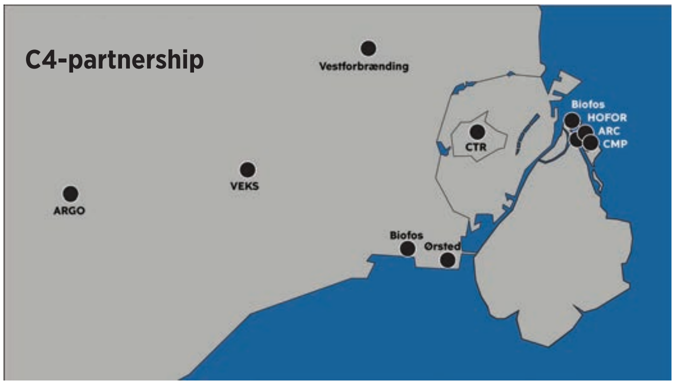


Figure 15. Carbon Capture Cluster Copenhagen (C4) is a partnership for carbon capture in the Capital Region. Source: Carbon Capture Cluster Copenhagen

H2RES

H2RES is a demonstration project with 2 MW electrolysis, to be located at Avedøre Holme, close to two 3.6 MW offshore wind turbines owned by Ørsted [12]. Ørsted heads the project and made the final investment decision in January 2021. The project is expected to produce and distribute approximately 1 tonne of green hydrogen per day for road transport use. The other partners in the project are Everfuel, NEL Hydrogen, DSV Panalpina, Green Hydrogen Systems, Energinet and Hydrogen Denmark. H2RES has received DKK 34.6 million in funding from EUDP, and the plant is expected to be operational by the end of 2021.

Green Fuels for Denmark

Green Fuels for Denmark is a partnership to produce green fuels for road, maritime and air transport in three phases[13]. The members of the partnership are Ørsted, Københavns Lufthavne, A.P. Møller – Mærsk, DSV Panalpina, DFDS, SAS, Nel, Everfuel and Haldor Topsøe, which ensures that the supply and demand for green fuels are linked more closely together.

The first stage is 10 MW electrolysis, where the hydrogen is used directly in buses and heavy goods vehicles. The plans for the second stage are to scale up to 250 MW in 2027, which, in combination with captured CO_2 from Greater Copenhagen, could produce green methanol and aviation fuel. The third stage aims to have 1.3 GW of electrolysis capacity in 2030 and total production of 250 000 tonnes of green fuels for buses, heavy goods vehicles, ships, and aircrafts.

3.3.2 Aarhus

Green transition and integration of waste heat from PtX

With its climate goals, the Municipality of Aarhus has set a course for climate neutrality in 2030. To achieve this goal, a close partnership has been set up between the municipalities and the different sectors[14,15], and Figure 16 illustrates how Aarhus sees its green transition (in Danish). District heating plays a central role with a combination of different types of heat production, including collective heat pumps, geothermal energy and heat from the two energy clusters in Lisbjerg and Studstrup. There is potential for PtX in these two energy clusters. There are currently no specific projects under way, but Ørsted is investigating the opportunities in Studstrup, and AffaldVarme Aarhus is also investigating other opportunities, for example in Lisbjerg.

AffaldVarme Aarhus is working on its investment plan up to 2030, where integration og PtX is seen as an option. Because the heating contract with the Studstrup plant does not expire until 2030, Aarhus has a slightly larger window in which to develop and integrate PtX projects than other big cities, where investment is needed earlier.

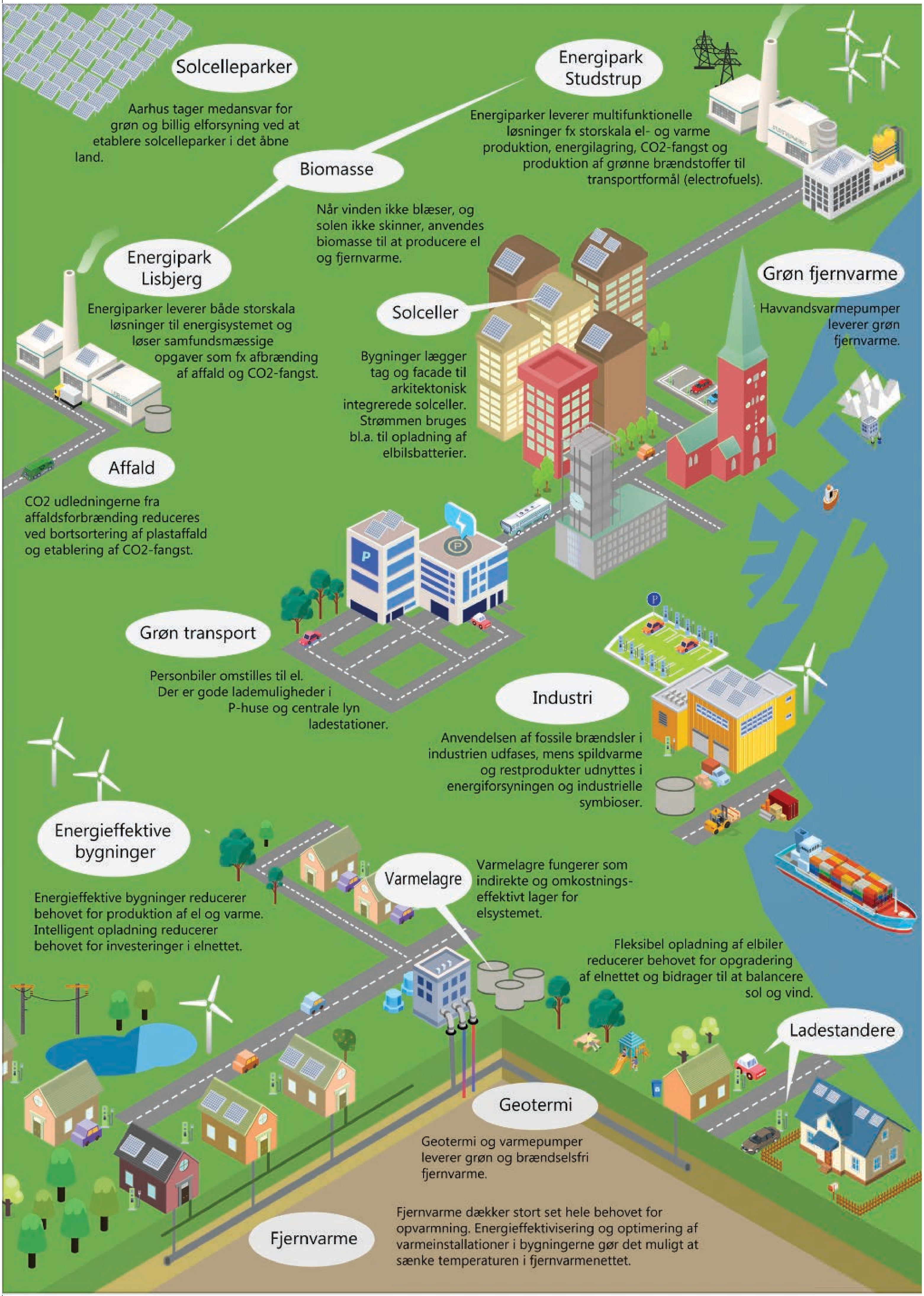
The energy clusters are at least as important as the energy islands – the energy clusters in large cities like Aarhus can help to electrify the city with renewable energy in every sector and deliver green heat to residents at a competitive price, while also playing a major part in the goal to reduce CO_2 through carbon capture. The energy clusters are nodes in the coordinated energy system that can ensure an economically responsible green transition.

Sources of CO_2

The energy clusters in Lisbjerg and Studstrup have large sources of CO_2 based on waste and biomass. They are thus central to the efforts for Aarhus to become climate-neutral, as there is potential here to capture CO_2 either for storage or for use in the production of green fuels. In Lisbjerg, there are around 500 000 tonnes of CO_2/year available, of which around 150 000 tonnes of CO_2/year are fossil CO_2, while Studstrup has around 1 million tonnes of CO_2/year available until 2030.

District heating is undergoing an ambitious green transition – away from coal, away from natural gas and, gradually, away from biomass.

Figure 16. The green transition in Aarhus is based on sectoral integration and collaboration across sectors. This includes, for example, the district heating system, heat storage, and the Lisbjerg and Studstrup energy clusters, where carbon capture and PtX are in play. Source: Municipality of Aarhus.



Solcelleparker
Aarhus tager medansvar for grøn og billig elforsyning ved at etablere solcelleparker i det åbne land.
Energipark Studstrup
Energiparker leverer multifunktionelle løsninger fx storskala el- og varme produktion, energilagring, CO2-fangst og produktion af grønne brændstoffer til transportformål (electrofuels).
Biomasse
Når vinden ikke blæser, og solen ikke skinner, anvendes biomasse til at producere el og fjernvarme.
Energipark Lisbjerg
Energiparker leverer både storskala løsninger til energisystemet og løser samfundsmæssige opgaver som fx afbrænding af affald og CO2-fangst.
Solceller
Bygninger lægger tag og facade til arkitektonisk integrerede solceller. Strømmen bruges bl.a. til opladning af elbilsbatterier.
Grøn fjernvarme
Havvandsvarmepumper leverer grøn fjernvarme.
Affald
CO2 udledningerne fra affaldsforbrænding reduceres ved bortsortering af plastaffald og etablering af CO2-fangst.
Grøn transport
Personbiler omstilles til el. Der er gode lademuligheder i P-huse og centrale lyn ladestationer.
Industri
Anvendelsen af fossile brændsler i industrien udfases, mens spildvarme og restprodukter udnyttes i energiforsyningen og industrielle symbioser.
Energieffektive bygninger
Energieffektive bygninger reducerer behovet for produktion af el og varme. Intelligent opladning reducerer behovet for investeringer i elnettet.
Varmelagre
Varmelagre fungerer som indirekte og omkostnings-effektivt lager for elsystemet.
Fleksibel opladning af elbiler reducerer behovet for opgradering af elnettet og bidrager til at balancere sol og vind.
Ladestandere
Geotermi
Geotermi og varmepumper leverer grøn og brændselsfri fjernvarme.
Fjernvarme
Fjernvarme dækker stort set hele behovet for opvarmning. Energieffektivisering og optimering af varmeinstallationer i bygningerne gør det muligt at sænke temperaturen i fjernvarmenettet.

3.3.3 Odense

Green transition and integration of waste heat from PtX

In Odense, the green transition is currently centered on phasing out coal power, and the transition is under way with the construction of large collective heat pumps and thermal storage facilities as well as the integration of waste heat. Fjernvarme Fyn receives waste heat from more than ten different businesses, including Kims chips, Albani and Facebook's data centre.

Fjernvarme Fyn is also open to integrating waste heat from PtX, and has analysed the options for PtX at the power plant site in Odense. Figure 17 illustrates the access to electricity, and therefore to hydrogen via electrolysis, and to CO_2, as well as the amount of heat that is expected to be available for integration into Fjernvarme Fyn's system.

Sources of CO_2

At the power plant site in Odense, there is potential for carbon capture and sources of CO_2 for synthetic fuels. The location offers several plants that have a large number of annual operating hours and are based on waste, straw and woodchips.

The straw-fired unit and the waste incineration plant are expected to be in operation up to around 2035, while a 150 MW biomass boiler will come into operation in 2023 with an expected lifetime of 25 years. A total of around 900 000 tonnes of CO_2 is expected to be made available, of which around 80 % will be biogenic CO_2.

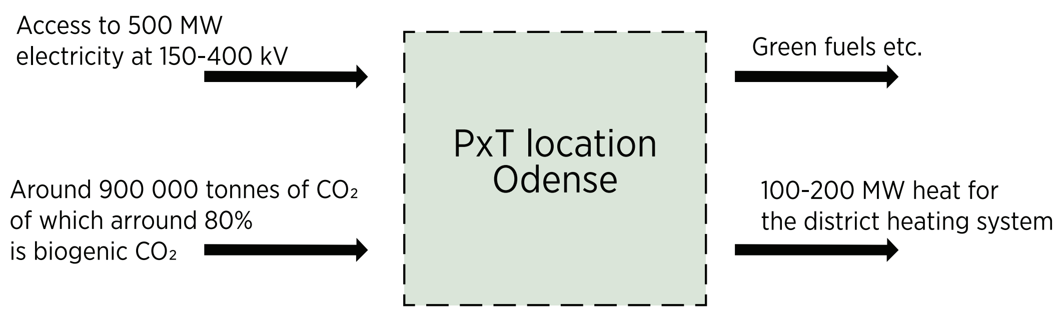


Figure 17. Fjernvarme Fyn's calculations for access to electricity and CO_2, as well as received waste heat at the power plant site in Odense. These are independent maximum values that illustrate the potential at the location. Following the conversion of unit 7 from coal to gas, there is also access to a larger gas pipeline of 700 MW of natural gas and biogas.

Fjernvarme Fyn receives waste heat from more than ten different businesses, including Kims chips, Albani and Facebook's data centre.

3.3.4 Aalborg

Green transition and integration of waste heat from PtX

The phasing-out of coal at the North Jutland power plant at the end of 2028 will help to establish the framework for the green transition of the heating supply in Aalborg. District heating in Aalborg already utilizes large quantities of waste heat from the Aalborg Portland cement factory, and the future plans also include a large thermal pit storage and large collective heat pumps with different heat sources such as district cooling, the Limfjord, ambient air, and waste heat. In total, 50 % of the heat is expected to come from waste heat. Aalborg has a target to achieve district heating without generating flue gas, meaning for example that biomass is not part of the plan to replace the heat from the North Jutland plant.

The Power2Met project aims to design and build a pilot plant for a complete power-to-methanol plant [16].

There is potential to develop PtX on the power plant site at the North Jutland plant, which offers plenty of space combined with strong connections to the power and district heating grid. Aalborg Forsyning also sees a synergy between the green transition of local businesses and PtX, and believes that it may be possible to increase the heat demand by 25 % in the summer period by bringing more businesses on board.

Aalborg Forsyning collaborates broadly on the green transition of the heating supply in Aalborg. This is done, for example, through Green Hub Denmark[17], a public-private partnership with strong local backing.

Sources of CO_2

The incineration of waste at Reno-Nord's plant is a potential source of green CO_2, which can be either stored or recycled into green fuels.

Aalborg Portland emits large quantities of fossil CO_2 and is working on making its production sustainable. Their green strategy has links to green district heating, carbon storage, and PtX.

3.3.5 Esbjerg

Green transition and integration of waste heat from PtX

Esbjerg is in the process of replacing coal-based heat from the Esbjerg power plant, which is being phased out in 2023. The total output of 350 MW is initially being replaced by a 50 MW seawater heat pump and a 60 MW woodchip boiler, which leaves room for heat contracts based on waste heat from PtX, for example.

DIN Forsyning supplies heat in Esbjerg and Varde and has a strategy for reducing both waste of resources and CO_2 emissions. There is room for waste heat in Esbjerg's district heating system, and up to 1/3 of the heat could come from PtX in the short term (2025).

In the period after 2030, the need for a total or partial phasing-out of energy from waste incineration needs to be investigated. DIN Forsyning and Energnist are seeking to extend their existing contract to 2033 by mutual agreement. As part of this, they are also investigating the opportunities for carbon capture, for example for local use or storage, if the economic framework is favourable.

Esbjerg sees itself as the best place in Denmark to develop PtX in the medium term based on its geographical location near the surplus power from the offshore wind farms in the North Sea and its ideal local infrastructure. Esbjerg already has a high volume of product shipping through the Port of Esbjerg, a large offshore service industry, and a well-developed road network to and from the port. Last but not least, the waste heat from large PtX plants can be obtained and integrated centrally into the district heating system at 70-80 °C.

Sources of CO_2

There is potential for carbon capture at the waste incineration plant, and there are many possibilities for what the carbon can be used for afterwards. There is potential for carbon capture at the large local biogas plants (Korskro, Ribe, Blåbjerg and others), for carbon storage in the Norwegian or UK fields in the North Sea, or for carbon use in the PtX production of green fuels. DIN Forsyning's new woodchip boiler is not expected to have enough operating hours to make it economically viable to construct a carbon capture plant there. The boiler could however be converted to biomass pyrolysis in the long term, as the infrastructure for biomass handling and the energy infrastructure is in place and the plant is considered suitable as part of a platform for producing fossil-free fuels and materials without the use of feedstock as a source of biogenic carbon.

Large-scale PtX project in Esbjerg

Copenhagen Infrastructure Partners (CIP) aim to build Europe's largest ammonia PtX plant, which will convert wind energy into carbon-free ammonia for fertilizer and marine fuel[18]. The plant covers 1 GW of electrolysis, and DIN Forsyning expects the waste heat from the PtX plant to be sufficient to cover approximately 1/3 of the heating demand of Esbjerg and Varde. The plant is expected to have the potential to reduce CO_2 emissions by up to 1.5 million tonnes and to create 100-150 permanent jobs within the green transition. Figure 18 shows the green products that will come from the PtX plant.

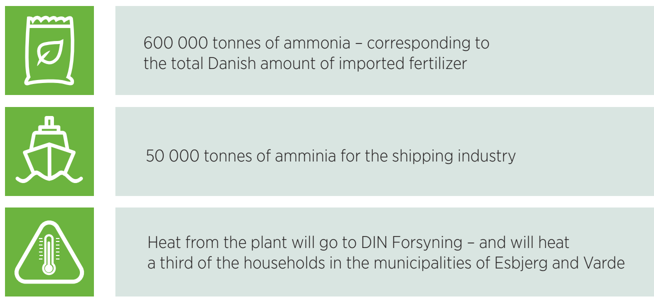


Figure 18. Green products from the anticipated PtX plant in Esbjerg. Source: CIP

The plant is expected to cost around EUR 1 billion and will be completed in 2026. The final investment decision is expected to be made in 2022/2023.

The location is not final yes, but access to land-based and maritime logistics chains is being taken into account from the start, and the plant's location in Esbjerg will be beneficial in terms of integration with the district heating system.

3.3.6 The Triangle Region

Green transition and integration of waste heat from PtX

Figure 19 shows the heat transmission grid in the Triangle Region. District heating in the Triangle Region took a giant green leap in 2018, when the Skærbæk power plant was converted from natural gas to woodchips. Furthermore, today, heat is supplied by waste heat from the Shell refinery and from the Energnist waste incineration. In the future, the heating is expected to be based to an even greater extent on waste heat, for example from local PtX plants.

In February 2021, 14 businesses and seven municipalities announced a PtX partnership with the aim of making the Triangle Region into a beacon for the production of green fuels and the integration of PtX and district heating [19]. The partners include Ørsted, Billund Airport, Shell, Green Hydrogen and TVIS.

Figure 19. Heat transmission in the Triangle Region combines heat production and local district heating areas via the TVIS district heating transmission grid (red lines). Source: TVIS.net

Sources of CO_2

There are multiple sources of green CO_2 in the Triangle Region: the Energnist waste incinerator in Kolding, the Skærbæk plant which produces power and heat from biomass, a number of biogas plants and the fermentation at the Carlsberg brewery. Green sources of CO_2 are part of the PtX partnership's strategy for the Triangle Region..

HySynergy

The core of the HySynergy project is a 20 MW alkaline electrolysis plant, which at 100 % capacity will be able to deliver around 8 tonnes of green hydrogen per day[20]. The green hydrogen is intended to replace fossil-based hydrogen at the Shell refinery in Fredericia. The plant is expected to come into operation in April 2022.

The temperature of the waste heat directly from the electrolysis will be approximately 70 °C, and the waste heat will be obtained and integrated into the district heating supply via the TVIS district heating grid. The quantity of waste heat from the electrolysis itself will grow as the units degrade. This is one of the parameters that will be followed closely by the project in the years after the plant comes into operation.

The participants in the project are Everfuel, the Shell refinery in Fredericia, Aktive Energi Anlæg (AEA), TREFOR El-net, Energinet Elsystemansvar, TVIS, and EWII. The project is receiving DKK 48 million in funding from EUDP out of a total project budget of DKK 104 million.

Everfuel is investigating the options for even larger plants at the Shell refinery. The initial output will be 300 MW in the first few years, and 1 GW in 2030.

3.4 Decentralised PtX – integration with local opportunities

PtX can also be combined with district heating outside the biggest cities, and this is where integration with biogas production, access to the gas grid and the potential for pyrolysis plants come into play. The waste heat can potentially be integrated into local district heating systems, and it is important to incorporate district heating from the start. Experience from collaborations between district heating and other types of waste heat shows that a strong local partnership can create lasting solutions.

As illustrated in the case study, the adaptation and value of the heat depends on the composition of the local district heating system. This is yet another reason to begin the dialogue between district heating companies and potential PtX plants at an early stage, in order to form a shared understanding of time frames and the opportunities to buy and sell heat.

Small-scale PtX plants are well suited to demonstrate technologies and integration of local opportunities, such as a biogas plant. Access to wind and solar power is an important parameter as well. The power can come either from a strong connection to the power grid or from local power generation.

Decentralised PtX plants can take many different forms; below are two examples.

3.4.1 GreenLab Skive

GreenLab[21] is a circular energy cluster for businesses that focuses on sustainability. The businesses in the cluster are connected together by what is called a SymbiosisNet, which can be used to share energy, resources and data. The businesses in GreenLab include Eurowind Energy, Quantafuel, NOMI 4s, Danish Marine Protein, and GreenLab Skive Biogas.

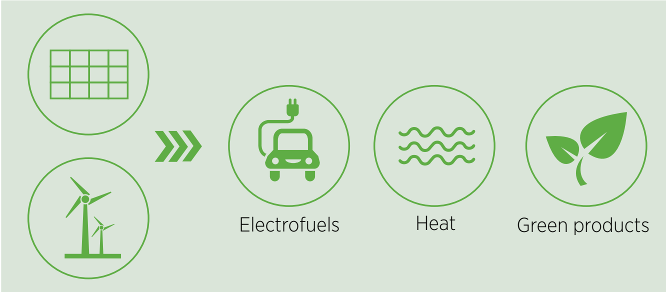


Figure 20. An illustration of the use of solar and wind energy to produce and share green fuels, heat and other green products at GreenLab Skive. Source: The introduction film to GreenLab, https://www.youtube.com/watch?v=RYrfOZxQ2Q0

As part of GreenLab, a 12 MW PtX plant is being constructed and is expected to come into operation in 2022. EUDP has provided DKK 80 million in funding for the GreenLab Skive PtX project out of a total project budget of DKK 146 million. The participants in the project are GreenLab Skive A/S, EuroWind Energy A/S, Everfuel Europe A/S, Eniig Holding A/S, E.ON DK A/S, GreenHydrogen ApS, Re::integrate ApS, DTU, Energinet Elsystemansvar, and DGC.

3.4.2 Ammonia production in PtX plants at Ramme near Lemvig

In December 2020, Skovgaard Invest, Haldor Topsøe, and Vestas unveiled plans for a PtX plant in Lemvig Municipality[22]. The plant is intended to be ready for operation in 2022 and will produce ammonia with power from wind turbines and solar cells. The plant is to be supplied with 10 MW, which will produce hydrogen for use in the production of around 5000 tonnes of green ammonia per year. Experience from the PtX plant in Lemvig Municipality will form the basis for more plants in West Jutland, while also demonstrating how to increase the value of wind energy through PtX.

3.5 Synergy with a green transition in business

The business sector accounts for a significant share of Danish greenhouse gas emissions. In 2018, manufacturing companies, trade and services consumed a total of 137 PJ of energy (excluding transport) and emitted a total of 3.2 million tonnes of CO_2, excluding process-related emissions such as the release of CO_2 from limestone in the production of cement. There is therefore a high potential for carbon reductions in manufacturing companies, trade, and services. A report[23] from 2020 evaluated the potential for reducing CO_2 emissions from industry by converting to district heating. It concluded that emissions can be reduced by 1.5 million tonnes of CO_2 per year if the conversion included space heating and process heat supplied at temperatures lower than 100°C. If the energy supplied at between 100 °C and 150 °C can be converted as well, the potential would increase by a further 1 million tonnes of CO_2. Overall, this corresponds to 80 % of the total CO_2 emissions from process energy for industry, trade, and services.

3.5.1 District heating is the crucial link

PtX processes creates waste heat and industries use process heat. It is therefore tempting to conclude that the two should be linked together. However, there are a number of challenges to linking them directly. PtX plants operate while there is demand and while electricity prices are favourable. The needs for process heat are governed by completely different parameters. This leads to poor timing between when the waste heat from PtX is available and the needs for process heat. Moreover, there will rarely be enough businesses situated close to the PtX plantto make a direct link mutually beneficial. In addition, a certain quantity is needed before it makes economicallysense to establish the waste heat demand. Inserting district heating as a link between the two can ensure that the needs of businesses and PtX are met and the challenges of a direct connection are avoided. This is illustrated in Figure 21.

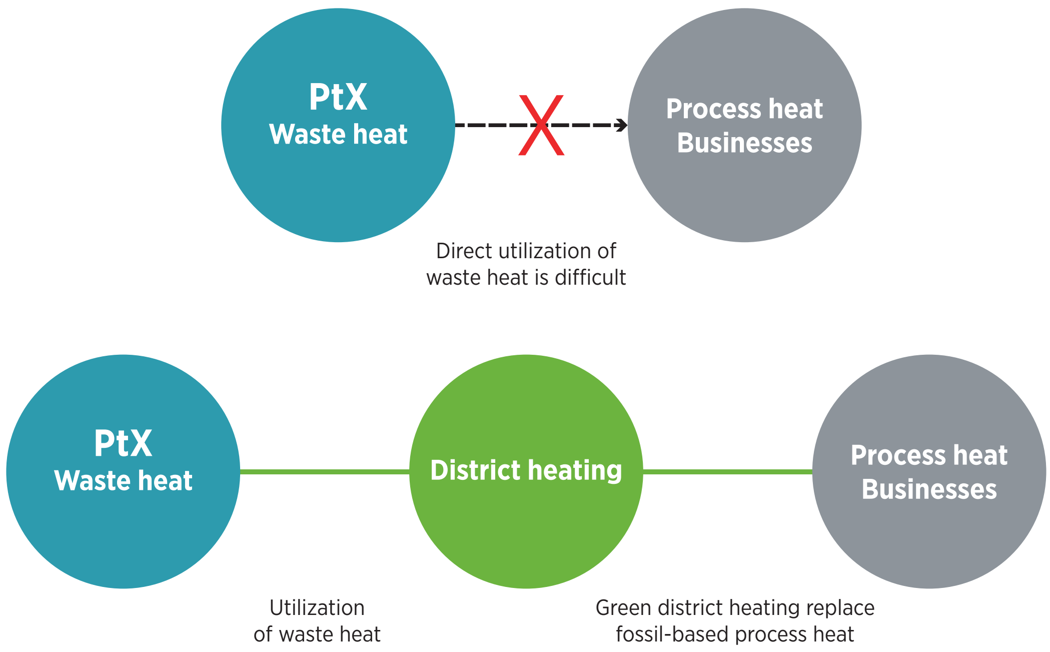


Figure 21. The business sector needs green alternatives to replace fossil process heat. The waste heat from PtX cannot be used directly in industrial processes (top), but it can be harnessed by means of integration with a district heating system (bottom).

It is a general characteristic of large, efficient green heat sources that harnessing them requires a district heating system. This is true not only of PtX, but also of geothermal energy, data centres, industrial waste heat and collective heat pumps based on wastewater, groundwater and seawater.

3.5.2 Creating value with sectoral integration

Partnerships makes most sense if all the parties gain something from it, and Figure 22 illustrates the advantages for the three parties of integrating both PtX and process heat with district heating. The businesses can use district heating as an alternative to constructing their own individual plants for sustainable process heat. Simultaneously district

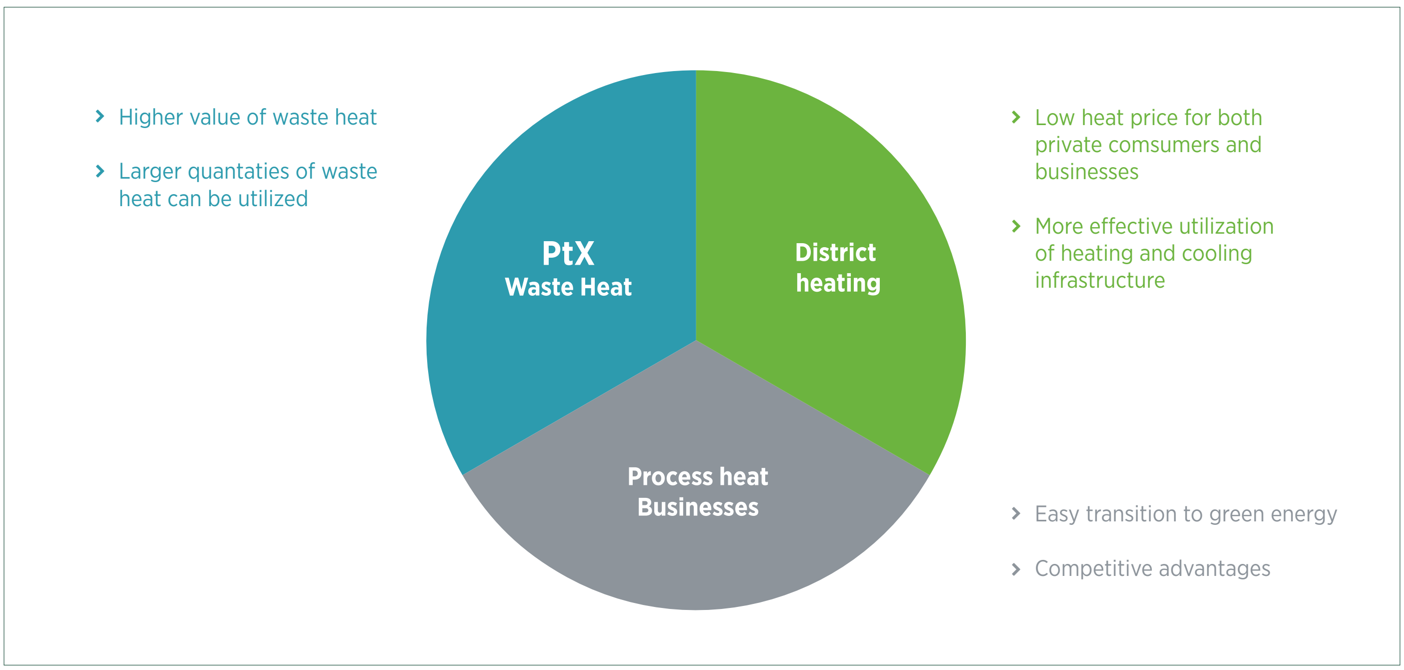


Figure 22. Sectoral integration creates value for PtX, district heating, and businesses with process heat. Any other, indirect value creation for society is not shown in the figure.

heating gains a larger volume of heat produced and heat drawn, which increases efficiency, and the PtX plants can sell more waste heat, probably at a higher price. Part of the explanation for this is that the need for process heat typically is evenly distributed over the year compared to the need for heating for buildings which varies with the seasons. For example, utilizing process heat increases the need for heat in the summer, which increases the value of heat and of integrating PtX and district heating.

3.6 Synergy with the green transition in agriculture and shipping

Ammonia (NH_3) is used today as fertiliser, and plays an important part as a carbon-neutral marine fuel. Ammonia production today is based on fossil sources and accounts for 1.8 % of the world's total CO_2 emissions. Switching to green ammonia production will therefore impact on a global scale.

Figure 23 (in Danish) shows the resources that need to go into, and the green products that will come out of, the expe-

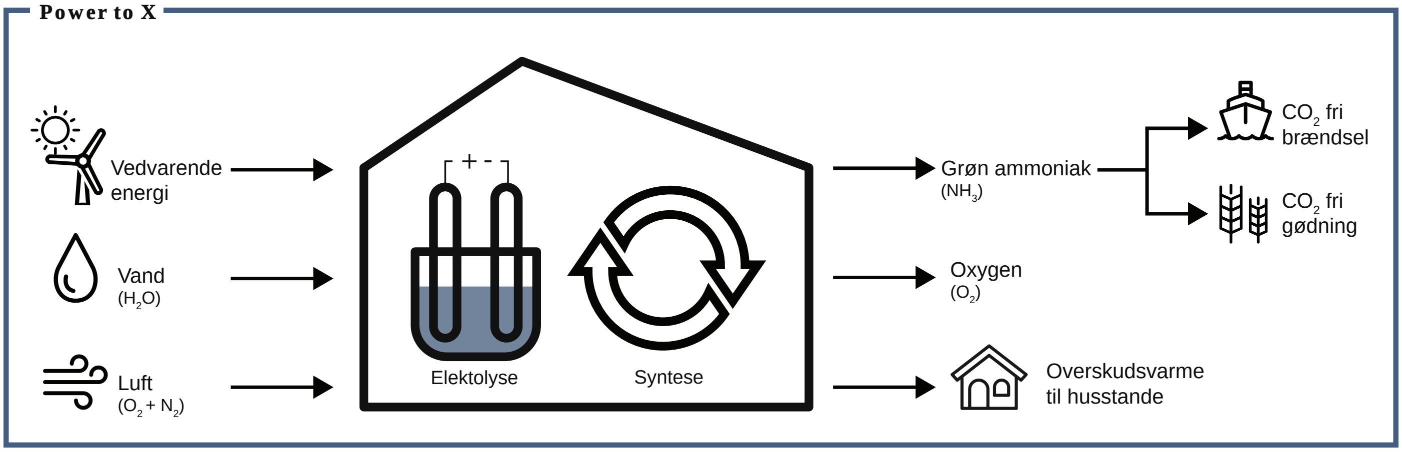


Figure 23. Illustration of a large-scale PtX plant for ammonia production in Esbjerg. The waste heat is expected to cover approximately 1/3 of the heat supply in Esbjerg and Varde. Source: Copenhagen Infrastructure Partners (CIP)

cted power-to-ammonia plant in Esbjerg. The figure also illustrates the underlying sectoral integration, in which power, water, agriculture, transport, oxygen, and district heating contribute to a green transition in many parts of society.

3.7 Denmark as a showcase for sectoral integration

The benefits to society of exploiting the synergies of sectoral integration are not just about an effective transition in Denmark. They also include future jobs and revenue from green exports. This is particularly true of the integration of PtX and district heating.

3.7.1 Denmark's strengths

When it comes to green energy exports, Denmark already has wind power and energy efficiency as two of its strengths. Its third strength is the district heating industry. By combining these three strengths when designing PtX technology, Denmark can play a part in defining what PtX and "sectoral integration" will look like in Europe and the rest of the world. Denmark is one of the places to go for inspiration for both PtX plants and the harnessing of waste heat.

Denmark is a world leader in district heating technology and advice, and its exports are rooted in strong businesses like Danfoss, Grundfos, Kamstrup, COWI, and LOGSTOR. The district heating sector accounts for 0.8 % of Denmark's total GDP, and in 2019 the district heating sector and suppliers made DKK 59 billion in sales and employed 22 300 full-time equivalents[24]. In the same year, district heating exports of goods and services reached a record high of DKK 7.6 billion.

3.7.2 The rest of the world is discovering district heating

There is still relatively little in-depth knowledge of district heating outside the Nordic countries, but countries like Germany, the Netherlands, the USA, the UK, and China are increasingly seeing district heating as part of their green transition. At the same time, more and more countries are drawing up PtX and hydrogen strategies. There is potential here to integrate PtX and the development of district heating at a strategic level in Europe, but there is still a challenge in identifying and prioritising the synergy. In a growing number of places, however, the large quantities of waste heat from PtX are helping to highlight the need for energy efficiency and therefore the opportunities of district heating systems.

The Netherlands can become a place where the combination of PtX and district heating takes off. The Netherlands is massively expanding its wind power and has ambitious plans for a green transition, driven in part by an urgent need to phase out natural gas production. In the Port of Rotterdam area, there are several plans for electrolysis plants with a capacity of 100-250 MW for the production of green hydrogen[25]. Calculations show that the port will be able to provide 6.4 TWh of heat in 2030, and that roughly half of that heat will come from hydrogen production. This figure is expected to rise to 12.5 TWh by 2050. That is the equivalent of heating for ½ million and 1 million households in 2030 and 2050 respectively, and there are plans to build regional infrastructure to connect the port to urban areas and greenhouses that need heating.

3.7.3 Demonstration in Denmark – the next step is export

A well-known recipe for a successful export is to invent and demonstrate it locally, show it off and sell it to the whole world. PtX can become a new strength for Denmark, but many countries are investing in creating jobs and exports, trying to win the PtX race. Consequently, there is a particular need to make use of the strengths that a country already has. For Denmark, these include the businesses in the district heating industry.

Denmark is leading within district heating technology and consultancy. Exports are rooted in strong businesses like Danfoss, Grundfos, Kamstrup, COWI, and LOGSTOR.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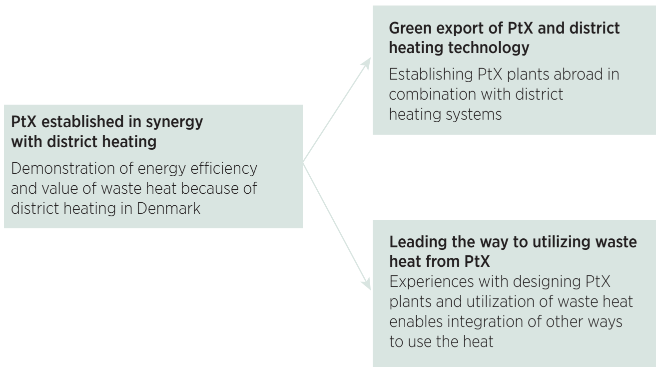


Figure 24. Demonstrating the integration of PtX and district heating in Denmark opens the potential for various types of green export, including green export that is not dependent on the simultaneous development of district heating in other countries.

By demonstrating not only different types of PtX in Denmark, but also successful harnessing of the waste heat, Denmark can secure an exceptional potential for green export. In a future that revolves around energy efficiency and sectoral integration, a partnership between the existing district heating industry and the emerging PtX industry will be a crucial factor.

4 CONCLUSIONS, CHALLENGES, AND RECOMMENDATIONS

Neither PtX, more offshore wind turbines nor district heating should be viewed as separate goals. By combining them thus achieving energy efficiency and sectoral integration, several goals may be realised simultaneously:

- An effective transition in Danish society, including within transport, agriculture and industry.
- A large, carbon-neutral heat source that is not based on incineration, for use in homes and businesses.
- More green exports and jobs

This report focuses on combining PtX and district heating. A series of synergies have been described, and economic case studies have been conducted examining the value of using PtX waste heat in district heating.

The report concludes:

- District heating can contribute to the success of PtX. The production costs of green hydrogen can be reduced if electrolysis and district heating are linked together. The financial improvements for hydrogen producers can help to accelerate the development of large PtX plants in Denmark.

- Heat from PtX is well suited for integration into district heating as part of a carbon-neutral district heating supply.

- The use of PtX heat for district heating promotes integration across sectors such as power, heating, transport, waste, industry, and agriculture. Integration with district heating means increased energy efficiency and sectoral integration.

- It can lead to increased green exports, if the Danish PtX strategy is designed in conjunction with Danish strengths such as wind power and district heating.

The report concludes with a summary of four challenges and associated recommendations.

4.1 Challenge #1: The value of integration with district heating needs to be made clear

There is a broad consensus that the heat from PtX can be used in district heating, but there has been no overview or concrete definition of the advantages of integrating PtX and district heating. Without a concrete definition and insight into how value is created, the positive effects of sectoral integration with district heating will continue to be overlooked. The risk is that the resulting PtX strategy will be unfit for purpose if the overall view of the links and value creation is inadequate.

The need for rapid climate action means there is a time pressure on the development of PtX. If Denmark wishes to invest in PtX as a new, major potential export, there is also time pressure from competition with other countries. If Denmark has ambitions when it comes to PtX, it is important for the right course to be set from the very beginning.

While the EU would like to see energy efficiency and sectoral integration, it is also struggling to have it defined in concrete terms and demonstrated in practice. The same applies to PtX and the conversion of private heating. This is a strong starting point for Danish PtX, wind power and district heating solutions to perform well in other countries.

District heating will improve the economy, increase energy efficiency, and accelerate the development of PtX in Denmark. These advantages form part of the foundation of a successful Danish PtX strategy.

Recommendations:

- A well designed Danish PtX strategy focusing on sectoral integration, energy efficiency and speed. District heating is an important part of a Danish PtX strategy.

- The value created by integrating PtX and district heating should be part of the technical foundation of a Danish PtX strategy and the planning of specific projects.

- Build district heating into the PtX export strategy.

4.1.1 How district heating creates value for the development of PtX

The following is a list of the ways in which district heating supports the development of PtX in Denmark:

- **Necessary heating infrastructure**

  - Potential for greater energy efficiency. All PtX processes involve energy loss in the form of heat. For alkaline electrolysis there is a potential for district heating to harness waste heat both straight from the hydrogen-producing cells and from the auxiliary systems. Approximately 10-25 % of the power fed into the plant can potentially be used for district heating instead of being wasted.

  - Heating infrastructure includes district heating pipes, heat storage and smart control, which connects district heating consumers with carbon-neutral heat sources. The district heating infrastructure forms the foundation that allow PtX heat to be reused for household heating and for green process heating in industry. Large PtX plants have the potential to form part of the supply of not just one city, but a large area of multiple cities if they are connected to district heating.

- **Better economy in PtX plants**

  - Improved competitiveness for PtX plants through the sale of heat to be reused in district heating.

    - The case study of a 20 MW electrolysis plant estimates that the direct revenue from district heating forms roughly 5 % of the total revenue when making full use of the waste heat (at high and low temperatures).

    - The hydrogen producers can save on cooling costs if the district heating can solve the issue of directing the heat away from the PtX plant.

  - More operating hours for the same PtX plant

    - Case studies show a greater number of profitable operating hours for the same electrolysis plant if it is integrated with district heating.

    - In calculations for a 20 MW electrolysis plant, the number of annual operating hours is increased by around 800 hours, leading to increased hydrogen production. In the example from the case study, this results in increased revenue from hydrogen, making up 16 % of the total revenue including district heating. Such figures are sensitive to the underlying assumptions, and the key point here is therefore that district heating contributes to increased hydrogen production and improved economy.

  - A greener hydrogen product. Some customers may be willing to pay more for hydrogen from a PtX plant, where a large portion of the energy loss is avoided and is instead reused in district heating.

- **A competitive advantage for Denmark in PtX**

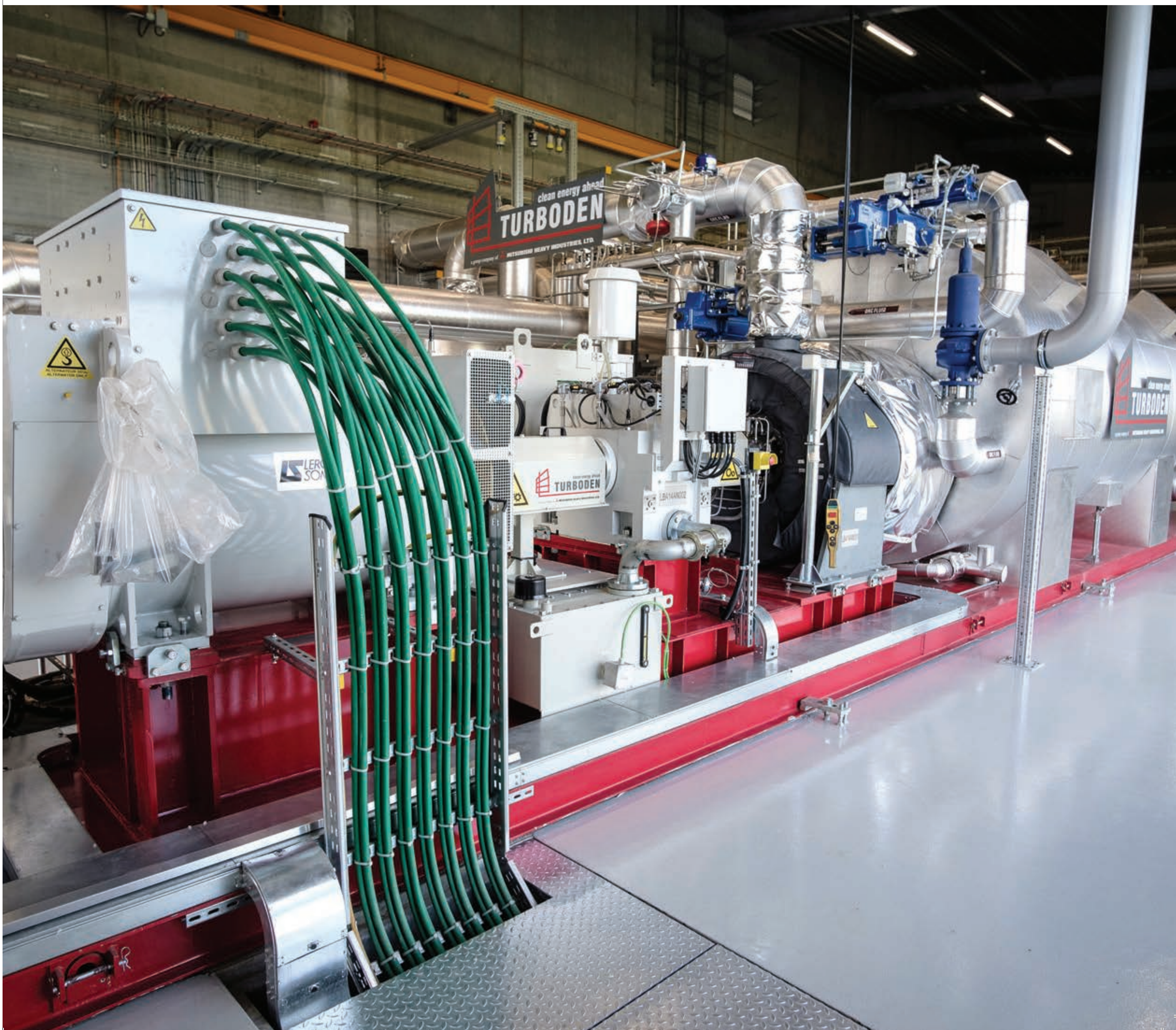
  - Technical assessments indicate that the price of hydrogen can be reduced by 5-10 % through integration with district heating, and that this will be enough to provide a competitive advantage in order to construct more hydrogen plants in Denmark.

- When it comes to green energy exports, Denmark already has wind power and energy efficiency as two of its strengths. Its third strength is the district heating industry. By combining these three strengths when designing PtX technology, Denmark can play a part in defining what PtX and "sectoral integration" will look like in Europe and the rest of the world.

- Denmark as a showcase. Demonstration of energy-efficient PtX solutions with harnessing of waste heat forms the basis for increased green exports in wind power, electrolysis, other PtX technology, and district heating.

- **CO_2 sources for the PtX production** of carbon-based green fuels. Easy accessible carbon sources are a competitive advantage, which district heating waste and biomass plants can help to deliver. This is relevant because concentrated sources of CO_2 can be a limiting factor for PtX.

    - In the Capital Region, the C4 (Carbon Capture Cluster Copenhagen) partnership expects a potential for carbon capture amounting to around 3 million tonnes of CO_2 each year. For comparison, calculations show that 8 million tonnes of green CO_2 will be needed each year if Denmark's projected aviation fuel needs (50 PJ) are to be green by 2030[26].



- **The location of a PtX plant** can be challenging because there are many needs that must be met in terms of infrastructure and logistics. Power plant sites often have access to district heating systems and can be attractive as PtX locations.
    - Each of the six largest district heating systems in Denmark has an attractive location for PtX with a potential connection for waste heat in the region.
- **Sectoral integration and energy efficiency.**
    - Heat is part of many processes across sectors, and district heating is the crucial link between places with too much heat and places with too little heat.
        - District heating delivers sectoral integration thanks to its many links to other sectors, heat storage on an hourly/daily/seasonal scale, diversity including non-electricity-based heat production, sources of CO_2, process heat for businesses, large quantities of waste heat and experience with smart control across sectors.
    - An energy system dominated by wind power, solar cells, and PtX will experience challenges in terms of costs and security of supply, particularly if it fails to create sufficient robustness through sectoral integration and energy efficiency.

4.2 CHALLENGE #2: INVESTMENTS IN ENERGY INFRASTRUCTURES

Denmark already has a well-developed energy infrastructure for power, heating and natural gas, and the existing structures form the starting point for the changes the energy infrastructures are set to undergo. Nobody can say exactly how the energy systems will need to develop. There are many open questions about reinforcing the power transmission grid, district heating infrastructure and future gas/hydrogen systems and about the speed and direction of technological development. For example, the temperature of PtX heat and district heating supply is important for energy efficiency, for synergy with district cooling, and for where best to feed PtX heat into the local district heating grid. Another example is that hydrogen transmission costs less than power transmission, according to Energinet[27]. This will make it more important to select a location based on a good power supply and a suitable heat base, and to build it into the hydrogen logistics plan.

There are many unknowns in the development of PtX technologies and the energy infrastructures for power, heating, gas, and hydrogen. No matter which path the development takes in the end, heating infrastructure is the foundation of sectoral integration and of the ability to recycle and create value out of the heat from PtX.

Recommendations:

- The PtX strategy needs to support the effective planning and placement of PtX plants, and integration with district heating should always be considered.
- Prioritise funds for infrastructure, including heat transmission, heat storage and improved integration of PtX into existing district heating systems.
- Learn from the experience of reusing waste heat from large data centres.
- Focus on reinforcing the power grid where necessary in order to prevent slow expansion, particularly expansion of the transmission grid, from acting as a barrier to the establishment of PtX sites with access to district heating systems or to the electrification of district heating.

4.3 CHALLENGE #3: IT NEEDS TO BE TESTED IN PRACTICE

The PtX technologies are fundamentally in place. The primary challenges are the large-scale implementation of projects, integration with district heating, framework conditions and the business case for green alternatives to fossil fuels.

It is still unclear what technologies and types of green fuels will prevail. It is important to solve the primary challenges while supporting the development of a variety of technical solutions.

Some of the primary challenges will be solved with financial incentives, subsidies, taxes, enough buyers of green fuels and the availability of affordable green power. Other challenges will need to be solved with investments in research, development, and demonstration (RD&D). However, coming up with the best solutions is not enough on its own. It is developing specific designs and testing them in practice that allows development to take off. This is directly linked to the prioritisation of funds for demonstration, development, and research with a focus on sectoral integration and energy efficiency.

Recommendations:

- Prioritise funds for the demonstration of plants with focus on integration of green power, district heating and sale of green products on both a medium and a large scale.
- More funds for research, development, and demonstration with a focus on the integration of PtX and district heating.

4.3.1 Specific recommendations for research, development, and demonstration

Below is a list of identified needs in terms of demonstration, development, and research that will support PtX development and the creation of value from the integration of PtX and district heating.

- Demonstration projects that focus on integration between PtX plants and district heating infrastructures with pipeline systems, heat storage, and sources of CO_2.
- Room for variation allowing multiple development paths to be tested.
- Development of technical and market integration and optimisation of power-hydrogen-heat-X. For example, optimisation and flexibility of the electrolysis operating temperature to achieve optimisations in both hydrogen production efficiency and energy efficiency in utilization of waste heat.
- Combination of infrastructure and storage in district heating and across different energy systems.
- Data, digitalisation and intelligent control of the integration between PtX and district heating, and how this integration can be optimised to support power and heating systems as well as the production of green products in PtX plants.
- Degradation of electrolysis cell stacks, which has an effect on both the efficiency of hydrogen production and

the quantity of waste heat. Development in the time and differences between different types of electrolysis.

- District heating and cooling as a replacement for traditional cooling units. This requires district heating to focus on selling a stable cooling solution rather than utilizing waste heat. It could allow PtX plants to save money on traditional cooling. Demonstration of PtX plants could further pave the way for greater integration of district heating with data centres.

- Integration between PtX, district cooling, and district heating. Development and demonstration of integrated technical and economical solutions based on synergy and increased energy efficiency between PtX, district cooling, and district heating.

- Development of different types of heat flow between PtX and district heating. Utilization of waste heat from hydrogen cells and auxiliary systems in district heating has been the main focus. District heating can flow in the opposite direction and supply standby heat as an alternative to electricity-based standby heat.

- Reduction in energy loss and harnessing of waste heat from PtX plants. Not just for district heating, but also new business opportunities.

- Synergy and new opportunities based on oxygen produced together with hydrogen in electrolysis.

- Knowledge sharing and general strengthening of collaboration across projects. Establishing strong clusters.

4.4 Challenge #4: Timing and framework conditions

Timing is one of the most important challenges if the potential for integrating PtX and district heating is to be harnessed successfully. The district heating companies have already made good progress in switching to 100 % carbon-neutral district heating by 2030. The conversion of heat production will happen on an ongoing basis as the existing units reach the end of their service life. Waste heat from PtX is one of a number of options here, but it will require collaboration and political will to bring together PtX plants, the expansion of the power grid and the green transition in district heating.

Framework conditions, regulations, support schemes and bureaucracy will have a significant effect on the speed and direction of PtX development in Denmark. It will also effect the ability of district heating to form part of the sectoral integration of PtX.

Integration between PtX and district heating generates value for society, and it is therefore important to ensure that the waste heat can be incorporated into district heating. There are a number of measures that are themselves good for an efficient green transition, and prioritising PtX in Denmark will reinforce the need for those measures.

Recommendations:

- Planning is needed in order to ensure the necessary timing between the development of PtX plants, the power grid, district heating and buyers of green products. This includes cooperation regarding the locations of PtX plants.

- Framework conditions and regulation of district heating to support the green transition and synergy with PtX.

- Prioritise CO_2 sources from waste and biomass as part of the Danish PtX strategy.

- Precise CO_2 framework conditions that support the climate targets, e.g. for the handling of negative CO_2 emissions and certificates.

- Secure and develop the heat demand for district heating so that heat from PtX can be used to the greatest extent possible.

- ew approach to electricity tariffs so that they do not undermine the integration of PtX and district heating and the electrification of district heating.

- Guarantee options for innovative projects that could have a high-risk profile.

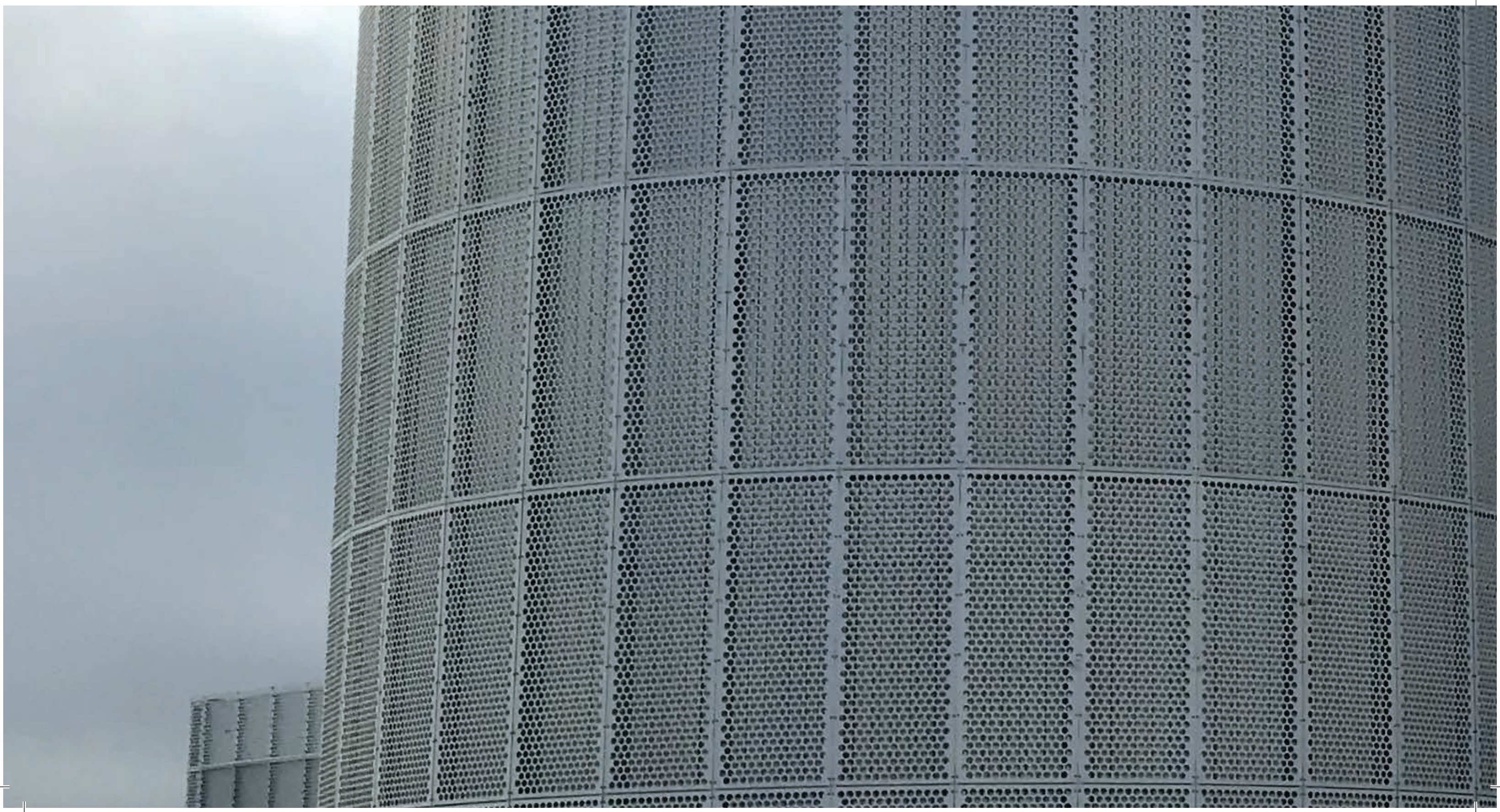
4.4.1 The primary purpose of district heating is the supply of heating – risks need to be managed

While district heating companies see the potential in reusing waste heat from PtX, they are not ignorant of the risks that come with it.

The district heating companies need to supply stable, affordable green heating. That goal can be achieved through gradual development, one preparatory step at a time. The decision to be taken ahead of each step needs to be carefully considered, because the consequences of a decision can continue long into the future and have an impact on infrastructure and large capital investments.

It is therefore important to consider not only where we want to go with the green transition, but also whether we have the right frameworks here and now, and whether we have set out the road signs to the future in the right way. Here are some of the considerations that district heating companies are making regarding decisions about PtX and the green transition in general:

- How certain can we be that the planned PtX plant will actually amount to anything? For how long will to the PtX plant produce and therefore supply waste heat? How much heat will there be available? What will the PtX plant's operating pattern, which determines when there will be waste heat available, be like?



- How does the timing fit? Can we fit together all the pieces of the puzzle when it comes to constructing a PtX plant, potential expansions of the power grid, integration with local biogas plants and the service life of existing district heating units? Can the conversion of a nearby natural gas area be integrated into plans for collaboration around waste heat from PtX?

- One alternative could be a plant owned and managed by the district heating plants themselves, but is that the right solution in the somewhat longer term? What other alternatives are there for heat production now and in the future?

- How can value be created for both the PtX plant and district heating? What limitations are there to signing waste heat contracts? There are risks to both parties, which need to be addressed in the contracts. For example, the PtX owners might need assurance that the district heating company will be able to purchase the waste heat for many years to come.

- How can we put together a robust district heating system and avoid dependence on a single heat supplier and limit vulnerability to changes in rules, taxes, electricity prices, PtX technology, electricity tariffs, financing, and bottlenecks in the power grid?

- What do the future frameworks for the district heating systems look like?

- How do we deal with the fact that, for PtX plants, district heating is only a small part of the equation? This could mean that the district heating company has little influence on decisions that could have major consequences.

- Should we make the decision now or wait?

The district heating companies are accustomed to making long-term decisions without knowing what the future will look like, but the complexity and time pressure surrounding PtX is at the heavier end of the scale. It is therefore important to have the right framework conditions for district heating and the integration of PtX and district heating.

APPENDIX A: ELECTROLYSIS TECHNOLOGIES

The term electrolysis covers the splitting of a substance using electricity. For example, water is split into hydrogen and oxygen in the reaction:

$$H_2O \Rightarrow H_2 + \frac{1}{2} O_2$$

An electrolysis cell consists of two electrodes (an anode and a cathode) and an electrically conductive medium (liquid, oxide, membrane). The process splits the molecules into electrically charged particles (ions), and the electrical energy is converted into chemically bound energy.

A collection of electrolysis cells is called a cell stack, or simply a stack.

There are three commonly used electrolysis technologies, which can be divided up by operating temperature range:

- Low temperature (alkaline and polymer membrane electrolysis)
- High temperature (ceramic/oxide)

Alkaline and polymer electrolysis are both commercialised technologies, while ceramic electrolysis is currently in development. However, ceramic electrolysis is expected to have the lowest costs and the highest efficiency in the future.

The individual technologies are discussed below, followed by a brief summary in which the requirements and performance of the individual technologies are compared in a table.

The figures used are taken from the section on electrolysis in the Danish Energy Agency's technology catalogue "Technology Data – Renewable fuels" [28], and from interviews with parties in Danish PtX projects.

GENERAL TERMINOLOGY

This appendix requires an understanding of a series of terms for evaluating efficiency and waste heat:

Higher heating value (HHV)

HHV is the total chemical energy content of a fuel, where combustion begins at 25°C and ends at 25°C. The HHV for hydrogen is 286 kJ/mol, or 141.88 MJ/kg.

Lower heating value (LHV)

Hydrogen combustion produces water vapour. The condensation energy of this water vapour is not always used, but may instead be lost to the environment. We may therefore choose to ignore the energy represented by the water vapour. The lower heating value is therefore only calculated on the basis of the useful heat – i.e. the heat that is not lost in the water vapour. The LHV for hydrogen is 119.96 MJ/kg, where combustion begins at 25°C and ends at 150°C.

Efficiency

Efficiency should be understood as the energy from combustion of the hydrogen produced in relation to the electrical energy used in the electrolysis process itself, i.e. without taking into account the electricity consumed by auxiliary systems such as compressors.

For the oxide technology (SOEC) in particular, the hydrogen produced needs to be compared both to the electricity for the electrolysis itself and to the energy used to generate water vapour for the electrolysis process.

During operation the cells will gradually degrade, which will cause efficiency to drop over the technical lifetime of the stack.

Waste heat from electrolysis and auxiliary systems

Waste heat can be seen as the proportion of energy that goes into the electrolysis process itself, excluding auxiliary systems, that cannot be released directly by burning the hydrogen produced. The amount of waste heat generated depends on the efficiency. The lower the efficiency, the more waste heat.

A proportion of the waste heat will be usable for district heating, and this proportion depends on the electrolysis technology. The temperature level given in "Technology Data – Renewable fuels" is 60 °C, while expectations of 70 °C have been indicated in interviews. Because of the degradation of the electrolysis cells, the contribution from waste heat will increase over time if hydrogen production is maintained at the same level. Below, it is assumed that a heat pump is not required in order to use 70 °C waste heat in the district heating system. However, not all district heating companies will be able to avoid this.

Additional heat will be generated by the auxiliary systems; this will remain constant over time. The temperature level is expected to be around 35 °C, which will require a heat pump if the heat is to be used in the district heating system.

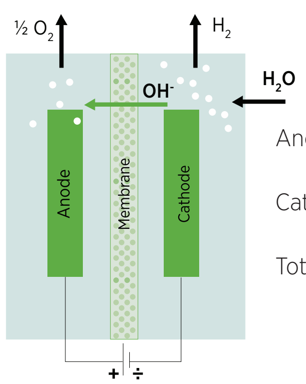
The following sections use the terms below to distinguish between the two contributions:

- Waste heat from the electrolysis process at high temperature (60-70 °C)
- Heat from auxiliary systems at low temperature (35 °C)

Alkaline electrolysis (AEL)

The alkaline principle is the most mature one, both commercially and technologically, and it is assessed on the Technology Readiness Level scale (TRL, 1-9) at 9, the highest possible level, for plants at MW scale. Plants at the GW level are lower in TRL.

The principle is shown, along with electrode reactions, in Figure A1. An aqueous solution of the base potassium or sodium hydroxide (KOH, NaOH) at 20-30 weight% is used to make the water conductive. The two electrode sides are separated by a membrane that the gases cannot pass through.



Anode: $2\ OH^- =< H_2O + ½\ O_2 + 2e^-$

Cathode: $2\ H_2O + 2e^- => H_2 + 2\ OH^-$

Total: $H_2O => H_2 + ½\ O_2$

Figure A1. Alkaline electrolysis – principle and reactions.

The operating pressure may vary depending on the type from atmospheric pressure to 35 bar, and research is also being done into achieving higher pressures. The advantage of working at high pressure is that the hydrogen produced can be stored directly in compressed form.

Production can be adjusted downwards within milliseconds to 10 % capacity, or adjusted upwards within seconds. After a cold start, on the other hand, the start-up time is around 30 minutes, implying that it is of interest to have a standby heat option from the district heating system so that the electrolysis plant can be kept warm and consequently started up more quickly.

The operating temperature may vary widely; in the literature it is specified at between 30 °C and 90 °C. However, "Technology Data – Renewable fuels" specifies it at 65-90 °C.

Plants with a capacity of ~20 MW_E are expected in the near future, with plans for plants of up to 1.3 GWE in the longer term in the project "Large-scale P2X in the City of Copenhagen" (see F under planned projects, Figure 4). However, the electrolysis technology for this has not yet been chosen.

Based on the lower heating value, AEL currently has an efficiency of up to 65 %, meaning that 65 % of the green power going into the electrolysis cells remains in the hydrogen. This does not take into account the power consumed by auxiliary systems, such as compressors, rectifiers, pumps etc.

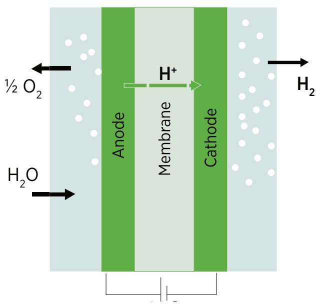
Of the energy consumed for the electrolysis itself, 10 % is converted into waste heat at high temperature, and this waste heat is considered suitable for use in district heating. The rest is considered to be lost in the form of heat into the environment, water vapour in the oxygen produced, and condensation energy in the water vapour produced during hydrogen combustion. The corresponding efficiency based on the HHV is ~77%.

The specified figures are summarised and supplemented in Table 2. Over time, the efficiency of the technology based on the lower heating value is expected to improve to 75 % by 2050.

There is little information available about how the degradation of the cells will progress over time, and therefore about how the high-temperature waste heat at 70 °C will develop. An increase in waste heat due to degradation may be expected over the course of the plant's service life. "Technology Data – Renewable fuels" gives an expected technical lifetime of 25 years for an AEL plant, with a service life for the stack itself of over 100,000 hours.

Polymer membrane (PEM)

This technology is called either "proton exchange membrane" or "polymer electrolyte membrane", but is commonly referred to as PEM. The membrane between the electrodes allows protons (H+) to pass from the anode to the cathode (see Figure A2).



Anode: $H_2O => 2H^+ + ½ O_2 + 2e^-$

Cathode: $2H^+ + 2e^- => H_2$

Total: $H_2O => H_2 + ½ O_2$

Figure A2. PEM electrolysis – principle and reactions.

PEM is a less mature and more costly technology than alkaline electrolysis, but allows for a more compact design and greater operational flexibility. The TRL is 8-9 for cells at the MW level.

The typical operating temperature is 50-80 °C, while operating pressures of up to 30 bar have been reported. A cold start is specified as requiring less than 20 minutes, and standby heat via the district heating system could again be worth looking at depending on the operating pattern. Upward and downward adjustment can be done in under a second.

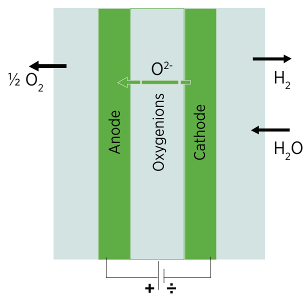
Based on the lower heating value, the technology catalogue currently specifies an efficiency of up to 64 % for PEM, corresponding to up to 76 % on the basis of the HHV. Again, 10 % is assessed as being usable for district heating.

In 2021, there is a plant of just under 4 MW_E in operation at Energiepark Mainz, while Air Liquide has just opened a 20 MW_E plant in Canada[29]. The technical lifetime is evaluated in "Technology Data – Renewable fuels" to about 20 years, while the service lifetime of the stack is specified at more than 25,000 hours of operation. With respect to the degradation of PEM cells, a loss of performance of 50 % has been reported after three years of idle time in the Helle I project for hydrogen injection into the gas gridt[30].

Ceramic – solid oxide electrolysis cell (SOEC)

The construction of and principle behind SOEC are markedly different from those for AEL and PEM. It does not involve converting liquid water, but water vapour, and the electrolyte consists of a solid oxide/ceramic that can conduct O_2 ions. The principle is illustrated in Figure A3. At present, there are prototypes below 1 MW in the demonstration phase (see "Technology Data – Renewable fuels", which specifies a TRL of ~6-7). There is currently a 750 kWE plant in Salzgitter.

It is also possible to convert CO_2 into CO using SOEC, which enables production of syngas, thus presenting a clear advantage further along the PtX value chain.



Anode: $O^{2-} => ½ O_2 + 2 e^-$

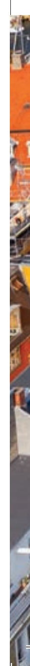
Cathode: $H_2O + 2e^- => H_2 + O^{2-}$

Total: $H_2O => H_2 + ½ O_2$

Figure A3. Electrolysis with SOEC technology – principle and reactions.

In addition to electricity used for electrolysis of water, SOEC also requires energy to evaporate the water before the process takes place. This can be done by supplying additional electricity or by feeding the water into the system as steam from other plants.

The operating temperature (over 600 °C) is significantly higher than for AEL and PEM. Depending on how the cells are operated (voltage level), for the process require heating or cooling, because the reaction is endothermic or exothermic depending on the temperature. However, the high operating temperature level implies that standby heat from district heating is not relevant.



The electrolysis cell itself can be operated almost without loss of energy, but the efficiency of the system will be reduced due to heat loss to the surroundings. The efficiency is expected to be approximately 75 % measured by the LHV, which corresponds to ~89 % efficiency at HHV. According to the assessment in "Technology Data – Renewable fuels", 7 percentage points of the 25 % energy loss fed into the electrolysis process will be high-temperature waste heat. This can be used for district heating, while the remaining 18 percentage points will be lost.

Technology	Technology readiness level (TRL)	Operation	Input	Output	Efficiency**	Regulation ability	Expected technical lifetime	Relevant for district heating
AEL	9	65-90°C 1-35 bar	Electricity Water	Hydrogen Oxygen Heat	65 % H_2 (LHV) 10 % DH 25 % heat loss	Cold start: ~ 30min Warm: up: ~sec down: ~ mS (10-100 %)	25 years	Yes
PEM	8-9	50-80°C 1-50 bar	Electricity Water	Hydrogen Oxygen Heat	64 % H_2 (LHV) 10 % DH 26% heat loss	Cold start: <20min Warm: up/down: < 1 sec (5-100 %)	20 years	Yes
SOEC	7	>600°C 1-10 bar	Electricity Water Heat (evaporation)	Hydrogen Oxygen (Heat)*	75 % H_2 (LHV) 7 % DH 18 % heat loss	Cold start: 12 timer Varm: up/down: ~sec (0-100 %)	10 years	To a lesser extent

Table A1. Overview and comparison of the three electrolysis technologies.

** Depends on operation temperature*

*** The efficiency of the electrolysis process without auxiliary systems. Efficiency is expected to increase in the coming years due to material improvements.*

Provided that the cells are kept at the operating temperature, it is possible to adjust between 0 % and 100 % within a few seconds. If the cells are cold they are in an inactive state, the startup time can be several hours depending on the design and type of the cell and stack. However, with a good operation strategy and insulation, the system can be kept close to operating temperature even when it is inactive.

The technical service life is evaluated in "Technology Data – Renewable fuels" to about 10 years, while the actual service life of the cell is assessed at three years. Over time, degradation means that the cell will need to operate at higher voltages, increasing the generation of waste heat.

Table A1 contains an overview and comparison of the three electrolysis technologies.

APPENDIX B: ASSUMPTIONS MADE IN CASE STUDIES

The following assumptions have been made in the individual business cases:

- Electrolysis plant is based on alkaline technology with a power consumption that includes auxiliary systems such as compressors, pumps, electronics etc. An efficiency of 70 % has been assumed for the actual hydrogen production based on an expectation that the technology will develop. However, a certain level of degradation, based on information from interviews, has been assumed. The figures applied will therefore not be completely consistent with "Technology Data – Renewable fuels".

- **Variable expenses:**
  - The variable OPEX is assumed to include electricity and water costs. Variable maintenance is not included.
  - Electricity prices in the form of hourly estimates from the Danish Energy Agency[31]. They are based on the hourly estimates for electricity prices in DK1 in 2022. The prices are DKK 344 per MWh on average, with a minimum of DKK 80 and a maximum of DKK 500 per MWh.
  - Water prices are based on prices from VandCenter Syd. It is assumed that concentrate from water treatment can be discharged directly into the sewer system. Furthermore, no waste water tax is paid for water used in the electrolysis. The costs of DKK 150 per hour for water and DKK 102 per hour for discharge to the sewerage[32] are significantly lower than the costs for electricity consumption.

- **Revenue**
  - Hydrogen prices. The International Energy Agency (IEA)[33] has evaluated the price of green hydrogen at between EUR 2.5 and EUR 5.5 per kg, corresponding to DKK 18.6 - 41 per kg. Green hydrogen is not yet produced on a large scale. There is accordingly a high degree of variation in production cost estimates. Correspondingly, blue hydrogen[34] is valued at EUR 2 per kg or around DKK 15 per kg. Conventional grey hydrogen is valued even lower at EUR 1.5 per kg regionally for Europe, which is equivalent to DKK 11 per kg.
  - Deliveries of waste heat at 35 °C and 70 °C. The electrolysis cells will degrade over the course of their service life, causing the quantity of waste heat at 70 °C to increase if hydrogen production is maintained at the same level. This also implies an increased power consumption. The individual case study uses a simple fixed average.
  - The sale of oxygen is not included, but the potential for sales may exist. For larger plants, there may even be production surpluses with respect to the market for oxygen.

APPENDIX C: VALUE OF WASTE HEAT

Value of the heat – method

District heating companies are obliged to supply cost-effective heating to ensure low heating bills for the consumers. In order to evaluate the value of waste heat from PtX for a district heating company, calculations of the annual operation costs for a typical district heating plant have been made in energyPRO. The calculations are divided into summer and winter months in order to evaluate seasonal changes in the value of waste heat from PtX.

The point of origin is a district heating company which receives waste heat from PtX in addition to the existing heat production. The difference between the calculated annual operating costs with and without waste heat from PtX can be seen as the maximum willingness to pay for the waste heat. The district heating company will never pay more for the waste heat than for the heat it can produce on existing units. The maximum willingness to pay is not the price the district heating company is actually willing to pay for the waste heat. Without a consideration of the risks, the maximum payment willingness would be the price at which the district heating company would be indifferent with regard to choosing whether to produce the heat itself or to purchase the waste heat. In an actual situation, the PtX plant and the district heating company need to agree on a contract which among other settles the price of the waste heat. Such a contract will be a negotiation. The contract will be influenced by the temperatures and quantities of heat compared to heat production for the district heating company and a series of risk assessments.

Value of the heat – results

The value of the waste heat from PtX depends on several factors. Three different types of district heating systems have been examined, shown in Table C1.

The three systems are based on different heat production units:

1. Natural gas only
2. Biomass and biogas for peak loads
3. A combination of biomass and an electrical heat pump, and biogas for peak loads

Table C1 shows how heat production is distributed across the different units in the reference, i.e. before the waste heat from PtX is used. The three district heating systems are otherwise identical and have an annual heat production of 140,000 MWh. This is equivalent to heating for 6,500 standard houses with a heat loss of 20 % in the grid and annual heat consumption per standard house of 18.1 MWh.

When the district heating system gains access to waste heat from PtX, the composition of the heat production changes. This is illustrated for Scenario 3 in Figure C1, in which the heat is produced by a biomass boiler and an heat pump. At the top is the reference situation, where heat annually is produced approximately 50/50 by the electric heat pump and the woodchip boiler. The base load is supplied by the heat pump, which is the primary heat producer in the summer months. In addition, the storage capacity is used to cover the peak load and avoid hours of high electricity prices. When the PtX plant is in operation, it can supply 2 MW of waste heat at 70 °C and 3 MW of waste heat at 35 °C. The waste heat displaces heat production from the heat pump and biomass boiler. The PtX plant supplies heat as a base load, as it is expected to have many annual operating hours. This can be seen in the middle and bottom graphs in Figure C1, which illustrate the use of 70 °C and 35 °C waste heat, respectively. Operating profiles have been calculated for the PtX plant based on the hourly-based electricity prices from 2022 described previously.

	Heat production in the reference	(Bio) Natural gas boiler	Woodchip boiler	Heat pump (ambient air)
1	Natural gas	100%		
2	Biomass	2.0%	98.0%	
3	Heat pump and biomass	1.2%	47.3%	51.4%

Table C1: Three scenarios for district heating systems with different heat productions for the reference situation.

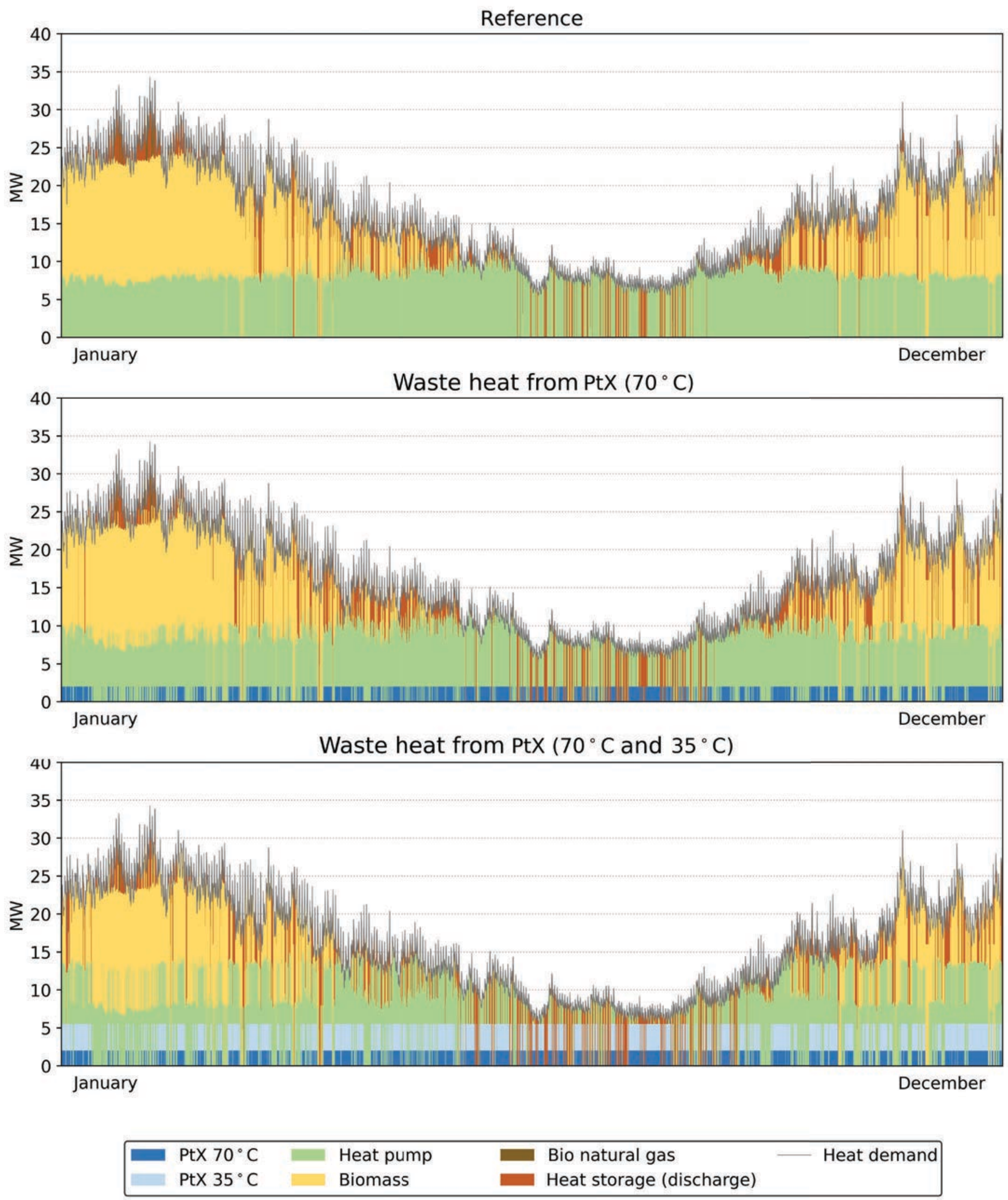


Figure C1: The composition of heat production over the course of the year for Scenario 3, in which the heat is primarily produced by a biomass boiler and an electric heat pump using ambient air. At the top is the annual operation pattern of the district heating system over the course of a year without waste heat from PtX. In the middle, the waste heat at 70 °C is used, which displaces production from the biomass boiler and the electrical heat pump. At the bottom, waste heat at both 70 °C and 35 °C is used, making up just under 20 % of annual heat production.

The value of the waste heat depends on the situation in which the heat is supplied. Figure C2 show the maximum willingness to pay for the three scenarios divided into summer and winter. There is a difference between the value of the heat in the summer and winter months and the value of the heat depends on the alternative heat production.

The maximum willingness to pay in Scenario 1 is over DKK 500 per MWh because the alternative heat is produced using natural gas. As mentioned earlier, the maximum willingness to pay is not equal to the price that the PtX plant can acquire for the heat. The district heating system in Scenario 1 is facing a green transition and should balance the willingness to pay for waste heat from PtX with an investment in alternative green heat production. This could be large ambient air heat pumps. In such an assessment, the willingness to pay will drop significantly and be more similar to the other two scenarios. The results for Scenario 1 are therefore not included in the subsequent analyses, because the calculated maximum willingness to pay is significantly higher than the district heating company's alternatives. It is very likely that PtX heat can be a part of the transition for the district heating company in Scenario 1, but the payment to the PtX plant will be significantly less than DKK 500 per MWh.

For Scenarios 2 and 3, the value of waste heat from PtX will be different in the summer and winter. This is because the waste heat displaces costly peak load production in the winter, and the COP factor of the heat pump is lower in the winter. The more costly the displaced heat production is, the more the district heating company is willing to pay for the waste heat, and vice versa. Based on the results for Scenarios 2 and 3, the subsequent analyses of the PtX economy assume a price of DKK 200 per MWh in the winter and DKK 150 per MWh in the summer for 70 °C waste heat from PtX. This is an estimate based on the calculated maximum willingness to pay shown for Scenarios 2 and 3 in Figure C2.

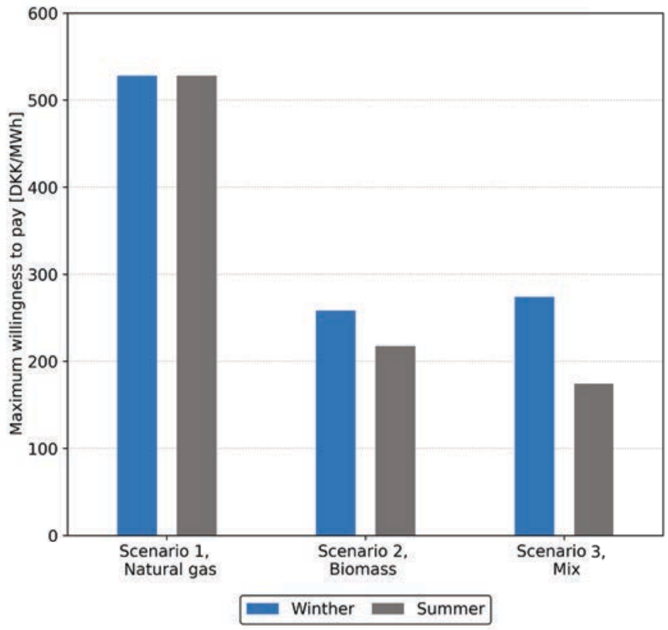


Figure C2: The maximum willingness to pay for 70 °C waste heat from PtX for the three district heating systems. Scenarios 2 and 3 have different values for willingness to pay in the summer and winter because the displaced heat production in the winter is more costly than in the summer. Scenario 1 has a high, calculated maximum willingness to pay, which does not correspond to the price at which the PtX plant can sell the heat. It indicates that the district heating system is facing a transition in which the price of heat could be reduced by investing in alternative heat production. One of the options for this investment is of course waste heat from PtX.

The temperatures of the waste heat depends on the flow from the PtX plant. Even small differences in the temperature of the waste heat can affect the district heating system. Flow is therefore an important parameter for optimising the temperature of the waste heat from the PtX plant. The primary PtX heat is 70 °C, and it is assumed that it can be integrated directly into the district heating grid without having to invest in a heat pump to raise the temperature. However, this is largely dependent on the supply temperature, which will vary between district heating companies. It will therefore not be possible for all district heating companies to use the PtX heat directly. It can generally be said that the higher the temperature of the waste heat, the less it costs to use it in district heating.

The waste heat at 35 °C has a value, which is lower than that of the 70 °C waste heat. A temperature of 35 °C is too low to be fed directly into the district heating system, and it is necessary to invest in a heat pump to raise the temperature. Because of the additional investment costs, the willingness to pay will be reduced significantly compared to the use of waste heat at 70 °C.

Figure C3 shows the maximum willingness to pay for the use of 35 °C waste heat for Scenarios 2 and 3. The difference between summer and winter is insignificant for this type of waste heat, so an overall annual willingness to pay is assumed. Based on the results from Figure C3, the subsequent analyses of the PtX economy assume a price of DKK 35 per MWh for Scenario 2 (biomass) and DKK 15 per MWh for Scenario 3 (mix of heat pump and biomass) for 35 °C waste heat from PtX. This is once again an assessment based on the maximum willingness to pay.

Table C2 shows what is displaced by the waste heat from PtX in the three district heating scenarios. In Scenario 3, the waste heat primarily displaces biomass, while the electric heat pump is only displaced to a smaller extent. The 70 °C waste heat makes up 7.0 % of the annual heat supply in total, while the 35 °C waste heat makes up just under 12.5 %. If both types of waste heat are used, the district heating system can receive a supply of just under 20 % per year of its annual heat needs from PtX heat.

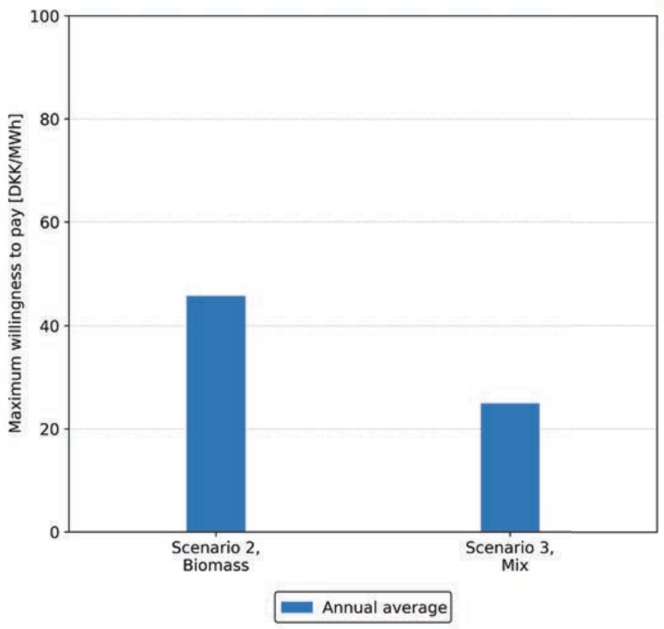


Figure C3: Maximum willingness to pay for 35 °C waste heat on an annual basis. The willingness to pay includes investment in an electric heat pump to raise the temperature of the PtX heat to the supply temperature of the district heating system. .

	Heat production in the reference	(Bio) Natural gas boiler	Woodchip boiler	Heat pump (ambient air)		
1	Natural gas	100%				
2	Biomass	2.0%	98%			
3	Heat pump and biomass	1.2%	47.3%	51.4%		
	Heat production at 70°C	(Bio) Natural gas boiler	Woodchip boiler	Heat pump (ambient air)	PtX 70	PtX 35
1	Natural gas	93.0%			7.0%	
2	Biomass	1.3%	91.7%		7.0%	
3	Heat pump and biomass	0.8%	42.7%	49.7%	7.0%	
	Heat production at 70°C + 35°C	(Bio) Natural gas boiler	Woodchip boiler	Heat pump (ambient air)	PtX 70	PtX 35
1	Natural gas	80.5%			7.0%	12.4%
2	Biomass	0.6%	79.9%		7.0%	12.4%
3	Heat pump and biomass	0.4%	34.8%	45.3%	7.0%	12.4%

Table C2: Heat production for the three scenarios in the reference situation, for utilization of PtX at 70 °C and for utilization of PtX at both 70 °C and 35 °C.

Sensitivity: Temperature of the waste heat

To illustrate the significance of the temperature of the waste heat from PtX, a sensitivity analysis has been carried out. The waste heat from PtX is changed to 2 MW at 60 °C instead of 2 MW at 70 °C but still 3 MW at 35 °C. Figure C4 shows that the value of the heat is reduced significantly if the waste heat is 60 °C instead of 70 °C for Scenario 3. The same effect can be seen to a lesser extent in Scenario 2.

When the waste heat is supplied at 60 °C instead of 70 °C, it has an effect on the rest of the district heating system. Even at 60 °C, it is still possible to integrate the PtX heat without investing in an additional heat pump to raise the temperature. However, this requires that the other heat production units provide additional output. For example, the reduced temperature from PtX will require, that the existing electric heat pump increases its temperature resulting in a lowered efficiency (COP value). This increases the operating costs for the system as a whole and therefore reduces the willingness to pay for waste heat from PtX. Here in particular, the supply temperature in the district heating system is an important parameter.

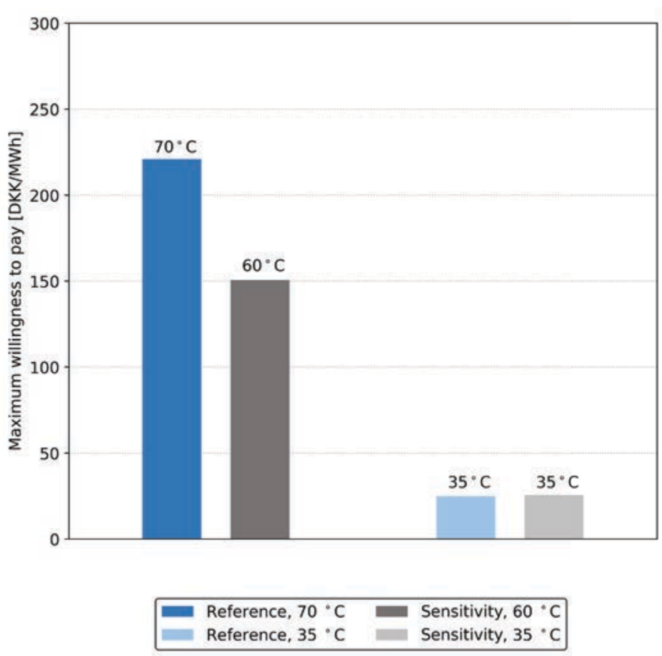


Figure C4: Maximum willingness to pay for 70 °C waste heat and for 60 °C waste heat on an annual basis for Scenario 3, and the maximum willingness to pay for 35 °C waste heat. The willingness to pay is lower for 60 °C waste heat because the other units need to provide additional heat output hereby increasing the overall costs.

Sensitivity: Degradation of the stacks in the PtX plant

As the cell stacks degrades, the heat generated from the PtX plant increases, entailing an increase in the quantity of waste heat at 70 °C. In this sensitivity calculation, the capacity of waste heat is increased to 3 MW of heat at 70 °C instead of the 2 MW of heat in the reference.

Figure C5 shows a slightly lower maximum willingness to pay for 70 °C waste heat. This is primarily due to an increased electricity consumption after degradation in order to maintain the production of hydrogen. This results in fewer operating hours with a contribution margin to the electrolysis plant. For the district heating system this means fewer hours in which more expensive heat production can be replaced.

The effect on the excess heat at 35 °C is the same, but the willingness to pay is reduced further. This is again due to the reduction in operating hours, which makes it more difficult to recoup the investment in the heat pump.

Figure C5 shows results for Scenario 3. The effect in Scenario 2 is similar.

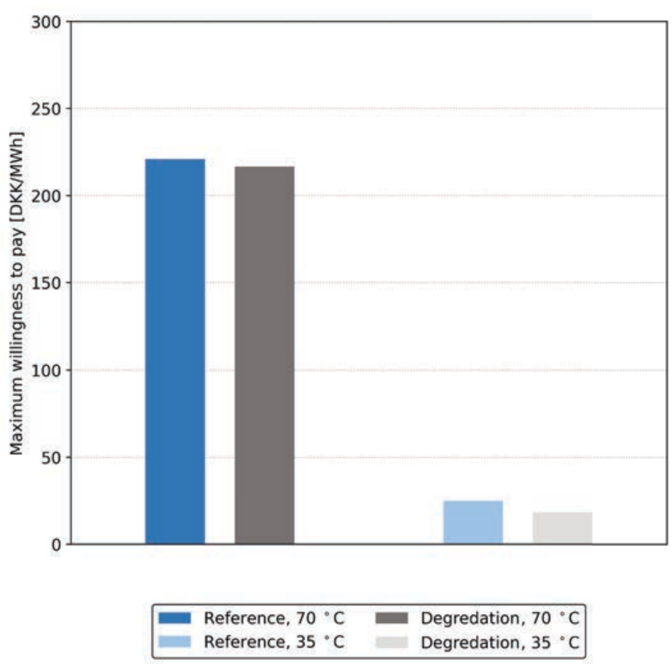


Figure C5: Maximum willingness to pay for 70 °C waste heat and 70 °C waste heat with a degraded stack in Scenario 3. The willingness to pay is lower with the degraded stack because the electrolysis plant has fewer operating hours and therefore does not replace as much costly heat production.

NOTES

1 This is an estimate. How much heat that can be used in a particular situation depends, for example, on the choice of technologies, the condition of the plant (degradation), and the potential for integration into the district heating system.

2 https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet

3 This is an estimate. How much heat can be used in a particular situation depends, for example, on the choice of technologies, the condition of the plant (degradation) and the potential for integration into the district heating system.

4 https://ing.dk/artikel/milliardinvesteringer-stoebeskeen-her-danmarks-ptx-planer-244204

5 https://brintbranchen.dk/wp-content/uploads/2020/10/VE-2.0-Brint-og-PtX-strategi-2.pdf

6 Because proportionality has been assumed in all figures with regard to plant operations, with the exception of water consumption and emissions, the results for sizes other than 400 MW_E will be proportional. For example, operating curves for 200 MW_E will be equivalent with the exception that the waste heat will be halved.

7 www.carboncapturecluster.dk

8 Winther Mortensen et al., SDU, 2019, A pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO_{2E}

9 https://en.energinet.dk/Gas/Gas-news/2021/04/15/Vision-European-Hydrogen-Backbone

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12 Ørsted takes final investment decision on first renewable hydrogen project (orsted.com)

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26 Winther Mortensen et. al, SDU, 2019, A pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO_2

27 Energinet, NYE VINDE TIL BRINT - PtX strategisk handlingsplan, Januar 2020, Dok. 19/07995-21 Offentlig/Public

28 Udkast til erstatning af afsnit fra 2018, se https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

29 https://www.airliquide.ca/en/air-liquide-inaugurates-the-worlds-largest-low-carbon-hydrogen-membrane-based-production-unit-in-canada/product/News-2021-01-26

30 https://energinet.dk/Om-publikationer/Publikationer/Brint-paa-gasnettet

31 https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet, opdateret 14.10.2020

32 Weighted according to the step pricing model

33 https://www.iea.org/reports/the-future-of-hydrogen

34 Hydrogen is referred to as “blue” when the CO_2 created in the production of hydrogen from fossil fuels is stored or recycled. If the CO_2 is emitted, it is referred to as “grey”.