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FLEXIBILITY OF POWER-TO-METHANOL IN 2030

An investigation of the flexibility provided through electricity consumption in different scenarios for 2030

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Summary

In 2030 the energy system in Denmark must be on its way to achieve a 100 % decarbonised society by 2045. Electrification of most sectors being a cornerstone to achieve this, while Power-to-X and other technologies supplement this, resulting in the future energy system to have a larger share of renewable energy source-based production units like wind turbines, photovoltaics, and biomass fuelled combined heat and power plants, to cover the energy demand. It is therefore essential that the power system is able to react to changes in both supply and demand to ensure a stable and reliable electricity system.

Even though all sectors of society must be decarbonised, not all can be completely decarbonised by means of using electricity directly, why other alternatives are needed. This is mostly in the energy intensive sectors like the transportation sector. Here Power-to-X technologies producing electro-fuels, are be seen a solution, to decarbonise these sectors. As the Danish Government have envisioned a total capacity of PtX to be 4-6 GW by 2030, there is a risk of introducing a large inflexible load to the power system. If the future power system is not flexible, then it comes with a high cost as grid reinforcements and expansions are necessary. As more refined e-fuels than hydrogen are likely to be produced and Power-to-methanol has a higher technology readiness level than power-to-ammonia, this thesis investigates "*How flexible can a Power-to-Methanol plant consume electricity from the electricity grid when participating in the day-ahead market in 2030, considering the technical restrictions of methanol production?*"

As the perspective of this report is 2030, it is essential that the conditions where the PtMethanol plant is operating in is investigated. These conditions are investigated within the Socio-Technical Transition Theory, where technology and markets as parts of society are analysed. Four scenarios are established to investigate how the plant will operate if different policies are effectuated in the future energy system. These are 0) a base scenario where the future energy prices for 2030 as well as tariffs and prices for feedstocks are used, 1) a scenario where the PtMethanol plant is connected to an externally owned wind farm enabling the PtMethanol plant to buy electricity from the wind farm when it is affordable, while still have the security of being connected to the grid, 2) is a scenario where a different tariff scheme is used, where the time of use tariffs are investigated, 3) investigates how a large-scale hydrogen storage and an oversized electrolyser affects the flexibility performance. To obtain all necessary information to model a PtMethanol plant these scenarios, a literature study is performed.

The scenarios are modelled from a techno-economic perspective using the business economic modelling tool, energyPRO. Additionally, flexibility metrics are established to measure the flexibility performance each scenario provide. These flexibility metrics were not applied to PtX before, but it was assumed that the concept flexibility metrics for demand side management in building energy services can be applied to a PtMethanol plant. The metrics are considering whether the scenarios primarily are operating in times of low electricity prices, as the assumption is that high electricity prices equal scarcity in electricity supply due to high demand, why flexibility is needed. Moreover, the metrics are evaluating if additional flexibility can be provided by the PtMethanol plant. This is counting both upward and downward regulation by changing the production by the plant. The performances are evaluated and analysed in a multi-criteria decision analysis. It can be concluded that all investigated scenarios are providing flexibility to the Danish electricity grid. Moreover, that both the electrolyser and methanol production unit can provide flexibility by ramping their production of hydrogen and methanol respectively. Additionally, this investigation shows that the scenario with hydrogen storage is the only one that provides more flexibility than the base scenario. This means on the other hand that a PtMethanol plant operating with a direct line to a wind farm or with Time-of-Use tariffs is less flexible that one without. A PtMethanol plant in 2030 is found to be able to provide load shifting. Through a sensitivity analysis it is also concluded that the electricity prices and prices for the sale of methanol are of most influence on the results. As the obtained price of methanol approaches the assumed cost of e-methanol, the flexibility of PtMethanol plants operating on the day ahead market is decreasing significantly.

Preface

This project is carried out by Nils Thomas Schneider and Zenia Lagoni as a master's thesis for the Sustainable Energy Planning and Management program at Aalborg University. The thesis was conducted in the period of 01.02.2023-02.06.2023.

We would like to thank Peter Sorknæs for the supervision, guidance and for highly valued inputs and reflections throughout the process. Furthermore, thanks to EMD International A/S and especially Marta Irena Murkowska and Anders N. Andersen for their contributions, reflections and feedback to this report.

Reading guide:

Throughout this report conversion rate of 7,45 DKK per EUR and 6,80 DKK per USD.

A period is used as thousand separator and a comma as decimal separator as an example: 2.000,1 kr.

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1 Introduction

In 2021 the Danish Government introduced a national strategy for Power-to-X (PtX), where PtX plays an important role in the transition from fossil fuel into a sustainable and CO_2 neutral society. PtX therein is defined as a summarizing term for technologies that produce hydrogen from electricity and water, also providing the possibility to further refine the hydrogen to so-called electrofuels (e-fuels). These are envisioned to replace currently used fossil fuels in the transportation sector. The heat created in their production is imagined to be used in district or process heating. To play a role in the transition from fossil fuels it requires the electricity production to be based on renewable energy sources (RES), and for refinement of the X-product into e-fuels, the often-needed CO_2 must either originate from sustainable sources e.g., biomass etc. or directly from the atmosphere to be sustainable. (Danish Ministry of Climate Energy and Utilities, 2021a)

As the processes for producing PtX are very energy-intensive, the strategy is stressing that the PtX fuels should only be used for purposes where direct electrification is not a possibility, e.g., due to technical delimitations or high costs. This mainly applies to heavy transportation, aviation, or in some parts of the industrial sector e.g., chemical processes. (Danish Ministry of Climate Energy and Utilities, 2021a) The *Climate Response 2045* report by H. Lund et al. (2021) also recommends that fuels for trucks should consist of 30% e-fuels like DME or methanol in 2030 and 55% in 2045 (H. Lund et al., 2021). Furthermore, this is underlined with analyses by the Danish Energy Agency which concludes that e-fuels from PtX might provide the cheapest CO_2-reduction for these prementioned sectors compared to other types of biofuels. Therefore, a total capacity of electrolysis of 4-6 GW by 2030 is envisioned Denmark’s national strategy for PtX (Danish Ministry of Climate Energy and Utilities, 2021a), H. Lund et al. (2021) expect up to 1,2 GW of electrolysis build by 2030 (H. Lund et al., 2021).

The increase in electricity demand through increasing PtX capacity among others requires an expansion of the electricity produced. The electricity produced shall be used for direct electricity consumption, energy conversion like PtX and storages. (Danish Ministry of Climate Energy and Utilities, 2021a, 2021b) The electrolysis plants are expected to operate flexibly by producing when green energy is in abundance and shutting down when energy from RES is low and when the electricity prices are high. The flexible operation of PtX plants is expected to lead to operation in times where settlement prices on electricity markets are more beneficial towards these plants, thereby increasing their economic performance. Furthermore, the flexible operation strategy can postpone or reduce needed reinforcements and investments in the electricity grid, since the system can be utilised more efficiently. (Danish Ministry of Climate Energy and Utilities, 2021a)

2 Future Challenges in Power System Flexibility with Fluctuating Renewable Energy Production and Inflexible Demands through Power-to-X

To investigate what flexibility is and why it is important, a basic understanding of power systems needs to be established. In order to maintain a well-functioning electricity grid, it needs to always stay in a balance between electricity production and consumption (P. D. Lund et al., 2015). To maintain this balance, these two have to be on the same level at all times. This balance is endangered through uncertainties and irregularities on each side. To meet these, a power system needs to be flexible. Flexibility can therefore be seen as a power system's ability to react to imbalances in demand and in supply. New technologies like PtX can provide challenges to maintain flexibility in a power system. (Babatunde et al., 2020) With the integration of fluctuating renewable energies like wind and solar power new causes for imbalances are introduced to power systems (Babatunde et al., 2020; Danish Energy Agency, 2015; Huber et al., 2014; P. D. Lund et al., 2015). The supply becomes less predictable through the integration of fluctuating energy sources. This lower predictability in turn leads to a higher need for flexibility in the power system to smooth their impact. Especially unexpected ramp down of these energy sources will lead to such issues. Wind power can experience an unexpected reduction of capacity of up to 100 % while solar can experience a reduction of roughly 70 %. Ramping up, even with unexpected high possibilities for production, can still be done according to expected production, by limiting the production. The actual experienced changes in current power systems are smaller, since these usually contain a mixed amount of energy sources, while still relying partly on fossil fuelled power plants. (Babatunde et al., 2020) As described in Chapter 1, until 2030 new technologies lie PtX might enter the electricity system, while others might leave. To determine the challenges changes in the Danish electricity system will introduce to maintaining flexibility in 2030, the expected developments are investigated.

2.1 The Future Energy System of Denmark

The future energy system in 2045 should be 100% decarbonised and therefore an increase in electricity consumption is essential. The increased electricity demand applies in all sectors in society, as both direct electricity consumption and as indirect demand when used to producing electricity-based fuels and heat to cover those demands. The current energy system is grouped into four sectors: heating, industry, transport, and electricity. (H. Lund et al., 2021). The heating sector in the future energy system is expected to be carbon neutral by 2035, where all gas used for individual heating must be supplied with sustainable gas (Danish Ministry of Climate Energy and Utility, 2022). Moreover, all gas and oil boilers must be phased out and replaced by heat pumps for individual heating and if possible, connected to district heating. The district heating plants must also be fuelled by sustainable biomass in a combination with electric boilers and large heat pumps, as well as large seasonal heat storages. The electric boilers and heat pumps in the future heating system require electricity to provide heat and are thereby contributing to a larger electricity demand compared to today. Heat demand is expected to increase from 46,16 TWh in 2030 to 49,33 TWh in 2045. (H. Lund et al., 2021)

The industrial sector should be electrified to the possible extend, while e-fuels must be introduced to decarbonise the rest. Heat pumps should be implemented to cover the remaining heat demand in the sector. Furthermore, sector coupling between industries and the district heating grid will increase the energy efficiency, as the excess heat from industries will be utilised in the grid. These initiatives will increase the electricity demand in the future compared today. (H. Lund et al., 2021)

For the transportation sector the decarbonisation is executed mainly through means of electricity and e-fuels. The share of electric vehicle and hybrid cars are assumed to be 1,4 million and 0,4 million respectively. However, the hybrid vehicles should only be used in the transition phase and are to be phased out before 2045. The e-fuels are produced in PtX processes as introduced in the previous chapter. The electricity for their production should be RES-based in order to produce carbon-neutral fuels, and thereby leading to an increase in electricity demand by this sector as well. (H. Lund et al., 2021)

Finally, the electricity sector should also undergo a transition into a decarbonised sector. In order for the previous sectors to transition successfully and operate based on electricity, it is necessary to integrate the fluctuating electricity supply with the fluctuating demand including more heat pumps, electric vehicles, industry and PtX. The energy system must therefore be made smart. As stated previously the electricity demand will increase if the other sectors of the energy system are electrified. *The Climate Response Report* by H. Lund et al. (2021) have estimated how electricity demand will evolve from 2020 until 2045 cf. Figure 2.1. (H. Lund et al., 2021)

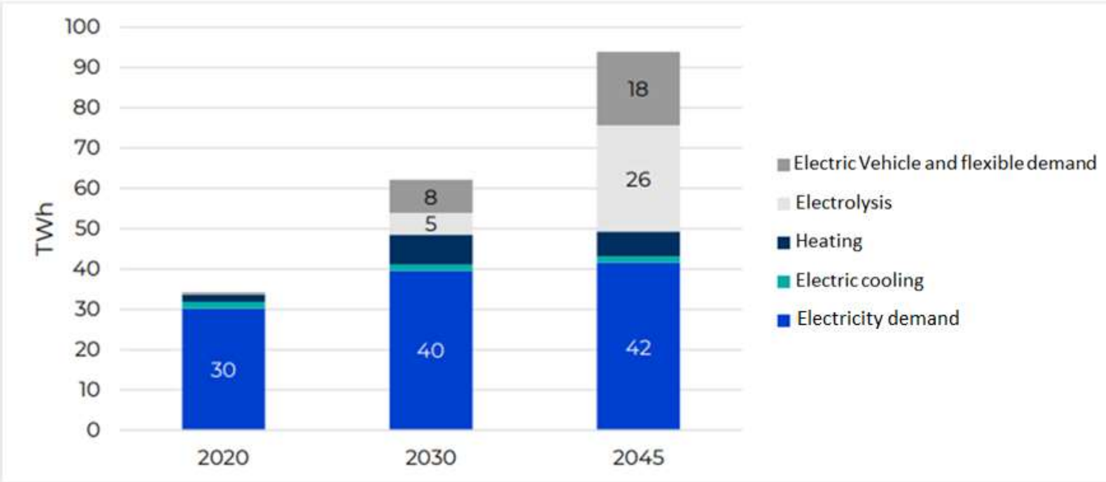

Figure 2.1: Development in electricity demand. (H. Lund et al., 2021)

In order to meet the electricity demand in 2045, which is expected to almost double from 2020 to 2030, the electricity production must be increased. To achieve this, H. Lund et al. (2021) suggest installing 5 GW of photo voltaic until 2030 and 10 GW until 2045. Moreover, wave energy must take a share of 130 MW in 2030, even though the technology is fairly new and require research and development before it can be implemented in large scale. Finally, more wind turbines must be installed, with installed capacity increasing to 11,4 GW by 2030 for on- and offshore wind turbines combined and to 19 GW by 2045. (H. Lund et al., 2021) The future energy system is thereby expected to consist of more intermittent and fluctuating energy production where flexibility in the system both on demand and supply side is essential to ensure a stable and robust system.

2.2 The Necessity of Flexibility in Power Systems

If a power system lacks the ability to react to predicted as well as unpredicted changes, this will cause negative effects. By 2030 more than half of the conventional power plants in Europe will be decommissioned (Taylor, 2021), which increases the necessity to have substituting technologies to secure a reliable supply of energy. In times with low water levels in water reservoirs in hydropower plants and if wind and solar contributions are less, then energy scarcity is an arising problem. In order to prevent a large blackout, it might be necessary to disconnect consumers, and thereby allowing more important consumers e.g., hospitals and datacentres to stay connected and supplied with electricity. These disconnected consumers would thereby provide flexibility to the power system, as their disconnection balances the amount of electricity generation and consumption in the power system. Issues with energy scarcity is mostly occurring in times of cold and calm weather in the morning and afternoon hours of the day since this is the time where the demand is highest. (European Council & Council of the European Union, 2022; Kriseinformation, n.d.) In summary, a lack of flexibility lead to not yet restrictive but limitation in consumption to regain the lost flexibility to the cost in a loss of comfort for consumers. A lack of flexibility can in other cases turn into bigger imbalances, that can in consequence lead to outages. (Electric Power Research Institute, 2016) Such outages will lead to a loss in comfort for private consumers while causing socio economic damages for a country's economy (Babatunde et al., 2020; Heffron et al., 2021). Babatunde et al. (2020) describe electricity as requirement for a functioning society, because it is needed in almost all parts of society (Babatunde et al., 2020). Such are assumed to be medicine, transport, lighting, food supply, or electronic payment as examples of sectors relying on the use of electricity. Therefore, electricity is assumed to be an important requirement to every-day life in Denmark. Due to this importance of electricity, flexibility of the power system is important to maintained on an adequate level to ensure a secure access to electricity.

P. D. Lund et al. (2015) suggest that there is a cost associated to a failure in maintaining an adequate amount of flexibility, namely a cost in the loss of welfare. In contrast to this stands the costs of maintaining that flexibility. In European countries the cost of maintaining flexibility is often less valued than the loss in welfare, which leads to a high degree of power system flexibility. (P. D. Lund et al., 2015) However, Energinet propose a practical change the electricity grid, where the security of supply in 2030 will be 99,993 % instead of the current 99,996 %. Thus, their customers will expect disconnection 38 minutes per year compared to the current 20 minutes. If the security of supply must be kept at 99,996 %, this comes with a high cost, which eventually is paid by the consumers. By allowing more interruptions for the consumers, this will be limiting the need for reinforcements in the grid. Moreover, Energinet (2022c) stress that a risk of power insufficiency might be higher in the future, when the system is more reliant of RES, which will lead to more outages especially in times of calm weather if the power system is not flexible. (Energinet, 2022d) However, ENTSO-E (2023) stress that reinforcement and strong interconnections are necessities to allow bidirectional power flows from the various flexibility sources i.e., consumers, producers, storages, and cross-sectoral. Moreover, the bidirectional power flows introduce new load conditions for the power system. Furthermore, rewards for flexibility providers as well as innovations in power electronics (i.e., inverters etc.) must be a part of the solution of have a flexible power system in the future. (ENTSO-E, 2023)

As suggested by Section 2.1 the electricity system in 2030 is made up of RE from fluctuating energy sources to a larger degree than currently. This has an impact on the need for flexibility, because through a higher share of fluctuating resources the energy supply losses a part of its flexibility. A lack of flexibility in the power system could also limit the amount of renewable energy sources used in an electricity system and thereby also limit the transition towards a decarbonised energy system. Therefore, to avoid described consequences of a lack in power system flexibility, other measures to maintain a reliable power system need to be emphasised on.

In the current power system, some effects are used to provide the system with a degree of flexibility, without taking active measures (Huber et al., 2014). Most significantly spatial smoothing is able to provide stability for the power system's frequency. The former being a geographical distribution of power generation as well as loads. If connected through sufficient transmission lines, the different conditions and number of actors can smooth absolute changes in the overall power system. This effect can especially be attributed to wind power but applies to solar power as well. (P. D. Lund et al., 2015) Besides there are also methods to actively provide flexibility in a power system.

2.3 Measures to Provide Flexibility

According to P. D. Lund et al. (2015), flexibility in the power system can be increased through different approaches covering both supply side and demand side (P. D. Lund et al., 2015). As flexibility provided through electricity generation is expected to decrease, measures on the demand side gain importance. The demand is also developing, with new demands introduced through electrification of other energy sectors and PtX. These new demands therefore need to provide an adequate amount of flexibility to be able to maintain a reliable power system.

2.3.1 Demand Side Management

Demand side management (DSM) is defined as strategies for affecting the patterns and magnitude of electricity consumption of the end-users. This can be done by reducing the consumption by peak shaving, conservation of energy or by increasing the consumption by valley filling or load growth. Subsequently it can also be done through rescheduling of the energy demand by load shifting. Figure 2.2 illustrates the different types of DSM. (P. D. Lund et al., 2015)

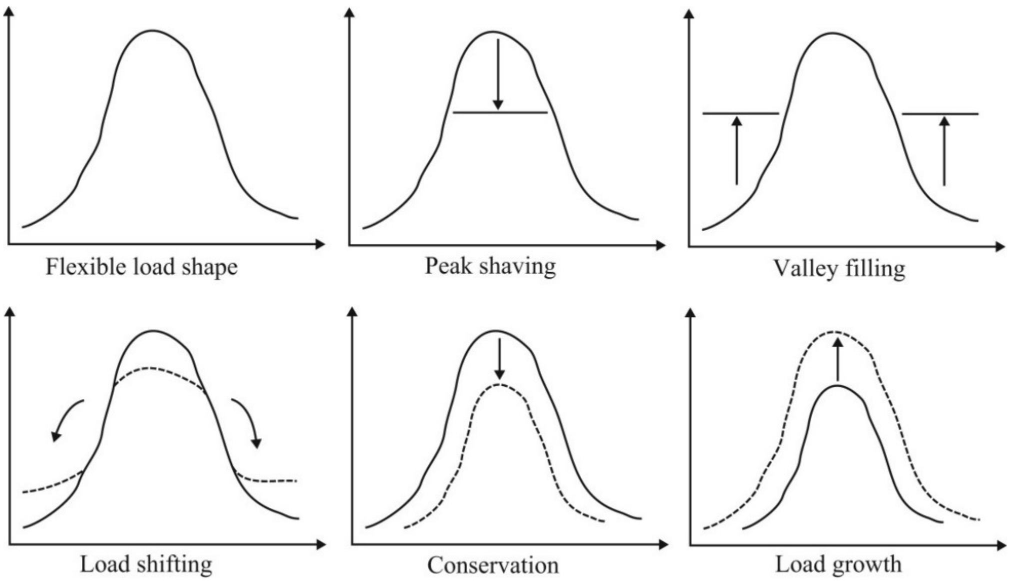

Figure 2.2: Categories of DSM. The Flexible Load Shape is the initial shape of the energy demand, whereas the others are the impact of different DSM strategies (P. D. Lund et al., 2015).

The purpose of peak shaving is to smooth peaks by reducing the demand for energy during such peaks. This can be done by means of batteries, by activation of an on-site power unit which is not connected to the public power system, or by temporarily downscaling of production by the end-users. (Wang et al., 2019) The latter one is energy conservation, which means that the energy demand is kept at the lower level (Constellation, n.d.). Like peak shaving, valley filling is a method of decreasing the difference between minimum and maximum power peaks during a period. In contrast to peak shaving, valley filling increases the energy demand in valley-periods. (Wang et al., 2019) Besides valley-filling, load growth is the only operation strategy aiming at increasing the energy demand. This is done by an increase of the electrical load, e.g., when a power plant upregulates their produced energy, due to a larger demand at the time. Heat pumps and thermal storages can also provide load growth in a system. (Jabir et al., 2018) Finally, in order to provide load shifting, the system often require an intermediate storage unit or a utilisation rate of less than 100% in order to be able to both increase and decrease the energy demand. Moreover, load shifting can be executed by moving flexible loads from peak-load periods to valley-load periods. Many loads have a technical limit of how much load shifting they can provide as their end-use function often require a specific amount of energy, e.g., a specific minimum temperature required etc. Load shifting is most beneficial compared to the other types of DSM as it allows continuity of the process while decreasing the energy demand, without compromising with the quality of the final product. This could be done via storage units as well, but if the conversion to storage is left out, the efficiency is higher. (P. D. Lund et al., 2015)

DSM can be used to provide flexibility to ensure a balance between production and consumption of energy. Moreover, DSM can benefit the energy system on various parameters, since it can be used for reducing price spikes, facilitate a shifting in the market power from the generation units to the consumers and replace and postpone expansion of the electric infrastructure due to a more efficient utilisation of the produced power. (P. D. Lund et al., 2015)

2.3.2 Supply Side

In most current power systems, the balance is currently mainly handled by the supply side. This is through regulation of the power output of e.g., power plants to obtain balance in the grid. According to P. D. Lund et al. (2015), the power plants can be divided into three flexibility categories: base load, peak load and load following plants. Baseload plants are conventional power plants like coal and nuclear. They preferably operate at nominal power, where ramping or shutdown of the plant are related with high costs and technical limits, and thus avoided. Peak units like gas turbines are used irregularly when the demand for energy is high. (P. D. Lund et al., 2015) These have a fast reaction time and are contributing to security of supply of energy during peaks. Moreover, investment costs for these peak units are lower compared to an oversized main plant able to meet peak demands. Some of the main characteristics of the peak units are that it should have a fast response time both for start and stop and always have a secure and stable energy supply when operating (Energi på Tværs, 2018). Lastly, a load-following plant is adjusting the power output as the demand fluctuates throughout a day (Nuclear Power, n.d.). Hydropower plants, gas turbines and storages can provide this type of flexibility, due to the requirement of fast start-up and ramping times. (P. D. Lund et al., 2015) Electricity storages can be used to both perform measure on supply as well as demand side (Electric Power Research Institute, 2016). They provide the possibility to detach the moment of electricity production from the consumption. Therein, *"A higher storage capacity allows the storage to respond to longer mismatches, while a higher power capacity allows responding to mismatches of higher magnitude."* (P. D. Lund et al., 2015).

2.3.3 Energy Units Providing Flexibility in the Current Danish Energy System

As described previously in this chapter, flexibility is essential to ensure a stable power system. This flexibility can be supplied through different measures. In Denmark it is mostly supplied by decentralised electricity production and consumption units like CHPs, electric boilers and heat pumps connected to district heating. The large number of CHPs in operation in Denmark could lead to a loss of flexibility if forced to be in operation because of heat demands they are supposed to supply. However, since heat is a form of energy that is storable, these CHPs do not present a large amount of inflexibility. This is done by shifting their energy production in time using heat storages that decouples the heat generation from heat demand in time. By combining the CHPs with heat storage, they can provide a form of supply side management. Concluding the usage of heat storage in combination with CHP provides the power system with flexibility. This effect is enhanced by the possibility of bypassing the turbine in CHPs, making them operate independently of the electricity market. Furthermore, the operation in combination with heat storage makes it possible to regulate the production of running units if imbalances occur. (Danish Energy Agency, 2015)

Also, different methods of producing the required heat for the heat demand provide flexibility. Through the usage of electric boilers or heat pumps, the production of heat is providing several options to influence the power system by also consuming electricity. This flexible electricity consumption can be used for DSM. Another measure used to maintain flexibility is the construction of interconnectors between regions, markets, or countries. These provide a higher spatial distribution and a smoothing of uncertainties or imbalances at a lower cost than other measures. (Danish Energy Agency, 2015)

If balancing a power system that contains a high amount of fluctuating renewable energy depending on the weather like wind energy, the weather forecast and thereby the forecast of wind power production becomes an important part of the power systems. (Danish Energy Agency, 2015) With accurate forecasts, bids placed by the wind turbines on the electricity markets are more accurate and thereby reduce the imbalances and the need for flexibility.

2.3.4 Electricity Markets Providing Flexibility

As mentioned, electricity markets play a role in the Danish system of procuring system flexibility. The biggest electricity market in Denmark is the day-ahead market, where approx. 70% of electricity in Denmark is traded daily. Through matching bids of production and demand a day before operation it ensures a general hourly balance of electricity demand and supply. The price setting mechanism is based on the merit order principle, meaning the highest accepted price for a selling bid will determine the price for all bids. Thus, the price is set by the final accepted bid to meet the predicted demand each hour. (Energinet, 2019) A high demand will thereby often lead to high prices, if the RES cannot meet the demand, and conventional power plants have to contribute as well. The day-ahead market already tries to achieve a certain predictability in the power system, since all bids are determined the day before. However, if the bids placed cannot be fulfilled, different markets are in place to ensure that these imbalances will be balanced. The intra-day market is based on more short-term trading of energy, closing an hour before operation and can thereby serves to correct imbalances stemming from uncertainties in the day-ahead market, like an unprecise weather forecast. (Energinet, 2019) If imbalances in a shorter timeframe occur, the market of ancillary reserves provides a platform for countering imbalances (Energinet, 2022a). It is divided into different markets. There are two market zones in Denmark based on the two synchronous grids. One is west of the Great Belt (DK1) and the other is east of the belt (DK2). This report investigates the DK1 markets as the share of wind energy is highest there compared to DK2 (Wanscher, 2022). It is assumed that therefore the current market structure and dynamics are therefore closer to those predicted for 2030.

In the DK1 market, there are 3 ancillary reserve markets: Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR). The first provides an automatic response to small deviations in frequency (Energinet, 2022a). It responds to drops in the frequency of 200 mHz by restoring the balance between generation and demand. Therefore, it can be provided by supply and demand as well. The providing units must be able to provide half of their capacity within 15 s and full capacity after 30 s. This capacity needs to be able to be maintained at least 15 min. (Energinet, 2019) The aFRR is used to indirectly restore the grid frequency during major imbalances, after the stabilisation of the frequency by the FCR (Energinet, 2022a). Units must be able to ramp to full capacity within 15 min. It can be supplied by demand or generation, which are activated by a signal from Energinet. (Energinet, 2019) The mFRR is manually activated and is meant to relieve the other reserves if imbalances occur due to restrictions or outages (Energinet, 2022a). It must be able to be supplied within 15 min (Energinet, 2019).

As market shares of said reserves and intra-day markets are comparatively small to the day-ahead market and weather predictions develop to more accurate forecasts, it is assumed that most flexibility that an electricity unit provides is provided through the day-ahead market.

2.4 Inflexible Loads and Production Units

Some units in the power system are inflexible in either energy production or consumption. Whether energy unit is flexible or inflexible is dependent on the service they provide and when this is provided or requested depending on if it is from supply side or demand side. (P. D. Lund et al., 2015) For inflexible production units the energy produced cannot easily be controlled by humans or units that run continuously due to costs. These units are usually operated at their nominal power, due to high costs or technical limits if regulating the power output or input. (Energy Transition Model, n.d.) Must run units can also be units which provide grid stability and system voltage i.e., large power plants. These are needed to maintain the grid frequency by means of large share of inertia. Moreover, plants that are required to operate since their end-product is used in other processes, e.g., CHPs which have to provide heat to the district heating system, or as a steam provider for industrial processes. However, CHPs are not considered must run units in Denmark, since they have the ability to store heat for later use or bypass their turbine and thus only produce heat. Despite of these options, some CHPs are producing power when the electricity prices are zero or negative.

This is due to high costs related to stopping the CHP if it is only for a short duration, or that the alternative heat sources are even more expensive e.g., activation of an oil boiler. Finally, there can also be technical and economical restrictions that are preventing the units to stop their power production. (Danish Energy Agency, 2015)

When it comes to inflexible loads, the units are operating as base-load units are within this category. The base-load units have a fixed energy consumption and can therefore not be regulated easily. This can be industrial processes which need to run constantly or consumers of electricity that do not respond to electricity prices i.e., individual households, companies, hospitals. (Energy Transition Model, n.d.; Heffron et al., 2021)

If the power system has a high share of inflexible loads, then required peak generation capacity must be increased to ensure a stable power system. Østergaard et al. (2015) stress that if individual heat pumps in Denmark follow the standard heating profile, the peak demand should be increased by 3%, whereas it for electric vehicles is 16% due to the time for changing being at the afternoon demand peak. Furthermore, a fixed energy demand is also decreasing the utilisation of fluctuating RES (i.e., wind and solar) and more dispatchable plants like CHPs will need to produce a larger share of the electricity needed to meet the energy demand daily. Moreover, Østergaard et al. (2015) present an increase in utilisation of offshore wind power of 1,4 % - 5,5 % if charging of electric vehicles is made flexible, and an even higher rate if storages are increased which is adding additionally 2,9 % higher utilisation of offshore wind energy. (Østergaard et al., 2015) Inflexible loads should thereby be considered in the planning processes for a carbon neutral society. In conclusion, to handle inflexible loads, the electricity generation has to maintain a high degree of flexibility otherwise, the possibility of imbalances in the power system and thereby damages to equipment or outages is increased. However, if the generation needs to remain flexible, it is not able to rely on inflexible fluctuating RE sources like wind and solar, thereby hindering the transition from fossil fuels.

As described previously, the share of PtX is expected to increase heavily in the coming years (see Chapter 1) to enable the full decarbonisation of the energy system (Danish Ministry of Climate Energy and Utilities, 2021a). There might be a risk of introducing a large inflexible load or new peaks in electricity consumption if PtX is introduced to the energy system. Therefore, an investigation of the flexibility that PtX technologies provide is highly relevant for the development of the power system in relation to its reliability and the experienced changes in welfare with changing degrees of power system flexibility.

2.5 Power to Methanol

As the future Danish energy system should include 4-6 GW of PtX in 2030, as envisioned in the national PtX strategy, it is likely that a part of the produced hydrogen will be used in synthetic fuels such as ammonia or methanol (Danish Ministry of Climate Energy and Utilities, 2021a). According to the Danish Energy Agency (2022) ammonia engines are at a Technology Readiness Level (TRL) of 4-5 and is thereby only in a prototype stage, while methanol engines have a TRL of 8-9 thereby being in commercial scale but yet not completely competitive. As the timeframe of this report is 2030, it is considered that ammonia engines might still not available as a commercially competitive solution, and that methanol engines might have become competitive. (Danish Energy Agency, 2022) Therefore, methanol production is assumed to be more relevant for road and shipping transport in 2030 and is main point of further investigation. Methanol can be used as fuel in the transportation sector and industrial sector where electrification is not viable due to technical limitations and process requirements such as temperatures (Dansk Energi, 2020). Furthermore, methanol and DME are expected to supply 30 % of transportation fuels demand by 2030 (H. Lund et al., 2021). Therefore, it is relevant to investigate the Power-to-Methanol (PtMethanol) technology in regard to its properties that could either provide flexibility to the power system or pose a challenge by introducing an inflexible load.

PtMethanol is defined as a process of splitting water (H_2O) into oxygen (O_2) and hydrogen (H_2), using the hydrogen to produce methanol (CH_3OH) by combining carbon dioxide (CO_2) and hydrogen in a hydrogenation process only employing electricity as energy source. Firstly, the hydrogen is produced by electrolysis. Electricity is used to separate the water molecules into hydrogen and oxygen. In order for the hydrogen to be sustainable, the electricity used must be produced from RES. (Danish Energy Agency, 2017) To form methanol a catalyst is used for combining hydrogen and carbon dioxide. This process is operated at 50-100 bar and with temperatures of 200-300 °C. Since the nature of the reaction that forms methanol is exothermic, meaning it produces energy by reacting, it produces enough energy to maintain the necessary temperature level required. The product formed in the methanol synthesis is called crude methanol, a mix of both methanol and water. Subsequently, the crude methanol is distilled to separate the methanol and water, resulting in pure methanol as the end-product (See Figure 2.3). (Cui & Kær, 2020)

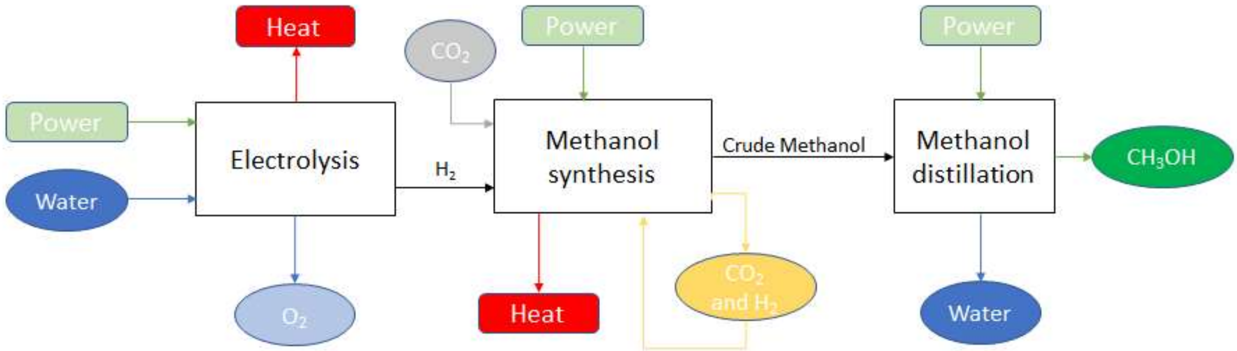

Figure 2.3: Schematic of Power-to-Methanol process, based on (Danish Energy Agency, 2017)

In the future energy system PtX, namely electrolysis, is often seen as a future contributor to a high power system flexibility (Danish Ministry of Climate Energy and Utilities, 2021a). Electrolysers are expected to have the ability to ramp up and down quickly. (Bessarabov & Millet, 2018; Buttler & Spliethoff, 2018; Danish Energy Agency, 2017; Lange et al., 2023; Schnuelle et al., 2019) This ability provides a possibility to quickly change planned production, shifting them from or into other times, thereby providing load-shifting. This is assumed to be possible as the amount of produced hydrogen or fuel is kept equal. However, these fuels need to be storable and therefore their production can be decoupled from their consumption in both time and place. As methanol production in combination with electrolysis will be a part of the future energy system, which is envisioned to provide flexibility to the power system, a question whether it will be able to provide such flexibility can be asked. Since both technologies are expected to only consume electricity, this flexibility will be limited to measures provided by DSM.

2.5.1 Power-to-Methanol and Flexibility

The topic of how PtMethanol can provide flexibility in the power system is currently still being researched upon. The methanol production is a well-known process but an electrified and RES-based process interacting feasibly with intermittent energy is fairly new. According to the article by Schnuelle et al. (2019) almost no literature on how PtMethanol can provide flexibility and operate flexible was found in 2019, underlining that this is a research gap. (Schnuelle et al., 2019)

A study by Chen & Yang (2021) stresses that process flexibility related to PtMethanol has high potential benefits when the RES share is high, where a significant reduction in costs can be achieved as lower prices of electricity are assumed then. They stress that electrolysers can operate as flexible loads whereas the chemical synthesis reactors used in the methanol production often require a more careful operation to be flexible. In addition, a potential "*of incorporating load flexibility in the chemical processes to improve the economics of integrating variable renewable energy"* through PtMethanol is mentioned. It is however not investigated if and how PtMethanol plants could provide flexibility only suggesting that different units in the PtMethanol plant will therefore need to be operated individually within the limits of flexibility they each can provide. (Chen & Yang, 2021)

In recent years it is reported that electrolysers can react quick to changes in their electricity supply (Danish Energy Agency, 2017; Schnuelle et al., 2019). Regarding methanol synthesis, Cui et al. (2022) suggested that theoretically it is possible for a to change its load according to a change in electricity supply (Cui et al., 2022). Ostadi et al. (2023) modelled a combined electrolysis and methanol synthesis plant. In modelling their plant, they concluded to model the methanol synthesis without any ability to react to electricity supply changes (Ostadi et al., 2023). Furthermore, the model by Ostadi et al. (2023) was conducted using a fixed price for electricity, while Cui et al. (2022) only investigated the technical possibility for a flexible operation. As PtMethanol is part of the 2030 electricity system, it is assumed to also be an actor on the electricity market, with its operation being influenced by fluctuating electricity prices. As this is not found to be investigated yet, this report therefore aims at an investigation of a combined PtMethanol plant, where all parts of the plant can operate with varying degrees of flexibility, reacts to changes on the electricity markets and whether this can provide flexibility to a power system by providing form of DSM.

3 Problem Formulation

As presented in Chapters 1 and 2 a power system must be kept in a balance of supply and demand. This balance is ensured by a degree of flexibility in both generation and consumption of electricity. With increasing shares of fluctuating energy sources, the flexibility of electricity generation is decreased. Therefore, it is important to maintain or increase the flexibility of electricity consumption. Power-to-X technologies playing a part in plans for the future energy system, are envisioned to achieve a highly flexible consumption through Demand Side Management. The term PtX summarises different technologies and while an electrolyser probably will be able to react quickly to changes in its electricity supply, hydrogen is only used as feedstock for methanol production in the case of Power-to-Methanol. As a Power-to-Methanol plant experiences more technical limitations to its ability to change loads, the flexibility of a combined Power-to-Methanol plant is questionable. This would also decrease the flexibility in consumption it might destabilise the power system, if Power-to-Methanol plants are built on a large scale. Different studies have investigated the possibility to operate such plants with varying degrees of flexibility, however these were not investigated on their interaction with electricity markets. Therefore, the following research question is formulated:

How flexible can a Power-to-Methanol plant consume electricity from the electricity grid when participating in the day-ahead market in 2030, considering the technical restrictions of methanol production?

The question aims at three different dimensions: Firstly, to what degree components of the Power-to-Methanol plant can ramp up or down their production with a corresponding change in electricity consumption. This should provide an overview on how flexible the technology is able to operate. Secondly, changes introduced by a changing electricity system until 2030 to the operational environment of a PtMethanol plant are researched. Then a PtMethanol plant is modelled with the retrieved information to investigate the implications of the operational environments on its operation. Thirdly, the operation obtained from the energy model is investigated regarding the flexibility that is provided by the operation.

Definitions of words

- *Flexible operation* is defined as a unit's ability to change their electricity consumption or production thereby, assisting to maintain equilibrium between supply and demand.
- *PtMethanol* is the entire plant used to produce methanol. This includes electrolysis, methanol synthesis and distillation, and auxiliaries such as pumps, valves etc.
- *Methanol production* is consisting of the synthesis and distillation units in the PtMethanol plant where methanol is produced from hydrogen and carbon dioxide and afterwards distilled into pure methanol. This is thoroughly described in Chapter 7.
- *Technical restrictions* are referring to the ramping capabilities and times as well as the limits of changing the electricity consumption of methanol production.

3.1 Limitations

This report investigates how a PtMethanol plant on a system level can provide flexibility and are thereby not investigating how different components like power electronics such as inverters and voltage control devices can be used to provide virtual inertia without rotating masses to replace conventional power plants (ENTSO-E, 2023). Moreover, flexibility is in this report regarded as the ability to react changes in electricity supply. Most flexibility is assumed to be provided through the day-ahead market, it is steered by the market's price setting mechanism and the resulting electricity prices. A conducted energy model of the PtMethanol plant is set to be operating on the day-ahead market. It is acknowledged, that the day-ahead market is limited in its means of providing flexibility, since all bids on the day-ahead market must be handed in on the day before operation. Imbalances on a shorter notice will not be handled on this market. The day-ahead market is nevertheless assumed to be the market where a PtMethanol plant will provide most flexibility to the electricity grid and therefore chosen to be modelled. Furthermore, this report is not investigating the monetary implications of providing flexibility or assessing what a suitable price for providing flexibility in 2030 would be.

4 Theoretical Framework

Here applied theories in the report are presented along with a description on how the theories are seen in context with the subject of this report as a theoretical approach. In sections 4.1 - 4.3 the used theories are described, while in Section 4.4 the developed theoretical approach is described.

As this report is investigating a new technology, namely PtMethanol, in the energy system in 2030, it is important to understand how technologies enter and influence market and society. To explain this, the Socio-Technical Transition Theory is chosen. Furthermore, since a single plant and its operation is investigated, a means of understanding the behaviour of individuals and organisations in economic systems has to be understood, which is explained by the Rational Choice Theory in this report. As this operation of a PtMethanol plant is modelled, it is furthermore important to understand the theory behind energy system models.

4.1 Socio-Technical Transition Theory

Technological transitions are defined by Geels (2002) as major changes in the way society function due to technological transformations and innovations, e.g., new transportation technologies, mobile phones for communication etc. Thus, technological transformations do not only include technological changes but also changes in the system it is applied into such as user preferences, regulation, infrastructure, markets etc. A technological transition does therefore require a change from one socio-technical configuration into a new one, where a substitution of the technology and changes in other aspects of society is needed. These changes do not happen easily, since society (i.e., regulation, user practices, infrastructure, etc.) is adjusted to the already existing technologies, and it is thereby difficult for new, radical technologies to integrate into society. However, this is possible if both technological and societal changes are made. This is defined as a socio-technical transitions. (Geels, 2002)

In general, the Socio-Technical Transition Theory (STTT) consists of a multi-level perspective (MLP), consisting of three levels: *Niche-innovations*, *Socio-technical regime,* and *Socio-technical landscape* (See Figure 4.1). Niche-innovations are located at the micro-level of the MLP. Niches are developed and generated here as radical innovations and are thereby different from the existing technologies. They often need a protected space to evolve in since they are not competitive on several parameters such as price and technological maturity until they evolve. Socio-technical regimes are located at the meso-level. (Geels, 2002) The regime consists of actors of society and institutions and the various social activities between these (Geels & Schot, 2007). The regime accounts for a dynamic stability for developments of existing technologies and changes within the regime can thereby occur without creating a new regime, since actors i.e., policymakers, firms, engineers, regulators etc. in the regime reproduce, maintain, and improve the system elements (Geels, 2019). These changes can provide room for a niche to rise into the regime and either change the regime or become a part of it. Finally, at the macro-level of the MLP the Socio-technical landscape is placed. It is constituted by external factors to society such as energy prices, wars, economic growth, environmental problems, and cultural and normative values. The landscape is even more rigid than the regime but does change slowly over time. (Geels, 2002)

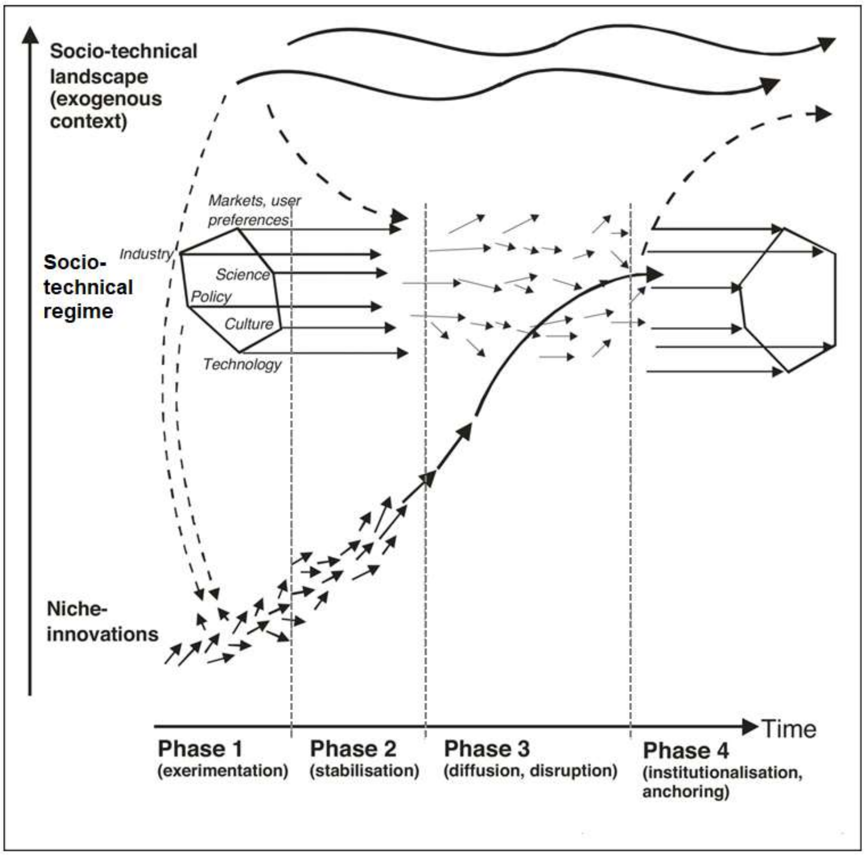

Figure 4.1: Socio-technical transitions in a multi-level perspective. Based on figure by (Geels, 2019)

As illustrated in Figure 4.1, the three levels of the STTT are dynamically connected and are influencing each other cf. the arrows. Pressures from the landscape can force a change in the regime and which then require an innovation by the niches. On the other hand, niches can change the regime if they succeed in having an internal momentum and evolving to take part in the regime. Since socio-technical transitions often have a long timeframe, it can be advantageous to separate then into four phases. As implied in the figure, the first phase is characterised with experiments and trial-and-error for the niches. Some of them survive while others change or fail to evolve. Over time a window of opportunity opens in the regime due to pressures from the landscape. This allows the niche to enter some markets through a stable, dominant design, constituting the second phase. The third phase is characterised by the niche adapting into the mainstream markets often due to improvements in price and performance, development of complementary innovations, and powerful actors supporting the innovation. Finally, the socio-technical regime is changed into a new one and is anchored the different aspects of the regimes. The new regime is then influencing the landscape as well. (Geels, 2019)

4.2 Rational Choice Theory

The Rational Choice Theory is a theory describing the behaviour of individuals in an economic environment. It is assuming, as the name implies, that individuals are able to make perfect rational choices. These choices are based on assessments that are aimed at optimising the individual's utility. For these assessments, individuals need a certain set of information. This information is assumed to be available to individuals without restrictions. These choices or decisions are thereby not influenced by emotions or impulsive actions, but are always based on rational, well performed, and informed calculations of the amount of utility each option provides for the induvial taking the choice. This utility for the induvial is the ultimate decision factor, as interest act only in their own self-interest. Based on this self-interest the individual is actively working on the maximisation of its utility, striving to achieve the most preferable outcome according to its self-interest. (Ganti, 2022)

Critics of this theory argue that Rational Choice Theory cannot apply to reality, since it assumes individuals to always take perfectly rational choices, while in reality these choices can be influenced by irrationalities and emotions. Furthermore, choices in Rational Choice Theory are based on availability of all relevant information. In reality, not all information needed to take the perfect decision might not be available to an individual, thereby hindering its ability to take a perfectly rational choice. (Ganti, 2022)

4.3 Energy Modelling

To investigate and understand the changes a new technology brings to an energy system, energy system models can be used. Furthermore, energy system models often provide decision support for political decisions on energy systems. Herbst et al. (2012) imply that the taken decisions and discussions about those are heavily influenced by the energy system model which can support different opinions or decision options. Therefore, it is important to understand the underlying assumptions behind energy system modelling that is employed to investigate energy systems or to provide decision support on energy policies. (Herbst et al., 2012)

Based on their conceptual framework, energy system models can be grouped into two categories: top-down and bottom-up models. Top-down describes energy models that investigate a national or regional economy and the effect of the energy sector on those. These models investigate the economics of the modelled system taking macroeconomic developments into account. In general top-down models try to balance demand and supply in a market by achieving the most favourable macroeconomic outcome. They lack technical detail which leads to a low capability of predicting technological change. (Herbst et al., 2012)

Bottom-up models also balance demand and supply. However, their focus is to predict changes in supply and demand from a technological perspective. If economic calculations are concerned, these models most often use a business economic calculation point of view. Since they accurately model energy technologies and units as well as their development, they are reliant on data availability. Furthermore, bottom-up models do not show the macro-economic effects of a change in technology. (Herbst et al., 2012)

Inside the bottom-up energy modelling approach, again several different types of models exist: partial equilibrium models, simulation models, optimisation models and multi-agent models. Partial equilibrium models focus on a region or part of the energy system. In theory they work similar to top-down models, however, since they focus on smaller parts of the energy system it is possible to introduce more technical details. Multi-Agent models allow for several independent agents, taking part in the energy markets, to be modelled. However, this requires additional data. Advantages of this approach are that market imperfections can be considered. Lastly there are simulation and optimisation models. Simulation models are, as their name implies, simply the simulation of an energy system with the given constraints, rules, and behaviours. They try to model the development of demand and supply technologies without a utility maximising approach, since other behaviours or preferences can be added into the rules. Optimisation models are aimed at achieving an optimal outcome under the given constraints. Therefore, they usually try to optimise the operation of all given technologies or plants to achieve an equilibrium. The optimisation is usually aimed at minimising the costs. In this approach it is only possible to model well specified and known technologies as operation costs or investment costs are needed for the optimisation. Furthermore, such models ignore the existence of market barriers and imperfections. (Herbst et al., 2012)

For modelling an energy technology in an energy model, different approaches can be taken. Here two opposite approaches to simplify energy conversion technologies in the context of energy system modelling are introduced: the white box and black box model. If a technology is modelled from a black box approach, the focus is on the inputs and outputs of that technology. (Afram & Janabi-Sharifi, 2015) That implies, that no knowledge of the technology needs to be known, because the processes happening "inside the black box" are not investigated. The in- and outputs could for example be provided through measurement data on comparable technologies or plants. This approach provides a very accurate model of single units or plants (Afram & Janabi-Sharifi, 2015). Since these single units can differ from other units of the same technology, the generalisation capabilities of this approach are comparatively weak.

White box models in contrast focus on modelling the technology through an understanding of the technology. Through that technical understanding the inputs and outputs can be quantified by calculations. This makes an energy model based on a white box approach less accurate if specific plants are concerned, as the black box is often relying on data measurements. The results from a white box model can be generalised better than the results of a black box model. (Afram & Janabi-Sharifi, 2015)

4.4 Theoretical Approach

The Socio-Technical Transition Theory is used as the foundation for the theoretical approach for this report. PtMethanol is expected to be a relevant part of the energy system in 2030. As this cannot be said for the current energy system and the current TRL of 6 -7 the technology and the energy system need to undergo changes to incorporate PtMethanol on a large scale (Cui & Kær, 2020). STTT is used in this report to understand how such changes are triggered and how different parts of the energy sector are influencing each other. If the STTT is applied to the energy sector, various pressures in the current landscape such as the Russian invasion of Ukraine leading to energy crisis to become independent on Russian (European Council & Council of the European Union, 2022), is creating an instability in the current regime. Thus, a window of opportunity for niches to rise and diffuse into a new regime is initiated. PtMethanol is seen as an advanced niche placed in the beginning of phase 3 according to Figure 4.1, since several plants are currently planned in DK1 (Danish Ministry of Climate Energy and Utilities, 2021a). Therefore, it is assumed that a chance for niche development currently exists and the PtMethanol niche develops to become part of the regime in 2030. PtMethanol would participate and influence a new established regime by 2030, as the regime also develops influenced by emerging niches. To assess these developments this report will cover the developments that the niche of PtMethanol is expected to take. Furthermore, different parts of the regime will be investigated regarding their changes until 2030: Technology and markets, user preferences. The changes and developments both will undergo are only investigated independently, as this report is aiming to investigate the effects of different regime developments will have on the changes in on the flexibility of PtMethanol as developed niche.

The report does not consider the cultural, scientific and industry dimensions of the regime, as well as mechanisms for creating the new regime or how the interactions within the regime are. The latter are assumed to be based on the current policy. The current policy is therefore assumed to not change until 2030 and can therefore provide a starting point for an investigation of technology, markets, and user preferences in the future regime. This means however that a change in policy is not considered in this report even though policies are acknowledged to be dynamic with changes in the dynamic stability of the regime or changes if a regime is broken up. The exclusion of several parameters of the regime is placing limitations on the report, the conducted energy model, and its results. These limitations are discussed in Chapter 11.

To gain an understanding of flexibility provided by PtMethanol in a regime developed until 2030 to be including PtMethanol, a bottom-up modelling approach is applied. The aim for the energy modelling is to make an investigation of the technical capabilities of a new technology and its performance regarding a specific energy supply and specific market conditions and user-preferences as part of the regime (see Section 4.1). This makes a thorough technical investigation of the possible niche development, niche accumulations and changes experienced in the regime until 2030 in regard to their impacts on the flexibility of a PtMethanol plant possible. Furthermore, changing policies and regulations are not included or investigated in the energy modelling, negating the advantages of top-down energy models. This is reflected by the limitation of not investigating changes in policy as part of the regime. By using a bottom-up approaches this will result in an accurate model which is still generalisable. To strengthen this modelling approach a white-box model of a PtMethanol plant is conducted. This leads to a level of precise technical data without relating the results to a specific plant.

The used bottom-up model will be modelled as an optimisation model, optimising after the operation costs. Since market participants are assumed to have a strict self-utility maximising behaviour (see Section 4.2), the optimisation of operational cost ensures the most beneficial outcome of the investigated period for the owner or operator of the investigated PtMethanol plant. This is still expected to be the user preference or behaviour of individuals or organisations as part of the regime in 2030. By only investigating an operation period, an investigation of investment costs is excluded.

5 Methods

As described in the Theoretical Framework, this report focuses on the changes in technology and markets that a future regime in 2030 has sustained as well as the developments of PtMethanol as a niche as a framework for an investigation of flexibility of a market based operating PtMethanol plant. To investigate the changes the selected dimensions of the regime might undergo, a literature study is employed, while the flexibility of PtMethanol operation is evaluated through a model of operation combined with flexibility metrics in an MCDA. This chapter introduces the selected methods, while acknowledging the limitations that are placed by selecting certain methods.

5.1 Literature Study

A literature study is used for gathering information and knowledge for a specific topic. The information can originate from articles, journals, books, etc. According to Eriksen (2016) a well-structured method for the literature study will result in a more efficient collection of data. This is done through four steps:

1. Preparation
2. Collection
3. Evaluation
4. Processing

Preparation is used to gain an overview of the topic and available information. The outcome of this step can be a list of keywords for further searches or different metrics the found literature must contain. (Eriksen, 2016) Furthermore, search engines to be used and several metrics for sources to be identified as relevant or not are preselected.

In this report, the literature study will primarily be used for gathering data related to the PtMethanol technologies used in the energy modelling as well as to gather an overview over the current regime and the foreseeable future changes to the regime. To ensure that the technical data is reflecting the current state, it is important that articles are as new as possible. Therefore, sources used in relation to investigate technologies have to be as new as possible to be seen as relevant. Moreover, peer-reviewed articles are preferred to ensure validity in the data. This validity is supported through the comparison of different sources. Sources used for theories and methods are allowed to be of older dates, as the information and conclusions these are drawing are not assumed to change drastically over the years. As an example, the Rational Choice Theory is still assumed to be applicable to the future regime, as it is expected that actors seek to optimise their utility etc.

The publish-restriction for technology related information is limiting the number of selected sources in the second step being Collection. (Eriksen, 2016) The collection will be done in different scientific databases: Web of Science, Scopus, Science Direct and Google Scholar. Each platform will be used to search for the same keywords. The found literature is evaluated in terms of relevance for the report and the quality of the data (Eriksen, 2016). As stated previously, this is ensured by the metrics applied to the data collection. Finally, the information collected from the sources is then applied in the following methods used in this report, constituting the fourth step of processing.

5.2 energyPRO

As tool for energy modelling, energyPRO is selected. It is a techno-economic modelling tool, developed by EMD International, where the behaviour of different technologies in an energy system can be modelled and optimised against economic parameters, such as taxes, tariffs, fuel prices, markets etc. The tool is mainly used for modelling specific plants including their conversion and storage units. The geographical scope is therefore often at the local scale. Nevertheless, a broader scale can be modelled if several plants are be connected through interconnectors or if plants are aggregated. (Østergaard et al., 2022) The tool can therefore be characterized as a bottom-up optimisation model, fitting into the described theoretical framework cf. Section 4.4.

The tool uses internal optimisation where internal rules and characteristics (costs, taxes, efficiencies, etc.) in energyPRO are affecting the operation of different units in the model. This results in the most economically feasible operation of the system in energyPRO. (Østergaard et al., 2022)

When building energy models in energyPRO different units, storage types and demands can be included. These can be defined by the user. For the conversion units (heat pumps, motors, electrolysers, etc.) the technical operation parameters like efficiencies and capacities can be assigned. Moreover, economic parameters such as costs, revenues, emissions, etc. can be assigned. Moreover, a user-defined unit can be selected and modified by the user. Technical characteristics can also be defined for storage units (batteries, heat storages, etc.). Furthermore, three different types of demands can be selected in the tool being heat, electricity, and cooling demand. Moreover, external conditions such as weather conditions and prices can be entered as time series and will influence the operation of the conversion units. (Østergaard et al., 2022)

When running the model, energyPRO offers two different solvers: analytic and mixed-integer linear programming (MILP). The analytic solver can be used for simple models whereas MILP is used for more complex models. (EMD International A/S, 2017) The MILP solver is chosen for this report. By choosing energyPRO as a modelling tool, some dimensions of flexibility, like voltage and frequency control, cannot be investigated, since these are not depicted in energyPRO.

5.3 Scenarios

To investigate how different operation strategies of a PtMethanol plan can provide flexibility to the energy system, different scenarios are defined. Godet and Roubelat (1996) define a scenario as "*a description of a future situation and the course of events which allows one to move forward from the original situation to the future situation.*" (Godet & Roubelat, 1996). Since the definition of a scenario is so broads, there is no consensus on a specific methodology when establishing scenarios. (Godet & Roubelat, 1996) In this report, the typology presented by Börjeson et al. (2006) are chosen. They define three categories of scenarios as illustrated in Figure 5.1.

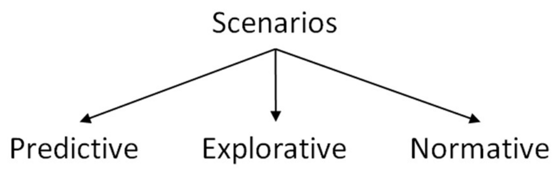

Figure 5.1: Typology for scenarios with three categories. Based on Börjeson et al. (2006)

Predictive scenarios are used for predicting how the future will be if different conditions occur. They are often aiming to present the effects of a given condition and are thereby often used to highlight possible challenges and opportunities that might arise if the specific condition is fulfilled. In order to do this, probabilities and likelihoods of different solutions are often used based on historical data. (Börjeson et al., 2006) This could be to investigate how the energy mix will be if all fossil fuels are substituted with RES, or how different developments of a niche will affect the ability to rise to the regime.

Explorative scenarios aim to investigate the results of specific conditions. The time horizon is often longer compared to the predictive scenarios and are therefore often used to investigate how a development or situation will influence a system over longer time. This is typically used to analyse how a strategy or policy is affecting the system and what the possible consequences are. Therefore, these scenarios often take a departure in the future. (Börjeson et al., 2006) This could be to investigate possible consequences of changing the electricity price from a tariff structure to a market structure.

Lastly, *Normative* scenarios are investigating how a specific target can be reached. (Börjeson et al., 2006) As an example, normative scenarios are often seen in relation to how agreement like the Paris Agreement is met.

As this report seeks to investigate the result of different operation strategies of a PtMethanol plant the scenarios required will be in the *Predictive* category. Börjeson et al. (2006) have defined two subcategories for predictive scenarios to be *forecasts and what-if* scenarios. Forecasts determine the most likely result of a specific development. It is often external factors that are influencing the result. What-if scenarios investigate the results of specific conditions in the near-future. (Börjeson et al., 2006) The What-if scenarios are found most suitable for this report as it enables to investigated how a PtMethanol plant provides flexibility under the conditions of predicted changes to the regime until 2030, and thereby it can be investigated which setup is more suited for a PtMethanol plant to provide flexibility to the power system.

5.4 Multi-Criteria Decision Analysis

A Multi-Criteria Decision Analysis (MCDA) is conducted to evaluate which of the what-if scenarios are most feasible in terms of providing flexibility based on defined criteria. Criteria are established and measured by different metrics. An MCDA can therefore assist in ranking, sorting and eventually choosing different results of e.g., energy models through a systematic approach. Løken (2007) presents three categories of MCDAs, where *Value Measurement Models* is found most suited for this report, as this can be used to compare different technologies and technological setups, while considering tangible and non-tangible values. This is primarily due to the Value measurement model aiming to identifying the best solution of decision-makers based on a set of criteria. In order to identify the best solution of the scenarios, a numerical value is assigned to each scenario, where the scenario with the highest numerical value is found most feasible. (Løken, 2007) The numerical value is calculated by the following formula:

Equation 1: numerical value for criteria

$$V(a) = \sum_{i=1}^{m} w_i \cdot v_i(a)$$

Where,

$V(a)$ is the total numerical value

w_i is the weight for the specific criterion.

v_i(a) is the value assigned in the ranking based on metrics. (Løken, 2007)

5.4.1 Measuring Flexibility of Demand Response

To be able to compare the flexibility of different scenarios, metrics will be developed to obtain quantifiable results for criteria. Literature provides different approaches and metrics to quantify or qualify flexibility. Here only approaches of quantification will be focused on, as energyPRO is providing quantitative results.

According to Heydarian-Forushani and Golshan (2020), metrics to quantify the flexibility of demand response measures have not been developed so far. Most metrics aim at quantifying the flexibility of power production instead of demand. (Heydarian-Forushani & Golshan, 2020) However, in recent years different approaches to quantify flexibility have been developed to investigate the energetic flexibility of residential and commercial buildings (Crawley et al., 2022; Li et al., 2021; Liu et al., 2022; Reynders et al., 2017; Stinner et al., 2016; H. Tang & Wang, 2021). These focus on the potential of building providing demand response applications mostly based on their heating systems.

Li et al. (2021) suggest using a flexibility factor (FF) to assess whether the investigated energy unit is operating during peak load or low load hours. Such an FF is used to assess flexibility provided by the PtMethanol plant through its simulated operation on the day-ahead market. (Li et al., 2021)

To give an indication of the grid load or stress put on the power system, the electricity price can be used as an indicator. It bases on the assumption, that the electricity system is under pressure, if electricity prices are high and the opposite applies if electricity prices are low. The electricity price is divided into three categories: High price, medium price, and low price, where the low prices is in the lower 10th percentile range and the high prices being in the upper 10th percentile. The electricity consumption of the PtMethanol plant is summed up in each of those price levels. The energy consumption during high-price times and low-price times is then used to calculate the flexibility factor according to Equation 2.

Equation 2: Flexibility Factor

$$FF = \frac{energy\ consumed_{low\ price} - \ energy\ consumed_{high\ price}}{energy\ consumed_{low\ price} + \ energy\ consumed_{high\ price}}$$

The flexibility factor calculated like this, will provide a result between -1 and 1. If it is -1, then it means that the electric consumption takes place in times of high prices and high stress on the power system. Thereby, the PtMethanol plant would not provide flexibility for the grid. If the FF equals 1, then all electricity is consumed in low price hours. Assuming low price times are times of abundant RE in the electricity grid, it is concluded that a higher FF suggests that a PtMethanol plant provides more flexibility through its operation.

Liu et al. (2022) build on the work Li et al. (2021), suggesting several different metrics that quantify the load changes happening after a signal for demand response was received. Such signal will not be investigated during this work, but the rather the possibility to react to such signals at any given time. This will be used to quantify the ability to provide additional flexibility. (Liu et al., 2022) Tang and Wang (2021) define several metrics, quantifying the maximum shiftable and postponable loads. Therefore, they calculated the thermal inertia in buildings and storage capacities based on how much energy they have shifted in time. This shiftable capacity is summed up over time and compared to the energy that consumed overall in a flexibility ratio (FR) (H. Tang & Wang, 2021). This provides a similar interpretation possibility as the metrics proposed by Liu et al. (2022), both providing an indication how much the investigated system can deviate from a planned operation.

Reynders et al. (2017) quantify flexibility as a shiftable capacity over time. To quantify this, they investigated storage capabilities and the demand of energy by a building. In their case, a change in operation must still maintain certain temperature levels. Therefore, their metric for flexibility is the maximum amount of energy consumed less or more until one of the temperature limits is reached. Their metric therefore gives indications on the amount of energy as well as the time horizon of flexibility that could possibly be provided. Furthermore, they suggest using a third metric to quantify added energetic losses or costs. (Reynders et al., 2017)

Stinner et al (2016) also assume flexibility as the ability to deviate from the planned operation. They assume that energy can be either consumed forcibly at a certain point and thereby providing downward regulation or by delaying to another time and thereby providing upward regulation. Three dimensions are acknowledged to be important in that: capacity, energy, and time of these operations. They suggest using a yearly indicator to quantify flexibility, that is provided while keeping a building temperature in a certain range (Stinner et al., 2016).

As all these metrics are developed to quantify the flexibility buildings appliances can provide to an energy system through a change in their electricity consumption. Therefore, it can be argued that these are not fit to apply to a PtMethanol plant. However, if divided into different components, both building energy systems as well as PtMethanol plants can be seen to use similar ones. Both have a certain demand of an "end energy": The building requires heat, while the PtMethanol plant requires a hydrogen supply to be able to the stable running methanol synthesis. Both systems make use of one or several energy conversion units, converting electricity into the form of “end energy” needed. Furthermore, energy storages providing system inertia can be included in both systems. Therefore, the aforementioned flexibility metrics are seen as partly applicable to PtMethanol plants.

As explained before, an FF is used to provide an indication of the flexibility provided through the PtMethanol plant’s operation. As the present studies suggest, a key part of flexibility is the possibility to deviate from a planned operation (Liu et al., 2022; Reynders et al., 2017; Stinner et al., 2016; H. Tang & Wang, 2021). These possible deviations are defined as the flexibility, supposed to be taken into account in the presented MCDA in Table 5.2. To rate those, metrics are developed for both up and downward regulation through flexibility. A ramp down of electric consumption provides upward regulation for the power system, while a ramp up in electric consumption provides downward regulation.

To quantify the flexibility that the PtMethanol plant provides additional to the day-ahead operation, a metric similar to the flexibility ratio presented by Tang and Wang (2021) is used. The operation of a PtMethanol plant in each scenario is simulated by energyPRO. Once the operation is known through the optimisation of operation in energyPRO, a function is used to identify both the maximum possible ramp down and ramp up capacities in each hour of the year, considering the ramping times and storage capacities.

This changed energy consumption will then be compared to the yearly energy consumption to receive a FR according to Equation 3.

Equation 3: Formula for calculating the Flexibility Ratio (FR).

$$FR = \frac{\sum_i^n E_{change,i}}{\sum_i^n E_i}$$

With

n being the hours of the year

$E_{chang\ ,i}$ being the hourly changeable electricity consumption

E_i being the hourly planned electricity consumption through operation on the day-ahead market

As two metrics are needed, one calculation is performed for lowering electricity consumption and one for increasing it. The purpose of these metrics is giving an indication on whether the plant could provide ramping and thereby more flexibility, without giving an indication whether regulation is technically needed in the power system.

To grade the introduced categories in each scenario, a coherent scale is developed. The developed scale of values ranges from 0 to 10, with integer steps in between, illustrated in Table 5.1. On this scale 10 is awarded to a scenario if it is very flexible, while 0 is awarded if a plant operates less flexibly.

Table 5.1: Grading scales for each criterion of the MCDA.

Value	FF	FR upward ramping	FR downward ramping
0	-1 – -0,82	0 – 8 %	0 – 8 %
1	-0,81 – -0,64	9 – 17 %	9 – 17 %
2	-0,63 – -0,47	18 – 26 %	18 – 26 %
3	-0,46 – -0,29	27 – 35 %	27 – 35 %

4	-0,28 – -0,11	36 – 44 %	36 – 44 %
5	-0,1 – 0,1	45 – 55 %	45 – 55 %
6	0,10 – 0,28	56 – 64 %	56 – 64 %
7	0,29 – 0,46	65 – 73 %	65 – 73 %
8	0,47 – 0,64	74 – 82 %	74 – 82 %
9	0,65 – 0,82	83 – 91 %	83 – 91 %
10	0,83 – 1	92 – 100 %	92 – 100 %

These grading scales are each including assumptions. The grading scale for the FF, which evaluates the flexibility provided through the default operation on the day-ahead market assumes, that operation in times of low prices is providing the grid with flexibility. Therefore, if the FF reaches 1, meaning all electricity was consumed during low price hours, the PtMethanol plant provides a high amount of flexibility and vice versa. The FRs for upward and downward ramping of the PtMethanol plant's electricity consumption indicate whether the plant could help in balancing the electricity market if there is an imbalance in the system within a certain hour. A high FR therefore indicates that the plant has the ability to provide such service in a high share of its operation.

5.4.2 Decisions Trees for Calculating the Flexibility Ratios

To analyse how the different scenarios are performing in accordance to the flexibility metrics, decision trees for each of the metrics have been created. To calculate the first metric, being the FF, the hours of operation in high and low-price periods are calculated. The decision tree can be seen in Figure 5.2. The resulting hours is then used in the formula for calculating the FF as described above.

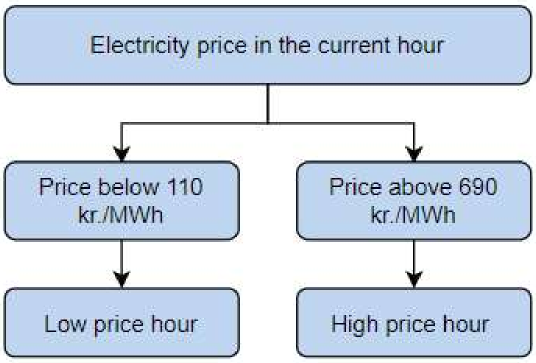

Figure 5.2: Decision tree for evaluating if the current hour is high or low used for FF

When calculating whether the PtMethanol plant could provide additional downward regulation by ramping the energy consumption by the plant up, the decision tree presented in Figure 5.3 is used. The electrolyser is the deciding factor for regulating up and down, as this is the most electricity consuming unit in the plant. The methanol unit is only using electricity for auxiliaries to e.g., maintain temperature.

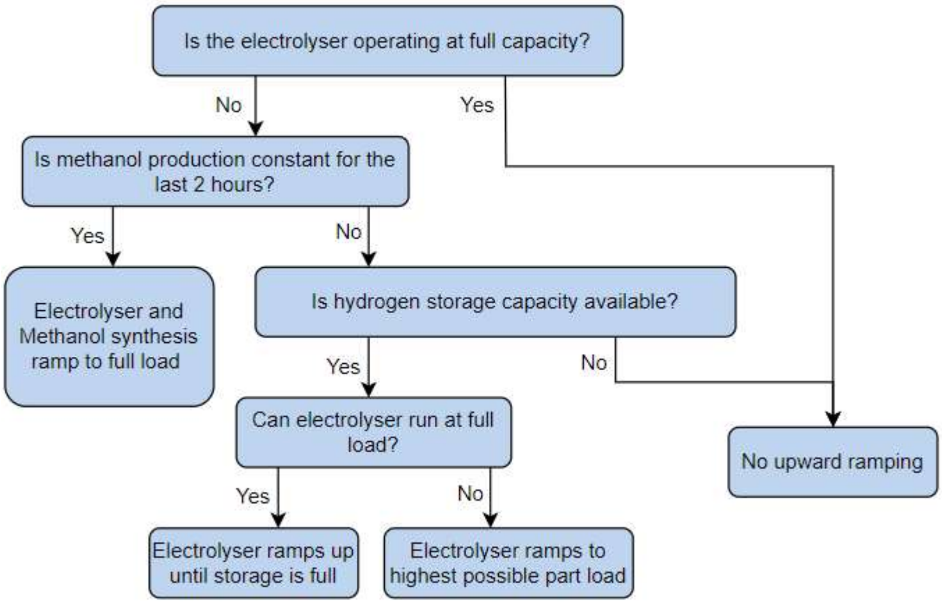

Figure 5.3: Decision tree for calculating FR upward ramping through downward regulation

According to Figure 5.3 the PtMethanol plant can only provide additional downward regulation if the electrolyser can ramp up its electricity consumption. If this is the case, then since the ramping time is 2 hours to obtain a steady state operation, the methanol production must be constant for the previous two hours cf. Section 7.2.2. If so, then the electrolyser and methanol synthesis ramp to full load to consume as much electricity as possible. However, if the ramping is not durable due the two-hour ramping restriction, the electrolyser can increase production and thereby charge the hydrogen storage if there is room for it in the storage. As not all of the scenarios are containing a hydrogen storage, the storage content will then be seen as 0.

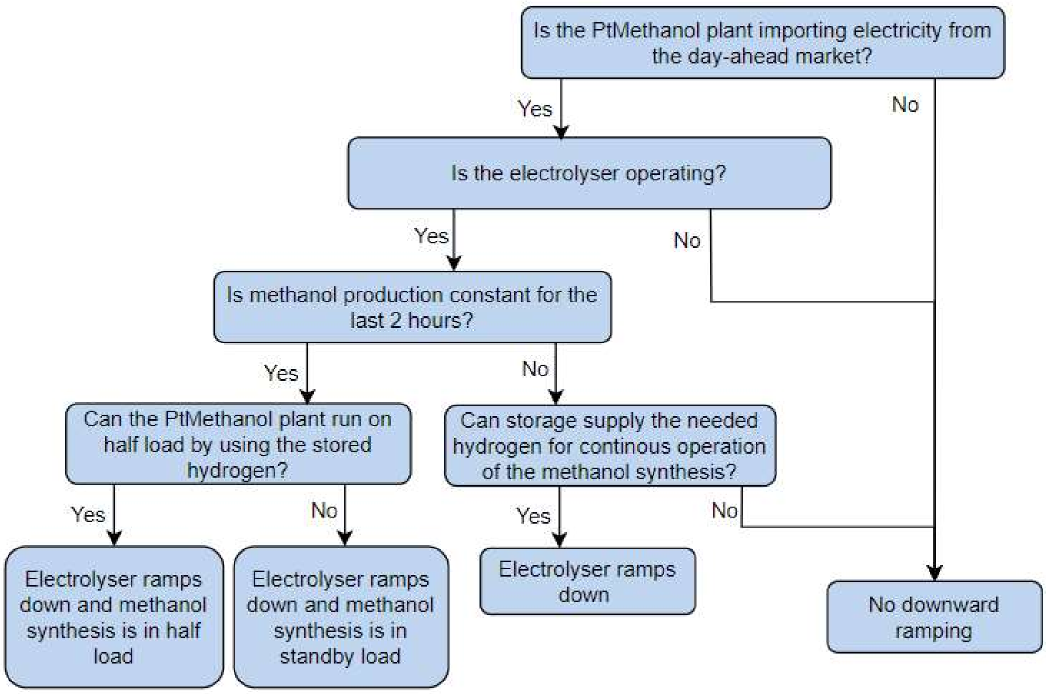

Figure 5.4: Decision tree for FR downward ramping through upward regulation

To analyse if the PtMethanol plant can provide additional upward regulation by lowering its electricity consumption the decision tree presented in Figure 5.4 is used. The plant can only provide downward regulation in hours where it is importing electricity from the day-ahead market, as this would be the only cases where the electricity system would be affected by the PtMethanol plant. Moreover, as the electrolyser is the most electricity consuming unit in the plant, this must be in operation in order to be able to ramp down. Then, as for the upward ramping, the methanol production should be constant for the next two hours. If this is the case, then if there is enough hydrogen stored for the methanol synthesis to consume, then the electrolyser will down completely, and thereby lowering the electricity demand greatly. If there is not sufficient hydrogen in the storage, the methanol synthesis goes in standby mode. Furthermore, if the methanol synthesis has not operated constantly in the previous two hours, then it cannot go to standby mode, therefore it is investigated whether the hydrogen storage can supply enough to ensure a continuous operation of the methanol synthesis while ramping down the electrolyser, or if downward ramping is not possible.

5.4.3 Developed Scales and Weights of Criteria

In order to investigate how the scenarios are performing, three criteria are defined and are presented together with their parameter range in Table 5.2.

Table 5.2: Criteria chosen for a MCDA on flexibility and feasibility of a PtMethanol plant in the day-ahead market 2030.

Criterion	Parameter range
Flexibility through day ahead operation (FF)	-1 to 1
Ability for additional upward ramping (FR up)	0 % – 100 %
Ability for additional downward ramping (FR down)	0 % – 100 %

The first criterion listed is covering the flexibility that is provided through the operation of the PtMethanol plant on the day-ahead market. This criterion is chosen, because the day-ahead market is providing the power system with flexibility already, as explained in Section 2.3.4. It is used to evaluate if the simulated operation provided by an energyPRO calculation is contributing towards a flexible power system. The first parameter deals with the system flexibility provided through operation on the day ahead market.

The second and third criteria selected are the ability of the PtMethanol plant to provide additional flexibility aside from the flexibility provided on the day-ahead market. These criteria are chosen, since not all imbalances can be handled on the day-ahead market, which is by its nature relying on forecasts of electricity production and consumption. Since it is settled a "day ahead" of operation, these forecasts can be inaccurate, leading to imbalances, as explained in Section 2.3.4. These are then balanced through more short-term markets. These criteria therefore aim at evaluating the ability or possibility of the PtMethanol plant to deviate from its planned production in the day-ahead market to take part in more short-term markets as intra-day or regulating power markets for both upward and downward regulation.

Each of the criteria is then assigned with a weight being a percentage based on the importance of the specific criterion is for the decision makers (Løken, 2007). In this report the flexibility is investigated from an overall system perspective through an objective approach. The criteria investigated deal with the actual flexibility provided to the system without relating it to the costs for this e.g., held by the Transmission System Operator (TSO) or the plant.

	Flexibility through operation at Day-Ahead	Additional upward regulation	Additional downward regulation	Weight
Flexibility through operation at Day-Ahead	1	2	2	55%
Additional upward regulation	0	1	1	22,5%
Additional downward regulation	0	1	1	22,5%

Figure 5.5: Weights for criteria used for the MCDA.

In Figure 5.5., "2" symbolises that the criterion on the left is valued more important than the criterion on the top. "1" symbolises the criteria to be equally important, whereas "0" symbolises that the criterion on top is more important than the one on left. As each of the criteria is weighed against itself, these are marked with as equally important and marked with yellow in the figure. The weight is calculated by taking the sum of the horizontal lines and dividing them with the matrix size. E.g., the weight for *Flexibility through operation at Day-Ahead* is calculated as: $w_i = 5/9 = 55{,}6\%$. The weights have been modified slightly afterwards, giving the scores in Figure 5.5. Hereafter, the results found in the energy modelling results are ranked for each scenario by a set of metrics for each criterion. These are thoroughly described in Section 5.4.1. This eventually gives a score on how each scenario is performing for each criterion. Hereafter, the results of the scenarios are compared based on their numerical value which is calculated based on the two parameters described. (Løken, 2007)

6 Research Design

To answer the formulated research question, the following research design is created:

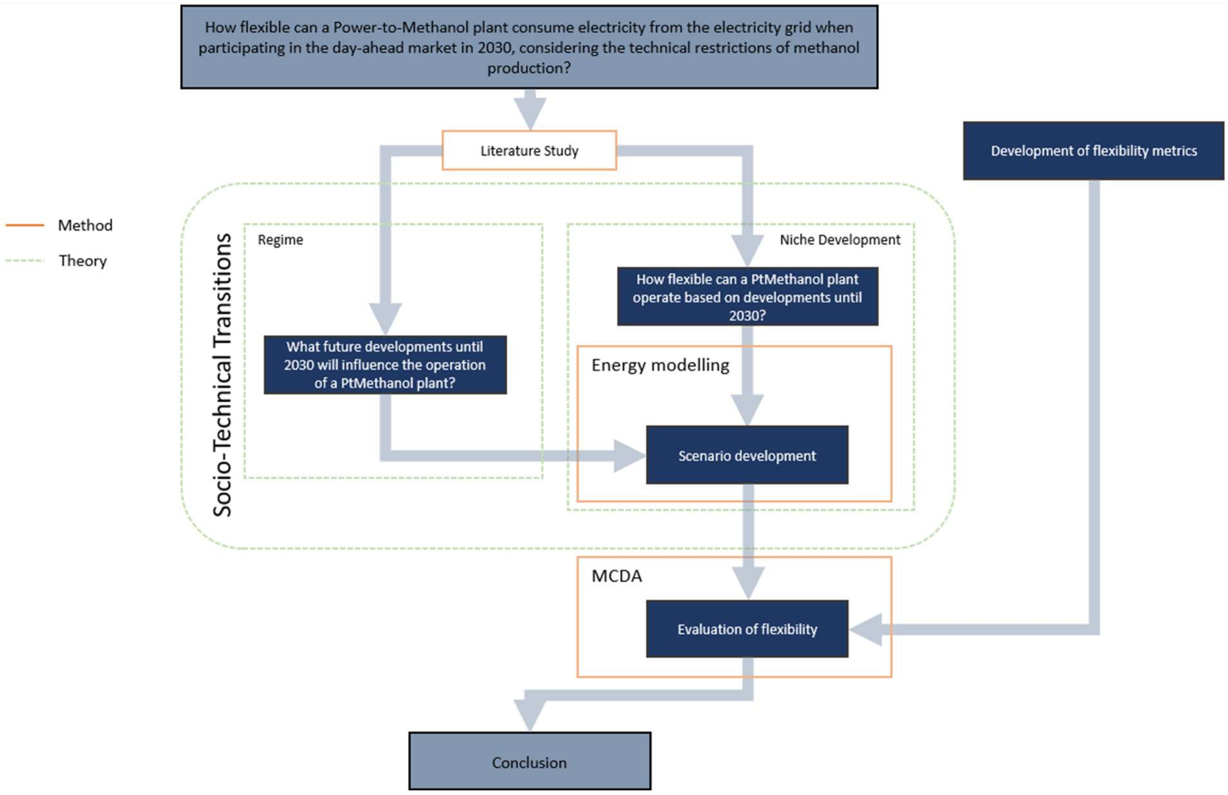

Figure 6.1: Research design

To answer the research question, as first step a literature study is performed to investigate PtMethanol plants as a niche to gain insight on the ability of PtMethanol to change its load and to obtain parameters to develop an energy model. Furthermore, the literature study is used to gain insights into the regime, PtMethanol can develop into, namely electricity and technology of the electricity sector that might be affecting PtMethanol as well as their future developments. Therein STTT is used to understand the process of development that both PtMethanol and the electricity sector undergo until 2030. The results of both will be used in energy modelling, providing the necessary information to be able to model a PtMethanol plant in a regime in 2030. Based on the obtained information, several scenarios of possible or likely developments are created.

These scenarios offer different operation environments in which the PtMethanol plant is modelled in energyPRO. The results from these models are then used in a further step to evaluate the flexibility that a PtMethanol plant can provide in the modelled scenarios. The flexibility is measured through flexibility metrics that were developed in Section 5.4 to quantify the flexibility of the PtMethanol plant in operation. The developed flexibility metrics are applied to the results obtained from the energy model in energyPRO. The obtained values are then used as criteria in an MCDA to determine which scenario is able to consume electricity in the most flexible way. The evaluation is conducted as a MCDA on several different aspects of flexibility. Each aspect is rated separately to provide an overall rating in the end on which the provided flexibility can be identified. Subsequently, sensitivity analyses are performed to investigate how sensitive the results are to changes in different parameters. The evaluation feeds into a conclusion and is also discussed in their relation to the landscape and costs that associated to each scenario.

7 State of the Art in Hydrogen and Methanol Production from Electricity

As described in Section 2.5, PtMethanol refers to a process where hydrogen is produced through electrolysis and then used to form methanol under the addition of carbon dioxide in methanol synthesis. In order to model those technologies from a white-box approach as decided upon in Section 4.4, a basic understanding of both technologies has to be established. Therefore, firstly different technologies of electrolysis are investigated in regard to their relevance to the flexibility of a PtMethanol plant in 2030 and their development until then. Following is an investigation of different ways of methanol production.

7.1 Electrolysis

Electrolysis is using electricity to split water into hydrogen and oxygen, as explained by Equation 4.

Equation 4: Chemical reaction of splitting water to hydrogen and oxygen

$$2\,H_2O \;\rightarrow\; 2\;H_2 + O_2$$

Several different technologies of electrolysis exist today. Most namely there are alkaline electrolysis, polymer electrolyte membrane electrolysis and solid oxide electrolysis. These are described in the following subsections.

7.1.1 Alkaline Electrolysis

Alkaline electrolysis (AEL) is based on two electrodes (an anode and a cathode) being submerged in an alkaline-solution and separated by a diaphragm. If electricity is applied to the electrodes, hydrogen forms at the cathode and oxygen at the anode. These are thereby already separated, leading product pureness reaching 99,9 %. AEL is a quite matured technology, with a Technology Readiness Level (TRL) of 9 (Bos et al., 2020) suggesting that AEL is an advanced niche according to STTT as it is not a part of the current regime yet. The following Table 7.1 presents a number of key facts on AEL. (Buttler & Spliethoff, 2018)

Table 7.1: Typical properties of current alkaline electrolyser systems

Alkaline electrolysis		
Electricity to hydrogen efficiency	51% – 66,5%	(Buttler & Spliethoff, 2018; Danish Energy Agency, 2017)
Load range	20% – 100%	(Buttler & Spliethoff, 2018)
Ramping time	< 5 min	(Buttler & Spliethoff, 2018)
Cold start time	Approx. 2 h	(Buttler & Spliethoff, 2018)
Operating temperature	60°C – 90°C	(Buttler & Spliethoff, 2018)
Operating pressure	10 – 30 bar	(Buttler & Spliethoff, 2018)
TRL	9	(Bos et al., 2020)

7.1.2 Polymer Electrolyte Electrolysis

Polymer electrolyte electrolysis (PEMEL) is another technology of electrolysis. It works similar to the AEL by placing two electrodes in a solution and applying electricity to produce hydrogen and oxygen. However, these electrodes are separated by a membrane, which they are also usually mounted on. This membrane exchange assembly is placed in an acidic solution. The technology makes it possible to form purer products than AEL, with a purity of 99,99 % while also able to be operated under pressure. (Buttler & Spliethoff, 2018)

Table 7.2: Typical properties of current polymer electrolyte membrane eletrolyser systems

Polymer Electrolyte Membrane Electrolysis		
Electricity to hydrogen efficiency	60 %	(Buttler & Spliethoff, 2018)
Load range	0% – 100%	(Bessarabov & Millet, 2018; Buttler & Spliethoff, 2018)
Ramping time	< 10 s	(Buttler & Spliethoff, 2018)
Cold start time	< 10 min	(Buttler & Spliethoff, 2018)
Operating temperature	50 °C – 80 °C	(Buttler & Spliethoff, 2018)
Operating pressure	20 – 50 bar	(Buttler & Spliethoff, 2018)
TRL	5-7	(Bos et al., 2020)

In literature the efficiency of PEMEL systems is presented as a wide range of 46 – 83 %. With the Danish Energy Agency (2017) giving it as 58 %, while researchers usually state higher efficiencies in a range of 64 – 83 % (Andika et al., 2018; Bessarabov & Millet, 2018; Danish Energy Agency, 2017; Kotowicz et al., 2022). Since the range presented in this literature is quite high and it is often not specified if these efficiencies only apply to electrolysis stacks or whole plants, the upper end of the range presented by Buttler and Spliethoff (2018) is assumed to be most accurate. Concluding an efficiency of 60 % is assumed for PEMEL currently (Buttler & Spliethoff, 2018).

7.1.3 Solid Oxide Electrolysis

Besides of AEL and PEMEL there is also a third technology present for electrolysis namely solid oxide electrolysis (SOEL). Here the two electrodes are covered in hydrogen and a steam stream is fed to the cathode, where hydrogen and an oxygen ion are formed. The steam fed to the cathode has to be heated to a high temperature of approx. 700 °C. This positively influences the efficiency, which is shown to be able to reach 80 % in experimental setups. Furthermore, SOEL could be used for a process called co-electrolysis, where more advanced e-fuels than hydrogen can already be produced in the same process as hydrogen. In SOEL, syngas, a mixture of CO and H_2, could be produced from steam and carbon dioxide. (Buttler & Spliethoff, 2018) Table 7.3 presents a range of typical SOEL properties.

Table 7.3: Typical properties of solide oxide electrolysis systems

Solid oxide electrolysis		
Electricity to hydrogen efficiency	76 % – 81 %	(Buttler & Spliethoff, 2018)
Load range	-100 % – 100 %	(Buttler & Spliethoff, 2018)
Ramping time	15 min	(Buttler & Spliethoff, 2018)

Cold start time	Several hours	(Buttler & Spliethoff, 2018)
Operating temperature	700 °C – 900 °C	(Buttler & Spliethoff, 2018)
Operating pressure	1 – 15 bar	(Buttler & Spliethoff, 2018)
TRL	3 - 5	(Bos et al., 2020)

As seen in Table 7.3, the load range of SOEL is from -100 to 100 % of nominal load. This refers to the fact that in theory the SOEL could also be used to produce electricity from hydrogen and oxygen. However, Buttler and Spliethoff (2018) imply that further research is needed to realise that possibility. The technology is described to still be in fundamental research. Furthermore, a main disadvantage of the high operating temperatures is a long time period required for cold starts. (Buttler & Spliethoff, 2018) This is assumed to limit the possibility of flexibility of the plant, as long as the possibility of reverse operation is not realised.

7.1.4 Development of Electrolysers until 2030

In order to model a PtMethanol plant that provides flexibility in the future energy system, one technology is be chosen to be modelled, as the technologies differ in certain properties like load ranges and efficiency. To take that decision for a time horizon of 2030 also the future developments of these technologies have to be included as decision variables. Since its low TRL and stage of fundamental research, SOEL is not assumed to be commercially available on a large scale in 2030 and thereby is excluded from further investigation in this report.

Regarding AEL and PEMEL, their main developments are expected to evolve around an increasing efficiency, the durability of cells and the costs of such electrolysers (Danish Energy Agency, 2017). The Danish Energy Agency (2017) predicted these parameters to develop as shown in Table 7.4.

Table 7.4: Development of key parameters of AEL and PEMEL (Danish Energy Agency, 2017)

Parameter	AEL		PEMEL	
	2020	2030	2020	2030
Efficiency [%]	66,5	68	58	65,5
Technical lifetime [a]	25	30	20	25
Investment costs [kr./MW_{el}]	650	450	925	650

As seen the development PEMEL is expected to be steeper than for AEL, which is attributed to the higher current TRL of AEL. Therefore, costs and efficiency are closer to each other, limiting the advantages of the AEL.

The PEMEL combines a set of advantages over the AEL, while developing in a way that decreases its main disadvantages of high costs, shorter lifetime, and lower efficiency. The advantages are especially interesting if investigating flexibility, since the lower ramping time, as well as minimal load in theory allow the PEMEL to react more flexible to a change in electricity supply. Furthermore, during a literature study detailed information on the ramping and part load behaviour of PEMEL was found. Therefore, PEMEL is picked as technology of electrolysis for the modelled PtMethanol plant.

7.1.5 Part Load Behaviour of PEMEL

Since this report investigates the amount of flexibility PtMethanol is able to provide and ramping times are seen as important factor if flexibility can be provided, the part load behaviour of electrolysers is also investigated. Buttler and Spliethoff (2018) suggest that the efficiency of an electrolysis system improves in part load. Using the term electrolysis system refers not only to the electrolyser itself, but the whole plant which includes a number of auxiliaries like water purification, inverters, pumps, compressors and more (Buttler & Spliethoff, 2018). The higher efficiency in part load is backed by Lettenmeier (2021), who illustrates the efficiency of an electrolysis system as shown in Figure 7.1.

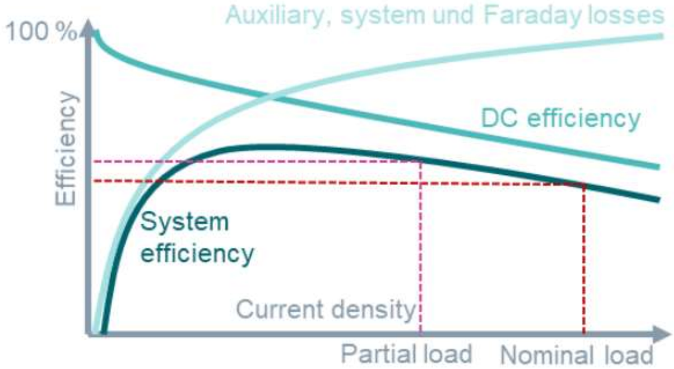

Figure 7.1: Efficiency over load on the example of a siemens electrolyser (Lettenmeier, 2021)

As seen, the system efficiency is influenced by the DC efficiency and the auxiliary system and Faraday losses. The latter refers to losses that are experienced because of the described auxiliaries in a plant (Lettenmeier, 2021). These are experiencing an increasing efficiency the closer the unit operates to nominal load, since these were sized to that point of operation. The DC efficiency relates to the efficiency of the electrolysis stack itself. As seen, this decreases the closer the unit operates to nominal load (Lettenmeier, 2021). Both curves together account for an interesting efficiency curve developing over the load. While sharply rising from certain point of minimum load it then increases further until a point of maximum efficiency is reached. According to Buttler and Spliethoff (2018) this point lies around 25 % for PEMEL systems. From that point, the system efficiency decreases as the increase in auxiliary losses becomes smaller while DC efficiency decreases almost linear. The highest reached efficiency in part load is increased by 10 %. (Buttler & Spliethoff, 2018)

7.2 Methanol Synthesis and Distillation

In order to model the methanol production that the PtMethanol plant can produce in the context of 2030, a more detailed investigation of methanol synthesis and distillation processes than in Section 2.5 is conducted.

As illustrated in Figure 2.3 the methanol is formed in a methanol synthesis following the electrolyser. Once the water has been split into oxygen and hydrogen by and electrolyser, the next step in the process is to produce methanol. This is done by mixing carbon dioxide and the hydrogen in a methanol synthesis process (Cui et al., 2022). The chemical process of producing green methanol through hydrogenation is presented in Equation 5.

Equation 5: Chemical reaction of the process of making methanol.

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

The hydrogenation process is relatively new compared to the currently mostly used process of syngas to methanol, why the TRL is assumed to be 6-7. (Cui & Kær, 2020)

For this study it is assumed that the design of a plant using that process as substantial influence on the flexibility provided by a PtMethanol plant. Therefore, especially the reactor design including its auxiliary systems is studied further.

7.2.1 Reactor Design

Cui & Kær (2020) suggest two different reactor types for the traditional syngas to methanol process: One is an adiabatic reactor, where the reactor is well insulated, why heat does not enter or leave the system. The other reactor is isothermal, where it is either cooled with water or gas to ensure a constant temperature. In a comparative study they conclude that the adiabatic or gas-cooled reactors both are suited for production of green methanol, while a water-cooled reactor is less suited. The distillation of products from the reactor is assumed to be the same, as it is not specifically investigated. (Cui & Kær, 2020)

All three reactors (adiabatic, gas cooled, and water cooled) consist of a methanol converter, in which the reaction described in Equation 5 takes place. It is filled with a catalyst bed in each case. The feeding gas, consisting of hydrogen and carbon dioxide in the case of green methanol, is heated and compressed before entering the reaction chamber. Exiting the methanol converter is a mixture of gases: methanol, water as well as carbon dioxide and hydrogen as the reaction takes place in an equilibrium. Water and methanol are then separated by cooling the temperature to achieve a phase chance from gaseous to liquid. The remaining gases can thereby be fed into the methanol converter again after being reheated and compressed as illustrated in Figure 2.3. (Cui & Kær, 2020)

Anicic et al. (2014) present two different approaches to convert hydrogen and carbon dioxide into methanol. While one of them is based on the direct reaction in Equation 5 and referred to as direct methanol synthesis, the other one is based on the so-called water-gas-shift, forming water and carbon monoxide first and then adding more hydrogen in a second reactor to form methanol. According to this, the carbon dioxide is converted to carbon monoxide before the methanol conversion is taking place. Both setups are including two reactors to form methanol. As the study is laid out as a comparison between these two production pathways, Anicic et al. (2014) reach the conclusion, that the direct pathway for methanol production performs better economically and at a higher energy efficiency. (Anicic et al., 2014) The reactor concept is adopted by Kourkoumpas et al. (2016). Here the plant uses two methanol reactors, where the products of each reactor preheat the feedstock. The products are then separated in a liquid and a gaseous phase. While the liquid phase consisting of methanol and water is fed into the first of three distillation columns, the gaseous phase is partly fed into the first and partly into the second reactor. The efficiency of hydrogen consumption to methanol production of this reactor is 82 %, based on the lower calorific value. (Kourkoumpas et al., 2016) Therefore, the energetic efficiency, taking all consumed energy into account is likely to be lower. Additionally, Chen et al. (2019) proposed as similar hydrogen to methanol plant in a study on the electrification of the chemical industry. It is based only one adiabatic reactor, with recycling of the gaseous phase of products to increase hydrogen yield. The separated liquid phase is separated in two distillation columns in series. An energy efficiency of the process of around 73 % is indicated. (Chen et al., 2019)

Different reactor designs have been presented; however little information is given about their behaviour if the hydrogen load changes. The hydrogen load of the methanol plant is seen as the determining factor for change in its load, since the electric load is directly coupled to this load through the operation of compression as well as heating and cooling systems, which scale with the quantity of mediums. As Cui et al. (2022) conducted a surrogate model for the flexibility of the methanol synthesis of a PtMethanol plant, the reactor design used in that study and introduced by Cui & Kær (2020) is chosen. Building on the report by Cui & Kær (2020), the adiabatic reactor was concluded to have a good potential when used for production of green methanol, mainly due to lower costs than for the gas-cooled reactor (Cui et al., 2022).

Within the reactor a catalyst is needed to produce the methanol and water. Copper-based catalysts have proven a good potential for green methanol production and are planned to be used in large-scale plants in Norway and Belgium. Additionally, the benefit of using a metal-based catalyst is that they are widely used in conventional methanol production. (Cui et al., 2022)

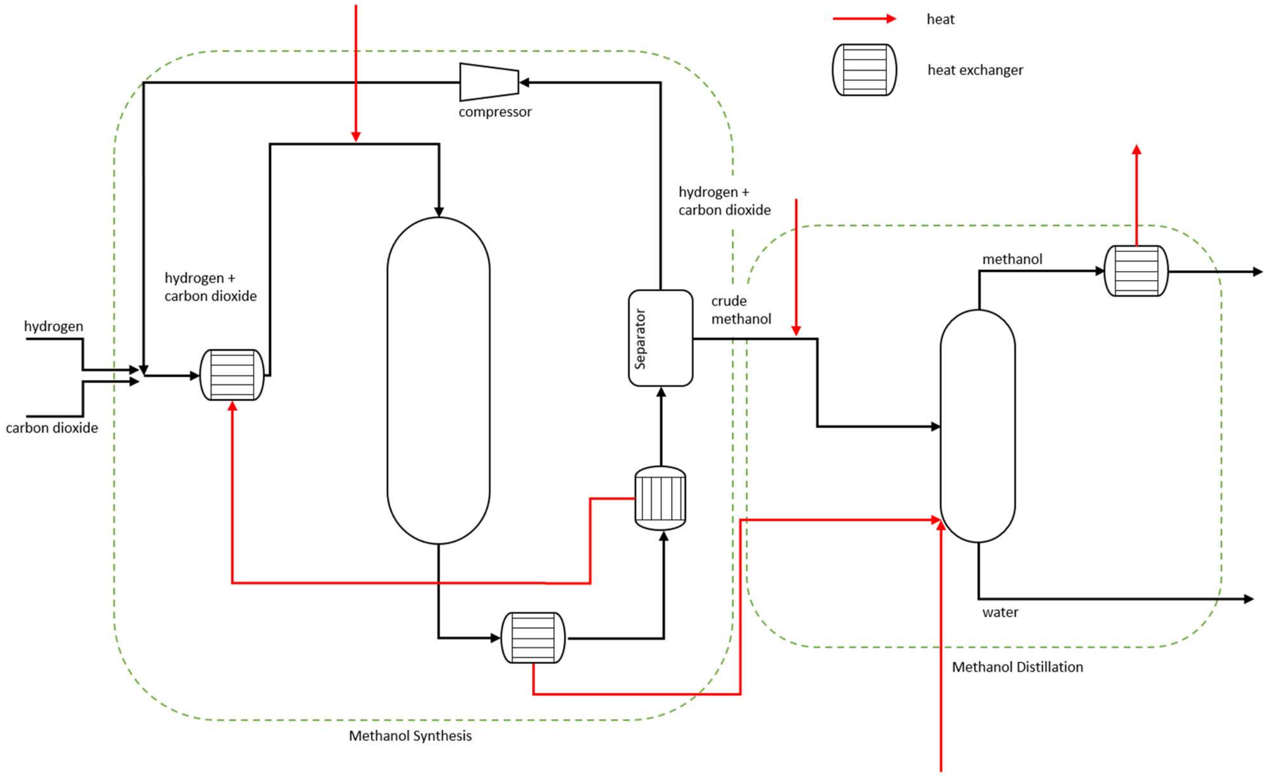

Figure 7.2: Reactor design for methanol production (Cui et al., 2022)

The feed gases which enter the methanol converter are hydrogen and carbon dioxide cf. Figure 7.2. They pass through a heat exchanger where they are preheated by the product gas of the methanol converter. If this is not sufficient to reach the entering temperature of 220 °C the feed gas is further heated by an electric boiler. The product gas, consisting of methanol, water, hydrogen, and carbon dioxide, is firstly passing through a heat exchanger which cools the products down and heats the distillation column. It is then further cooled down through the described process of preheating the feeding stream. (Cui et al., 2022)

After passing through these heat exchangers, the water and methanol are separated from the remaining hydrogen and carbon dioxide through further cooling the gas mixture until water and methanol condense. The remaining hydrogen and carbon dioxide remain in gaseous from, are compressed and fed into the fee gas stream to be preheated again. The obtained mixture of liquids water and methanol, called crude methanol is separated from each other through distillation of the methanol. The crude methanol is preheated in a boiler to 75 °C and then enters the distillation column, which is in turn heated by the hot product gas exiting the methanol converter. Water and methanol are exiting the distillation column in different phases and therefore in quite pure conditions. The gaseous methanol is then cooled to 55 °C where most of the methanol condenses. (Cui et al., 2022) The condensed methanol can then be used or sold as e-fuel.

7.2.2 Dynamic Behaviour

In their study Cui et al. (2022) model the response of a Methanol plant to changes in its hydrogen load. They conclude that it is possible to ramp such a plant between 100 % and 50 % of the nominal or full load, without heavily influencing the efficiency. Furthermore, their model shows that such a reactor would have slight deviations from the steady state that it is operating at, while achieving a semi steady state again after two hours and a stable steady state after 20 h. (Cui et al., 2022)

Regarding the system efficiency for the methanol synthesis and different studies are assuming an efficiency of approx. 77 % (Bos et al., 2020; Cui et al., 2022; Kotowicz et al., 2022). Furthermore, Kotowicz et al. (2022) stress that the system efficiency for methanol synthesis is highly affected by the power consumption by the auxiliaries (Kotowicz et al., 2022). As dynamic operation of methanol plants with different load lines has not been studied widely, the methanol plant in this report is assumed to be able to ramp between 50 % and 100 % of full load as it is the case for the model by Cui et al (2022). They concluded a methanol synthesis and distillation (referred to as methanol production in this report) process to have an efficiency of 77,1 % at full load and 75,4 % at half load. For the modelling of the combined process of methanol production, the change of efficiency comparing part load to full load is simplified in order to simplify the model, and the methanol production's efficiency is set 75 % for this report. (Cui et al., 2022)

Table 7.5: Typical properties of methanol synthesis and distillation process

Methanol production		
Methanol production efficiency	75 %	(Cui et al., 2022)
Load range	50 – 100 %	(Cui et al., 2022)
Operating temperature	220 °C	(Cui et al., 2022)
Operating pressure	31 bar	(Cui et al., 2022)
TRL	6-7	(Cui & Kær, 2020)

8 A perspective on the Danish Electricity System in 2030

As the PtMethanol plant modelled in this report is operating as a part of the Socio-Technical Regime of 2030 it is important to investigate the circumstances and predictions of the future regime. As "a *scenario is typically defined not only as model output, but also as the set of parameters and qualitative assumptions that influence model outcomes."* (Prina et al., 2022). This section is analysing the predictions by several institutions, taking it as a starting point for an investigation of Technology and Markets in the 2030 regime. This is done with the target to obtain relevant information to develop what-if scenarios in which a PtMethanol plant is modelled.

PtMethanol as a niche is described as developing until 2030 and the same can be set for the regime that is strives to be part of. This chapter therefore aims at an investigation of developments in the regime, which influence a PtMethanol plant. As described in Figure 6.1, the outcome of this investigation is used to develop what-if scenarios to model the described PtMethanol technology in. Therefore, the investigation of regime developments is focused on things that will have a direct influence on the operation of PtMethanol in 2030. To recall, a regime in general is made up of six dimensions as illustrated in Figure 4.1: Industry, science, culture, policy, technology and market, user preferences. Only the changes of technology and markets are investigated, as these are assumed to have the largest influence on the operation of a PtMethanol plant. These two dimensions are also seen as important towards the niche development of PtMethanol. Thereby, through the development of what-if scenarios, the report aims at an investigation whether certain changes in the technical and market dimensions of the regime are facilitating flexibility of the PtMethanol plant. The policy, making up one dimension of the Socio-Technical regime is assumed to not be changing at large. Because of this, current strategies and roadmaps developed for the development of the electricity system, are seen as important sources to predict these. Even though development in policies is not investigated, current policies might shape the technology and markets dimensions of the regime in 2030. The technological makeup of the electricity system in 2030 is described in Chapter 2. These changes from the current system are expected to influence other dimensions as well e.g., the market and user preferences through different marginal costs, that impact electricity prices through the price mechanisms on the markets. These in turn can have an impact on user preferences. Furthermore, that change in technology is increasing the need for power system flexibility (see Chapter 7). This might be handled through a change in policy or market structure to provide more incentives to provide the power system with flexibility.

As these three parts of the regime are deemed the most influential towards the operation of a PtMethanol plant, this chapter will focus on an investigation of policy, technology, and markets. Policy is investigated on the base of currently existing development plan, strategies as well as position papers of institutions in the Danish energy system. Changes to the technology dimension are seen as the changes from the current to the expected electricity system in 2030. The development of market and user preferences is investigated mainly through the expected development of the market by the Danish Energy Agency in the so-called Market Model 3.0 (Danish Energy Agency, 2021b). It is investigated in regard to its proposed measure how to maintain flexibility, as well as its implications for a PtMethanol plant. This document is taken as a point of origin for a more detailed investigation of changes that are proposed in it. Furthermore, the changes in technology and the market are expected to have a significant impact on energy prices on the day-ahead market where the PtMethanol is operating.

The observed changes feed into the development of what-if scenarios that should give an indication on how the regime could have evolved until 2030.

8.1 The 2030 Electricity System

The changes the Danish energy system is expected to undergo until 2030 will require electrification of different sectors (H. Lund et al., 2021). This will cause the electricity consumption to rise, leading to a need for higher electricity generation capacities as well. If the produced methanol from a PtMethanol plant is used to cover transport fuel demands, the developing PtMethanol niche might be seen as part of the change that the regime dimension of technology undergoes. As mentioned already, 4 – 6 GW of electrolysis are envisioned to be built by 2030 (Danish Ministry of Climate Energy and Utilities, 2021a). This compares to a current yearly peak of 6 GW in electricity consumption, thereby potentially doubling the peak load. However, H. Lund et al. (2021) is expecting only 1,2 GW of electrolysis to be built until 2030 (H. Lund et al., 2021). These number differ by almost 5 GW and the actual build capacity of electrolysers is expected to be in between these given numbers. The yearly energy consumption is also expected to increase through further electrification of heating and road transport through electric vehicles (H. Lund et al., 2021).

To cover this risen electricity demand, electricity generation is expected to rely on biomass, biogas, and wind, solar and to a small degree wave power. The power plant capacity installed in Denmark is expected to decrease from 6 to 4 GW. These power plants are however still expected to provide base and peak loads, while still operating less than today. In contrast to the overall decrease in power plants, H. Lund et al. (2021) expects an increase in gas-fired small-scale CHPs, which are preferably using biogas. The demand of biogas is expected to increase to 9,7 TWh yearly. The target for solar capacity is proposed by H. Lund et al. (2021) to be 5 GW, while wind power is targeted to have capacity of 11,5 GWh. (H. Lund et al., 2021)

As mentioned, electrolysis should be built on a large scale by 2030 as well as methanol should be supplying a significant part of the energy demand of the transportation sector. Thereby, it is assumed that PtMethanol is going to be part of the technological regime in 2030. As it is part of the regime, synergies might develop between PtMethanol and other parts of the regime. These can relate to either an output of PtMethanol being used by another actor or an input of PtMethanol being supplied in more favourable terms.

Lastly PtMethanol is consuming a lot of electricity and depending on its actual flexibility, it might be a large consumer of electricity produced either wind or solar power, being able to react to changes in their generation.

8.2 Market Model 3.0

As the electricity system undergoes changes and flexibility is challenged, the Danish Energy Agency (2021b) provided a strategy for the development of the Danish electricity market. This document briefly summarises the status quo and then formulates goals for the future state of the electricity system. The time horizon that is envisioned, is 2030. (Danish Energy Agency, 2021b)

The Danish Energy Agency (2021b) proposes goals, structured into five main goals:

- All actors must be able to contribute to a flexible electricity market.
- A flexible electricity market must ensure a robust energy system in balance.
- Cost-Effective expansion of the grid through flexibility.
- The regulation of monopolies must promote a flexible electricity market.
- The electricity market model must be at the forefront of developments. (Danish Energy Agency, 2021b)

The influence and importance of these five goals on potential PtMethanol plants in the Danish context is briefly analysed.

The first goal aims at having as many actors involved on the electricity market as most possible. It is assumed that more small and decentralised players can take part in the electricity market. Thereby a lot of actors that have no experience on the electricity markets, as well as low willingness to invest, take risks and a mix of technologies enter the electricity market. Such actors could be households amongst others. Including so many and diverse actors in the market, can be done by aggregators. These group several actors and handle their consumption and production as one. (Danish Energy Agency, 2021b) Since this aims at achieving more flexibility to a price as low as possible, such actors can be considered competitors to PtMethanol in relation to providing flexibility. However, a smaller scale PtMethanol plant could also take part in the business model of such an aggregator.

The second goal aims at maintaining Denmark's energy security, which is provided through flexible generation and consumption of energy. Main consideration is to maintain that flexibility while integrating more renewable energies into the energy system. Therefore, the market frame is to promote the usage of new and sustainable technologies. Furthermore, the need for flexibility is to be communicated as transparent as possible, by a suggested published development trend of the needed system services for the following 3-5 years. (Danish Energy Agency, 2021b)

Moreover, the second goal is referring to fair price signals that are meant to be the main incentive for actors in the market to provide flexible generation and consumption. As such Energinet is to assess whether scarcity prices can assist in providing flexibility on the balancing market. Such scarcity prices are suggested supplements on top of the electricity price that was settled upon the market, to strengthen the incentive to balance the power system in times of imbalances. (Danish Energy Agency, 2021b) Scarcity prices or other price signals to provide flexibility on the balancing market are highly relevant for a PtMethanol trying to provide flexibility on the day-ahead market, as part of the balancing market. It should therefore be investigated how such price signals would influence the operation of a PtMethanol plant and the flexibility it is providing. At the same time this can give an indication if tools like scarcity price can serve to increase the flexibility of actors on the electricity market.

The third goal focuses on that a cost-effective expansion of the electricity grid should be ensured through a flexible electricity market. One measure of this is to establish local flexibility to limit bottlenecks. The Danish Energy Agency (2021b) predict that more bottlenecks on a local scale will arise in areas where it is difficult to get the electricity from producers to consumers. Moreover, for cases where the demanded grid capacity is bigger than the actual capacity, e.g., for charging electric vehicles, and will then affect the security of supply. Local flexibility will then mitigate these bottlenecks in a limited geographical area. Moreover, flexibility can help mitigate the approaching need for grid reinforcement due to limits in grid sufficiency, which is costly for Energinet and thereby the consumers, since the grid then will be operate more efficiently cf. Figure 8.1. (Danish Energy Agency, 2021b)

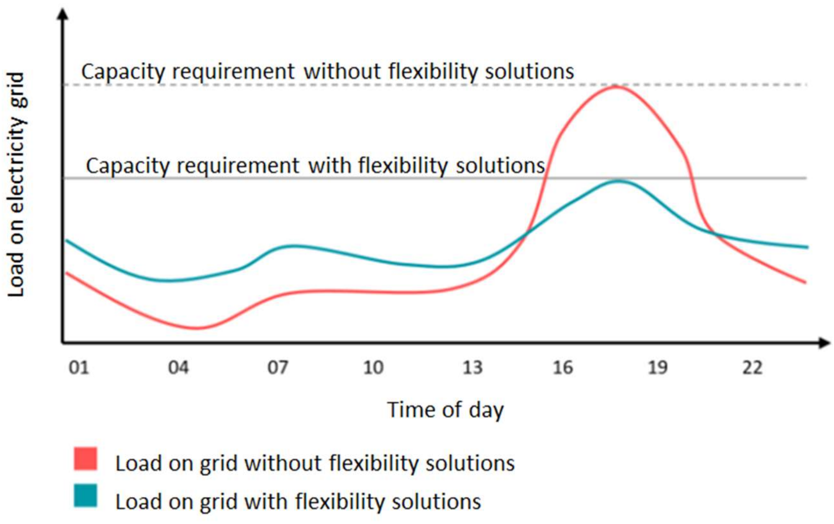

Figure 8.1: Predictions for load on grid with and without flexibility solutions. Based on (Danish Energy Agency, 2021b)

In order for local flexibility to operate efficiently, transparency of where in the grid the bottlenecks are occurring is necessary. (Danish Energy Agency, 2021b) This will be beneficial in relation to the strategical placement of PtMethanol units to analyse if they can provide local flexibility in a specific case. This would however require an investigation of geographical placement of a PtMethanol plant in relation to bottlenecks in the grid, which is not performed in this report. Moreover, the Market Model 3.0 suggests that flexible tariffs are introduces e.g., geographical or time differentiating tariffs (Danish Energy Agency, 2021b). Currently, the tariffs are charged pr. kWh, but since the expenses held by Energinet are not proportional to the consumed electricity since some are fixed, this strategy expected to be changed. The Danish Utility Regulator is currently processing several proposes of such changes. One possible option is geographical differentiating connection fee for production units. Moreover, limited grid access where customers of the grid can be disconnected if bottlenecks or imbalances etc. are occurring in the grid but then receiving a tariff discount. Furthermore, Energinet is currently investigating if time differentiating tariffs should be implemented. These tariffs should reflect the changing load in the grid during a day and should thereby incentivise a load shift to cheaper hours with less load and thereby provide flexibility. (Energinet, 2022c) Such changes in tariffs might affect the operation of a PtMethanol similar to scarcity prices, as they originate in the same idea of making it more expensive to consume electricity in times of scarcity. Both concepts might therefore be investigated in a scenario that features dynamic tariffs which apply in times of stress on the power system or energy scarcity.

The fourth goal is that to ensure a cost-effective transition into a more sustainable energy system in the future, where prices are kept as low as possible and transportation of electricity is not a barrier, monopolies such as Energinet and utility companies must be kept. According to the Market Model 3.0, higher prices for transportation of electricity might lead to higher expenses for consumers, affect the competitiveness for companies and eventually affect the profitability of establishing PtX plants. It is expected the electricity system operators will demand new grid services and products to ensure a stable and functioning grid. (Danish Energy Agency, 2021b)

The fifth and final focus point in the Market Model 3.0 is to ensure a continuity of development in the electricity system in the future. This shall be done through data collection and involvement of stakeholders. Examples of needed data and knowledge are how price signals for flexibility should be settled, which system services are needed, mapping of the flexibility potential, etc. The Market Model 3.0 must therefore be updated and refitted along with the development of the system. (Danish Energy Agency, 2021b)

The effects of expected developments of electricity markets and system have on the operation of a PtMethanol plant are mostly derived from the need to increase the power system's flexibility or to introduce measures to decrease that need. Therefore, it is concluded that the investigation of the flexibility of PtMethanol is highly relevant as this influences the power system flexibility. The Danish Energy Agency expects a change in tariff schemes or scarcity prices to incentivise flexible energy consumption. This is seen as the most influential developments towards the operation of a PtMethanol plant. Furthermore, changes to the reserve markets, as described in Section 2.3.4, are hinted. These involve the increase of transparency in the reserve market, likely leading to a more open market for special regulation and possibly new measures to maintain power might be introduced. As the document is very vague on the nature of such changes and the operation of a PtMethanol plant is only investigated in relation to the day-ahead market, such developments are investigated in more detail.

8.3 Other Influences on the Operation of a PtMethanol Plant in 2030

In order to simulate the operation of the PtMethanol plant in 2030, the parameters used must be in line with expected developments of market and technology dimensions of the regime. Therefore, these are based on predictions and assumptions including uncertainty, as developments might be influenced by unforeseen developments. As apparent through the investigation of the Market Model 3.0 tariffs are expected to develop. Besides tariffs also electricity prices and taxes, other feedstock prices as well as prices for the sale of products are influenced by changes to the regime. Therefore, a closer investigation of those is performed in this Section. The parameters gained from an investigation of regime development are thereby purely economic.

8.3.1 Electricity Prices

The Danish Energy Agency (2023b) is assuming that the day-ahead electricity price in DK1 will increase compared to the 2021 prices. The electricity price is calculated in the techno-economic tool by the Danish Energy Agency called 'Ramses', where detailed information for production and consumption of electricity is included. (Danish Energy Agency, 2023b) The predicted electricity price in 2030 dependent on prices for fuels and CO2-quotas and is therefore presented with a range:

Table 8.1: Yearly average elspot price in DK1 by 2030 (Danish Energy Agency, 2023b)

Elspot price in DK1 in 2030 [kr./MWh]		
Low price	Medium price	High price
340	440	610

The price does not include the large variations and increases in fuel prices which are seen in 2021 and 2022, since it is using a normal year for predictions where 2014 is selected for the Ramses model. Moreover, since the electricity price in DK1 is closely related to and affected by the neighbouring countries and the technological development for hydrogen, which are subject to considerable uncertainty, the hourly prices should be used with consideration. (Danish Energy Agency, 2023b) A time series of expected hourly prices in the elspot market in DK1 in 2030 are found in the *Analysis Prerequisites for Energinet* (Danish Energy Agency, n.d.).

8.3.2 Tariffs

Tariffs on electricity consumption are defined as payments towards the TSO per unit of consumed electricity. In theory tariffs can also be paid towards Distribution System Operators (DSOs), however since the electric capacity of the modelled PtMethanol plant will exceed several hundred MW, it is assumed, this plant connects directly to the TSO grid since the DSO grid has insufficient transmission capacities (Energinet, 2022b). Tariffs related to the distribution grid is therefore not included.

Just as the electricity process, the tariffs are also assumed to develop in the future regime. As projection of tariffs are often subject to uncertainty due to multiple parameters affecting the needed changes in tariffs, Energinet (2022c) have therefore created three scenarios of development for tariffs to include this. This has resulted in a low and high scenario as well as a base scenario. The low-price scenario is assumed to apply if the electrification happens faster than expected, where the high-price scenario will apply if the process is slower or if some consumers are exempt from tariff payments. As it can be seen in Figure 8.2, the electricity tariff is assumed to be 150 kr./MWh until 2025. (Energinet, 2022c) The same tariff height is assumed for the base scenario in 2030 due to the historical trend portrayed in the figure. The tariff scheme used in the base scenario is assuming a flat tariff structure with a payment for consumed energy.

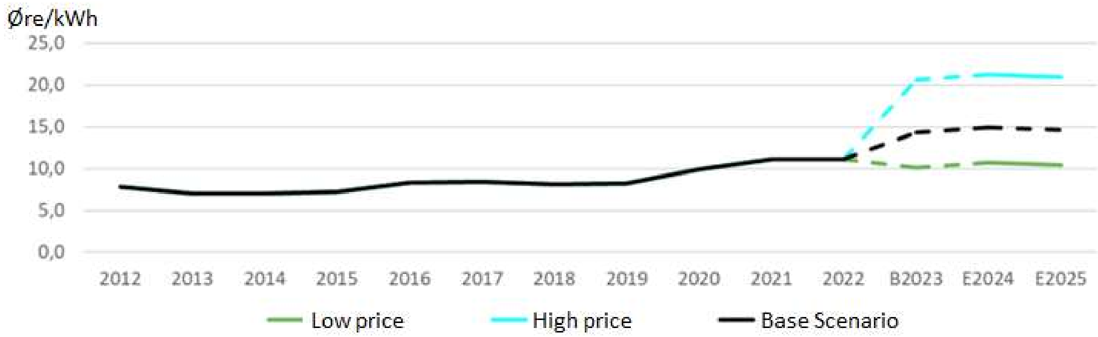

Figure 8.2: Historical and predicted development of tariffs. Based on Energinet (2022c)

8.3.3 Taxes

As PtMethanol is consuming electricity for industrial purposes for producing hydrogen and methanol, the tax for consuming electricity in this case is 40 kr./MWh in 2023 (PwC, 2023). This is assumed to be the same level in 2030, due to historical trend, where it has been at this level since 2014 (Beese, 2014). Besides of tax for electricity, it might be possible that PtMethanol plants could get subsidies when consuming carbon dioxide. According to the *Green Tax Reform* by the Danish Government (2022), Carbon Capture Storage (CCS) units should have a subsidy of up to 850 kr./ton carbon dioxide captured by 2030. The reform does not state anything related to a subsidy or taxation of actors consuming carbon dioxide to produce e-fuels. (Danish Government, 2022) According to Green Power Denmark, the subsidy for CCS should apply to processes where the captured carbon dioxide is used to produce carbon dioxide neutral fuels as methanol. On the other hand, instead of receiving a subsidy, e-fuel production could also be exempted for paying taxes. (Plechinger, 2022) Because carbon dioxide is only acting as a feedstock in the energy model and the process of the actual carbon capture is not modelled, the PtMethanol plant is expected to not receive such subsidies. These subsidies could however have an impact on the price that is paid for carbon dioxide as a feedstock.

8.3.4 Prices for Feedstocks and Products

The price for methanol that can be obtained in 2030 is not studied or predicted widely. However, a study by Bos et al. (2020) assumes that the price that can be obtained for methanol will range around 4,1 kr./kg. In comparison they conclude in their study, that the costs for PtMethanol to be produced from wind energy is around 800 €/t being 5.960 kr./t. (Bos et al., 2020) As the modelled PtMethanol plant should show a feasible operation, a selling price for methanol produced based on the cost for methanol of 5.960 kr./t is selected. The price of carbon dioxide as a feedstock is selected as 330 kr./t (Cordero-Lanzac et al., 2022; de Oliveira Campos et al., 2022). To summarize, the economic assumptions taken from the investigation of a 2030 regime are presented in Table 8.2.

Table 8.2: Economic assumptions used in the base model.

Economic assumption	Rate	Source
Avg. elspot price	440 kr./MWh	(Danish Energy Agency, 2023b)
TSO tariff	150 kr./MWh	(Energinet, 2022c)
Electricity tax	40 kr./MWh	(PwC, 2023)

Costs of carbon dioxide	330 kr./t	(Cordero-Lanzac et al., 2022; de Oliveira Campos et al., 2022)
Price of Methanol	5.960 kr./t	(Bos et al., 2020)

8.4 Dynamic Tariffs

In general electricity tariffs are expected to be a tool to promote flexible electricity consumption. They a can provide price signals which incentivises consumer to react to imbalances in the grid. Thereby a tariff scheme that is changing in accordance with times of power abundance and scarcity might indirectly provide DSM. Such tariff schemes, which are changing over time are defined as dynamic tariffs. (Freier & von Loessl, 2022) Others consider local DSO electricity markets handling flexibility (Aguado & Paredes, 2023), but as the PtMethanol in this report is connected to the TSO grid, this is not investigated further.

Dynamic tariffs can be categorised into four types: Time of use (ToU), real-time pricing (RTP), critical peak pricing (CPP) and peak time rebates (PTR). ToU tariffs are already used in various Danish grid areas, by different DSOs (Bhagwat & Hadush, 2020). They refer to tariffs that are changing periodically. This might include several different price levels, with most commonly distinguishing between peak demand and off-peak times. RTP is a way of pricing electricity according to price changes on the electricity market. This happens with the same time resolution. CPP is a tariff which is rather stable, excluding certain times, where the power system experiences a lot of pressure. In these times the tariff is raised. PTR work in a similar way as CPP. However, the peak time they refer to is a peak time in which consumption favourable. In such times these tariffs would offer a lower rate for consumption. (Bhagwat & Hadush, 2020; Freier & von Loessl, 2022)

While DSO tariffs in Denmark already are dynamic, tariffs to the TSO are currently paid as a fixed amount per kWh of consumed electricity (Energinet, 2022b). Taking further developments until 2030 into account, it might be likely that more advanced dynamic tariffs are introduced into the Danish tariff structure. This is underlined in the Market Model 3.0, which notes the importance of price signals in providing flexibility as scarcity prices, which are a measure of CCP. Energinet (2022b) formulated a strategy to develop its tariff system. Included are, amongst others, the development of ToU tariffs and capacity payments. The latter is supposed to be paid on the capacity which needs to be reserved in the grid for a facility connected to the grid in combination with another tariff. ToU tariffs could be to be categorized in three times: peak around 18:00 on working days, a lower tariff at night, and a medium tariff in the remaining time. (Energinet, 2022b)

As these tariffs are not yet implemented nor have clear time schedule, they are used to develop a scenario. This scenario differs from the base scenario through implanted ToU tariffs on electricity consumption by the Danish TSO Energinet.

8.5 Synergies of PtMethanol in the 2030 regime

As mentioned before in Section 8.1, PtMethanol as part of the regime might form synergies with other parts of the regime or niches. As such PtMethanol could be a large-scale consumer of RE based electricity. This might be realised by directly connecting the PtMethanol plant with the respecting renewable electricity production e.g., a set of wind turbines. April 20th, 2023, the Danish Parliament adopted a proposal by the Minister for Climate, Energy and Utilities, Lars Aagaard, that consumers to be connected to an energy producer through a direct line and thereby not through the public grid (Danish Ministry of Climate Energy and Utility, 2023). The need for this change in the law is, that the previous legislation for electricity, the TSO and DSOs were obliged to connect all consumers to the grid regardless the cost. The new changes in the Electricity Act introduces direct lines between producers and consumers in the grid. A direct line is defined as a:

"*Electricity connection that is […] intended for the direct supply of electricity from a company's electricity production facilities to the company's own facilities or subsidiaries or specific customers, and which fully or partially replaces the use of the collective electricity supply networks.*'' (Lars Aagaard & Danish Ministry of Climate Energy and Utility, 2023)

The purpose of having direct lines is to ensure better conditions for green and innovative technologies e.g., PtMethanol plants, while ensuring an efficient utilisation of the grid. The introduction of direct lines can thereby postpone and limit the need for grid expansion and reinforcements. (Danish Energy Agency, 2021b; Lars Aagaard & Danish Ministry of Climate Energy and Utility, 2023) A direct line connection should be seen as an exception to the rule of having a public grid and should therefore only be considered if it is the most feasible solution from a socio-economic perspective. However, Green Power Denmark (2023) stress that other parameters than costs should be considered when calculating the socio-economic feasibility. This could be the time since the planning and construction time of a direct line is assumed to be less compared to an expansion of the grid. This is however not included in the adopted change. (Green Power Denmark, 2023)

According to the adopted change of law, the lines could be implemented at the 10 kV level and above, and therefore also applicable for the transmission level. Direct lines can have a socio-economic benefit if as they would incentivise co-location of the two parties e.g., a wind farm and a PtMethanol plant. Moreover, co-location would support the integration of RE, as the need for transportation of the RE-based energy is minimised. (Danish Energy Agency, 2021a). The consumer will still have the possibility to be connected to the public grid while having a direct line to e.g., a wind turbine farm. When receiving electricity from the producer, the consumer is still obliged to pay electricity taxes for the received power, as this is traded between the two parties. (Danish Ministry of Climate Energy and Utility, 2023) The electricity taxes presented in Table 8.2 applies to this scenario. The Danish Energy Agency (2023a) have provided an application guide, where a set of criteria are given which, the system must comply with in order to have a direct line connection. One of the units in the system must be new and the direct line and additional grids must not be longer in total than a connection to the public grid. In this report, it is assumed that the placement of the PtMethanol plant will comply with the rules presented by the Danish Energy Agency (2023a). (Danish Energy Agency, 2023a)

Another possible synergy that the niche of PtMethanol is able to achieve, is niche accumulation with hydrogen storages. The storage of hydrogen in this case refers to a method of storing hydrogen with hydrogen staying the medium of storage. As such, either compression to high pressure or liquification of hydrogen are possibilities for direct hydrogen storage (D. Tang et al., 2023). Danish Energy Agency (2018a) points out that currently no large-scale hydrogen storage systems are available (Danish Energy Agency, 2018a). Therefore, large scale hydrogen storages are considered a niche in this report. As until 2030, a large capacity of hydrogen production enters the regime, a way of storing or distributing needs to be established. Hence, it is assumed that large scale hydrogen storage systems are available in 2030. Tsiklios et al. (2023) suggest that the storage of hydrogen in caverns could be a feasible way but energy intensive way to store hydrogen on a large scale (Tsiklios et al., 2023). As direct hydrogen storages become a more feasible way of storing hydrogen, it has a strong on the operation of a PtMethanol plant. Therefore, a scenario, including a large-scale hydrogen storage is developed.

8.6 Summary of Scenarios

In conclusion, a base scenario including economic parameters from an investigation of the future regime is formulated. These parameters are electricity prices on the day-ahead market, increased TSO tariffs, as well as taxes on the consumption of electricity, the price obtained for selling methanol and a feedstock price for carbon dioxide. Three further scenarios are developed. The first of those is a PtMethanol plant that is directly wired to a site of renewable electricity production. The second scenario predicts changes in the TSO consumption tariff structure towards ToU tariffs. A third scenario is investigating the integration of a large-scale hydrogen storage into the PtMethanol plant. The scenarios developed from the base Scenario are illustrated in Figure 8.3

Figure 8.3: Developed Scenarios for the operation of a PtMethanol plant in 2030

It should be stressed, that Scenario 2 is determined by external actors while Scenarios 1 and 3 can be influenced by decisions taken by the operator of a PtMethanol plant. However, all Scenarios are determined on changes the regime might undertake until 2030 and developed as what-if Scenarios. As the subject of investigation with these scenarios is not to provide decision-support for investments taken by the plant operator nor someone else but an investigation of the flexibility of electricity consumption, the scenarios are comparable based on their possible influence on the operation of a PtMethanol plant. Comparing these different Scenario might also provide insight into developments of niches or the regime that benefit PtMethanol more than others.

9 Energy Modelling

The model aims at investigating the flexibility provided by PtMethanol plants in 2030. It is therefore decided to model a generic PtMethanol plant operating on the DK1 day-ahead market. In this chapter, the approach in modelling is explained, by first explaining the technical dimensions of the base model followed by descriptions of the three additional scenarios.

9.1 Scenario 0: DK1 Day-Ahead

The model of the PtMethanol plant in Scenario 0, which is conducted in energyPRO, is presented in Figure 9.1.

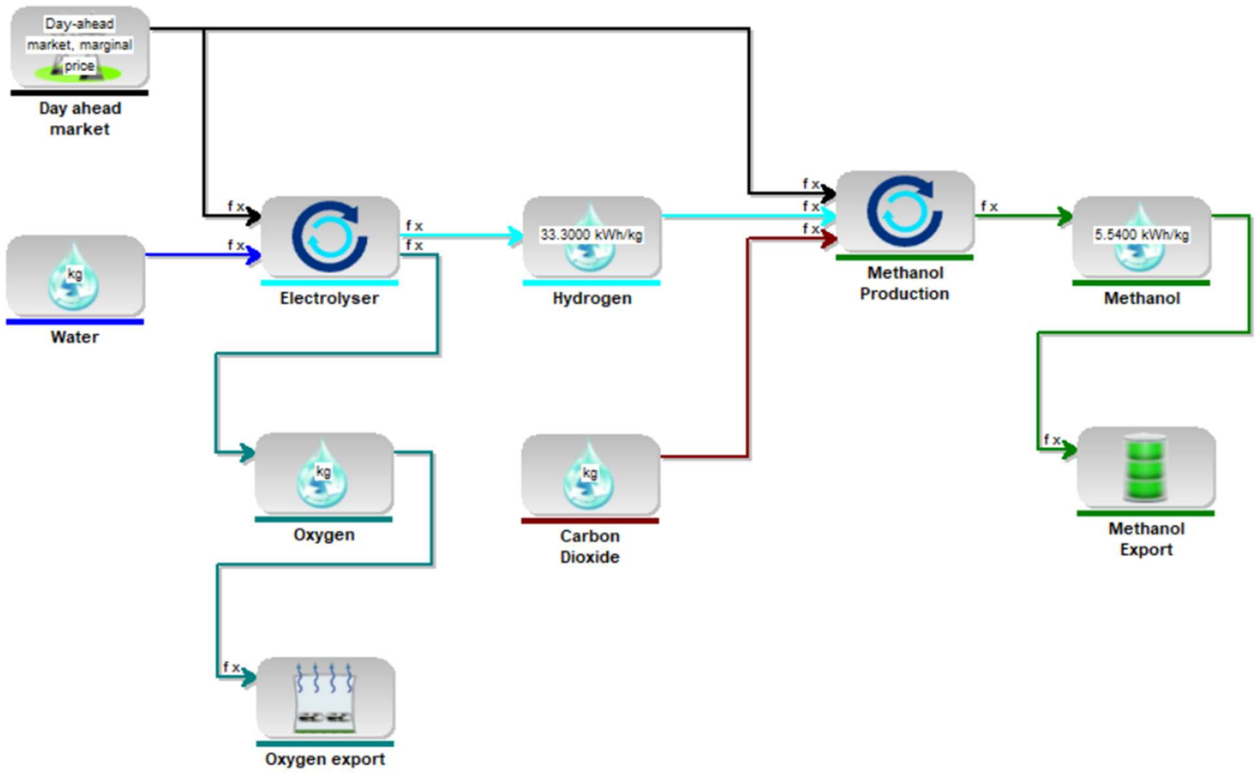

Figure 9.1: Basic model of a generic PtMethanol plant in 2030 operating on the DK1 day-ahead market

The unit “Electrolyser” is a PEMEL. It is using electricity bought from the modelled day-ahead market and water to produce hydrogen and oxygen. “Water”, “Hydrogen” and “Oxygen” are modelled as fuels, with only “Hydrogen” having a heating value based on its lower heating value of 33,3 kWh/kg. The hydrogen is then fed into the unit “Methanol Production” together with another fuel without heating value “Carbon Dioxide”. The unit then produces “Methanol” under the use of electricity bought at the day-ahead market as well. The “Methanol” has a lower heating value of 5,54 kWh/kg. In order to obtain a working model, the produced fuels also have to be consumed. Therefore, two boilers are added: “Oxygen export” and “Methanol Export”. These are set to produce no heat, able to run in part load, and able to consume all produced oxygen or methanol respectively.

9.1.1 Electrolyser

The unit “Electrolyser” mostly modelled with the parameters in Table 7.2. Since these parameters are expected to develop until 2030, the efficiency is however slightly adjusted. To do that not only the nominal efficiency but also the efficiency in part load needs to be adjusted. The current nominal efficiency of a

PEMEL electrolyser is expected to develop until 2030, to reach 65,5 %, as presented in Table 7.4. Therefore, the electrolyser is modelled with a nominal efficiency of 65,5 %. In addition, also the part load behaviour needs to be investigated. Since the efficiency there is divided in into efficiency of the auxiliaries and efficiency of the electrolysis stack, both are treated separately. As the auxiliaries are largely made up of matured technologies as pumps, inverters, and compressors as well as electric heating, the technical enhancements in their efficiencies are assumed to be very minor. Thereby they also do not change the new part load behaviour. Concluding the increase in nominal efficiency is triggered by a change in stack efficiency. If referencing Figure 7.1, this would lead to a raised curve of DC efficiency, which in turn will influence the overall system efficiency. It is assumed that by raising the curve the point of the highest efficiency in part load moves to the right and therefore to a higher percentage of nominal load. This change is assumed to be from roughly 25 % of nominal load to roughly 40 % of nominal load. The load curve modelled for the electrolyser modelled in energyPRO is shown in Table 9.1, while the efficiency of hydrogen production is plotted in Figure 9.2.

Table 9.1: Load curve of the modelled PEMEL electrolyser system in energyPRO

Load	Electricity consumption [MW]	Water consumption [kg/kg H_2]	Hydrogen production [MW]	Oxygen production [kg/kg H_2]
100 %	500	8,937	500 · 65,5 %	7,937
40 %	200	8,937	500 · 40 % ·65,5 % · 110 %	7,937
0 %	0	8,937	0	7,937

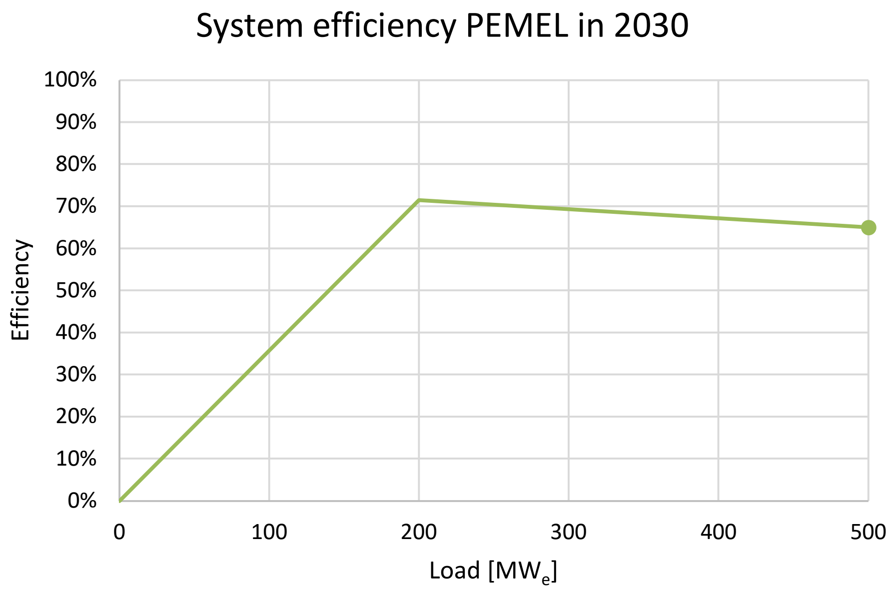

Figure 9.2: Efficiency of the modelled in PEMEL over electric load

This will have some implication for the operation of an electrolyser in energyPRO, since the operation in part load is more efficient, meaning more products can be produced to lesser costs through buying the feedstock electricity. Therefore, the operation in part load might still be feasible at higher electricity prices than the operation in nominal load. Consequently, this behaviour is modelled in energyPRO.

The oxygen and water production and consumption are modelled based on the hydrogen production. The mass balance of the chemical reaction is used to determine the minimum requirements for water consumption and the produced oxygen for every produced kg of hydrogen.

Since PEMEL is known to able to react very fast to changes in electricity supply, ramping times are not modelled in this model. The hourly resolution determines the load changes to occur hourly and all ramping times found in literature do not exceed 15 min. (Bessarabov & Millet, 2018; Buttler & Spliethoff, 2018; Lange et al., 2023)

9.1.2 Methanol Production

The unit “Methanol Synthesis” is modelled based on the methanol production unit presented in Section 7.2. Its size is determined by the maximum hydrogen production by the unit “Electrolyser”. This is illustrated in Table 9.2.

Table 9.2: Load curve of the modelled methanol synthesis unit in energyPRO

Load	Hydrogen consumption [MW]	Electricity consumption [MW]	Carbon Dioxide consumption [kg/kg Methanol]	Methanol production [kg/kg H_2]
100 %	500 · 67,5 %	See Equation 7	1,3735	5,2999
50 %	500 · 67,5 % · 50 %	See Equation 7 · 50 %	1,3735	5,2999
Stand-by	0	25 % of total energy consumption in nominal load	0	0

The methanol production, as well as the carbon dioxide production are determined by the mass balance provided by the chemical reaction (Cui et al., 2022). Per consumed 1 kg hydrogen roughly 5,3 kg of methanol are produced.

Since no data was found in literature that clearly indicated the electricity consumption of methanol production system in operation or in stand-by, it was based on the hydrogen consumption and energy efficiency, as it is assumed to increase and decrease with load, as it is mainly caused by compressors and additional heating or cooling duties. The energy efficiency is calculated as follows:

Equation 6: energy efficiency of a methanol production unit

$$energy\ efficiency = \frac{methanol\ production}{hydrogen\ consumtpion + electricity\ consumption}$$

Hydrogen production is assumed as known, since it is the parameter that determines load and size of the plant. The methanol production is only reliant on the hydrogen consumption, assuming perfect conversion of hydrogen and carbon dioxide according to the mass balance. As the energy efficiency is known to be around 75 % through a literature study in Section 7.2, the electricity consumption is modelled like follows:

Equation 7: electricity consumption of a methanol production unit

$$electricity\ consumption = \frac{methanol\ production}{energy\ efficiency} - hydrogen\ consumption$$

This method of modelling however only applies to an operating methanol production inside its operating envelope of 50 – 100 % of nominal load.

Since Chapter 7.2 shows that a methanol production unit should be operated continuously and not shut down because of its high operating temperatures and consequences towards components like the catalysts an approach is taken, that should ensure a continuous production. However, another mode of operation is included as well, which is called stand-by. This mode ensures a stable temperature through an assumed electric heating of the plant. It is shown in Table 9.2 as load line for standby. The electricity consumption in this operation mode is assumed to be able to sustain the temperature of the reactor, which is sustained by the created heat in operation mode. All losses in operation mode are assumed to be heat losses by a difference of the operating temperature to the surrounding temperature. Since this temperature is assumed to be the same in stand-by, the losses are also assumed to be the same. Therefore, the electric consumption needs to be high enough to cover those losses, equalling 25 % of total energy intake during nominal load.

To model the slower reaction kinetics, a restriction on the load changes that can happen within a certain timeframe is given in energyPRO. Load changes are not allowed to occur more often than every 2 hours, since the reaction needs two hours to reach a semi stable state after changing the hydrogen load (see Section 7.2). In addition, a fictive payment is included that is attached to turn offs of the methanol production unit, to force it to run continuously. Finally, the simulated base model is optimized in operation over the duration of 1 year.

9.2 Scenario 1: DK1 Day-Ahead with Direct Line from Wind Farm

In order to model the scenario in energyPRO the model requires a wind farm. As the main scope of this scenario is to analyse how the PtMethanol is operating when supplied with energy from a wind farm in a direct line constellation, the planned wind farm, Thor Offshore Wind Farm, in DK1 is chosen. This is purely to being able to have a park capacity to use in energyPRO as well as having wind profiles to simulate the actual production. Thor Offshore Wind Farm will have an installed capacity of 1000 MW and will be installed in the North Sea cf. Figure 9.3 (Energinet, n.d.).

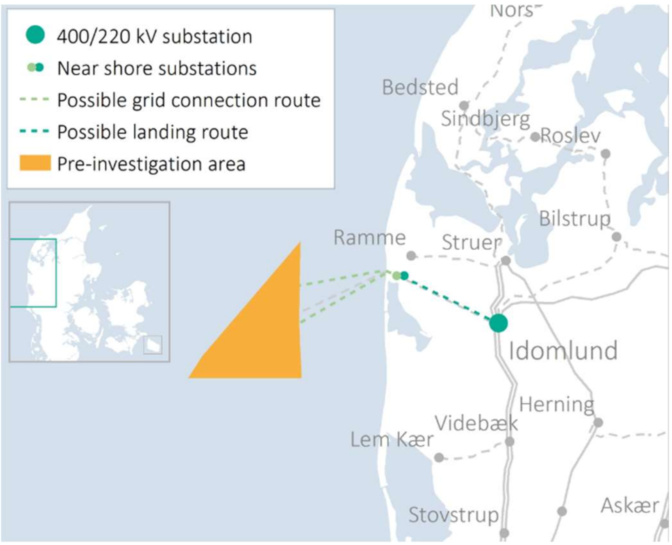

Figure 9.3: Placement of Thor Offshore Wind Farm (Energinet, n.d.)

The farm will consist of 72 Siemens Gamesa wind turbines with a nominal power of 14 MW each. (Siemens Gamesa, 2023) As the power curves for the SG 14-236 DD wind turbines by Siemens Gamesa could not be obtained, an estimation of the power curve has been made based on an upscaling of the power curve for an 8 MW Wind turbine by Siemens Gamesa (SG 8.0-167) to the 14 MW needed (Golroodbari et al., 2021).

The model for analysing direct line scenario is based on the base model where a wind farm is added as presented in Figure 9.4:

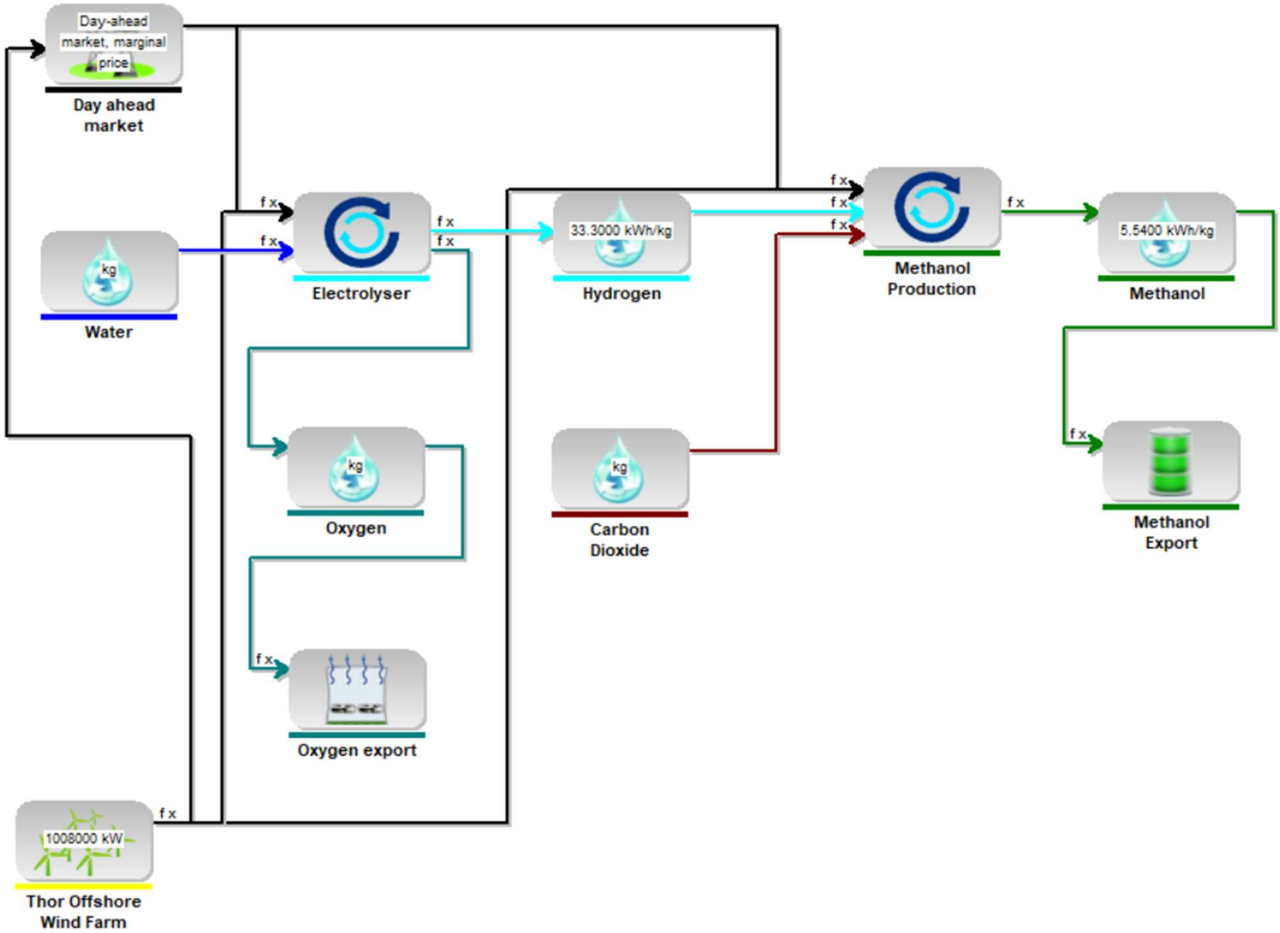

Figure 9.4: energyPRO model for scenario 1 with a direct line to Thor Offshore Wind Farm

In order to calculate the power production from the wind farm, the "wind farm" module in energyPRO is used. ERA5 data have been used to provide wind velocity data for the area in 2022, which has been chosen as reference year, as this is the newest full year available. The ERA5 data is based on historical metrological data, and is continuously updated with new measurement, which are available 5 days before the current day. (Copernicus et al., n.d.; Tsiklios et al., 2023)

As the wind farm is operated by an external actor, their economic performance is not included in the model. It is simply modelled as a different source of electricity to an agreed expense for the produced electricity, meaning the PtMethanol plant is paying the wind farm owner for the provided electricity. This price is determined on the levelized cost of electricity from offshore wind turbines of roughly 250 kr./MWh in 2030 in Denmark (Danish Energy Agency, 2016). This introduces a limitation to the energy model as it does not assume the wind farm operator to behave according to Rational Choice Theory. Instead, the wind farm is selling electricity to the PtMethanol plant, whenever there is production available without considering possible higher market prices and is curtailed in cases where the electricity price on the day-ahead market drops below a level where it is more beneficial for the PtMethanol plant to buy electricity at the market.

9.3 Scenario 2: DK1 Day-Ahead with Dynamic Tariffs

This scenario will contain ToU tariffs as described in Section 8.3.2. Since the tariffs are expected to change and Energinet hints towards a similar tariff structure than that of DSOs, ToU tariffs with similar time blocks as current DSO tariffs for assumed (Energinet, 2022b). Therefore, tariffs by N1 A/S a DSO in the DK1 market area are investigated (*Spørgsmål Og Svar Om Timetariffer*, n.d.). Peak hours are defined only on working days in winter (October to March), from 17:00 to 20:00. Medium tariff applies during workdays in summer and winter from 7:00 to 22:00 if peak hours do not apply. Off-peak tariff applies the remaining times, being weekends and holidays, and at night.

The expected distribution of tariffs on working days in winter and summer is illustrated in Appendix A. The height of the tariff is based on a basic assumption, that a tariff is a tool to cover the TSO's expenses without creating a profit. Therefore, it is assumed, that the average tariff level paid should equal the expected tariff scenario from Figure 8.2 of 150 kr./MWh. This leads to the three tariff levels presented in Table 9.3 and the tariff structure presented as an exemplary week in winter and summer in Figure 9.5.

Table 9.3: Payments in a time differentiating tariff in 2030

ToU tariff	
Peak hour tariff	88,15 kr./MWh
Medium tariff	176,29 kr./MWh
Off-peak hour tariff	352,59 kr./MWh

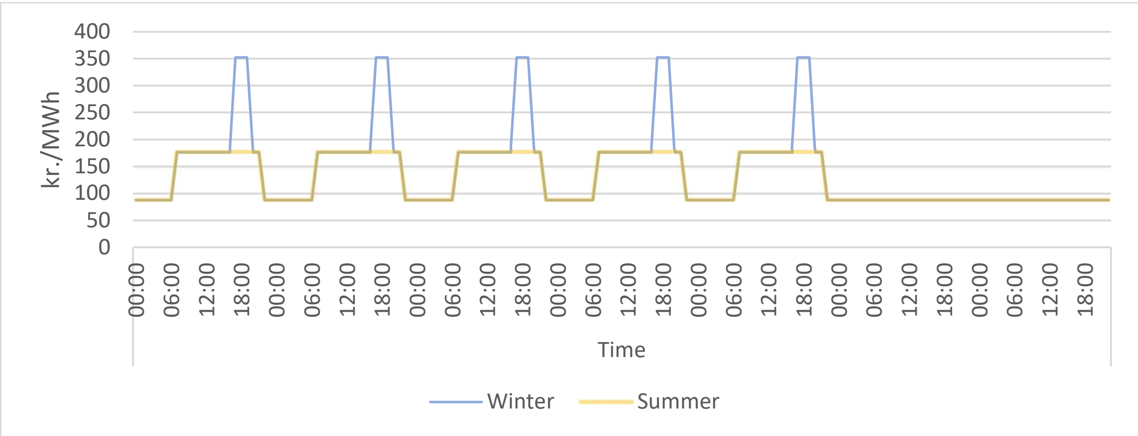

Figure 9.5: ToU tariffs for electricity consumption in Scenario 2

9.4 Scenario 3: DK1 Day-Ahead with Hydrogen Storage

The third scenario is modelled based on the base scenario with an added hydrogen storage between electrolysis and methanol production. This is done, because it is believed, that this can decouple the electricity consumption from the methanol production to a larger degree. In doing that, electricity consumption is likely to achieve a higher degree of flexibility, as it is not directly linked to the constant consumption of methanol anymore.

In a study on renewable methanol production Chen et al. (2021) investigated the levelized energy cost of an energy system based on certain mix of electricity supply, an undefined capacity of electrolysis, fuels cells, hydrogen storages and a constant demand of hydrogen for methanol synthesis. They optimised the cost for energy in such a system, by changing the storage capacity as well as the amount of overcapacity of renewable energy production and the price of dispatchable energy to. The investigation showed that the levelized cost of energy is improving with higher storage capacity. This development was found to be only significant up to a capacity of 18 hours of methanol production. If the storage capacity was bigger the marginal benefit would significantly decrease. As the capacity of electrolysis is undefined, there is no indication given of a preferable size of an electrolyser. (Chen et al., 2021)

The storage capacity of the hydrogen storage is chosen to be big enough to supply the methanol production with hydrogen for 18 hours. As for the modelling of the system, the capacity of the methanol production stays the same to ensure comparability between the scenarios among a similar methanol production. Therefore, in the electrolyser is increasing in capacity. It is assumed to double in capacity, to be able to charge the storage within 9 hours. Every other parameter is staying equal to Scenario 0. The storage is included in the energyPRO model by including a storing capacity on the produced hydrogen fuel. The hydrogen storage is given the restriction of being charged to exactly 50 % both in the beginning and in the end of the optimisation period. The changes to parameters from the base model are illustrated in Table 9.4.

Table 9.4: Parameters changing from Scenario 0 to Scenario 3

Parameter	Changed from	to
Electric capacity of electrolysis	500 MW	1.000 MW
Storage capacity of hydrogen	0 kg	177.273 kg

In reality a physical hydrogen storage is associated with an energy loss, since energy is needed to either liquify or compress the hydrogen. Such energy losses are not modelled to simplify the model in energyPRO.

10 Results

The results obtained through the optimisation of the operation strategy of the PtMethanol plants in the different scenarios and the conducted MCDA are presented in two different sections. Firstly, the obtained information from the optimised operation strategy as well as the derived flexibility metrics are presented. Secondly the results of the MCDA are described and interpreted. Lastly, the results are investigated in sensitivity analyses for different parameters.

10.1 Modelling Results

The results of the optimised operation are presented through selected key outcomes for all scenarios. These key outcomes are:

- Flexibility factor
- Flexibility ratio for upward ramping
- Flexibility ratio for downward ramping
- Operational efficiency of the electrolyser
- Operational efficiency of the methanol synthesis
- Yearly produced methanol
- Yearly imported electricity
- Yearly net operational income

The results each model deliver for each of the parameters is listed in Table 10.1, while an exemplary week of operation is plotted in Appendices B to E respectively. The chosen week of operation is from 20th of March to the 27th of March, chosen because it is a week that depicts both low and high average prices.

Table 10.1: Results obtained by the energy model in energyPRO and the calculation of related flexibility metrics

	Scenario 0: Base model	Scenario 1: Direct Line	Scenario 2: Dynamic Tariff	Scenario 3: Hydrogen Storage
Flexibility factor	0,555	0,841	0,419	0,885
Flexibility ratio for upward ramping	0,682	0,160	0,542	1,787
Flexibility ratio for downward ramping	0,600	0,553	0,611	0,831
Operational efficiency of the electrolyser [%]	67,88	65,80	67,43	67,90
Operational efficiency of the methanol synthesis [%]	72,11	72,60	72,81	74,76
Yearly produced methanol [t]	258.189	347.883	278.828	457.511
Yearly imported electricity [GWh]	2.751,1	843,8	2.967,6	3.171,2
Yearly operational income [mio kr.]	8,59	827,5	69,9	347,2

The presented FR for downward ramping in Table 10.1 show how much energy the plants can spontaneously reduce their electricity consumption by in relation to their overall electricity consumption. It therefore provides an indication of the ability of the plant to provide short term upward regulation for the grid. The FR for upward ramping shows the same, but for the plants' ability to provide short term downward regulation to the power system.

The FF is a factor that shows whether all electricity is consumed in hours where electricity consumption is beneficial for the grid if it equals 1, or whether the electricity consumption takes place in times where electricity consumption is not beneficial to the power system if it is closer to -1.

The yearly operational efficiency refers to the efficiency of all energy outputs in relation to all energy inputs over a year. It lies between the efficiency at nominal load and the peak efficiency at part load for the electrolyser, while the efficiency of the methanol production in all scenarios is slightly below the assigned efficiency in Section 7.2 which was 75 %. Therefore, in all scenarios, the electrolyser is sometimes operating in part load to reach the higher operational efficiency than nominal (cf. Figure 7.1). The methanol production however operates at the same efficiency in part and full load. A value lower than the nominal efficiency is expected however, as the total electricity consumption is included into the yearly operational efficiency, as it equals the overall produced energy divided by the overall consumed energy, meaning all electricity consumed during stand by operation is included in the operational efficiency. Therefore, it is lower than the stated nominal efficiency as soon as the plant enters stand by operation at least once a year. As both units' yearly operational efficiencies are behaving as expected, it is concluded that the white-box modelling approach that was chosen, lead to an accurate portraying of the unit's operational behaviour in energyPRO. The yearly operational efficiencies give an indication of the operation mode the units are running in. As the operational efficiency of the electrolyser in Scenario 1 is the closest to the stated nominal efficiency, it can be concluded that the electrolyser is operating at full load most often in this scenario. The number of stand-by operation hours in Scenario 1 is similar to other scenarios without storage technologies. Thereby, the operation hours in Scenario 1 are similar to Scenarios 0 and 2, but the PtMethanol plant operates closer to full load more often. As the state of stand-by operation is the one consuming the least electricity in scenarios without storages, it is assumed to be used in times, when day-ahead electricity prices are too high for feasible operation. In Scenario 1 the possibility to consume electricity from the wind farm at a fixed price of 250 kr./MWh exists, thereby making direct line operation feasible even if day-ahead prices are too high. As the number of stand-by hours seems similar in Scenarios 0 to 2, it indicates that this possibility does not exist often, meaning that if day-ahead electricity prices are high, often there is no or not enough electricity production from the wind farm to make a feasible production of methanol possible. The operational efficiency of the methanol production is the highest in Scenario 3, indicating that the least hours of stand-by are experienced, while the efficiency of the electrolyser is the highest. The higher efficiency of the electrolyser can be explained by the oversizing, as this makes it possible to operate in part load more often.

The fact that every unit is running in stand-by at least part time makes the PtMethanol plants in all Scenarios must run units, with electricity consumption at all times. The electricity consumption in this stand-by operation is however lower than in most other operation modes. This is illustrated in Appendices B to D, where all scenarios consume electricity at all times, limiting the flexibility provided to the power system. This could develop to be problematic, if as explained in Section 2.2 a time of power scarcity ensues, the plant then has to be supplied with electricity. Furthermore, grid capacity always has to be reserved for a PtMethanol plant. In the case of the modelled plant with an electrolyser of 500 MW electric capacity, the stand-by consumption is close to 100 MW. The effect of stand-by consumption is reflected in the FF, as it never reaches a score of 1. This means that none of the investigated scenarios makes it possible for a PtMethanol plant to only consume electricity in hours where the consumption is beneficial to the power system.

Investigating the plotted weekly examples of operation from energyPRO in appendices B to E, it becomes apparent that Scenario 3 is able to achieve the lowest valley and highest peak loads. The weekly operation example from energyPRO in Appendix C shows, that Scenario 2 experiences a lot of ramping in comparison to other scenarios. As the FRs are developed on the assumption that the PtMethanol plant is only able to change its load every two hours due to the reaction stability, regular ramping decreases the FRs significantly independent of the load that the plant is operating at. The FR for upward ramping of Scenario 1 is the lowest of all scenarios, because it operates closer to full load more often, thereby not being able to ramp up significantly. A PtMethanol plant operating with direct line to a wind farm has therefore not strong capability of providing short term downward regulation in the power system. It can be concluded that an electrolyser operating close to full load limits the additional flexibility a PtMethanol plant can provide.

The possibility for downward ramping is the highest in Scenario 3, as it experiences the most hours of operation as indicated by the operation efficiencies. Therefore, it has the best ability to provide short term upward regulation to the power system. In general, a relation between imported electricity and capability for downward ramping is observed. The lower the amount of imported electricity, the lower the FR for downward ramping. This is caused by the fact, that if no electricity is consumed from the grid, no upward regulation can be performed through DSM measures.

Regarding the flexibility it can be observed that the flexibility factor of the scenarios producing the most methanol is higher. This means that the direct line and the hydrogen storage scenarios provide the most flexibility to the electricity grid by their operation on the day-ahead market. However, all scenarios are consuming more electricity when it is beneficial for than power system than when it is not, as indicated by their FFs bigger than 0. The FF is likely influenced by the methanol production, as the methanol production is taking place in hours where a low electricity price is observed. By increasing this production, while still only running at part load or stand-by in times of high prices these plants provide more flexibility. This additional flexibility must be discussed in relation to the power system, as the electricity consumption cannot be decreased in times of high prices, thereby not increasing the flexibility in such times but only in times of low prices through higher consumption. Thereby it can be concluded that a PtMethanol plant is most suited to provide load growth in relation to the described measures of flexibility in Figure 2.2.

The scenario based on ToU tariffs provides the smallest amount of flexibility to the power system through its day ahead operation, while being very beneficial to the economical outcome. As this is happening through lower tariffs in certain hours, it can be concluded that the PtMethanol plant is able to flexibly react to such price incentives. The flexibility for the power system is most likely lower, as the tariff scheme that was selected is based on ToU in an DSO grid 2023. Therefore, several factors that are expected to develop from 2023 until 2030 can be expected to make these peak times less fitting and appropriate in 2030 to apply to TSO tariffs. Such factors are having an influence on the times where the power system is under pressure are the higher amount of renewable energies in the grid and the amount of international interconnection. As the electricity consumption of the PtMethanol plant is shifted into different times if comparing Scenario 2 to Scenario 0, it can be concluded that a PtMethanol is suited to perform load shifting to a degree, as a part of the load must be always maintained through stand-by consumption. It is however leaving more possibilities to ramp up or down units based on the planned day-ahead operation than the direct line scenario. Thereby it could provide more additional flexibility to the power system e.g., through taking part in the regulating market. The highest amount of additional ability for ramping and regulation can be provided by the PtMethanol plant including a hydrogen storage, as indicated by the highest FR both for upward and downward regulation. Moreover, Scenario 2 has higher methanol production and especially a higher operational income than Scenario 0. As Scenario 2 with Dynamic Tariffs was built under the assumption, that ToU tariffs would promote flexibility, it is an unexpected result that it provides the least flexibility through its planned operation. The tariff scheme however proves beneficial to the yearly operational income of the Methanol plant as it is higher than this of the base model, while the methanol production as the only means of generating revenue is only increasing by 8 %. This attributed to the lower tariff that can be observed in most hours of the year. A dynamic tariff scheme can greatly benefit the integration PtMethanol plant into the regime, as it clearly incentivises the PtMethanol plant to consume electricity flexibly in hours where the tariff is lowered in comparison to a flat tariff scheme.

While the methanol production in Scenario 0 is lowest, the methanol production in the scenario involving a hydrogen storage is 52 % higher and the highest of all scenarios. This is most likely caused by the higher degree of freedom for the electrolyser to operate and charge the storage whenever cheap electricity is available. Furthermore, the electrolyser in that scenario is oversized and thereby can produce more hydrogen to a lower price leading to a more stable operation of the methanol production. This also influences the flexibility ratios, as the upward ramping ratio is exceeding the scale at 178 %. This is probably caused by the oversizing of the electrolyser. As it is oversized, it operates at lower loads for most of the year and thereby offers more possibilities to upward ramping and thereby downregulating the power system. The oversizing furthermore results in a limited comparability between the scenarios, changes to the investigated setup are made. It is still relevant to investigate the impact these changes make on the flexibility that a PtMethanol plant provides. To make the scenarios more comparable flexibility metrics that relate to the electric capacity of each plant or the added investment costs might have been developed.

The yearly net operational income seems not to be directly linked to the amount of yearly methanol production, as the highest operational income is achieved in the direct line scenario. This can however be explained through the changes in operational expenditures between the scenarios, since especially in Scenario 2 the costs for electricity are different, as it is to large degree supplied with electricity by a wind farm to a cost that lies 190 kr. below the average yearly day-ahead price for electricity.

10.2 Graded Results

The described FFs and FRs of all scenarios are used to conduct and MCDA according to Section 5.4 to evaluated which of the developed scenarios is providing the highest amount of flexibility to the power system. The achieved grade of each scenario as well as the weighted overall grade which each scenario achieved are listed in Table 10.2, and graphically illustrated in Figure 10.1.

Table 10.2: Results of the MCDA for the analysed scenarios

Grading				
	SC0	SC1	SC2	SC3
FF	8	10	8	10
FR upward regulation	7	1	5	10
FR downward regulation	6	5	6	9
Overall Grade	**7,3**	**6,9**	**6,9**	**9,8**

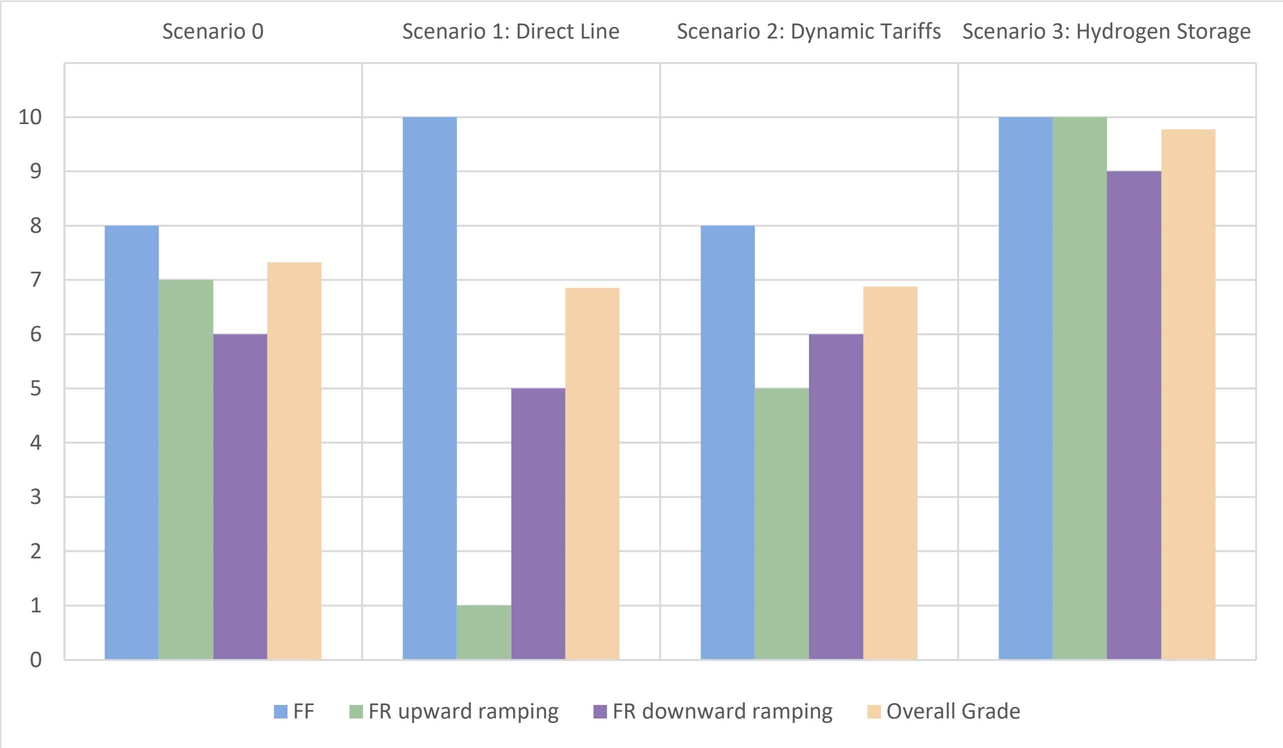

Figure 10.1: Graphical illustration of the grades achieved by all scenarios in all MCDA criteria

All scenarios achieve grades that lie in the upper third of the grading scale. Thereby, it can be concluded that all scenarios allow for a high degree of flexibility provided to the power system through electricity consumption. The highest grade that was achieved on a scale from 0 to 10 is 9,8 by the scenario including a hydrogen storage. It is found to be able to provide significantly better possibilities for additional up- and downward regulation than all other scenarios, which can be attributed to the storage and the oversizing of the electrolyser. Scenario 0 achieves the second highest overall grading with a grade of 7,3, with also achieving the second-highest result for both flexibility ratios. It is therefore able to provide more additional flexibility. Scenario 1 and 2 achieve the lowest results of 6,9. In general the observed differences in gradings are highest for the FR for upward regulation, while being the smallest for the FF. As the achieved grades for the FF are all close the upper limit of the scale, this reduces the visibility of differences. A higher resolution of the grading scale would have increased the visibility of differences between each scenario.

As the only scenario that obtains a better overall grade than Scenario 0 is the scenario including a hydrogen storage and an oversized electrolyser, it can be concluded that a synergy between large scale hydrogen storages and PtMethanol is the only investigated development that leads to PtMethanol being a more flexible actor in electricity systems. However, Scenario 1 is operating very flexibly in planned operation as indicated by the high grade for the FF but has a lower ability to provide additional flexibility. Therefore, regime development to allow direct lines can increase the flexible operation of a PtMethanol plant from a power system perspective, while in that case other energy units would need to provide additional flexibility if needed. As more flexibility is achieved through day-ahead operation, it might lower the need for grid reinforcements. Scenario 2, much like Scenario 1 is decreasing the flexibility of the PtMethanol plant by a regime development. This development being ToU tariffs on the TSO level would economically benefit the PtMethanol plant, however, leads to the lowest flexibility provided to the power system.

10.3 Sensitivity Analyses

A sensitivity study is conducted to investigate how sensitive the results for each scenario are. The three criteria used for evaluating how the scenarios are performing in relation to flexibility are compared in the sensitivity study. This is done on the base of the developed flexibility metrics and their ranges. The results of the MCDA are not investigated in the sensitivity study, as the resolution of the grading scale might distort the sensitivities. The study is separated into two overall categories: generic changes and model specific changes. For the generic changes the same parameters are changed in all four scenarios and compared to the results in Section 10.1, whereas the model specific changes only investigate changes in a specific model.

10.3.1 Methanol Selling Price

The first sensitivity analysis investigates how the methanol price is affecting the flexibility the PtMethanol plant can provide. As the PtMethanol plant is operating in 2030 the price for methanol is subjected to uncertainty. It is therefore investigated how a change in methanol selling price is affecting the result. The International Renewable Energy Agency & The Methanol Institute (2021) (IRENA) state that the expected future market price for green methanol is between 250-630 USD/t in 2050. Taking the technological development for the technology into account the higher level (630 UDS/t) is assumed to be a suited price in 2030, and thereby leading to a price of 4,82 kr./kg when including a conversion rate. To investigate how a higher price for methanol would affect the flexibility performance, the current cost prices estimated by IRENA is used. They state current costs for green methanol to be between 8,16 kr./kg and 16,32 kr./kg. (International Renewable Energy Agency & The Methanol Institute, 2021) Even though these are the cost for producing the methanol and not actual market price, these are assumed valid as this would be the minimum price the plant would need to be feasible. Everything above should just generate revenue, and from a price perspective led to an even higher price. Therefore, the two limit prices and the average price is used. The prices used for the sensitivity analysis are presented in Table 10.3.

Table 10.3: Methanol prices used for sensitivity analyses.

Description	Kr./kg.
Modelled Methanol price	5,96
Current cost of e-methanol avg (2023)	12,25
Current cost of e-methanol lower (2023)	8,16
Current cost of e-methanol higher (2023)	16,32
Expected future methanol price	4,82

The prices are inserted into all the scenarios, and the resulting flexibility metrics are presented in Figure 10.2 sorted by changed parameters.

All figures in the sensitivity analyses (Figure 10.2 – Figure 10.7) illustrate the sensitivities of the developed flexibility metrics and not the obtained grades in the MCDA towards changes parameters. The results of the sensitivity analysis are grouped by scenario and flexibility metric. The changing parameters are indicated by different colouring. The change of the flexibility metrics can be observed on the x-axis in a range from -0,5 to 2.

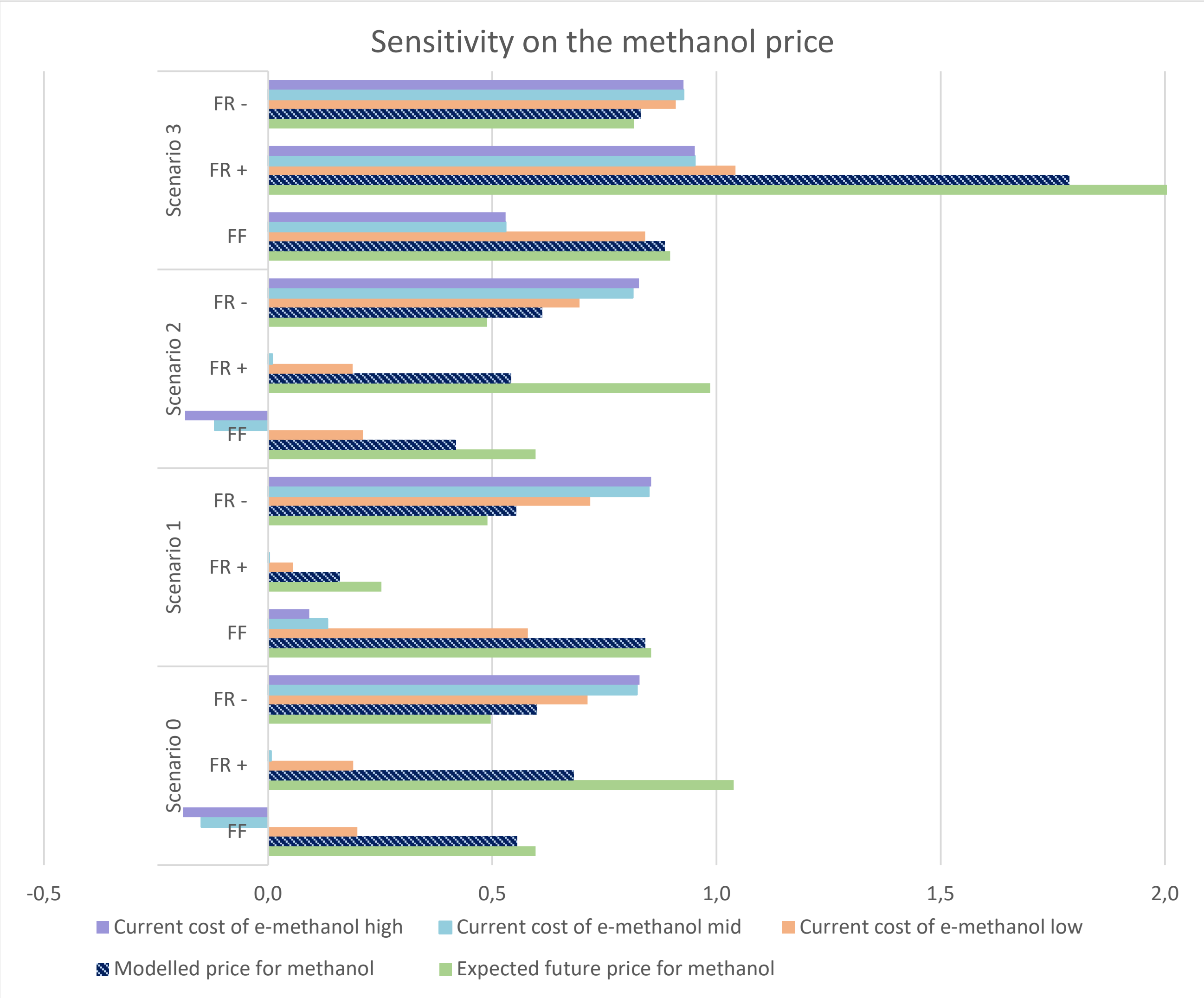

Figure 10.2: Sensitivity analysis on the price reached for the sale of methanol

Regarding the FF Figure 10.2 shows that higher prices generally lead to a lower result and thereby less flexibility provided through operation. Lower sales prices for methanol lead to slightly more provided flexibility, as the PtMethanol plant would operate more in part load to lower the electricity demand. A similar result can be observed for the FR for upward ramping, while an opposite sensitivity is observed for the FR for downward ramping. The changes in FRs are explained by the changes in feasible operation in each simulation. As higher prices for methanol lead to feasibility of production in hours with higher electricity prices, thereby leading to more operation and full load hours. In turn the possibility to further ramp up the plant decreases while the possibilities to ramp down increase, due to the change in full load hours. A similar sensitivity can be observed for costs as higher costs lead to less feasible operation, and less full load and operation hours while lower costs lead to the opposite and lower FFs and FRs for upward regulation.

In general, the Scenario 0 and 2 show similar sensitivities to the price of methanol, while the sensitivity shown by Scenario 3: Hydrogen storage is the smallest, with mostly the FR for upward ramping being affected. Both Scenario 0 and 2 are the only scenarios reaching a negative FF if methanol prices are reaching a level of 12,25 kr./t or higher. This indicates that the PtMethanol plant is not operating flexible if the price for methanol is high, but even lead to a need for additional flexibility in the power system. This is also reflected in the FR for downward ramping as it is close to 0. That indicates a very high number of full-load hours, effectively making the PtMethanol plant a must run unit.

As the used higher prices for methanol were determined on the cost of e-methanol, it can be assumed, that PtMethanol plants need to sell methanol close to these prices to operate feasible. Such a feasible operation is clearly limiting the flexibility provided on the day-ahead market as indicated by the decreasing FFs, while also decreasing the FR for upward ramping and increasing the FR for downward ramping. This is because of the higher prices obtained through the sale of products, PtMethanol will experience more full loads hours. At this point, an investigation of a techno-economical feasible operation of a PtMethanol plant is needed to be combined with an investigation of the flexibility provided through such operation to determine whether a PtMethanol plant can feasibly provide flexibility for the power system.

10.3.2 Price for Carbon Dioxide as a Feedstock

The second parameter investigated is the influence of the feedstock price of CO2 on the flexibility performance. As the price used in the modelling is an estimate of the price by 2030 this is subjected to uncertainty. As suggested by Danish Energy Agency (2018) the price is calculated with a change of ±40 % (Danish Energy Agency, 2018b). The prices can be found in Table 10.4. The results of the sensitivity analysis can be seen at Figure 10.3.

Table 10.4: CO_2 prices used for sensitivity analyses.

Changing carbon dioxide price [kr./kg]		
Modelled	**Lower sensitivity**	**Higher sensitivity**
0,33	0,198	0,462

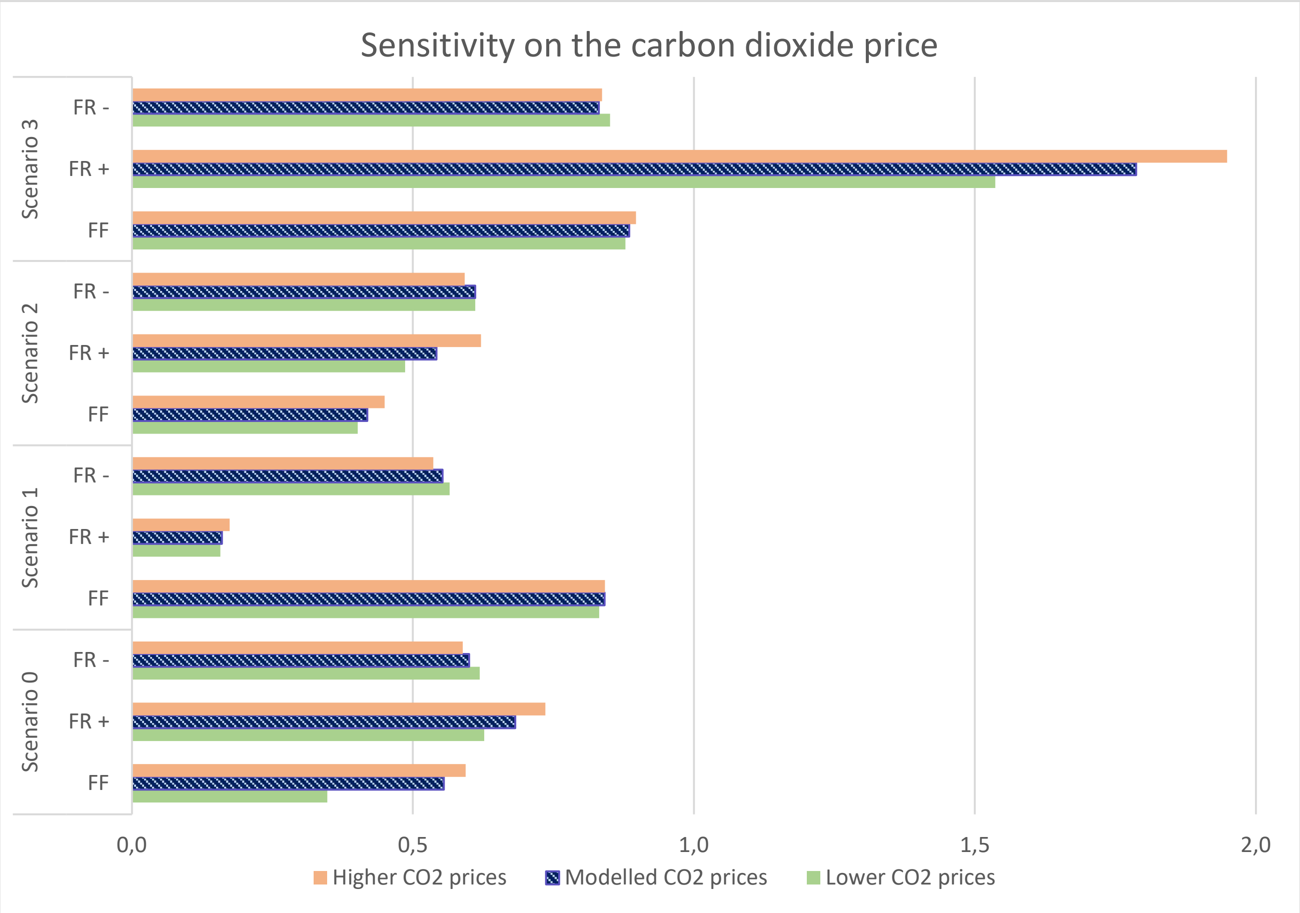

Figure 10.3: Sensitivity analysis on the price of carbon dioxide

The illustrated sensitivities of the carbon dioxide prices generally seem to be lower than the ones for changes in the methanol prices. They can however be attributed to the same effect as explained in Section 10.3.1. Higher prices of feedstocks generally lead to less hours where operation is feasible and thereby to more operation in hours with lower prices, increasing the obtained FF. Through less operation, the FR for upward ramping increases while the other FR increases. This can be seen in all scenarios. However, the sensitivities seem to be higher in the case Scenario 0 and lowest in Scenario 1. The highest sensitivity is observed for the FF of Scenario 0 and 1. These FFs decrease steeply with a low price for carbon dioxide, for Scenario 0 the FF would decrease enough to be lower than Scenario 2's FF. Therefore, the influence of prices for feedstock on flexibility, seems to be lowered if developments of the regime, like different tariffs, direct lines or a hydrogen storage are considered.

10.3.3 Electricity Prices

Since the PtMethanol is dependent on electricity and the price for this to run, a sensitivity analysis is conducted to investigate how different day-ahead electricity market prices are affecting the flexibility performance. As presented in Table 8.1 in Section 8.3.1 the expected medium day-ahead price is 440 kr./MWh in 2030 according to the Danish Energy Agency (2023b). They presented a lower and higher price depending on future fuel prices and energy mix etc. The sensitivity analyses are therefore conducted with these lower and higher averages. The time series used in the original model have been normalised as fitted to have an average of 340 kr./MWh and 610 kr./MWh. (Danish Energy Agency, 2023b) The time series are used for all scenarios. The results are presented in Figure 10.4.

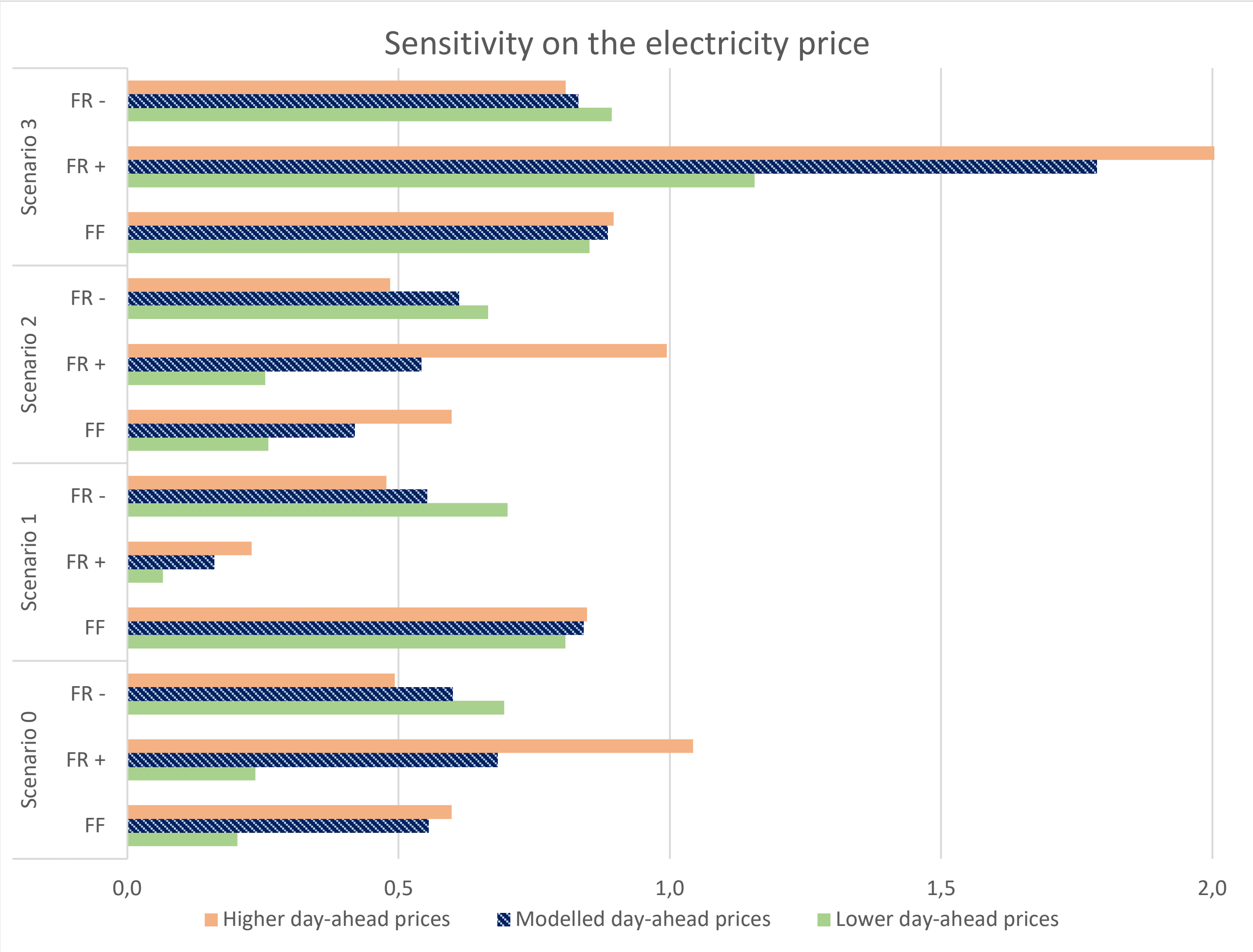

Figure 10.4: Sensitivity analysis on the day-ahead market prices of electricity

In general, a trend is observed that with higher day-ahead electricity prices more flexibility is provided through the planned operation, indicated by the FF. With higher prices the FR for upward regulation also increases in each scenario, while the FR for downward regulation decreases with increased prices. This is observed because, as explained before, with higher feedstock prices, feasible operation is possible in less hours.

The sensitivities shown by Scenario 1 and 3 are smaller than sensitivities shown by Scenario 0 and 2, with an exception being the FR for upward ramping, which shows significant changes as well. Therefore, their flexibility is less dependent on the electricity price. This is explained by the methanol production in both scenarios, which is more decoupled from the electricity price. Especially in Scenario 1 the entire PtMethanol plant is decoupled from the day-ahead electricity price, as most electricity is bought from the wind farm to a fixed price.

10.3.4 Electricity Consumption Tariff

Finally, the electricity tariff used in the model was chosen based on the prediction by Energinet (2022c) described in Section 8.3.2. Each of the tariff scenarios by Energinet (2022c) are used for this sensitivity analysis to see how the electricity tariff will affect the flexibility performance in the modelled scenarios. The average values used in the sensitivity analysis are 100 kr./MWh for lower sensitivity and 210 kr./MWh for higher sensitivity. The results are shown in Figure 10.5. (Energinet, 2022c)

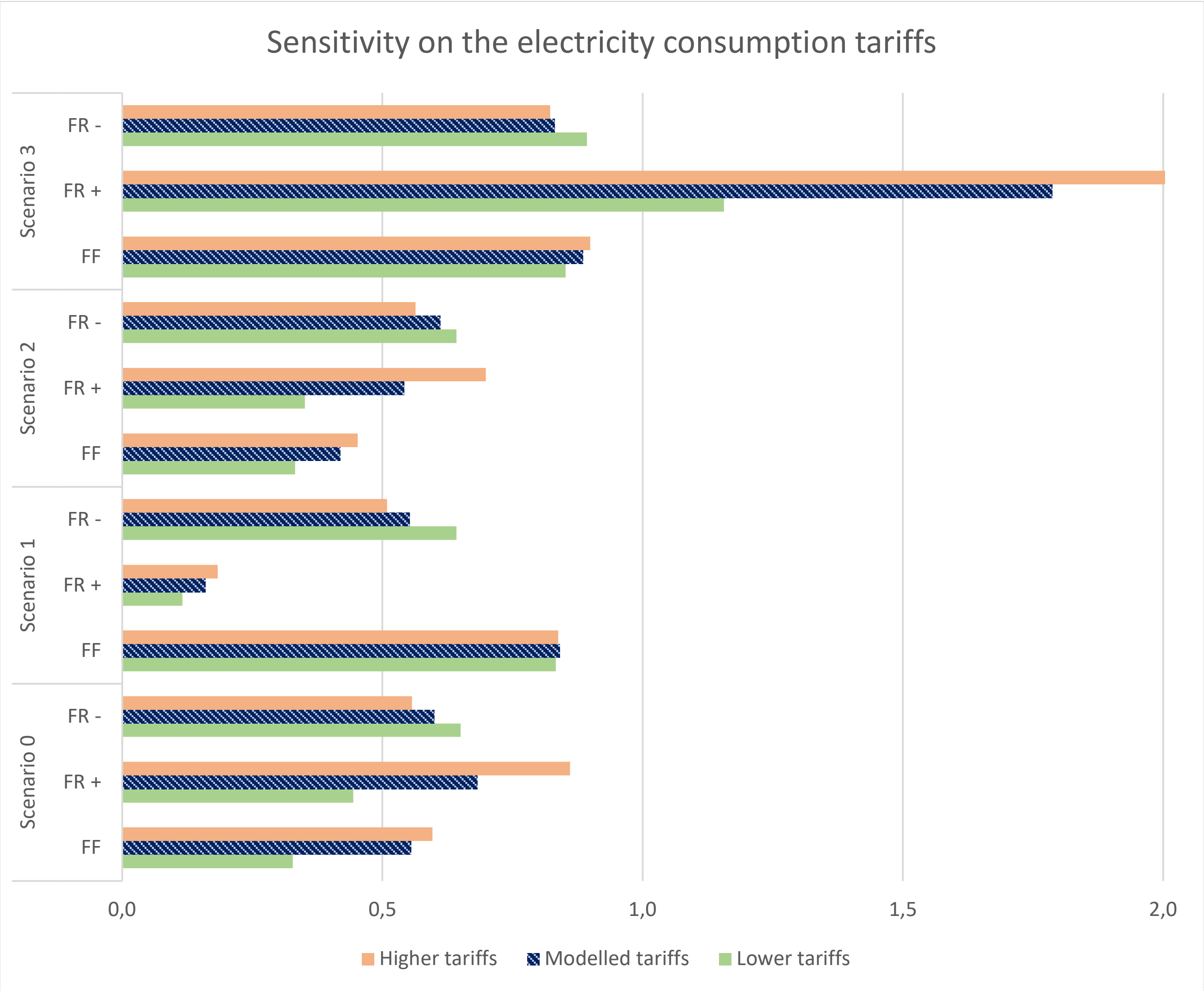

Figure 10.5: Sensitivity analysis for the electricity tariff

The changes a change in tariffs introduces to the results are observed to be the biggest for Scenario 0 and 2. The sensitivity of the model for Scenario 1 is smaller in this case, as tariffs only apply to imported electricity and the import of electricity is significantly lower in this case (see Table 10.1). The sensitivity of all scenarios shows that high tariffs can be used to increase the flexibility of actors in the day-ahead market. In general, the observed sensitivities for the electricity consumption tariff are very similar to the sensitivities experienced by changes in the day-ahead electricity price. Therefore, similar conclusion can be drawn. Table 10.1: Results obtained by the energy model in energyPRO and the calculation of related flexibility metrics

10.3.5 Scenario Specific

This section is describing the method and results of the scenario specific sensitivity analyses. Firstly, the sensitivity analyses conducted for the Scenario 1: Direct Line are presented. Subsequently for Scenario 3: Hydrogen Storage.

Scenario 1: Direct line

In the original model the PtMethanol plant is paying 250 kr./MWh for the electricity received from the wind farm, based on the levelized cost of electricity for wind turbines. This levelised cost is however subject to uncertainties, such as raw material prices or learning effects (Danish Energy Agency, 2016). Therefore, a sensitivity analysis on this price is carried out for the payment for electricity from the wind farm changing by 40 % (Danish Energy Agency, 2018b). In addition, also other payment scenarios like a payment according to day-ahead market electricity prices might be agreed on with the wind farm operator. For the day-ahead coupled payment the time series is attached to the electricity the PtMethanol plant is receiving from the wind farm. As for the original scenario, the electricity tariff is only paid when importing from the grid. The results can be seen in Figure 10.6.

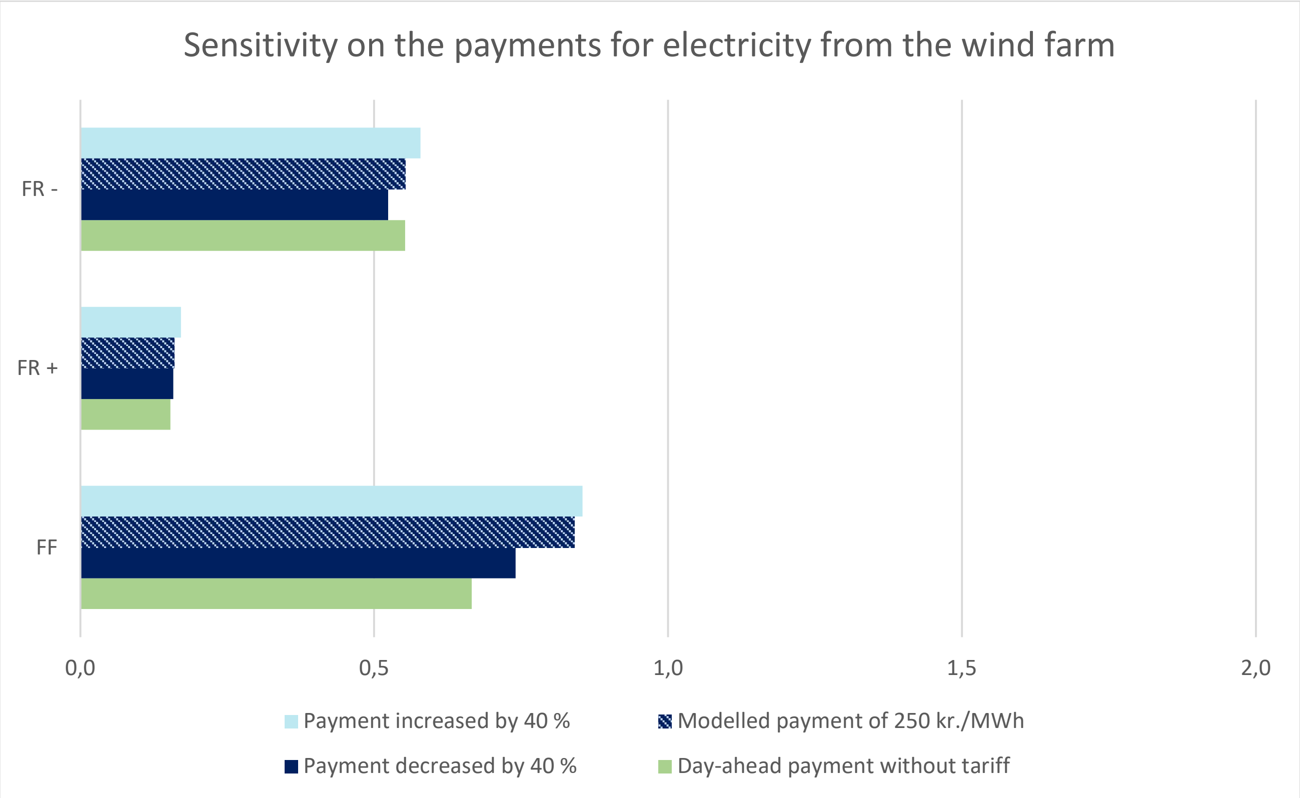

Figure 10.6: Sensitivity analysis on parameters specific to Scenario 1: Direct Line

It can be seen in Figure 10.6, that Scenario 1 sensitive to changes in the price paid for electricity bought from the wind farm. In the cases of fixed prices, in hours of high prices in the day-ahead market, the electricity will be bought from the wind farm at a fixed low price compared to the market. This again because of lower feedstock prices resulting in more feasible operation. However, the sensitivity experienced for the day-ahead payment without a tariff is unexpected.

The illustrated results a similar development than the other investigated developments. If costs are increasing, so does the possibility for upward ramping, while the FF and Fr for downward ramping decrease.

Scenario 3: Hydrogen Storage

Regarding scenario specific sensitivities for Scenario 3, the sizing of the electrolyser and the hydrogen storage are investigated. The sizes of both the storage and the electrolyser are decreased by 25 % and 50 %, while the size of the electrolyser is also increased by 25 %. The storage size is not increased as it is believed that the benefit of a storage above the chosen capacity experiences loss in the marginal benefit of the storage size. The operation of the plant is then simulated for each case individually and for the same decrease in both. Furthermore, to test the lower limit, the hydrogen storage size is decreased to 2 h of discharging. The results of this sensitivity are illustrated in Figure 10.7.

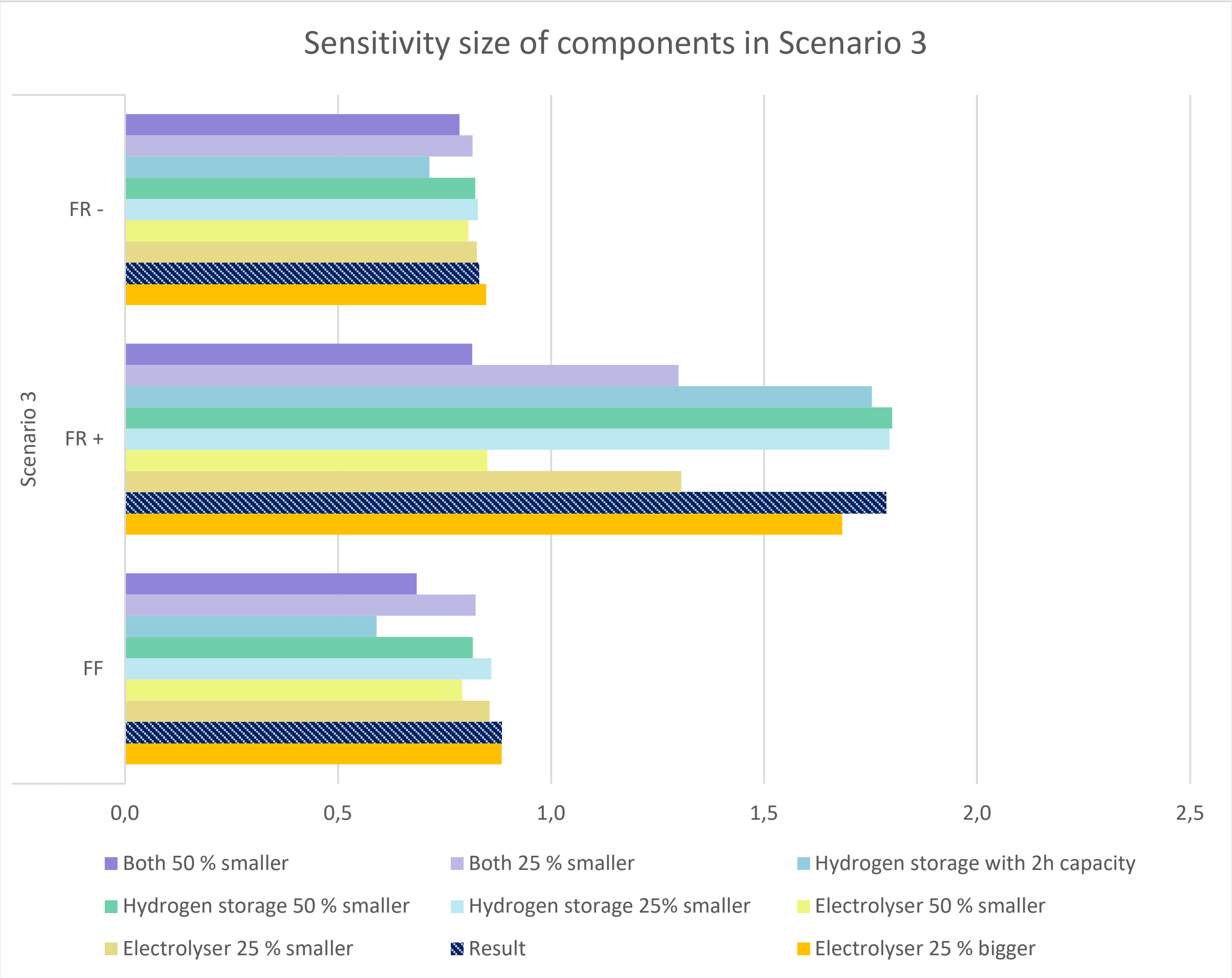

Figure 10.7: Sensitivity analysis on parameters specific to Scenario 3: Hydrogen storage

Sensitivities regarding the increase of the electrolyser's capacity are minor, with the FF and FR for downward ramping increasing very slightly, while the FR for upward ramping experiences a drop. This decrease is explained by the storage capacity which Is often closer to a full storage. Therefore, it can be concluded that further increasing the electrolyser size above the size of two times the hydrogen consumption of the methanol production, would yield no additional benefit for flexibility. If in contrast the electrolysers size is decreased, all flexibility metrics decrease. The experienced change in the FR for upward ramping is the most significant, while the other metrics change less significant. As the observed sensitivities towards an electrolyser that is 50 % smaller and thereby equals the electrolysers in the other scenarios are only significant for the FR for upward ramping, it can be concluded by the slight change in the FF, that oversizing of an electrolyser does not yield a significant benefit for the flexibility through planned operation, if a large-scale hydrogen storage is present. A change in hydrogen storage capacity, introduces slight decreases for all flexibility metrics. If the storage is halved in capacity to 9 h of operation for the methanol production, no significant changes are observed, while if the storage is downsized to only 2 h the lowest FF and FR for downward ramping can be observed. For the flexibility of a PtMethanol operating on the day-ahead market plant to benefit from a hydrogen storage, the size of the hydrogen storage must at least be able to sustain several hours of methanol production. Additionally, if both storage and electrolyser are downsized, the observed changes are higher than if only one of the components is changes in size.

10.4 Summary of Results

Through the grading of the flexibility metrics in the MCDA each modelled scenario achieved, it can be concluded that a PtMethanol plant can provide flexibility both in planned operation on the day-ahead market and providing additional flexibility. Therefore, the PtMethanol plant provides flexibility to the power system in all modelled scenarios. The flexibility provided is lowest in Scenarios 1 and 2, where Scenario 1 provides more flexibility through its planned operation, while Scenario 2 has a bigger ability for additional ramping and regulation. The most flexibility is provided by the PtMethanol plant in Scenario 3. It is also the only scenario in which a development in the regime lead to more flexibility provided to the power system. As the PtMethanol plants in all Scenarios provide flexibility, they are able to perform DSM. Through a comparison of Scenario 0 and 2 the ability of a PtMethanol plant to provide load shifting could be shown. Furthermore, it is concluded that a PtMethanol in all Scenarios can only decrease its electricity consumption to a certain level, thereby being categorised as a must run unit. This fact is limiting the flexibility these plants can provide to the power system.

Additionally, the sensitivities were investigated for economic parameters in all scenarios, while for Scenario 1 and 3 additional parameters were investigated. The economic parameters chosen for the sensitivity were based on expected ranges for each parameter or if high uncertainty was expected but no ranges found in literature, a change of roughly 40 % was investigated.

Scenario 3: Hydrogen storage shows the lowest sensitivity towards these economic parameters, while it shows its highest sensitivity towards a downsizing of both electrolyser and hydrogen storage at the same time in relation to the methanol production. Furthermore, the sensitivity study on the electrolyser size showed that a further oversized electrolyser is not increasing flexibility of a PtMethanol plant. Furthermore, if the electrolyser is not oversized in Scenario 3, the FF does not experience significant change. Therefore, oversizing an electrolyser with storage increases the flexibility of a PtMethanol only slightly. It can be generalised, that higher expenditures and lower revenues lead to more flexibility, especially provided through the operation on the day-ahead market. Lower costs and higher revenues lead to less flexibility provided. The same effect can be observed for the FR for upward ramping, while the FR for downward ramping is less sensitive to changes in economic parameters. The highest sensitivity towards an economic parameter is observed for selling price of methanol. If the price of methanol approaching the level of expected cost of e-methanol, the flexibility provided through the planned operation on the day-ahead market, indicated by the FF, decreases significantly, even to values below 0, indicating more electricity consumed in hours with high prices than in hours with low prices. As only with these higher methanol prices feasible operation is assumed, this leaves a question, whether PtMethanol can feasibly provide flexibility for the power system.

11 Discussion

This chapter discusses the previously presented results, theoretical framework and chosen methods. In addition, the taken limitations, simplifications and assumptions are discussed toward their impact on the results, as well as to bring this work into context with other research as well as current developments.

11.1 Results

The results presented in Chapter 10 are affected by different assumptions taken in order to model and evaluate the flexibility performance each scenario provided. This is counting both economic and technical assumptions. The impact these assumptions have had on the results are discussed here.

As presented in Figure 10.1 all scenarios achieve grades in the upper third of the grading scale. This led to the conclusion that all scenarios provide conditions in which a PtMethanol plant can operate with a high degree of flexibility and provide such to the power system. However, as these grades are not compared to other energy technologies, it cannot be assessed whether PtMethanol is providing more or less flexibility than current energy units. Thereby, no evaluation whether the provided flexibility is high or low in comparison to the need for flexibility could be performed. Furthermore, Scenario 3, including a hydrogen storage and an oversized electrolyser was found to be the most flexible. This is seen as an expected result as the storage makes it possible to decouple the methanol production from the price fluctuations on the day-ahead market for electricity. The oversizing of the electrolyser lead to a very high FR for upward ramping which, further increased the obtained rating. As a bigger electrolyser in comparison to all other scenarios naturally has more upward ramping capabilities as a similar demand has to be met, the comparison to the other results is questionable.

Regarding the economic assumptions, these mostly concern feedstock for the processes, electricity, and the methanol price, as presented in Table 8.2. The price of methanol is selected based on a prediction of the cost of e-methanol, which introduces uncertainty to the model, as it is not a prediction of the 2030 market prices of e-methanol. In the sensitivity analysis only the fixed yearly prices for methanol were investigated, and it is likely that other price mechanism might introduce bigger sensitivities. As a fluctuating spot prices for methanol are existing, it might be possible for the PtMethanol plant to take part in this methanol market and thereby also sell methanol at variable prices. Moreover, a market for e-methanol might be part of the regime in 2030, considering the global landscape pressures to achieve a decarbonised society by 2045, where methanol and other fuels must be carbon neutral. Participating in a methanol spot market would introduce a new time series for the energy model in energyPRO. As the prices for methanol then would differentiate over time, it could be beneficial to include a methanol storage in the models. This could be used in the operation strategy by the plant to sell the methanol in times of higher prices while still operating flexibly on the electricity inputs from the day-ahead market, and thereby increase the revenue for the plant. To the results it has the possibility of decreasing the flexibility provided by the PtMethanol plants. Since if electricity prices are high und through the relation of e-methanol to the electricity price the spot for e-methanol will also increase. This could lead to feasible operation at all times, thereby reducing flexibility through similar effects as seen in the sensitivity on higher methanol prices.

Carbon dioxide as a feedstock is also assumed to have a fixed price in the modelling but could as well differ over time depending on the source of this. If the source is a biproduct from an external company, this could be bought at the same price as the external company would have to pay in taxes for the emitted carbon dioxide, or a fixed price agreement could be established between the external actor and the PtMethanol plant to limit the emission of carbon dioxide by the external plant. On the other hand, if a fluctuating price for carbon dioxide is used instead, then a storage for carbon dioxide could be implemented in the models. This would add to additional costs for the PtMethanol plant with would influence the selling price for methanol to cover these expenses. Furthermore, consideration on whether the of carbon dioxide as a feedstock is available at the time of use was not investigated in this report. A limited availability of feedstocks or a limited export capacity for products, would very likely limit the flexibility measured through all developed metrics, if a carbon dioxide storage is not implemented in the models. In addition, similar restrictions could apply to the sale of products, limiting the operational flexibility if no sufficient storage volumes for said products exist. Concerning outputs of the plant, it might be possible that oxygen is used to industrial purposes, while some industries might be able to supply carbon dioxide or process heat to reduce the electricity consumption of electrolysis or methanol synthesis. If considered in the modelling, this could have made the scenarios having a higher score in the FF as the need for buying electricity to maintain the temperature would be lowered. However, since the development of industry as part of the regime is not investigated, these synergies are excluded. Furthermore, synergies between PtMethanol plants and district heating companies seem to be possible, since PtMethanol is producing a significant amount of waste heat. If utilisation of excess heat was considered in the modelling, the heat could be seen as an end-product by the plant, which then would change the operation strategy of the PtMethanol plant, and thereby also the flexibility performance. In addition, technical requirements for the use of said waste heat have to be met, as temperatures have to be sufficiently high. Generally, it can be stated that it is likely that a lower price for feedstocks will result in more flexibility and less flexibility provided if the opposite occurs.

Besides of the feedstocks, the electricity consumed is also of large impact to the results of this report. The PtMethanol plant is modelled to only being able to buy electricity the day-ahead market. In reality it would be likely, that such a plant would participate in other markets as well. Such markets could be either the intra-day market or the reserve markets. Due to their lower market volume these markets might be not as relevant for a PtMethanol of the size that was modelled. However, participation in reserve markets is expected to change the FF, while it would require developing different metrics than the developed FRs, as these only provide information of the possibility to provide regulation to the grid. It would then be necessary to include a time series of the actual amount of regulating capacities in each hour including a bidding price for the plant. Moreover, it should be considered, that not all bids would be accepted, as other participators might be chosen in some hours.

11.1.1 Assumptions Used for Scenarios

For the scenarios modelled different assumptions affecting the results have been used. In the energyPRO model for Scenario 1, two different time series are used: one for electricity prices and another one for wind velocity to calculate the possible production of a wind farm. Both of those time series are expected to influence each other, as higher electricity prices can be observed if the amount of electricity production from wind power is low. In addition, the time series for wind velocity used is measured in 10 meters height. As the hub of the turbines are much higher, a time series for the velocity in a correct height would have resulted in more production by the wind farm and thereby affecting the results by increasing the FF and overall grade of the scenario. Moreover, the time series for electricity price and wind velocity are not from the same year, it is not sure that in hours of high wind contribution is in the same hours where there are low electricity prices. This influences the FF of Scenario 1, as it might be possible that in hours of very high prices, the PtMethanol plant can consume electricity at the agreed fixed price from the wind farm. This would worsen the results of this scenario.

Scenario 2 experiences a similar effect. There the ToU tariffs are designed based on the current ToU tariffs by a DSO in northern Jutland. Thereby, the tariff structure inherited an assumption of when the electricity grid is in need of upregulation, which is mostly in winter in the evening hours on workdays. As the FF uses price limits to determine the need for flexibility in the power system, the time series for prices might not reflect the same peak hours in the grid as peaks in an electricity system might be linked stronger the supply as they are currently, inheriting more seasonal changes. Therefore, the ToU tariffs selected might be incentivising the electricity consumption in peak hours through accidentally lower tariffs, leading to the lowest FF for Scenario 2. As the modelled PtMethanol plant is expected to be connected to the TSO grid, the peak hours in the grid in 2030 might differ from the current peak hours. A more detailed investigation would be needed to design a more fitting ToU tariff to the TSO grid. This could be avoided by investigating real-time pricing, which would be adjusted according to either expected prices for electricity or need for flexibility in the power system. Real-time pricing tariffs would thereby most likely increase the resulting grade of Scenario 2, especially increasing the FF and the grade obtained for it.

11.2 Flexibility Metrics

All developed flexibility metrics are developed on the base of the yearly provided flexibility through total energy consumption. All these are then related to the overall energy consumption of each scenario, providing no possibility to compare the absolute amount of flexibility that is provided. The FF was developed on the assumption that day-ahead electricity prices are an indicator of the type and time of flexibility measures the power system demands. In times of high prices upregulation through lower demand is needed and in times of low prices downregulation through higher electricity demand is needed. Therefore, it only gives an indication of flexibility based on prices and not on the flexibility provided in times of a technical need for it. This could have been improved if compared to a time series of amounts of regulative capacities, however, since the results are for 2030, hourly values for regulation are not available.

The developed flexibility metrics and especially the developed FR for downward ramping are the subjects of simplifications. The FR for downward ramping for example is neglecting the amount of downward ramping that is possible to be provided by ramping the PtMethanol plant to 50 % of nominal load if a storage is included in the scenario. Including this would most likely improve the MCDA results of the storage scenario. Furthermore, both FRs are only measuring the possibility of ramping and thereby providing regulation or participating in the reserve markets. They do not actually investigate whether it would be feasible to participate in these markets and how the provided flexibility would change if so.

Besides of the metrics having an impact on the flexibility performance, energyPRO does also have an impact. There is a bias build into the flexibility metrics using that assumption that as energyPRO always selects a flexible operation, since energyPRO is optimising the operation after the operational costs instead of actually operating the system most flexibly. As the FF is assuming that prices and need for flexibility is corelated, the results of the MCDA are expected to decrease in grades, if other assumptions to quantify the need for flexibility was applied. The decrease will occur as energyPRO is operating to at lowest cost possible, which most often will be in hours of low electricity prices. These hours are having a positive impact on the FF, so if the FF was developed from another assumptions, as the need for flexibility and prices are not always congruent. If the FF was considering of the plant could operate flexibly in hours of actual needed regulation capacities e.g., in the reserve markets, the scores would have been lowered as the PtMethanol plant strives to produce as much as possible due to the business-economic considerations. It is therefore important to stress that the selected method for conducting a MCDA has a large impact on the results, as different methods give different results. The weights used in the MCDA have an influence on the results, as they are multiplied to the value of the specific scale cf. Equation 1. However, a change in the weights would not change the overall picture that much. If taking a look at Table 10.2, then if the FRs were weighed higher, then Scenario 1 would be values even less whereas the others would see an increase in overall grading. If the FF were weighed more, then the overall grade would not change much, since Scenario 3 would still have a higher overall grade due to the other metrics as well. Additionally, if the scaling had a higher resolution, then the scenarios might have received other numbers, however this would not have led to changes in the overall grading.

The developed flexibility metrics all show the flexibility in relation to an amount of energy consumed by the specific plant. This provides an indication of whether the operation is flexible. However, it does not show the amount of flexibility a unit provided, as with these relations only the relative flexibility is shown. Furthermore, through only showing relative flexibility, the fact that all unit are de facto must run units is not reflected in the flexibility metrics. Thereby a major dimension of flexibility of consumption is overlooked. Furthermore, an additional metric could have been considered, namely the operational costs for providing flexibility. If the costs are too high to provide flexibility feasibly, then no one would provide it in an open market. A cost metric could have investigated the costs in each scenario which could have provided a monetary perspective to flexibility for each scenario. However, as the PtMethanol plant is not identical in all scenarios, the investment costs should also be included in the models. When adding these costs in the energyPRO models, this will also influence the overall performance of each scenario, and the full load hours are expected to decrease, as the plant would operate in less hours, as the revenue for selling methanol should cover more expenses. The costs related to providing flexibility could also be lowered if a national subsidy scheme is introduced in the future regime. As stated in Section 8.2 the Danish Energy Agency (2021b) stress that flexibility is required to minimise the expenses for grid reinforcements, why it could be a solution for the state to provide subsidies to plants providing flexibility, if this would be cheaper than the expenses for improvements in the grid.

11.3 Theories and Methods

The theoretical framework, described in Section 4.4, provides the underlying assumptions for this report, from which methods were chosen and the investigation conducted. Theories will be discussed first. As PtX and PtMethanol more specifically are assumed to become part of the 2030 energy system, the Socio-Technical Transition theory was chosen to explain this development. As PtMethanol is defined as a niche, this niche is expected to develop to become part of the regime. This development is furthermore assisted by increasing landscape pressures as the energy crisis triggered by a war in Ukraine. As this new regime was investigated, not all dimensions of regimes were investigated. This is due to the perspective this report takes through the rational choice theory, saying that individuals try to maximise their utility. Combined with the assumption that the operator of a PtMethanol plant behaves that way, changes on policy, culture, science, and industry were not investigated. Changes to technology are acknowledged in investigating the future energy mix and designing scenarios including an offshore windfarm and large-scale hydrogens storages, without investigating their influence on other dimensions of the regime.

As the theory explains however, all dimensions of a regime need to be considered to change towards including a niche, however it is assumed that the niche will be part of the regime in 2030 without an investigation whether the regime changes favourably to the niche to incorporate it. Furthermore, the not investigated dimensions place limitations on the scope of this report and thereby of the model and the obtained results as well.

Only the technical flexibility provided through the expected operation on the day-ahead market, which is based on the short-term marginal costs, is investigated, why the fixed operational and investment costs are not included in scenarios. Therefore, energyPRO was chosen as the energy system modelling tool, as it optimises the yearly operation based on the operational costs. As bottom-up model, energyPRO is well fit to investigate the techno-economic aspects of PtMethanol. Therefore, it is also only taking the direct influences of a change in the regime into account e.g., changed tariffs or changes in electricity prices. It is unfit however, to investigate how the change in technology, described in Section 8.1, has an influence on the need of flexibility or on other parts of the regime.

As predictive what-if scenarios were used to predict the future in regime in 2030, the development of scenarios was not focused on developing very accurate scenario of the regime in 2030 but to develop scenarios possibly having an influence on a PtMethanol plant's operation and thereby provided flexibility to the grid. Therefore, it remains to be seen, whether the developed scenarios are applying to the future regime or not, however, the scenarios can give an indication of which developments in the regime would benefit PtMethanol as a niche as well as its flexibility provided.

Considering the method for conducting the MCDA, it is important that all relevant criteria have been accounted for according to Løken (2007). As discussed previously, there is a risk that not all parameters have been considered in this report, where costs for providing flexibility is one example of this. However, in order to avoid the criteria and metrics being biased towards one specific scenario, these have been selected before the development of scenarios. The scales were settled on as objectively as possible striving for portraying each metric with the most suited scale. Nevertheless, the scales could have been improved if relevant actors had been interviewed previously. This could have been the TSO, PtMethanol operators, power system experts, etc. These actors could have provided additional inputs for what is interesting and important according to their perspective, when considering system flexibility. This could result in the metrics and scales for each criterion to be even more precise.

11.4 Energy Modelling Assumptions

While the selected methods mostly pose limitations on this report, different assumptions and simplifications were taken to model a PtMethanol plant from a techno-economic perspective in energyPRO. These can be classified into two general categories: Economic assumptions and technical assumptions.

In energyPRO a day-ahead market was modelled which is an economic assumption. This can be done by attaching a time series for settlement prices and a time series for a price prognosis to the market. As the latter was not attached all models operate on the premise of perfect knowledge on the day-ahead settlement prices in the investigated timeframe. With this perfect knowledge energyPRO will optimise the operation to the most optimal point under the given restrictions. As this perfect foresight cannot be assumed for PtMethanol plant in reality, the obtained operation strategy likely differs slightly from an operation strategy in reality, which is prone to mistakes in forecasts and price predictions. Modelling a more realistic operation strategy might have changed the obtained grades and flexibility metrics as predictions might have been to high or low, thereby increasing or decreasing results. Furthermore, since PtMethanol is seen as part of the 2030 regime it is assumed that such a plant is already part of the market prediction that make up the time series used for the day-ahead settlement prices. A plant of roughly 300 MW production capacity of methanol might however have an impact on electricity prices, as it is part of the price setting mechanism.

As far as technical assumptions go, the choice of a restriction to the ramping of the methanol synthesis unit in Figure 9.1 can be discussed. This is based on a study conducted for a PtMethanol plant on a much smaller scale, which suggests that a methanol synthesis unit needs two hours to reach a semi-stable state in its reaction after ramping. Not placing that restriction and allowing the methanol synthesis to ramp freely, would change the results of all models as well as the MCDA. The methanol would be able to react to price signals quicker, thereby improving the results of the flexibility metrics for all scenarios. Especially the scenarios that do not include a storage could show significant improvements compared to Scenario 3.

Another technical assumption taken for methanol production is for the plant to be able to go to stand by. Especially the modelled electricity consumption in that state is prone to uncertainty, since this is estimated to equal the heat loss during full load operation. If the assumed stand-by consumption is lower, the flexibility provided by all scenarios will most likely be higher, as lower valley loads can be reached, thereby increasing all flexibility metrics. Without the ability to go to stand by, especially the flexibility metrics for Scenario 0 to 2 would decrease, indicating less operational flexibility. For Scenario 3 this influence is smaller as the operational statistics show, that it is using the standby operation less often than the other scenarios. The modelled efficiency in all part load states is the same, even though it is suggested that it might be slightly lower in half load than in nominal load. In addition, this efficiency as well as the selected efficiencies for the electrolyser are predictions this report tries to take on the future technology in 2030. Therefore, a different development of efficiencies is possible as today's efficiencies are lower than the ones modelled. Most of the technical assumptions in the models are originating from two sources: (Buttler & Spliethoff, 2018) and (Cui et al., 2022). This places a risk, as the quality of results in this report very much relies on their quality of results as well as applicability. To mitigate this, other sources were used during the literature studies, to gain an understanding of processes and comparing values for e.g., efficiencies or ramping times.

11.5 Comparison to Previous Research

The literature studies conducted for Chapter 7 showed that research on how and if a PtMethanol plant can provide flexibility when participating in a day-head market. Previous studies have investigated the units independently of each other, where Buttler and Spielthoff (2018) argued how the efficiency would behave in part load behaviour. It is however not deeply researched in relation to flexibility. As for the methanol production, previous study by Cui et al. (2022) investigated how a change in hydrogen supply is affecting the unit, but not if it is dependent on the electricity prices. This report has investigated exactly this, namely how the electrolyser unit and the methanol production units will operate in part load, and that they can provide flexibility when participating in the Danish day-ahead market for electricity. Moreover, no previous research was found that modelled the PtMethanol in a 2030 context where prices in an hourly resolution had been used. When using the predicted price time series by the Danish Energy Agency, the prices are more like the prices assumed to be in 2030 as the changes predicted to be implemented in future are accounted for. This means that prices are already influenced by PtX-technologies, and the introduction of the 500 MW PtMethanol plant investigated in this report will thereby not influence the overall prices.

Additionally, this report also combined flexible operation of a PtMethanol plant with metrics to quantify flexibility, which is not found to be done before. The FF metric was originally developed for buildings, however, is used for an energy unit in this report. This is assumed valid as they both are electricity consumers, and that the demands (heat for buildings and a flexible hydrogen demand for the methanol production) are independent of the electricity prices. For buildings, the heat is requested by the tenant, often without considering the electricity price (in times without energy crisis) (Berg, 2022). This could be the same for PtMethanol, where hydrogen is essential for the methanol production unit, which is not demanding as much electricity as the electrolyser. The FF metric in the housing and the PtMethanol context is therefore used to investigate if electricity is used in high or low-price hours. This is not found to be done for PtX-technologies previously.

11.6 Outlook

As this study only investigates the flexibility of PtMethanol plants, no indication can be given whether the amount of flexibility is high or low in comparison to other technologies present in the 2030 energy system and competing PtX technologies. This could provide a starting point for further research as the capabilities of flexibility PtMethanol provides might be compared to present technologies providing flexibility to the power system. Through the selection of the model the report is limited from investigating the investment costs that are associated with every scenario. These however have a significant importance for the feasibility of providing flexibility with PtMethanol. Therefore, further research on the cost of which a certain amount of flexibility could be provided is needed. It is suggested to furthermore develop a coherent way of quantifying the flexibility for such comparative studies on the cost of provided flexibility. The flexibility measured in this report is very much based on a need for flexibility based on electricity prices. This could provide the base to develop different metrics that can give a better indication of the flexibility provided by an energy unit based on the technical need of flexibility in the power system.

12 Conclusion

To answer the research question of "*How flexible can a Power-to-Methanol plant consume electricity from the electricity grid when participating in the day-ahead market in 2030, considering the technical restrictions of methanol production?"* different scenarios of operation environments in 2030 were developed. The flexible electricity consumption is assumed to benefit the grid as well if electricity is consumed if prices are low and not consumed if prices are high. To measure and evaluate the flexibility of the PtMethanol plant three flexibility metrics are developed: a flexibility factor, giving an indication of flexibility provided through operation, and two flexibility ratios giving an indication of possibilities for ramping and thereby providing flexibility on shorter time horizon than the day-ahead market. These metrics were weighed against each other in a multi-criteria decision analysis (MCDA) to determine the overall flexibility each developed scenario contains, with the flexibility factor seen as most important.

To understand the changes of both the investigated technology of PtMethanol and also the changes of the energy system until 2030, as well as their interrelations, Socio-Technical Transition Theory is used. The energy system is investigated in regard to technologies and markets and user preferences, as these are seen as highest influences on the operation of a PtMethanol plant which is operated by a person or organisation behaving according to Rational Choice Theory, trying to maximise own utility. Therefore, all developed scenarios are modelled in energyPRO, as this optimises the operation strategy and thereby provides the economical most beneficial operation for the operator of the PtMethanol plant as results.

The developed scenarios are Scenario 0, which has the PtMethanol plant 500 MW electrolysis capacity operating in a DK1 day-ahead market, with a prediction of electricity prices in 2030, an increased electricity consumption tariff and a price for the sale of methanol based on the cost of methanol. All other scenarios are based on Scenario 0, with changes to some parameters. Scenario 1 sees the PtMethanol plant connected to an offshore wind farm through a direct line. Therefore, no payments of consumption tariffs and electricity prices for electricity consumed from the offshore windfarm are assumed. This scenario provided the highest operation income, while ranking as the least flexible scenario in the MCDA. However, it was found to consume electricity mostly in times when it was beneficial to the electricity system, but the graded flexibility was limited by the very low capability of providing short term downward regulation to the power system. A sensitivity analysis on the payments for electricity of the windfarm showed that the flexibility provided through planned operation is robust towards such payments. Scenario 2 differs from Scenario 0 in the applied tariff scheme, as it was found that different tariff schemes might be introduced to promote more flexible electricity consumption that also favours the power system's flexibility. Therefore, a tariff scheme based on ToU tariff with three price levels was introduced. That scenario shows the lowest flexibility provided through the planned operation, while the initial assumption was that it would promote flexible operation. The reason for the low rate of flexibility is to be found in the distribution of the three tariff levels, where most hours are with a low tariff, resulting in the plant to operate more in general, leading to lower ability to provide additional flexibility. However, this scenario results in lowered operation costs compared to Scenario 0. ToU tariffs therefore are found not be suitable to provide more flexibility to the power system on the transmission level. Especially the flexibility factor of Scenario 2 was low, indicating more electricity consumption in times when it is less beneficial for the power system through the changes tariff scheme. The last developed scenario, Scenario 3, was developed as it was found that the niches of PtMethanol and large-scale hydrogen storages might achieve a positive niche accumulation. Therefore, it included a large-scale hydrogen storage to store hydrogen form the electrolysis as feedstock for the methanol production. Furthermore, the electrolyser was oversized in comparison to the methanol production. This scenario was found to be most flexible and thereby provides the most flexibility to the electricity grid. This is primarily due to the separation of the units, where they can operate flexibility independently of each other, as the electrolyser, which is the biggest electricity consumer in the plant, can charge the storage in low price hours. This allow the methanol production to operate in more hours, as hydrogen can be provided from the storage. A specific sensitivity study showed that this result is more flexible towards the size of the electrolyser than the sized of the storage which was set to 18 hour of methanol production originally. To answer the research question, flexibility metrics were developed to quantify the flexibility provided to the power system and an MCDA was performed to assess how flexible a PtMethanol is able to operate under the given conditions in each scenario. All simulated plants were found to be providing flexibility through their planned operation, as indicated by the FF, while the biggest differences are observed in the flexibility ratios for additional flexibility. Concluding that a PtMethanol plant operating with a continuous methanol production on the electricity day ahead-market in 2030 provides the most flexibility if it is equipped with a large-scale hydrogen storage and the electrolyser is oversized. A PtMethanol plant under these conditions was found to both consume electricity in the most beneficial way for the power system, thereby operating flexible, and to have the highest capability to provide short term regulation to the power system to increase its flexibility. Furthermore, the only investigated development in regime or niche that is found to increase flexible operation of a PtMethanol plant in comparison to the Scenario 0 is the positive niche accumulation investigated in Scenario 3.

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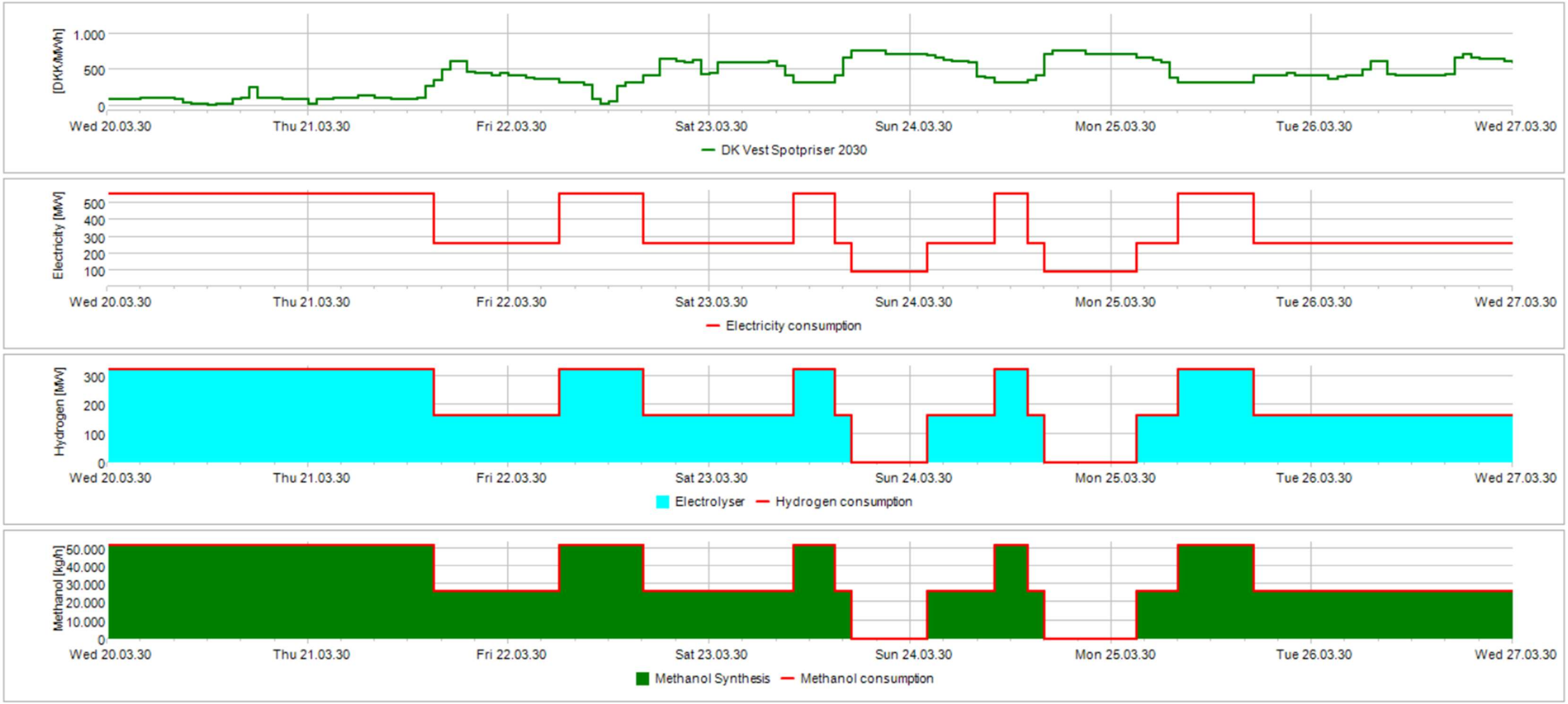
14 Appendices

Appendix A: Time series for time of use tariffs

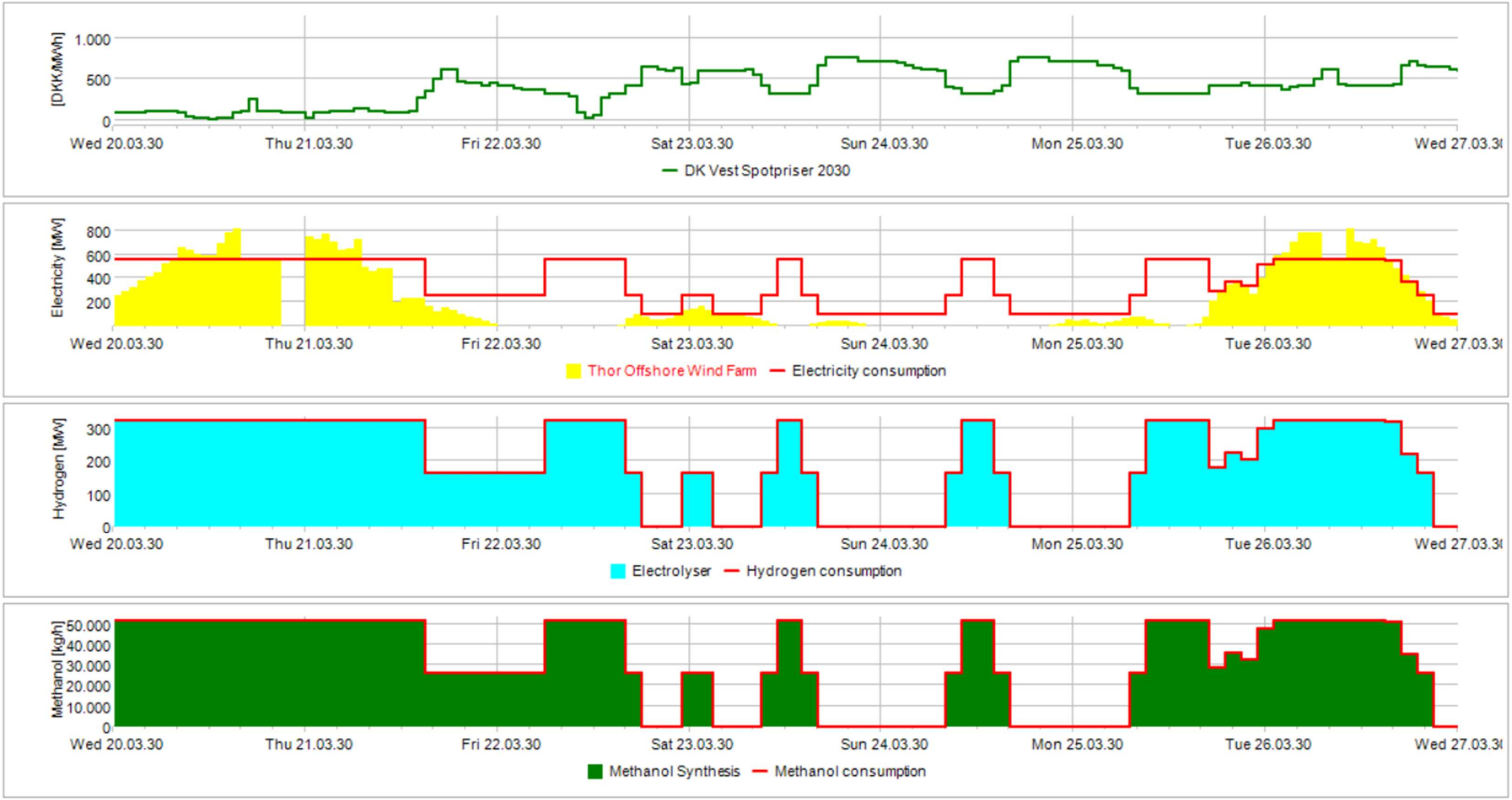
Time	Winter Tariff [kr./MWh]	Summer Tariff [kr./MWh]
00:00	88,15	88,15
01:00	88,15	88,15
02:00	88,15	88,15
03:00	88,15	88,15
04:00	88,15	88,15
05:00	88,15	88,15
06:00	88,15	88,15
07:00	176,29	176,29
08:00	176,29	176,29
09:00	176,29	176,29
10:00	176,29	176,29
11:00	176,29	176,29
12:00	176,29	176,29
13:00	176,29	176,29
14:00	176,29	176,29
15:00	176,29	176,29
16:00	176,29	176,29
17:00	352,59	176,29
18:00	352,59	176,29
19:00	352,59	176,29
20:00	176,29	176,29
21:00	176,29	176,29

22:00	88,15	88,15
23:00	88,15	88,15

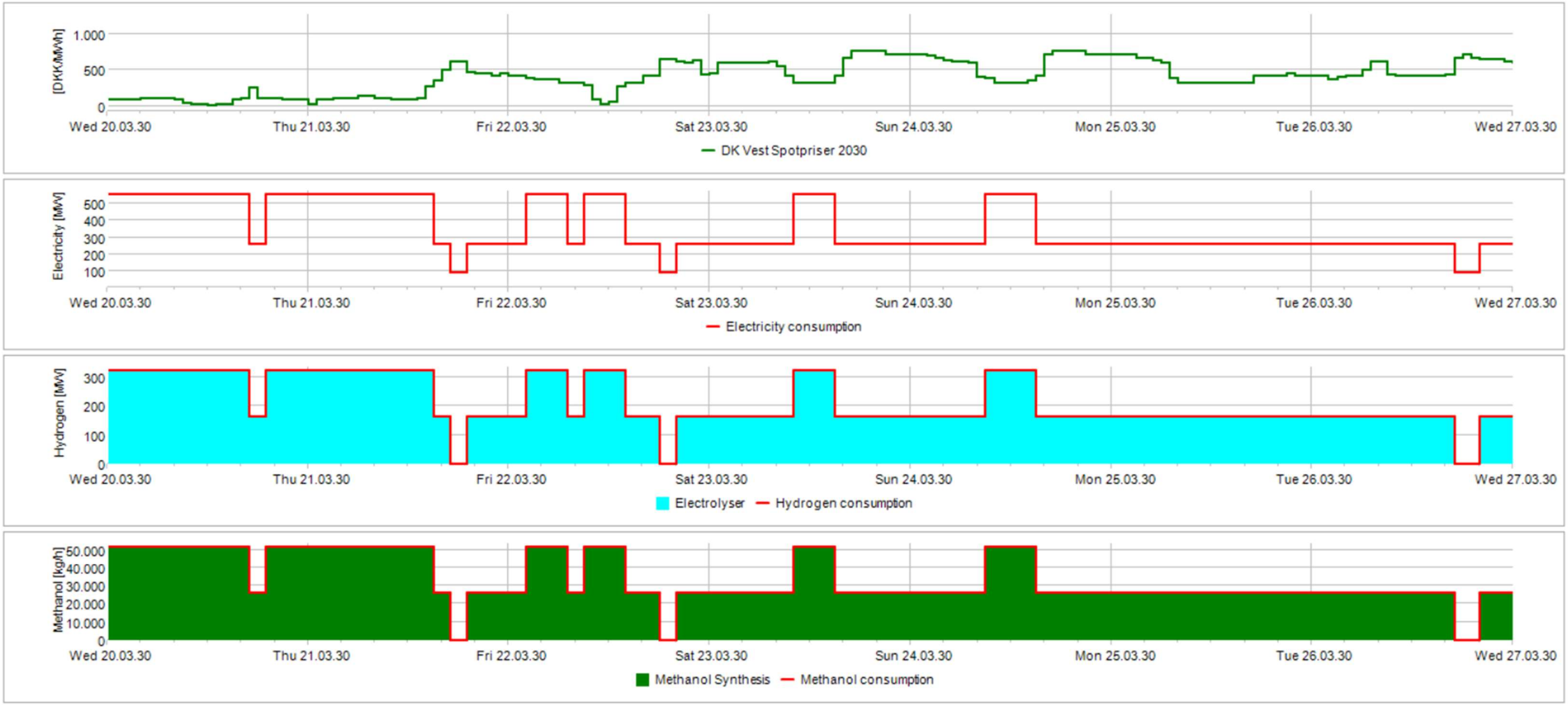
Appendix B: Production, graphic report Scenario 0



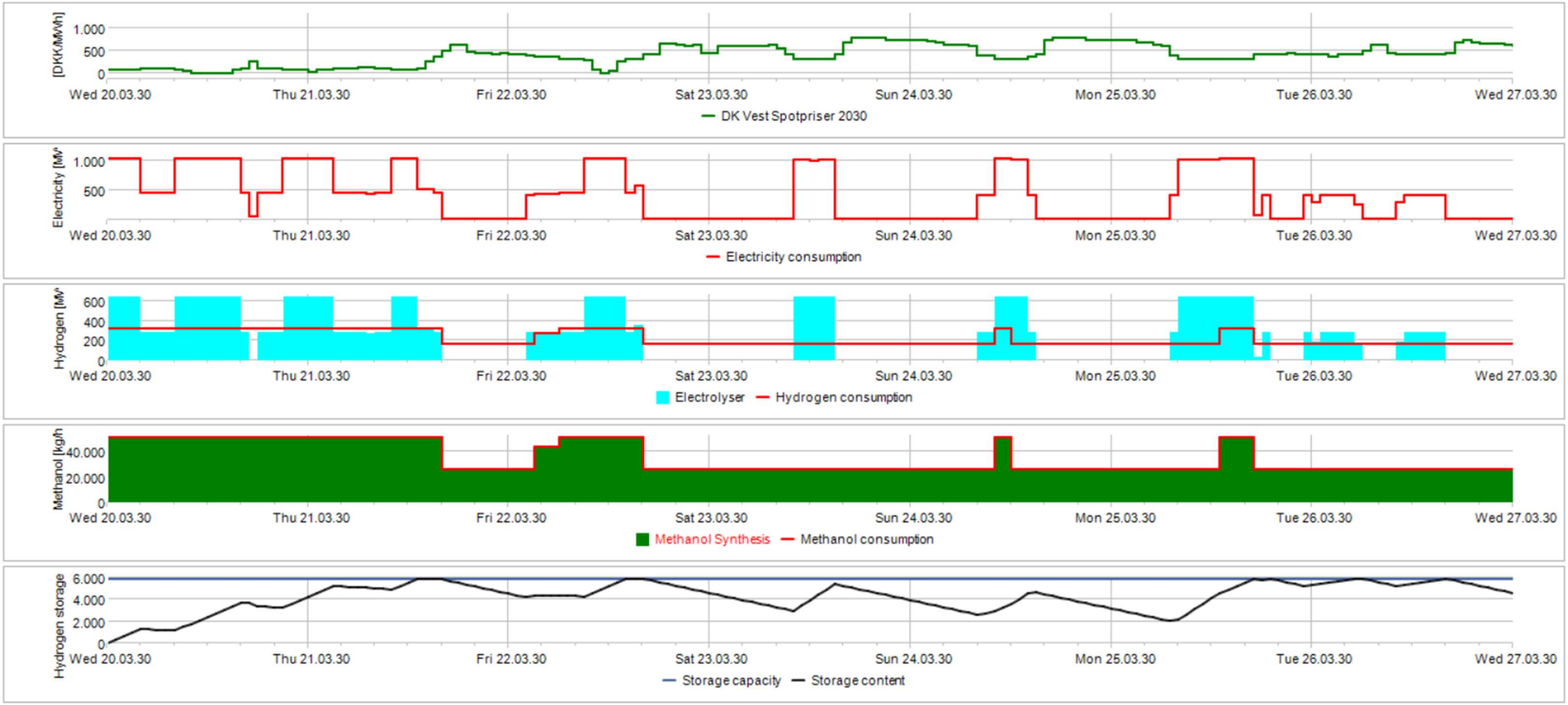
Appendix C: Production, graphic report Scenario 1



Appendix D: Production, graphic report Scenario 2



Appendix E: Production, graphic report Scenario 3



Appendix F: Annual energy conversion Scenario 0

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MethanolplantScenario0.epp

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5000

Energy conversion, annual

Calculated period: from 01-01-2030 00:00 to 01-01-2031 00:00

Electricity consumed by energy units:

New Day ahead market:

	Of Annual
Electrolyser	2.389.732,1
Methanol Synthesis	361.335,4
MethanolExport	0,0
Oxygen export	0,0
Total	2.751.067,5

Hours of operation:

New Day ahead market:

	Total [h/Year]	Of Annual hours
Electrolyser	8.759,0	100,0%
Methanol Synthesis	8.759,0	100,0%
Out of total in period	8.760,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of Annual hours
MethanolExport	7.959,0	90,9%
Oxygen export	7.959,0	90,9%
Out of total in period	8.760,0	

Various key figures:	Turn ons	Full load hours [hours]	Utilization factor [%]	Total efficiency [%]
Electrolyser	1,00	4.991,25	56,98	67,88
Methanol Synthesis	0,00	4.991,25	59,26	72,11
MethanolExport	95,00	4.991,25	56,98	0,00
Oxygen export	105,00	4.991,25	0,00	0,00

Fuels:

By fuel

	Fuel consumption	Fuel production	Offered fuel	Fuel not used
Water	435.372.855,6 kg			
Hydrogen	48.715.844,6 kg	48.715.844,56 kg	0,00 kg	0,00 kg
Oxygen	386.657.063,5 kg	386.657.063,53 kg	0,00 kg	0,00 kg
Methanol	258.189.093,7 kg	258.189.093,69 kg	0,00 kg	0,00 kg
Carbon Dioxide	354.622.439,4 kg			

By energy unit

Electrolyser		
Hydrogen	0,0 MWh	1.622.237,5 MWh
Methanol Synthesis		
Hydrogen	1.622.237,5 MWh	0,0 MWh
Methanol	0,0 MWh	1.430.367,5 MWh
MethanolExport		
Methanol	1.430.367,5 MWh	0,0 MWh
Oxygen export		
Total	3.052.605,0 MWh	3.052.605,0 MWh

By energy unit (in original fuel units)

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Appendix G: Annual energy conversion Scenario 1

MethanolplantScenario1.epp

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5000

Energy conversion, annual

Calculated period: from 01-01-2030 00:00 to 01-01-2031 00:00

Electricity produced by energy units:
New Day ahead market:

	All periods [MWh/year]	Of Annual production
Electrolyser	0,0	0,0%
Methanol Synthesis	0,0	0,0%
Thor Offshore Wind Farm	3.187.157,3	100,0%
Total	3.187.157,3	100,0%
Of annual production	100,0%	

Electricity consumed by energy units:
New Day ahead market:

	Of Annual [MWh/year]
Electrolyser	3.321.817,4
Methanol Synthesis	468.720,9
MethanolExport	0,0
Oxygen export	0,0
Thor Offshore Wind Farm	0,0
Total	3.790.538,3

Peak electric production:

Electrolyser	0,0 MW-elec.
Methanol Synthesis	0,0 MW-elec.
MethanolExport	0,0 MW-elec.
Oxygen export	0,0 MW-elec.
Thor Offshore Wind Farm	887,3 MW-elec.

Hours of operation:
New Day ahead market:

	Total [h/Year]	Of Annual hours
Electrolyser	8.759,0	100,0%
Methanol Synthesis	8.759,0	100,0%
Thor Offshore Wind Farm	7.589,0	86,6%
Out of total in period	8.760,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of Annual hours
MethanolExport	7.871,0	89,9%
Oxygen export	7.871,0	89,9%
Out of total in period	8.760,0	

Various key figures:	Turn ons	Full load hours [hours]	Utilization factor [%]	Total efficiency [%]
Electrolyser	1,00	6.725,02	76,78	65,80
Methanol Synthesis	0,00	6.725,02	79,31	72,60
MethanolExport	131,00	6.725,02	76,78	0,00
Oxygen export	139,00	6.725,02	0,00	0,00
Thor Offshore Wind Farm	202,00	3.161,16	0,00	0,00

MethanolplantScenario1.epp

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Energy conversion, annual

Fuels:

By fuel

	Fuel consumption	Fuel production	Offered fuel	Fuel not used
Water	586.619.526,5 kg			
Hydrogen	65.639.520,9 kg	65.639.520,93 kg	0,00 kg	0,00 kg
Oxygen	520.980.076,3 kg	520.980.076,29 kg	0,00 kg	0,00 kg
Methanol	347.882.882,3 kg	347.882.882,31 kg	0,00 kg	0,00 kg
Carbon Dioxide	477.816.760,6 kg			

By energy unit

Electrolyser		
Hydrogen	0,0 MWh	2.185.795,9 MWh
Methanol Synthesis		
Hydrogen	2.185.795,9 MWh	0,0 MWh
Methanol	0,0 MWh	1.927.271,1 MWh
Methanol Export		
Methanol	1.927.271,1 MWh	0,0 MWh
Oxygen export		
Total	4.113.067,0 MWh	4.113.067,0 MWh

By energy unit (in original fuel units)

Electrolyser		
Water	586.619.526,5 kg	0,0 kg
Hydrogen	0,0 kg	65.639.520,9 kg
Oxygen	0,0 kg	520.980.076,3 kg
Methanol Synthesis		
Hydrogen	65.639.520,9 kg	0,0 kg
Methanol	0,0 kg	347.882.882,3 kg
Carbon Dioxide	477.816.760,6 kg	0,0 kg
Methanol Export		
Methanol	347.882.882,3 kg	0,0 kg
Oxygen export		
Oxygen	520.980.076,3 kg	0,0 kg

Appendix H: Annual energy conversion Scenario 2

MethanolplantScenario2.epp

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Energy conversion, annual

Calculated period: from 01-01-2030 00:00 to 01-01-2031 00:00

Electricity consumed by energy units:
New Day ahead market:

	Of Annual
Electrolyser	2.598.053,6
Methanol Synthesis	369.591,6
MethanolExport	0,0
Oxygen export	0,0
Total	2.967.645,2

Hours of operation:
New Day ahead market:

	Total [h/Year]	Of Annual hours
Electrolyser	8.759,0	100,0%
Methanol Synthesis	8.759,0	100,0%
Out of total in period	8.760,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of Annual hours
MethanolExport	8.111,0	92,6%
Oxygen export	8.111,0	92,6%
Out of total in period	8.760,0	

Various key figures:	Turn ons	Full load hours [hours]	Utilization factor [%]	Total efficiency [%]
Electrolyser	1,00	5.390,25	61,54	67,43
Methanol Synthesis	0,00	5.390,25	63,38	72,81
MethanolExport	113,00	5.390,25	61,54	0,00
Oxygen export	124,00	5.390,25	0,00	0,00

Fuels:
By fuel

	Fuel consumption	Fuel production	Offered fuel	Fuel not used
Water	470.174.772,7 kg			
Hydrogen	52.609.989,0 kg	52.609.989,00 kg	0,00 kg	0,00 kg
Oxygen	417.564.840,4 kg	417.564.840,39 kg	0,00 kg	0,00 kg
Methanol	278.827.668,9 kg	278.827.668,92 kg	0,00 kg	0,00 kg
Carbon Dioxide	382.969.500,1 kg			

By energy unit

Electrolyser		
Hydrogen	0,0 MWh	1.751.912,5 MWh
Methanol Synthesis		
Hydrogen	1.751.912,5 MWh	0,0 MWh
Methanol	0,0 MWh	1.544.705,2 MWh
MethanolExport		
Methanol	1.544.705,2 MWh	0,0 MWh
Oxygen export		
Total	3.296.617,7 MWh	3.296.617,7 MWh

By energy unit (in original fuel units)

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Appendix I: Annual energy conversion Scenario 3

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MethanolplantScenario3.epp

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Energy conversion, annual

Calculated period: from 01-01-2030 00:00 to 01-01-2031 00:00

Electricity consumed by energy units:
New Day ahead market:

	Of Annual
Electrolyser	2.826.834,8
Methanol Synthesis	344.389,6
Methanol Export	0,0
Oxygen export	0,0
Total	3.171.224,3

Hours of operation:
New Day ahead market:

	Total [h/Year]	Of Annual hours
Electrolyser	8.759,0	100,0%
Methanol Synthesis	8.759,0	100,0%
Out of total in period	8.760,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of Annual hours
Methanol Export	8.683,0	99,1%
Oxygen export	4.812,5	54,9%
Out of total in period	8.760,0	

Various key figures:	Turn ons	Full load hours [hours]	Utilization factor [%]	Total efficiency [%]
Electrolyser	1,00	2.952,87	33,71	67,90
Methanol Synthesis	0,00	5.905,98	67,64	74,76
Methanol Export	17,00	5.905,98	67,42	0,00
Oxygen export	509,00	2.952,87	0,00	0,00

Fuels:

By fuel

	Fuel consumption	Fuel production	Offered fuel	Fuel not used
Water	515.154.016,4 kg			
Hydrogen	57.642.920,7 kg	57.642.920,68 kg	0,00 kg	0,01 kg
Oxygen	457.511.157,8 kg	457.511.157,77 kg	0,00 kg	0,00 kg
Methanol	305.501.702,4 kg	305.501.702,41 kg	0,00 kg	0,00 kg
Carbon Dioxide	419.606.256,1 kg			

By energy unit

Electrolyser		
Hydrogen	0,0 MWh	1.919.509,1 MWh
Methanol Synthesis		
Hydrogen	1.919.509,1 MWh	0,0 MWh
Methanol	0,0 MWh	1.692.479,4 MWh
Methanol Export		
Methanol	1.692.479,4 MWh	0,0 MWh
Oxygen export		
Total	3.611.988,5 MWh	3.611.988,5 MWh

By energy unit (in original fuel units)

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