IEA Bioenergy
Technology Collaboration Programme

Modelling full-scale implementation of CCUS at large wood chip fuelled CHP plant in Denmark

Skærbæk CHP plant, WP2 Case Study Report

Contribution of IEA Bioenergy Task 32 to
Inter-Task Project (ITP) Management of biogenic CO_2: BECCUS Phase 2

IEA Bioenergy: Task 32 Biomass Combustion

August 2025

Skærbæk CHP plant. Photo: Morten Tony Hansen

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Preface

Bioenergy combined with carbon capture and utilisation or storage, also known as bio-CCUS or BECCUS is a concept that has been discussed in climate change mitigation research for quite some time. However, implementation has only become the subject of serious consideration within governments and private actors within the last 5 years. The reasons for this are largely related to four factors that are somewhat entwined:

a) an emerging awareness of the need for BECCS and other negative emissions technologies if there is to be any chance for the Paris 1.5°C target to be reached,

b) increased interest in buying carbon negative or neutral products and value of biogenic CO_2,

c) rising CO_2 prices, and

d) the rapidly decreasing costs of electricity generation from solar & wind (and expectations of similar developments for electrolysers) that have made BECCU options based on power-to-X technologies more cost-effective.

In light of this, identifying and implementing approaches for how BECCUS systems can be deployed and integrated in ways that maximise benefits in terms of climate change mitigation - as well as in terms of energy system integration and sustainability ambitions more broadly - is highly important.

BECCUS INTER-TASK PROJECT

Phase I

During the 2019-2021 triennium, IEA Bioenergy Task 40 worked together with Tasks 36, 44 and 45 on an inter-task project called Deployment of BECCUS value chains that focused on understanding the opportunities for, and obstacles to, deployment of BECCUS in different sectors. Focus was on trying to cut across the full set of factors that determine successful deployment, from technology readiness, to business model viability and design of policy and regulatory frameworks.

Phase I findings

Factors determining successful deployment of BECUSS include technology readiness, business model viability, upstream supply chain set up, and current and expected public policy design. The investigations indicate that while the majority of the required individual BECUSS technology components can largely be considered proven, there is still R&D needed into finding models for on-the-ground deployment. Supply chain set up and possibly alterations of existing supply chain concepts are important. Many concepts are looking for viable business models for the captured carbon. Thus far, the focus is on utilising rather storing the carbon. Lack of governance with corresponding support measures and regulations for carbon storage pose a challenge. A synthesis report summarising phase I findings, as well as publications covering case studies topical reports, and system studies can be found on the IEA Bioenergy, Deployment of BECCUS value chains website[1].

[1] https://www.ieabioenergy.com/blog/task/deployment-of-beccus-value-chains/

Phase I suggestions for further work

Research and development are still required to identify models of on-the-ground deployment that make the most sense from techno-economic and climate perspectives. This includes aspects such as specific designs, deployment scales and choice of site locations. In addition, there are many questions remaining when it comes to process and supply chain integration as well as policy design and implementation. Answers to the above questions can assist in addressing key and most complex questions, i.e., *in a given situation should biogenic CO_2 be sequestered, or utilised? Which type of facilities (i.e., bioenergy installations) shall best provide BECCS and/or BECCUS under certain criteria (economics, CO_2 emissions mitigation potential etc.)? What are the main challenges for commercialising BECCUS projects and the lessons learnt thus far? How to monetise the carbon negative products that bioenergy can deliver? How to govern the different energy system services when targeting a high level of CO_2 emissions mitigation? And related to this, what factors and parameters should guide this decision-making process?*

Phase II

Phase II of the BECCUS Inter-Task Project is more diverse in its scope, with a stronger emphasis on cross-sector and cross-country learning about implementation of BECCUS projects using different energy conversion processes (WP2-WP4). A further goal is to shed some light on the effects of the integration of BECCUS facilities and systems within the overall energy system and its interaction with other energy system services (WP5). In addition, although we tend to refer to “BECCUS” as a unified concept, we also emphasise and analyse the important differences between BECCS and BECCU, not least from the perspective of potential business models and policy development (WP6). An understanding of the impacts of BECCUS on overall climate system in terms of potential for CO2 mitigation is addressed (WP7) and all different aspects covered are analysed jointly and policy recommendations provided (WP8). This approach allows for a systemic consideration of how to take different BECCUS applications to deployment, thereby building upon, but going beyond, Phase I. IEA Bioenergy Task 40 works together with Tasks 32, 33, 34, 36, 44 and 45.

Summary

The Skærbæk CHP plant is located in the Western part of Denmark where it delivers heat to one of Denmark's largest district heating systems. The TVIS (in English - Triangle Area Heat Transmission Company) supplies heat to the towns of Vejle, Kolding, Fredericia and Middelfart. Today, the Skærbæk CHP plant delivers app. 50% of the heat and the remaining part portion is delivered mainly by surplus heat from the local refinery and heat from by the waste incineration plant in Kolding. This is supplemented by peak load boilers based on oil or natural gas. The Skærbæk plant today uses approximately 550,000 tonnes of wood chips per year.

The aim of the study is to analyse the consequences of investment in CCUS technology at the Skærbæk plant. The study analyses the following three scenarios for development of the plant:

- **BAU.** In this scenario, the setup is a continuation of the current operation, a business-as-usual scenario. The Skærbæk Power Station has the option to produce heat and electricity, either in combined generation or a separate generation. The other heat production units in the district heating system are assumed to continue operation with the same capacity as today.

- **CCS.** This scenario considers the inclusion of a CO_2-capture system (CC-plant), which aims to capture and store carbon dioxide deriving from the woodchip boiler for potential future storage (S). In the analysis two different versions of the CCS-Scenario are analysed: one version with capture of a fixed yearly amount of CO_2 (CCS fixed) and one version with optimization of the sale of CO_2 with an assumed market price for CO_2 (CCS Market).

- **CCUS.** This scenario entails the incorporation of carbon capture, storage, and utilisation at the Skærbæk Power Station. Unlike the 'CCS-scenario', where CO_2 is captured and stored for potential sale, all or part of the CO_2 can be directed to an electricity-powered methanol production facility with hydrogen provided by a large electrolyser. The production capacity of the methanol process is dimensioned to match the CO_2-production from the biomass boilers at full capacity. The amount of methanol produced over the year is assumed to be fixed and based on 4,500 full load hours operation of the methanol plant. However, it can be chosen to run the biomass boilers for more than 4,500 full load hours to provide more heat and power. Also, during this operation, CO_2 could be captured and sold at an assumed market price.

The analyses of the scenarios focus on the year 2035.

The energy market model Balmorel has been applied to analyse the different scenarios. The district heating system is modelled on an hourly basis with individual representation of all production units and an hourly consumption profile for the heat demand. Also, a large heat storage is part of the system and is modelled as part of the optimisation. For modelling the CCUS technologies at the Skærbæk plant, the advanced OptiFlow module of the Balmorel model has been applied. This allows for modelling of energy and mass balances of the different process of the CCUS technologies (carbon capture, heat pumps, electrolysers, methanol synthesis etc.).

An overview of the production from the Skærbæk CHP plant is shown in Table 1 below. The main results and conclusions from the analyses are:

- In the BAU-scenario, the number of operating hours of the Skærbæk CHP plant increases compared to today. This is due to the assumed development in fuel and power prices and the development of the framework for waste plants in Denmark. All told, this sees the Skærbæk CHP become more competitive and increases heat production from app. 3.5 PJ today to 4.5 PJ in 2035. Also, the plant is competitive in the power market when power prices are moderate and high, and the plant produces app. 230 GWh of power in condensing mode.

- In the CCS-scenarios, the operating hours of the plant are further increased, especially in the CCS Market Scenario. The district heating generation increases further, and a significant part of the district heating generation is delivered as surplus heat from the CC-facility. The operation of the CC facility requires electricity resulting in a lower net electricity generation compared to BAU. Electricity consumption attributed to the carbon capture and storage amounts to 159 GWh, about 28% of the electricity generation of the plant. In the CCS Market scenario, almost all CO_2 is captured.

- In the CCUS-scenario, a significant shift is observed in the dynamics of net electricity production, transitioning from positive to negative on average over the year. District heating generation is further increased compared to the other scenarios and in this scenario the heat production from the Skærbæk plant can cover almost all the district heating demand in the TVIS area. Most of the heat generation is delivered as surplus heat from the CC-plant, the electrolysers and the methanol plant, while the CHP plant delivers process heat for the CCUS-processes and increases power production in condensing mode. The negative net electricity generation underscores the energy-intensive nature of the CCUS process, necessitating a substantial power input of app. 3.2 TWh.

- Hydrogen production is optimized for periods when the electricity value is low, while district heating demand proves significant only in winter months.

Table 1: Overview of the annual production from the Skærbæk CHP plant in the analysed scenarios in 2035.

Skærbæk plant	BAU	CCS Fixed	CCS Market	CCUS
Wood chip consumption (GWh)	**2,091**	**2,204**	**2,486**	**2,486**
Full load hours	**6,150**	**6,482**	**7,312**	**7,312**
Net electricity generation (GWh)	**558**	**409**	**317**	**-2,615**
Condensing	178	256	375	543
Backpressure	385	314	219	54
Bypass	-5	-1	-1	-0
CC plant		-56	-97	-97
CC heatpump		-86	-148	-148
CO2 storage		-17	-30	-13
Electrolyzer				-2,916
Methanol plant				-31

H2 storage				-6
District heating generation (GWh)	**1,214**	**1,368**	**1,477**	**1,690**
Flue gas condensation	135	142	160	160
Backpressure	769	627	437	108
Bypass	310	81	79	0
CC plant		86	149	149
CC heatpump		432	746	746
Electrolyzer				464
Methanol plant				439
Cooling	0	0	-93	-374
Captured CO_2 (kiloton)	0	434	749	749

Figure 1. Silent, electrohydraulic wood chip cranes in Skærbæk. Photo: Morten Tony Hansen.

Introduction

In light of Denmark's ambitious climate goals outlined in the "Klimalov", which mandates a 70% reduction in CO_2 equivalent emissions by 2030 compared to 1990 and aims for climate neutrality by 2050, the imperative to explore innovative solutions has become paramount [1]. In response, Ørsted secured a Carbon Capture and Utilization (CCUS) tender in May 2023, committing to capture 430,000 tonnes of CO_2 per year over a 20-year period from two biomass-fired power plants [2]. This initiative is mandated to be operational by 2026.

The momentum towards sustainable practices in Denmark continued in August 2023 with the announcement of a new tender focused on negative emissions (NECCS). Anticipating an annual capture of 500,000 tonnes of CO_2 from 2026 onwards, this initiative represents an important step towards realising Denmark's climate objectives [3]. Bolstering these efforts, a comprehensive CCS strategy was endorsed by a substantial majority in Parliament on 20th September 2023 [4]. The strategy earmarks a budget of 3.6 billion euros for two forthcoming tenders, collectively targeting a minimum annual capture and sequestration of 2.3 million tonnes of emissions over 15 years, commencing in 2029. This encompasses not only the objectives set by the recent tenders but also builds upon them, striving for a total capture of at least 3.2 million tonnes per year, including initial commitments.

Against this backdrop, the task at hand involves the modelling of the interaction between a biomass Combined Heat and Power (CHP) plant and Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU). The Skærbæk Combined Heat and Power Plant has been identified as a pertinent case study for this investigation. The study aims to scrutinise the full-scale implementation of CCUS technologies. By delving into these technologies within the context of a biomass-fired CHP plant, the analysis seeks to elucidate the consequences of adding these technologies to the operation of the plant and the district heating system.

The Skærbæk power plant case study

This section introduces the case study of the Skærbæk combined Heat and Power Plant that currently contributes to the district heating for 60,000 residences in the Triangle Region of Denmark, located along Kolding Fjord in Southern Jutland [6].

SKÆRBÆK CHP PLANT

The Skærbæk CHP plant is located in the Western part of Denmark between Fredericia and Kolding and has undergone a transformative evolution since its establishment in 1951 [7]. Initially based on coal, the plant has evolved to meet climate targets.

As of today, the Skærbæk plant is owned and operated by Ørsted, a Danish energy company. The plant's current layout comprises a natural gas CHP plant, commissioned in 1997, with an electrical capacity of 392 MW. Additionally, two wood chip-fired boilers with flue gas condensation, operational since 2017, provide steam for the same turbine as the natural gas boiler.

The plant's infrastructure includes a heat storage tank with a capacity of 25,000 m^3, further enhancing operational flexibility. Notably, the Skærbæk CHP plant is a substantial biomass consumer, utilising approximately 550,000 tonnes of biomass per year [8], [9]. The Skærbæk CHP plant's geographical location, between Fredericia and Kolding, positions it strategically to serve the surrounding regions, contributing to heating for residents of Fredericia and the broader Triangle Region [10].

The plant's recent conversion from natural gas to wood chips [8], [11] has allowed for increased flexibility in fuel selection and thus operational efficiency. The transition involved the installation of two 160 MW wood chip boilers, a boiler building, and infrastructure improvements, including the renovation of the power station's quay and the installation of flue gas pipes.

Figure 2: The Skærbæk CHP plant. Source: TVIS.[2]

TVIS DISTRICT HEATING SYSTEM

The TVIS District Heating is one of the largest in Denmark, delivering heat to Kolding, Vejle, Middelfart and Fredericia and smaller towns (see Figure 3).

The main production units are the Skærbæk CHP plant, Crossbridge refinery, and waste combustion from Kolding Plant. Additionally, some smaller local production contributes to the heat and a back-up system, comprised of natural gas and oil boilers ensuring that the thermal energy demand will be supplied, and comprising the peak load reserve.

In 2022, the district heating network achieved a yearly heat production of 6.6 PJ, comprising 50% biomass, 25% waste, and an additional 25% from surplus heat.

[2] https://www.tvis.net/nyhed/baeredygtigbiomasse/

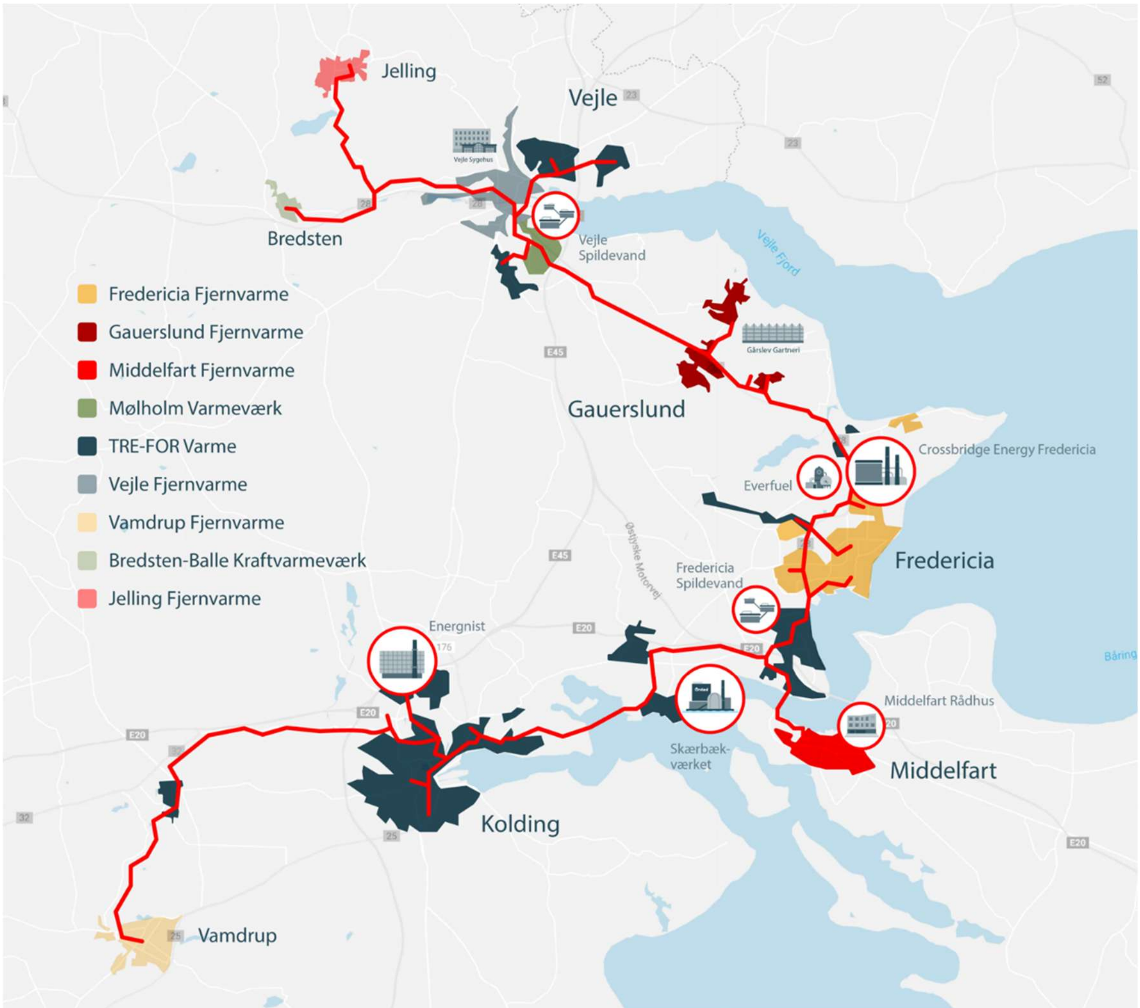

Figure 3: District heating system in the 'Triangle Region'. Source: TVIS.

Scenarios for development of the Skærbæk CHP plant

The Skærbæk plant has a favourable position as it is close to possible off-takers and infrastructures. It is close to port facilities for shipping CO_2 or green fuel. Additionally, the TVIS district heating network can use surplus heat from CCUS.

In the current study, three distinct scenarios are investigated and simulated to assess the future landscape of the Skærbæk Power Station under different layouts. The carbon emissions from the woodchip boiler in the Skærbæk CHP plant, a result of biomass combustion, presents an opportunity to reduce CO_2 emissions through CCS and CCUS. To comprehensively assess the benefit of changing the Skærbæk CHP plant, this study will scrutinise two prospective scenarios alongside the current baseline. These scenarios, denoted as 'CCS' and 'CCUS,' will be thoroughly examined to evaluate their impact on energy production and carbon emission during operation. Bioenergy with Carbon Capture, Utilization, and Storage (BECCUS), is playing a crucial role in Denmark's transition towards a sustainable and carbon-neutral energy future.

It will take several years to develop and implement the technologies and scenarios at the Skærbæk CHP plant. All the scenarios therefore focus on the year 2035.

BAU SCENARIO

In this scenario, called the 'BAU Scenario', the Skærbæk Power Station has the option to produce heat and electricity, either in combined generation or a separate generation. The set up is similar to the current situation. In this case, the CO_2 from the woodchip boiler is released into the atmosphere.

CCS-SCENARIO

The 'CCS-scenario' considers the inclusion of a CO_2 capture system (CC-plant), which aims to capture and store carbon dioxide deriving from the woodchip boiler for potential future storage. This scenario introduces the CC-plant, which requires a portion of steam from the wood chips boiler and an additional supply of electrical power for the energy supply of the CC-plant, which uses amines as the catalyst. The process also generates surplus heat that can potentially be injected into the district heating network.

In the analysis, two different variants of the CCS-Scenario are analysed: one version with capture of a fixed yearly amount of CO_2 and one version with optimization of the sale of CO_2 according to an assumed market price for sequestered biogenic CO_2.

CCUS-SCENARIO

The 'CCUS-scenario' entails the incorporation of carbon capture, storage, and utilisation at the Skærbæk Power Station. Unlike the 'CCS-scenario', where CO_2 is captured and stored for potential sale, part of this can be directed to an electricity-powered methanol production facility, which also transforms electricity into hydrogen via an electrolyser. The methanol production process, in turn, generates an additional amount of heat for the district heating system. The methanol process is dimensioned to match the CO_2-production from the biomass boilers at full capacity.

In this case, the amount of methanol produced over the year is assumed to be fixed and based on 4,500 full load hours operation of the methanol plant. However, it can be chosen to run the biomass boilers for more than 4,500 full load hours to provide more heat and power. Also, during this operation, CO_2 could be captured and sold at an assumed market price for sequestered biogenic CO_2.

Modelling approach and general assumptions

The Balmorel energy system model serves as the foundational framework for the in-depth simulations conducted in this study. Balmorel is a fundamental partial-equilibrium model finding least-cost solutions based on assumptions such as the development of fuel prices, demand development, technology costs and characteristics, renewable resource potentials, policies, weather data and other essential parameters.

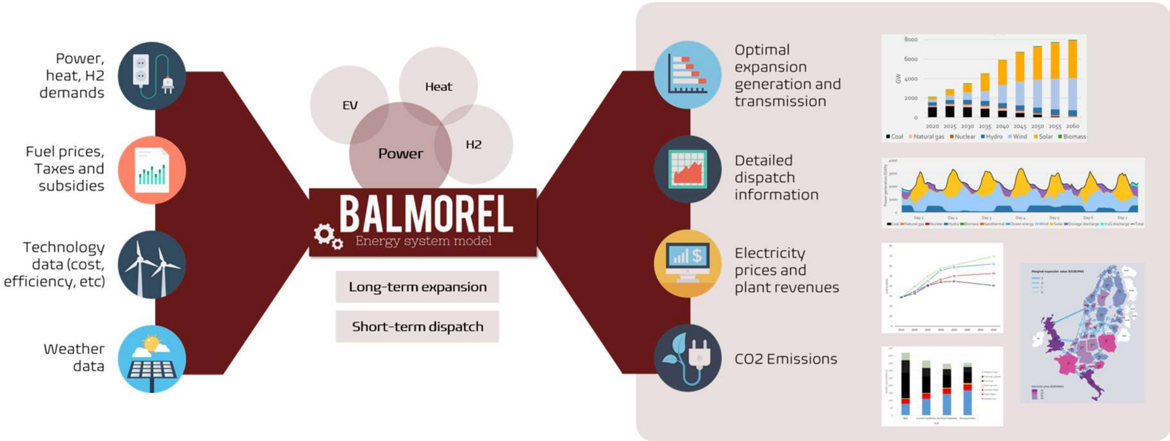

Figure 4: The Balmorel energy system model.

Fundamental to this study is the modelling of the North European energy system in Balmorel to provide essential input on the development of the electricity market used for optimizing the plant. Detailed modelling extends to heat consumption, production units, and network constraints within the TVIS district heating system.

A crucial aspect of this study involves the use of the OptiFlow module, an extension of Balmorel, enabling detailed modelling of different processes at the Skærbæk plant. OptiFlow facilitates the comprehensive understanding of mass balances and energy conversion processes, contributing to a detailed representation of the energy processes at the plant. Balmorel can generate results on an hourly basis. Building upon a basic Balmorel model of the CHP plant, enhancements have been made to incorporate representations of carbon capture plants, electrolyser and methanol production. This model expansion includes features such as CO_2 capture, intermediate CO_2 storage, compression plant(s), and considerations for transport and storage costs.

The District Heating System plays a pivotal role in the integrated energy system model, seamlessly combining the plant and the power system. Through detailed modelling of the North European energy system and the TVIS district heating system, including network constraints and heat consumption, this study achieves a holistic understanding. The application of the OptiFlow module further enhances modelling capabilities.

GENERAL ASSUMPTIONS

To model the development of the energy system and dispatch of different plants and technologies in the three scenarios, a number of general assumptions have been established for the 2035 scenarios. The table below displays assumed fuel prices for woodchips, natural gas, oil and municipal solid waste, which are all fuels used in plants in the TVIS district heating system. Also, the price for CO_2 is an important assumption for this study and a price of 160 EUR/tonne has been assumed for 2035 based on the IEA World Energy Outlook 2023, the Announced Pledges Scenario. The power price is based on an electricity price projection made by Ea Energy Analyses modelled with the Balmorel model in a version of the model that covers most of Europe.

Table 2: Price projections for the year 2035 in EUR/GJ.

Prices			2035
Fuel prices	Woodchip	EUR/GJ	8.4
	Natural Gas	EUR/GJ	8.1
	Oil	EUR/GJ	15.2
	Municipal waste	EUR/GJ	-4.7
CO_2 quota price		EUR/ton	160.1
Power price		EUR/MWh	60.1

Figure 5 displays a duration curve of the forecasted hourly electricity prices from the above-mentioned European version of Balmorel, that are used as an input for the modelling within the current study. Examining the input electricity prices for Denmark DK1 in 2035 highlights a considerable variability, with a mean of €60/MWh, a maximum of €160/MWh, and a minimum of €2/MWh. The standard deviation of €37/MWh suggests substantial price fluctuations.

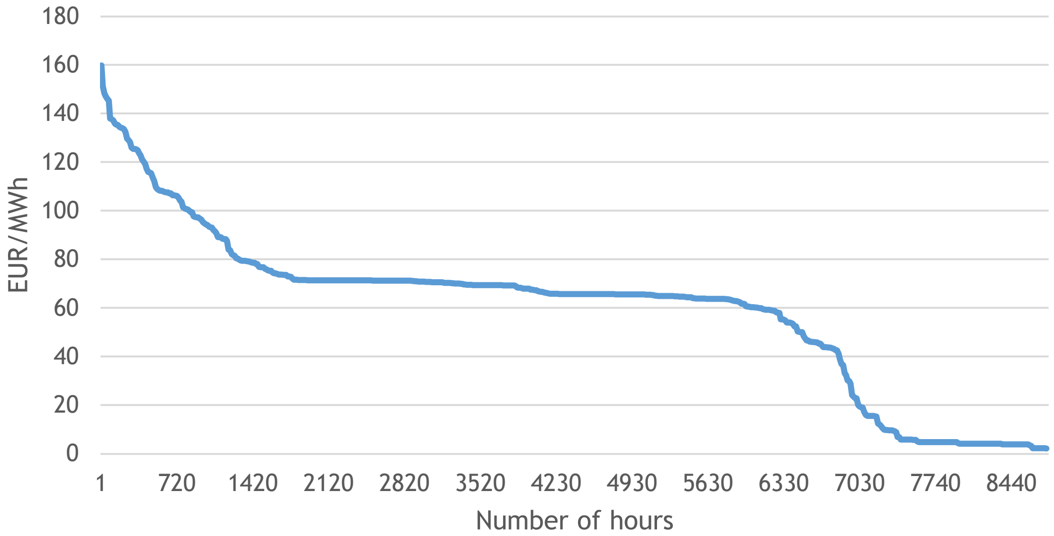

Figure 5: Duration curve of electricity prices in the year 2035.

Modelling of three scenarios for the Skærbæk CHP plant in OptiFlow

This section presents a detailed technical overview of the Skærbæk plant, outlining its key components and the interconnections to present the fundamental technical factors guiding the case study. Specifically, the section will focus on the technical modelling of plant components and the optimisation model in Balmorel and Optiflow. Figure 6 shows the plant layout in 'CCUS' scenarios, which comprises the three main areas. 'Skærbæk Plant' is the current system layout, 'CCS Facility' is the CCS plant, and 'Power-to-Methanol' is the facility of components when methanol production is also included. For each 'area', a description of components accompanies the detailed technical layout diagram, providing a visual representation of the interconnected components and their functions within the CCUS system at Skærbæk. The description provides a detailed exploration of the primary assumptions and detailed specifications that govern each component. All data is based on publicly available sources, and all components are in line with the specifications from the most updated Danish technology catalogue. Components cost and performances refer to year 2035.

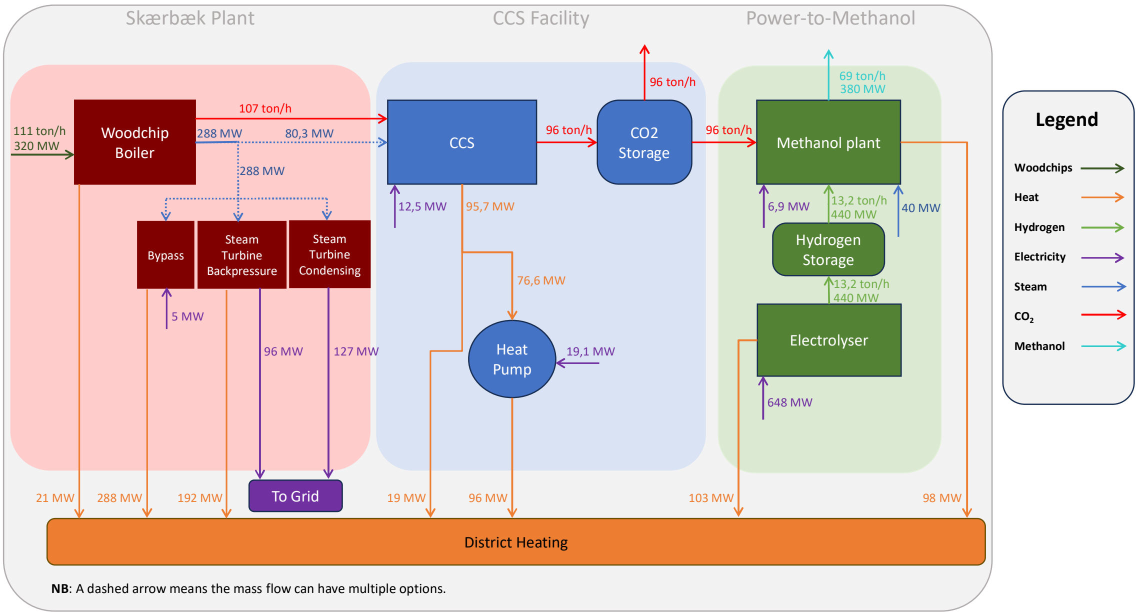

Figure 6: Diagram layout showing the design of the Skærbæk plant in the CCUS scenario.

- **Skærbæk Plant:** It comprises a woodchip boiler and a steam turbine that simultaneously produces heat and electricity. The heat is sent to the TVIS district heating system, and the generated power serves the electricity network. In this system all the CO_2 produced is sent to the atmosphere.
    - **Woodchip Boiler**: Assuming an input capacity of 320 MW and an efficiency of 90% from fuel to steam. At full load the boiler produces 107.1 tonnes CO_2/h.
    - **Steam Turbine**: Sized based on the maximum steam produced from the Woodchip Boiler, assuming a simple Rankine cycle.

- **CCS Facility:** The CCS facility is composed of a CCS plant, a storage facility, and a heat pump. The CCS plant has steam, electricity, and flue gases as input, producing pure CO_2 and additional heat that can be used for district heating. A portion of the produced heat is sent directly to district heating, while the remaining part is directed to a heat pump for increased temperature, ensuring compatibility with the district heating system. If CCS is coupled with a CHP plant, part of the steam should be directed to the CCS system. Additionally, also part of the electricity should be sent to the CCS. Using the CCS plant, the CO_2 produced from the woodchip boiler can be stored or reused, decreasing the carbon footprint of the Skærbæk plant.
    - **Carbon Capture:** Post-combustion CO_2 capture is assumed, with amine as a catalyst and 20% heat availability at 90°C and 80% at 50°C.
    - **CO_2 storage:** Assuming no specific operation mode, with the mass flow input assumed equal to the maximum storage output. The evaluation ensures the system's capability to operate at maximum capacity, although storage sizes are not optimized at this stage.

- **Heat Pump:** For the heat pump a COP-value (coefficient of performance) of 5 has been assumed.

- **Power-to-Methanol Plant:** This is composed of an electrolyser, hydrogen storage and a methanol plant. Having hydrogen, electricity, steam, and CO_2 as input, the methanol plant produces methanol and high-temperature heat for the district heating system, contributing to the system's diversified and sustainable energy solutions.
    - **Methanol Plant:** Sized considering the maximum CO_2 mass flow input from CC-Plant.
    - **Electrolyser:** The Alkaline electrolyser is powered by 648 MW of electricity at maximum capacity, producing hydrogen and heat sent to the H_2 storage and the district heating, respectively.
    - **Hydrogen Storage:** A short-term hydrogen storage has been included to provide some flexibility in the production.

- **District Heating System (DHS) network:** Functioning as the backbone of heat distribution, the DHS receives heat from both the Skærbæk Plant and the CCUS plant.
- Modelling of the TVIS district heating system

The Skærbæk CHP plant delivers district heating to the interconnected TVIS system and heat production in the system is optimised in the modelling on an hourly basis to deliver heat at the lowest overall cost. The table below provides an overview of the heat production units in the system (Table 3). The Danish market for treatment of combustible waste is in the process of being liberalised and the plants will therefore compete for getting waste for their plants in the market. The operation of the waste boiler and the waste CHP (owned by Energnist) is based on an assumed market price for the waste and no lower or upper limitations for the use of waste are applied. The surplus heat is from the refinery Crossbridge and is expected to be available all year and delivered at price of 0 EUR/GJ.

The district heating system includes a large steel tank for heat storage that is used to optimise the dispatch of the heat production units.

Table 3: Heat production units in the TVIS district heating system.

Installed capacity	Fuel	Power	Heat	Storage volume
	MW	MW	MW	MWh
Waste CHP	26	6	17	
Waste boiler	30		28	
Surplus heat	55		55	
SKV	320	127	309*	
Heat storage tank	179		170	1,359
Oil based peak units	535		500	

**309 MW is in full bypass mode including flue gas condensation. In backpressure mode SKV can generate 214 MW heat.*

The total heat consumption in the district heating system is assumed to be 6.4 PJ including grid losses in 2035.

Model results for the three scenarios

This section provides an overview of the main results, comparing the scenarios for Skærbæk CHP plant. The results are displayed for the BAU, CCS, and CCUS scenarios, highlighting heat production, fuel consumption and plant performance.

BAU SCENARIO

In the BAU scenario, the Skærbæk Combined Heat and Power (CHP) plant delivers approximately 4,400 TJ of heat, which corresponds to around 70% of the total district heating supply, as shown in Figure 7. The remaining heat demand is covered primarily by surplus heat and waste incineration sources.

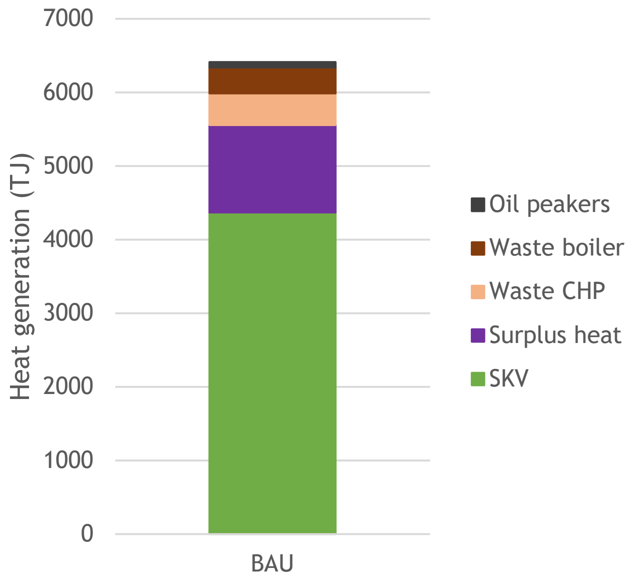

Figure 7: Annual heat generation in the BAU scenario for the TVIS system in the year 2035 given in TJ.

The annual fuel consumption is shown in the figure below (Figure 8) and it can be seen that the Skærbæk plant uses app. 7.5 PJ of wood chips. This corresponds to 6,500 full load hours of operation of the boilers.

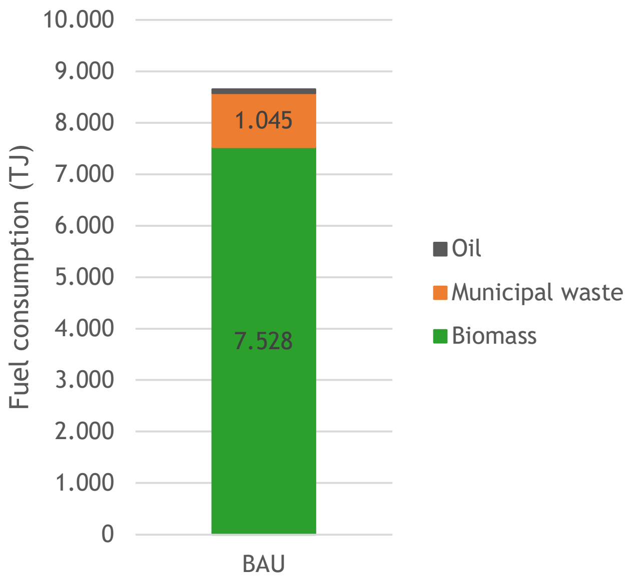

Figure 8: Annual fuel consumption generation in the BAU scenario for the TVIS system in the year 2035 given in TJ.

It can be seen from Figure 9 that the majority of heat production from Skærbæk occurs during the winter and spring/autumn seasons, with some generation in the summer, particularly during periods of high electricity prices. Examining the detailed results, the heat demand across various weeks is distributed among different sources, including Waste CHP, Surplus heat, Waste boiler, SKV, and Oil peak units, highlighting the need for an array of energy sources contributing to meet the district heating system's requirements. Planned outages for SKV, Waste CHP and Boiler plants is sequential, starting in week 25, with 3 weeks per plant.

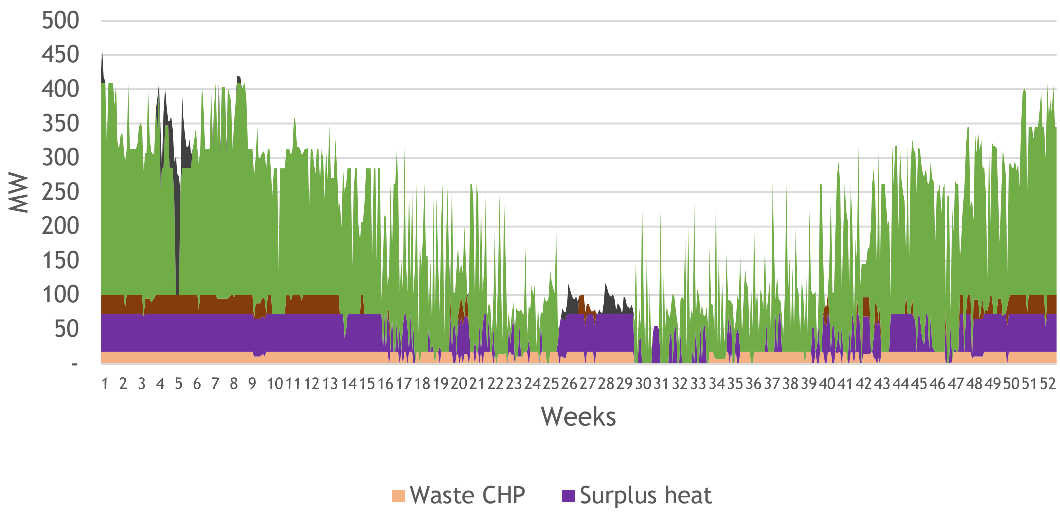

Figure 9: Hourly heat generation in the BAU scenario for the TVIS system in the year 2035 given in MW.

The figure below (Figure 10) displays the duration curve for heat demand and supply in the BAU scenario.

In this figure the production from the heat storage is also included and it can be seen how the production from the storage gives options for more flexible production of the different heat production units in the system.

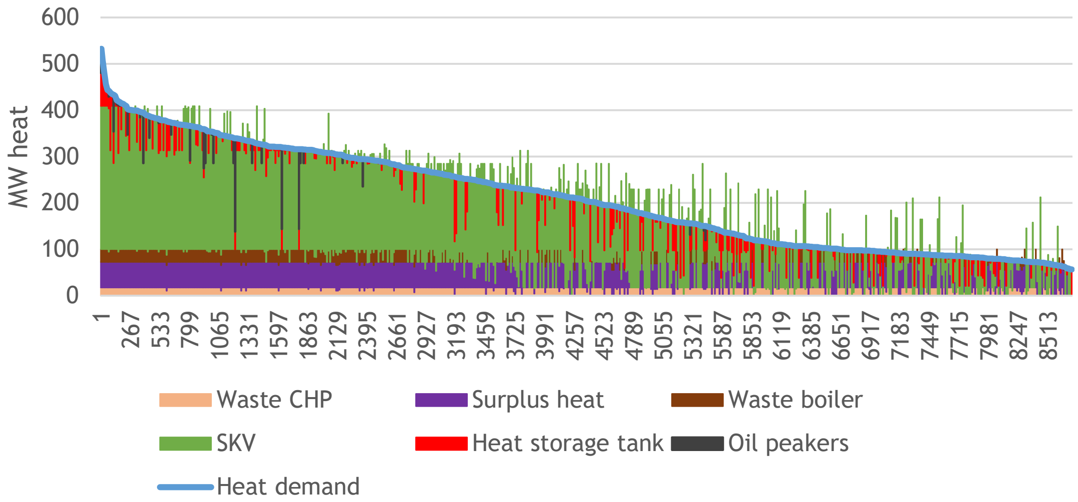

Figure 10: Duration curve for heat demand and supply in the BAU scenario.

The figure below (Figure 11) displays the fuel consumption as well as the power and heat generation of the plant in different operating modes. The majority of the heat is delivered in back pressure mode, but during some periods of the year, when heat demand is high or power prices are low, the plant is operated in bypass mode with no electricity generation. The plant is also operated in condensing mode when power prices are high and/or heat consumption is low.

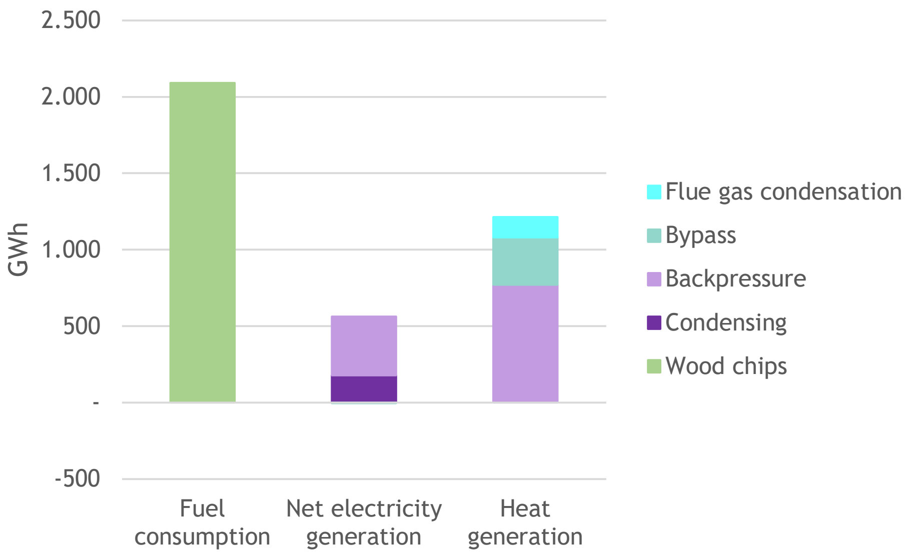

Figure 11: Input and output of the Skærbæk plant in the BAU scenario.

The figure below (Figure 12) shows more details on the power production. The power generation is sorted in a duration curve based on the level of the power prices. The operation in condensing mode is focused on hours with high prices. During periods with low prices the plant is either closed down, running in bypass mode or running at the minimum generation level for the turbine.

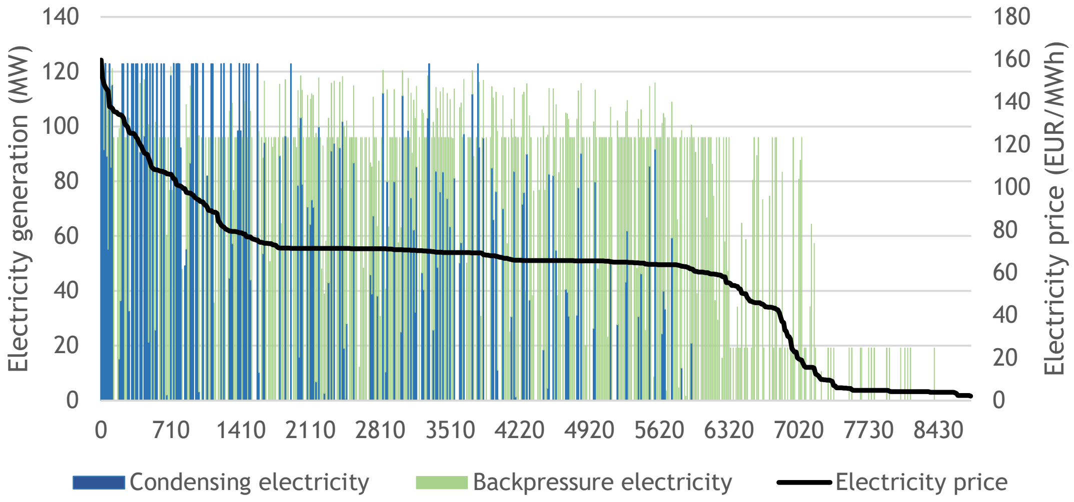

Figure 12: Duration curve for electricity prices and the corresponding electricity generation in 2035 for the Skærbæk plant in the BAU scenario.

CCS SCENARIO

As explained earlier the CCS scenario includes modelling of a carbon capture facility at the Skærbæk plant including production of surplus heat from the process. The CCS scenario is modelled in two variants:

- CCS Fixed. Capture of a fixed yearly quantity of CO_2 corresponding to 4,500 full load hours operation of the wood chip boilers.
- CCS Market. Optimised capture and sale of CO_2 according to an assumed market price for sequestered biogenic CO_2. A net revenue of 133 EUR/ton CO_2 has been assumed reflecting an assumption of the value of storing biogenic emissions and subtracting the assumed costs for transportation and storage.

The figure below (Figure 13) displays the annual heat generation in the BAU, CCS Fixed and CCS Market scenarios. In the CCS Fixed scenario, heat generation increases from app. 4,500 TJ to app. 5,000 TJ. The fuel consumption only sees a small increase, but the heat generation is larger because of the production of surplus heat at the CC-plant. In the CCS Market scenario, the heat generation increases further. When economically optimising the CO_2-capture and the sale of CO_2 sequestration the use of fuel increases.

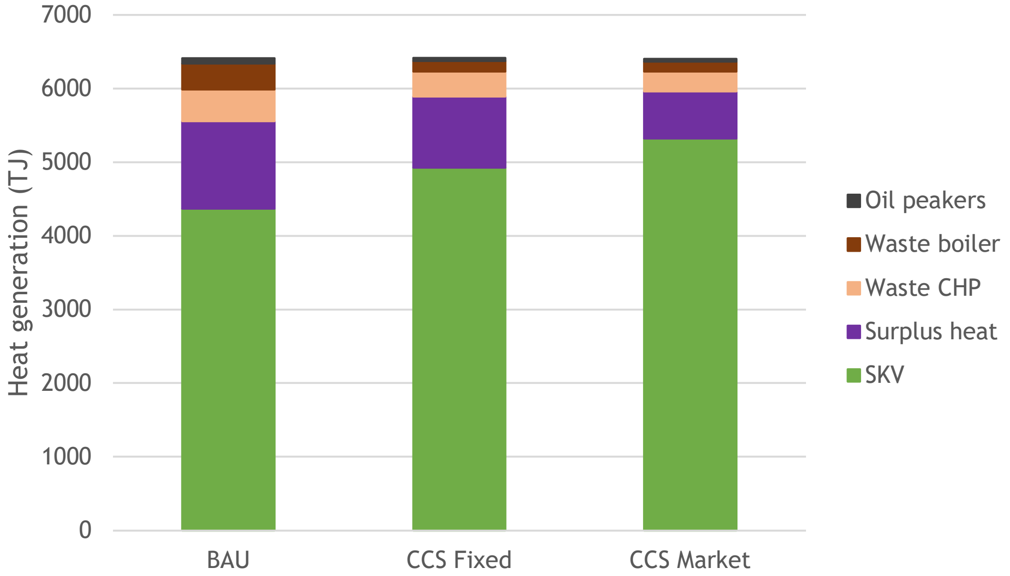

Figure 13: Annual heat generation in the three scenarios for the TVIS system in the year 2035 given in TJ.

The two figures below show the hourly heat generation from the different heat production units in the district heating system over the year. Results are displayed for both the case with fixed CO_2-capture and with economic optimisation. When comparing the two figures it can be seen that Skærbæk increases heat generation when the production and CO_2 capture is optimised economically and displaces heat generation from other sources (surplus heat and waste).

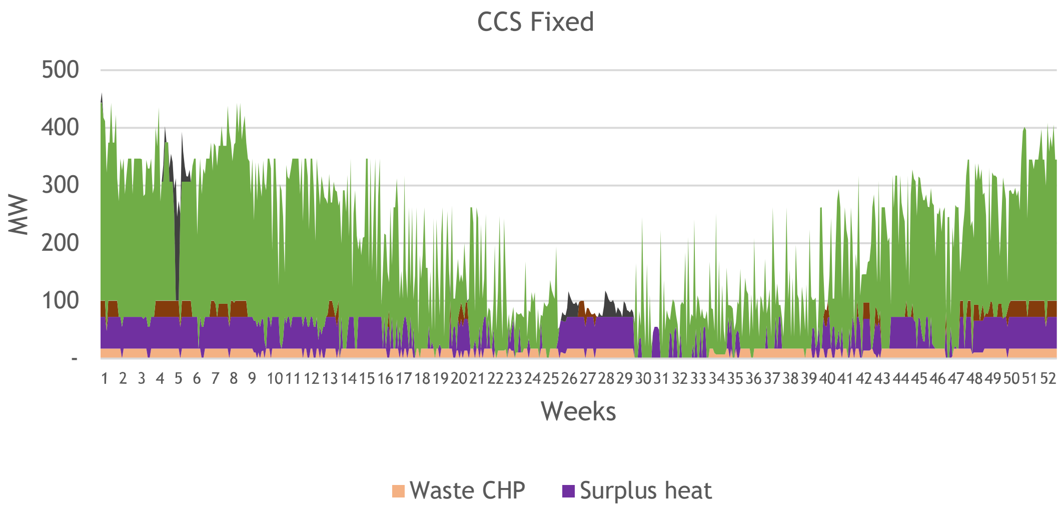

Figure 14: Hourly heat generation in the CCS Fixed scenario for the TVIS system in the year 2035 given in MW.

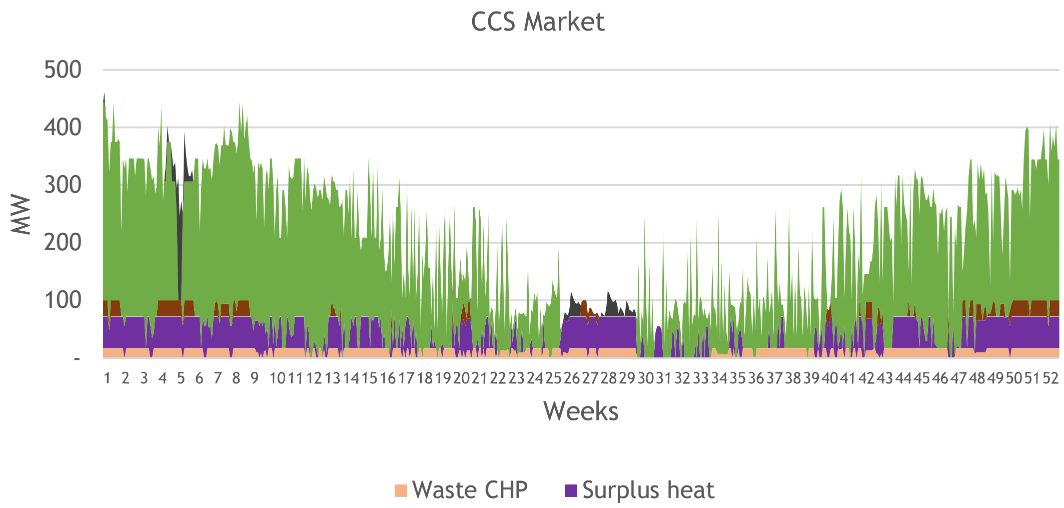

Figure 15: Hourly heat generation in the CCS Market scenario for the TVIS system in the year 2035 given in MW.

The figure below (Figure 16) illustrates what part of the Skærbæk plant delivers the heat production in each of the three cases. In the BAU scenario, most heat is delivered from operation of the turbine in back pressure mode, and some heat is delivered from the flue gas condensation facility and directly from the boiler when operating the plant in bypass mode. When operating the CC-plant, steam is extracted from the turbine as energy supply for the CC-plant. In this operation mode a large part of the heat is delivered as surplus heat from the CC-plant, either directly through heat exchangers or by use of the heat pump.

The electricity generation and consumption of the plant is shown in the figure below (Figure 16). Because of the electricity consumption of the CC-plant and since the power production is reduced when steam is extracted for the CC-plant the net electricity generation decreases quite significantly with CC installed at the plant.

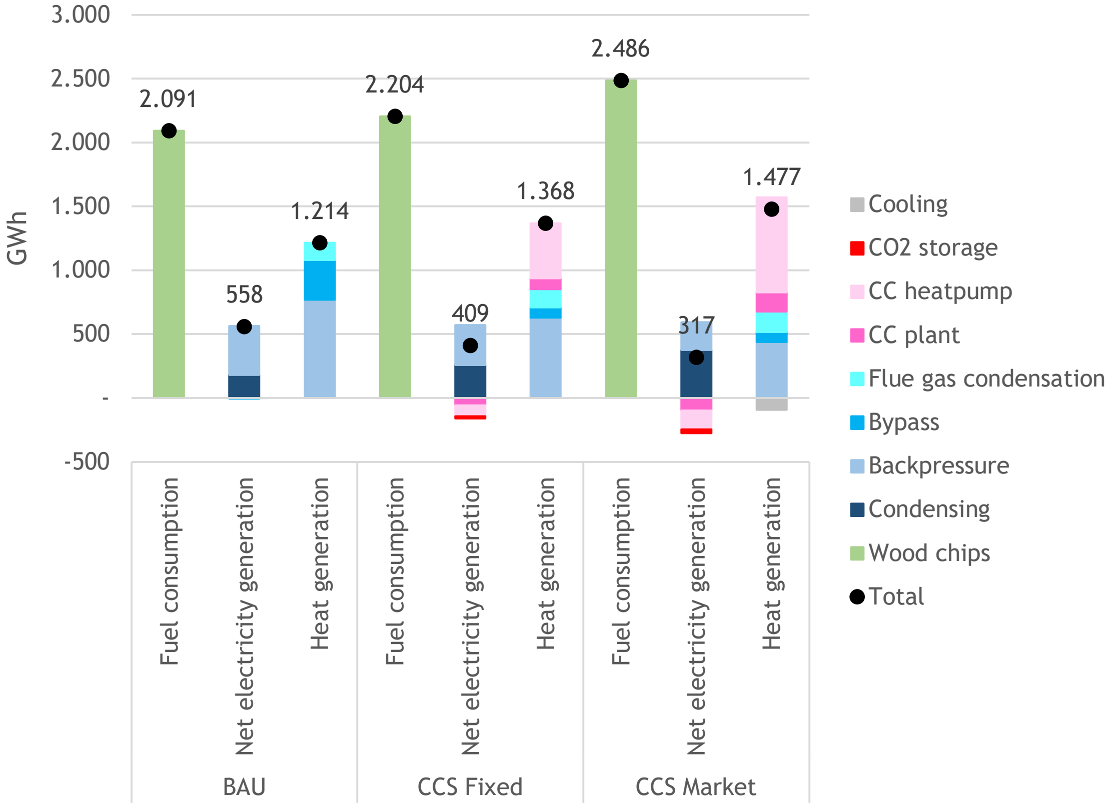

Figure 16: Annual fuel consumption, heat and electricity generation on the Skærbæk plant in the three scenarios in the year 2035 given in TJ.

The CO_2-emisions, both capture and non-captured, are displayed below in Figure 17. In the CCS Market scenario, almost all CO_2 is captured. This indicates that with the assumed framework conditions it is always the best economic solution to run the CC-plant while running the wood chip boilers.

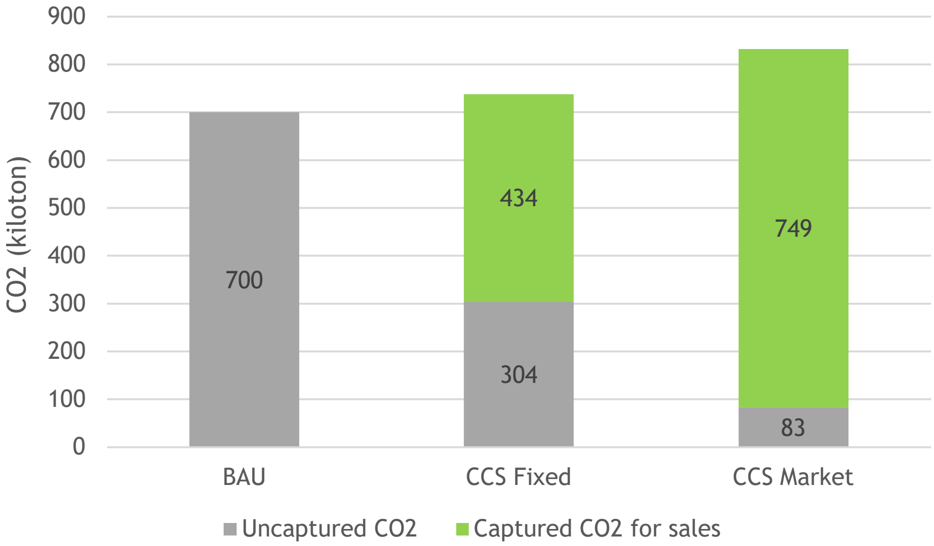

Figure 17: Annual CO_2 flow on the Skærbæk plant in the three scenarios in the year 2035 given in TJ.

CCUS SCENARIO

In a scenario where the Skærbæk CHP plant is equipped with CC-technology, electrolysers and methanol production, the surplus heat from the different processes increases the heat production from the plant significantly. As shown in the figure below, the heat generation of the plant increases to app. 6,100 TJ, effectively fulfilling almost the entire district heating demand.

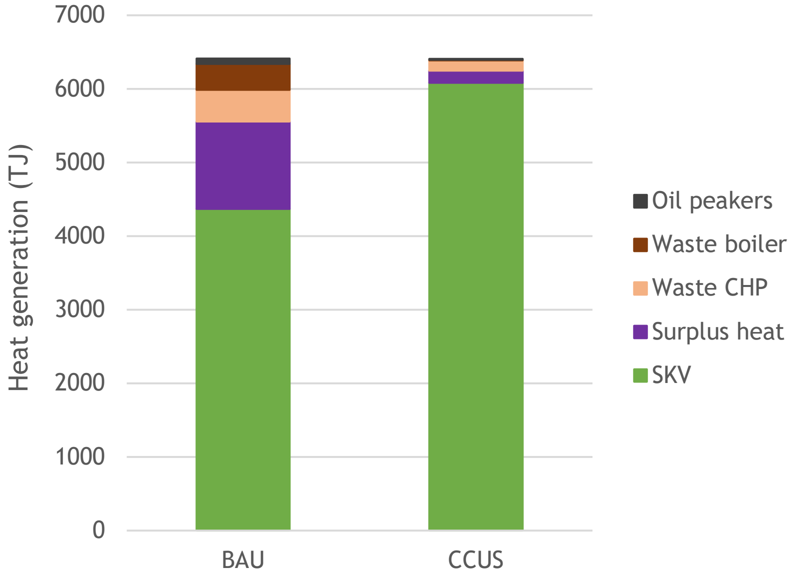

Figure 18: Annual heat generation in the two scenarios for the TVIS system in the year 2035 given in TJ.

There is significant heat generation throughout the year as shown in the figure below.

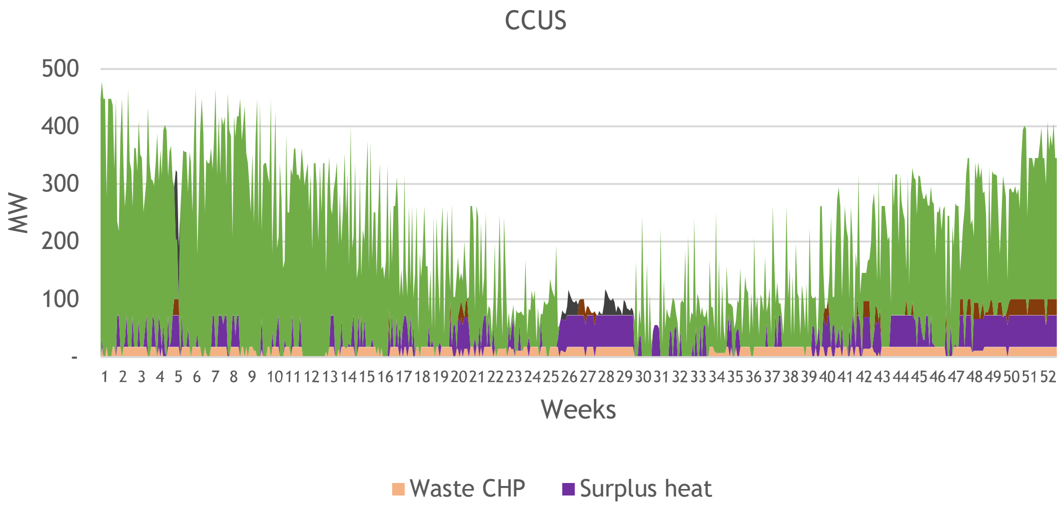

Figure 19: Hourly heat generation in the CCUS scenario for the TVIS system in the year 2035 given in MW.

The duration curve below shows that the Skærbæk plant covers most of the heat demand and that the heat storage is used to make the generation more flexible.

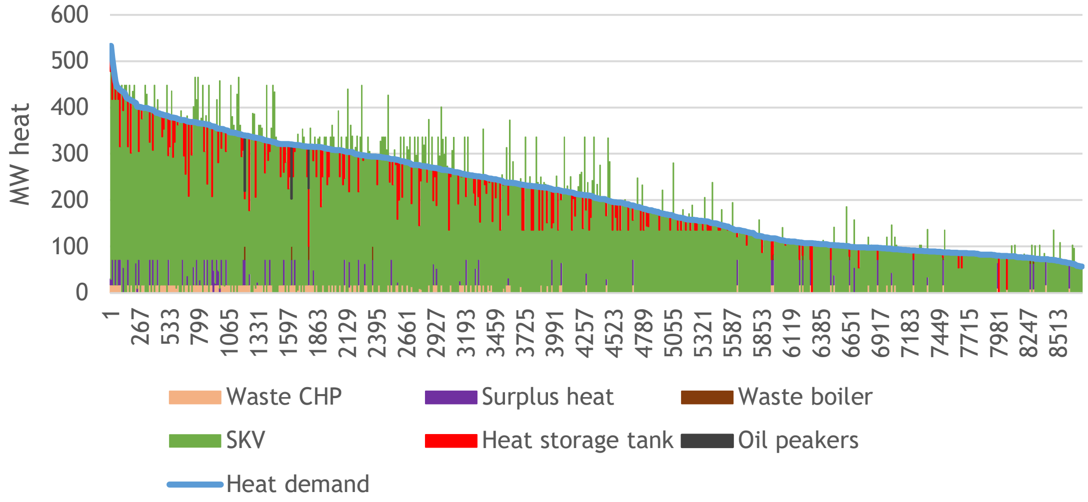

Figure 20: Duration curve for heat demand and supply in the CCUS scenario

The figure below illustrates what part of the Skærbæk plant delivers the heat production in the BAU and CCUS scenarios.

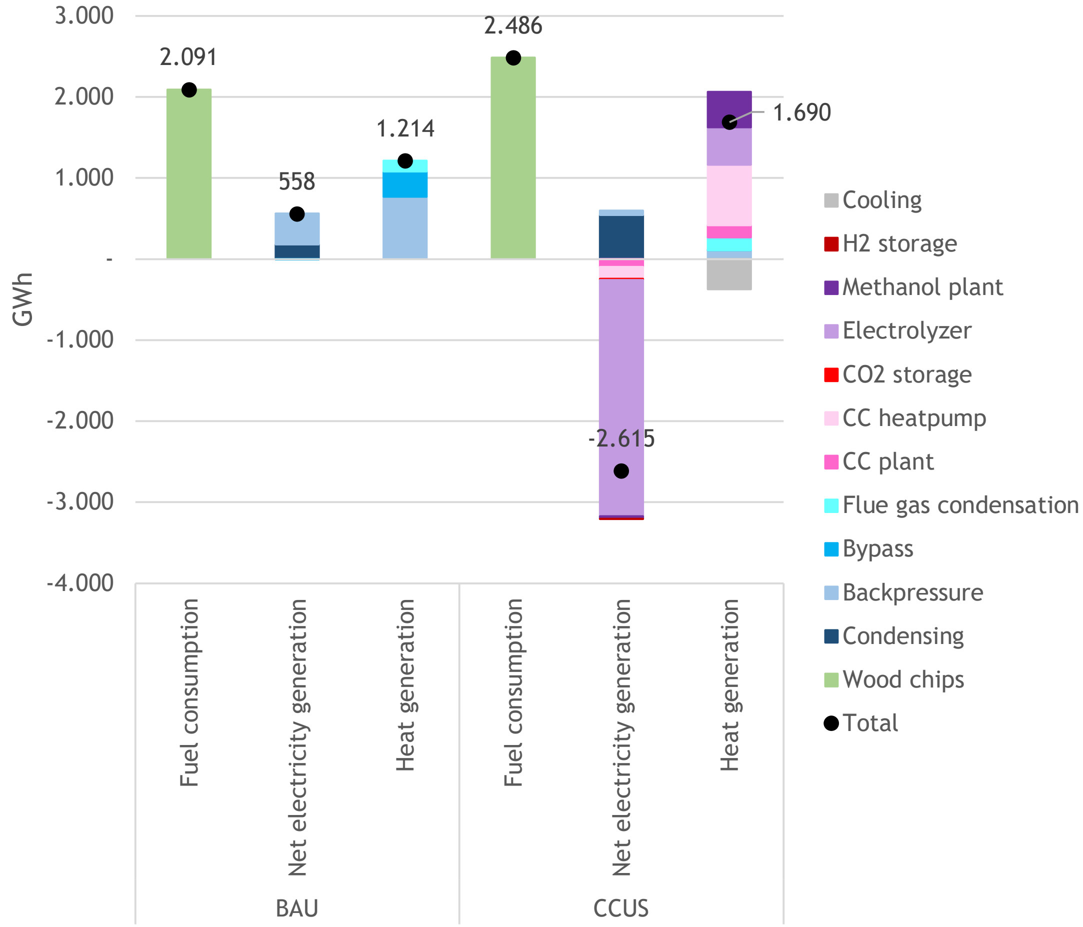

Figure 21: Annual fuel consumption, heat and electricity generation on the Skærbæk plant in the two scenarios in the year 2035 given in TJ.

In the CCUS scenario, a significant part of the boiler's energy production is used for process heat in the CC-plant and in the methanol plant. This means that the direct heat generation from the boiler and turbine is reduced significantly. On the other hand, surplus heat from the CC-plant, electrolyser and methanol plant gives a large contribution to the heat production. Also, the large quantity of excess heat from the CCUS-process means that a significant part of the heat needs to be cooled away.

However, a consequential trade-off manifests in the net electricity generation, which experiences a substantial reduction from 647 GWh in the BAU to -2,593 GWh with CCUS. This negative net electricity generation underscores the energy-intensive nature of the CCUS process, necessitating a substantial power input of app. 3.2 TWh.

As shown below, the total generation of CO_2 from the boilers increases in the CCUS scenario because of increased operation hours. About half of the CO_2 is captured for use in the methanol plant and the remaining CO_2 is captured and stored.

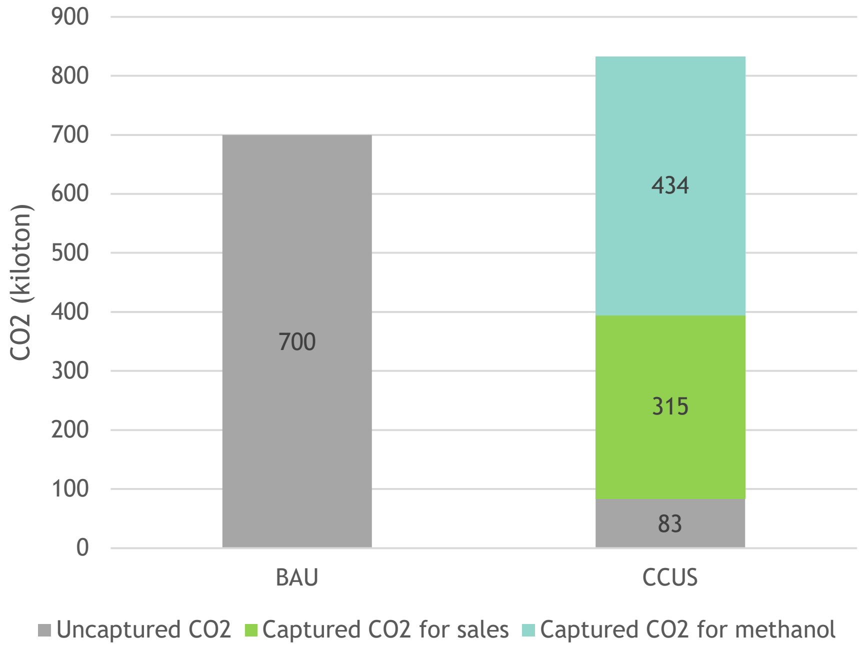

Figure 22: Annual CO_2 flow on the Skærbæk plant in the two scenarios in the year 2035.

Analysing the duration curve for the electrolyser shown in Figure 23 reveals that the electrolysers are operated when electricity prices are the lowest. The cost of electricity is the most important economic factor in the methanol production and electrolysers are therefore optimised to run during the hours with lowest electricity prices. However, the fact that the methanol plant must operate for 4,500 full load hours means that the plant also needs to operate during hours with moderate electricity prices.

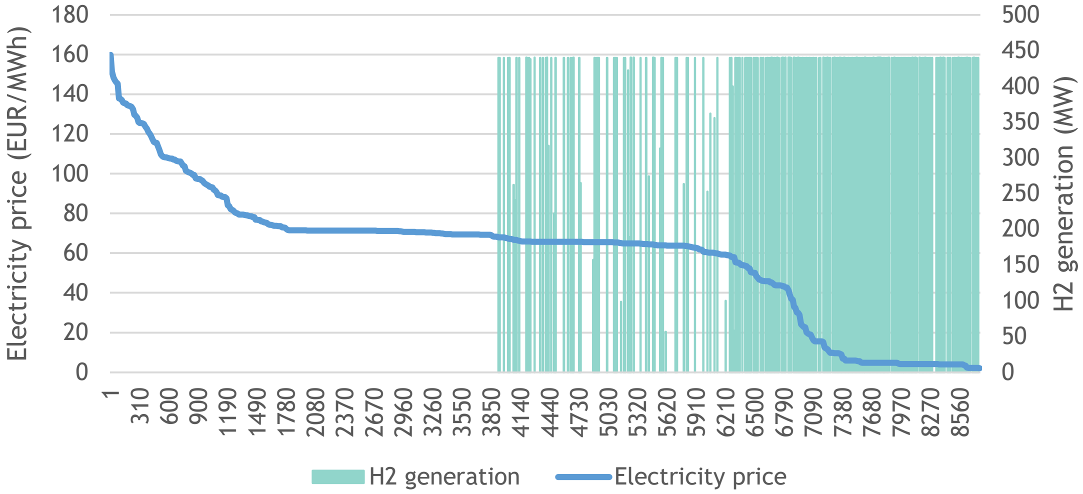

Figure 23: Duration curve of the electricity price in Western Denmark and the corresponding hydrogen generation.

Finally, examining the trend depicted in Figure 24 unveils the optimization mechanisms deployed within the plant in response to electricity price fluctuations.

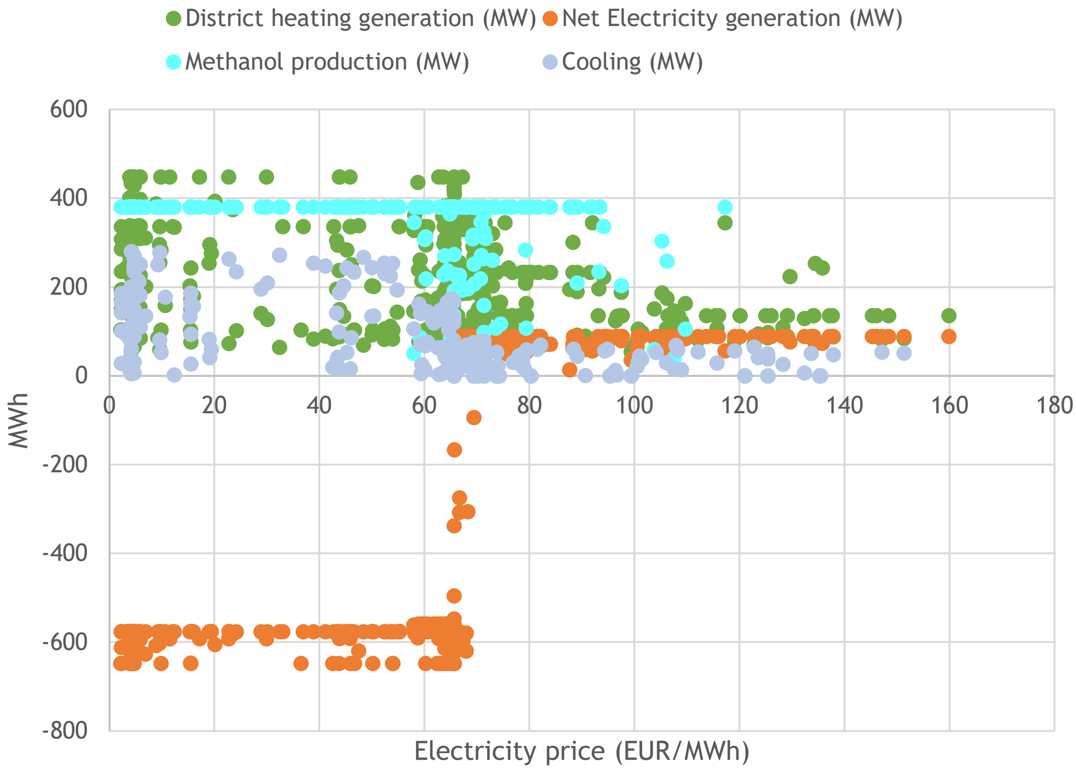

Figure 24: XY-diagram of different generation modes on Skærbæk (Y-axis) at different electricity prices (X-axis)

When the prices are lower than roughly 70 EUR/MWh, corresponding to the lower half of the price spectrum, the system exhibits a peak methanol production of 380 MWh alongside a distinct negative net electricity generation.

As prices exceed 50% of the maximum threshold, methanol production becomes economically unviable, prompting cessation. This shift allows the CHP facility to have a positive net electricity generation and deliver power to the grid.

Conclusions

An overview of the production from the Skærbæk CHP plant is shown in Table 4 below.

Table 4: Overview of the production from the Skærbæk CHP plant in the analysed scenarios in 2035.

Skærbæk plant	BAU	CCS Fixed	CCS Market	CCUS
Wood chip consumption (GWh)	**2,091**	**2,204**	**2,486**	**2,486**
Full load hours	**6,150**	**6,482**	**7,312**	**7,312**
Net electricity generation (GWh)	**558**	**409**	**317**	**-2,615**
Condensing	178	256	375	543
Backpressure	385	314	219	54
Bypass	-5	-1	-1	-0
CC plant		-56	-97	-97
CC heatpump		-86	-148	-148
CO2 storage		-17	-30	-13
Electrolyzer				-2,916
Methanol plant				-31
H2 storage				-6
District heating generation (GWh)	**1,214**	**1,368**	**1,477**	**1,690**
Flue gas condensation	135	142	160	160
Backpressure	769	627	437	108
Bypass	310	81	79	0
CC plant		86	149	149
CC heatpump		432	746	746
Electrolyzer				464
Methanol plant				439
Cooling	0	0	-93	-374
Captured CO_2 (kiloton)	0	434	749	749

The main results and conclusions from the analyses are:

- In the BAU-scenario, the operating hours of the Skærbæk CHP plant increases compared to today. With the assumed development in fuel and power prices and the development of the framework for waste plants in Denmark, Skærbæk CHP becomes more competitive and increases the heat production from app. 3.5 PJ today to 4.5 PJ in 2035. Also, the plant is competitive in the power market when power prices are moderate and high, and the plant produces app. 230 GWh of power in condensing mode.

- In the CCS-scenarios, the operating hours of the plant are further increased, especially in the CCS Market Scenario. The district heating generation increases further, and a significant part of the district heating generation is delivered as surplus heat from the CC-facility.

- In the CCUS-scenario, a significant shift is observed in the dynamics of net electricity production, transitioning from positive to negative on average over the year. District heating generation is further increased compared to the other scenarios and in this scenario the heat production from the Skærbæk plant can cover almost all the district heating demand in the TVIS area. Most of the heat generation is delivered as surplus heat from the CC-plant, the electrolysers and the methanol plant, while the CHP plant delivers process heat for the CCUS-processes and increases power production in condensing mode.

- Hydrogen production is optimized for periods when the electricity value is low, while district heating demand proves significant only in winter months.

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