Feasibility study of Power-to-Methanol in Denmark

Aalborg University
Department of Planning

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Writers confirm, that no plagiarism has occurred during the writing of this report.

Abstract

The purpose of this study is to research how a Power-to-Methanol facility can achieve a yearly production of 130.000 tons methanol and what is the socioeconomic feasibility of Power-to-Methanol. A simulation model of the Power-to-Methanol system showed that the LCOE of methanol would be 160% more expensive than the cost of bunker oil with the same energy density taken into account. But in the sensitivity analysis it was shown that with a reduction of tariffs by 100% and a CO2 tax of 450€/ ton bunker oil, the LCOE for methanol would have cost of 796 €/ton compared to the 840€/ton for bunker oil. Further it was found that the Power-to-Methanol contributes with socio-economic benefits of stability of the electricity grid, job creation and CO2 reductions. But with production of methanol with CO2 capture at the incineration plant "Reno Nord", this would lead to an emission of 71.24 tons fossil based CO2. Therefore it can only be called green methanol and CO2-neutral if the CO2 are captured by DAC.

Furthermore it has been shown that the electricity price have significant impact of the LCOE of methanol. Therefore, it will be advantageous to have an optimized pricing strategy in relation to the Nord pool market or bilateral agreements to ensure security of supply and low electricity prices.

Lastly the immaturity of Power-to-Methanol on this scale must be taken into account for the results of this project.

Preface

This project is the master thesis made on the 4th semester master Sustainable Energy Planning and Management at Aalborg University. This project will research the feasibility of Power-to-Methanol in Denmark

The project writer would like to thank the supervisor of the thesis, Frede Hvelplund for guidance throughout the project.

Reading guide

The project is divided into chapters, subchapters and subsubchapters which the table of contents is an overview of. The chapters are numbered chronological from 1 to 9.
Throughout the study references are made, which is numbered by Vancouver standard [Number] and further information about the references can be seen in the reference list at the end.
Figures and tables are throughout the study numbered according to the chapter and order in which they appear.
When the project was handed in, an appendix "Calculations" was attached, which is an excel document with the project's calculations and graphs.

Nomenclature

Abbreviation

CO_2	Carbon dioxide
H_2	Hydrogen
O_2	Oxygen
CAPEX	Capital expenses
DAC	Direct Air Capture
DKK	Danish krone
DSO	Distribution System Operator
GWh	Gigawatt hour
KWh	Kilowatt hour
LCOE	Levelised Cost of Energy
MJ	Megajoule
MW	Megawatt
MWh	Megawatt hour
O&M	Operation and maintenance
OPEX	Operational expenses
PEM	Proton Exchange Membrane
PtX	Power-to-X
€	Euros

Contents

1 Problem analysis

1.1 Climate goals for CO2 reduction

32 years ago, the Danish energy industry and Danish society began to get used to a new reality: Climate policy. In 1990, Denmark became the first country in the world with a specific climate goal, CO2 emissions were to be reduced by 20% from 1990 till 2005. This was pioneering work and has to that extent changed Danish society and policy in a more sustainable direction [1]. And in 2020 Denmark got their first climate law which is legally binding. The purpose of this climate law is for Denmark to reduce CO2 emissions in 2030 by 70% compared to the level in 1990, and that Denmark achieves to be climate neutral by 2050 with the Paris Agreement's goal of limiting the global temperature rise to 1.5 °C [2]. Figure 1.1 shows the total CO2 emissions in Denmark from 1990-2019.

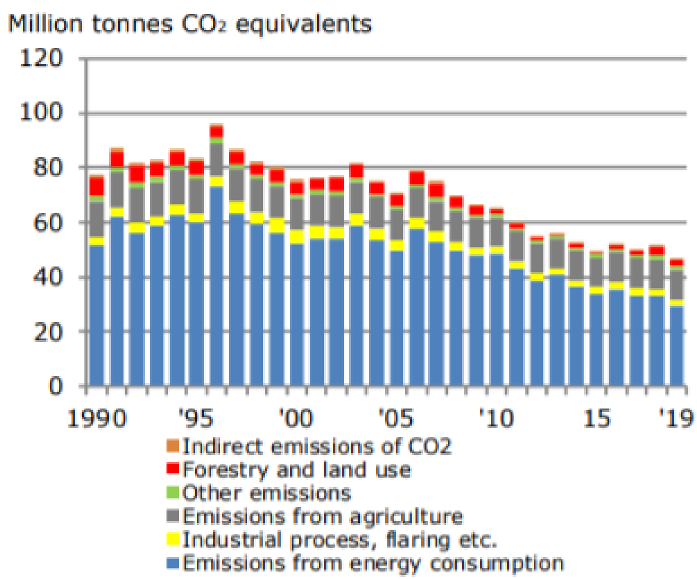

Figure 1.1: The total CO2 emissions in Denmark from 1990-2019 derived from different sectors [3]

Here it can be seen that the total CO2 emissions from 1990 till 2019 has decreased from 78 million tonnes CO2 equivalents to 45, which is a percentage reduction of 42%. So in 30 years, Denmark has manged to reduce CO2 emissions by 42%, which means that in order to comply with the climate law of 70% before 2030, there must be an additional 28% reductions over the next 10 years. Therefore, it is extremely important that the pace is set and that action is taken in the sectors that have so far been seen as difficult to change from fossil to sustainable fuels. Figure 1.1 also shows that approximately two thirds of the total CO2 emissions is caused by emissions from the energy consumption. The emissions from the energy consumption is Denmark is further detailed in figure 1.2

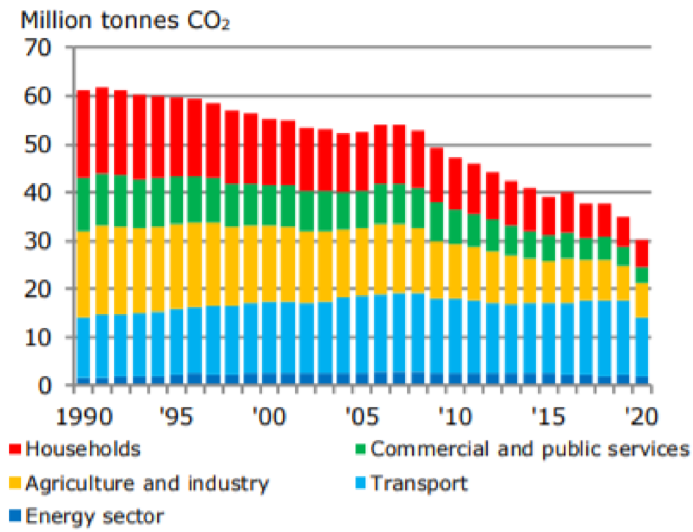

Figure 1.2: Adjusted graph of the Danish CO2 emissions from energy consumption divided into sectors [3]

Figure 1.2 shows the CO2 emissions from the energy consumption in Denmark from different sectors. Figure 1.2 is an adjusted graph compared to previous figure 1.1, which means that it is adjusted for fuel linked to foreign trade in electricity and climatic variations in relation to a normal temperature year, and is why the two figures differs a bit. But the overall outcome is the same, a reduction. However, this reduction is not uniform across all sectors. From figure 1.2 a significant decrease in the sectors; "Households", "Agriculture and industry", and "Commercial and public services" can be seen, whereas emissions from the "Energy sector" have been constant but also minimal throughout the period. But looking at the "Transport" sector a different pattern can be seen because since 1990 the CO2 emission from transport in Denmark has increased, except in 2020, where a substantial decrease caused by Covid-19 could be seen. But now that Covid-19 is no longer a socially critical disease, it is expected that emissions from transport will return to the same level as before if no further action is taken. In Denmark road traffic (cars, busses and trucks) is dominant regarding emissions in the transport sector, which stands for approximately 90%, whereas the last 10% is distributed between military purpose, trains, airplanes and ships. So in order to reach the climate goals in 2030 and 2050, it is essential to reduce the CO2 emissions in the transport sector. Electrification is believed to have a huge role in the transition away from fossil fuels, and electrification of cars, small busses and trucks, is often the smartest and most cost-effective solution. It is however, far from all of the transport sector which can be be electrified. The heavy transport sector, such as big trucks, ships and airplanes is a bigger challenge to make sustainable because of the huge amounts of energy needed. But in order to achieve the goal of climate neutrality in 2050 solutions and change is needed. And the reason why the emission from airplanes and ships are small in Denmark is because of the territoriality principle, which means that Denmark is only responsible for the emissions within its borders. So emissions from international shipping and aviation are not included in the green accounts for Denmark or any other country, which is questionable. But the EU has ambitions to change this in their new plans called "Fit for 55", because as a step towards climate neutrality, the EU has increased its climate ambition for 2030 and committed itself to reducing emissions by at least 55% by 2030, where plans of including shipping and aviation into regulation schemes are being discussed. If this is adopted, it will provide an even greater incentive to find alternatives to fossil fuels in heavy transport, which will give increased focus on the technology Power-to-X.

1.2 Power-to-X process

Power-to-X (PtX) is defined as the process by which electricity (Power) is converted to an energy carrier and the (X) is thus just a symbol of what type of energy carrier it is about. These energy carriers can be used in sectors where electrification is not an obvious option. Eg. in heavy industry and heavy transport. Therefore, PtX is a necessity to achieve an emissions-neutral society but in order to achieve this the PtX facility must live up to some sustainable requirements. How this can be realised and how the process works is shown in figure 1.3.

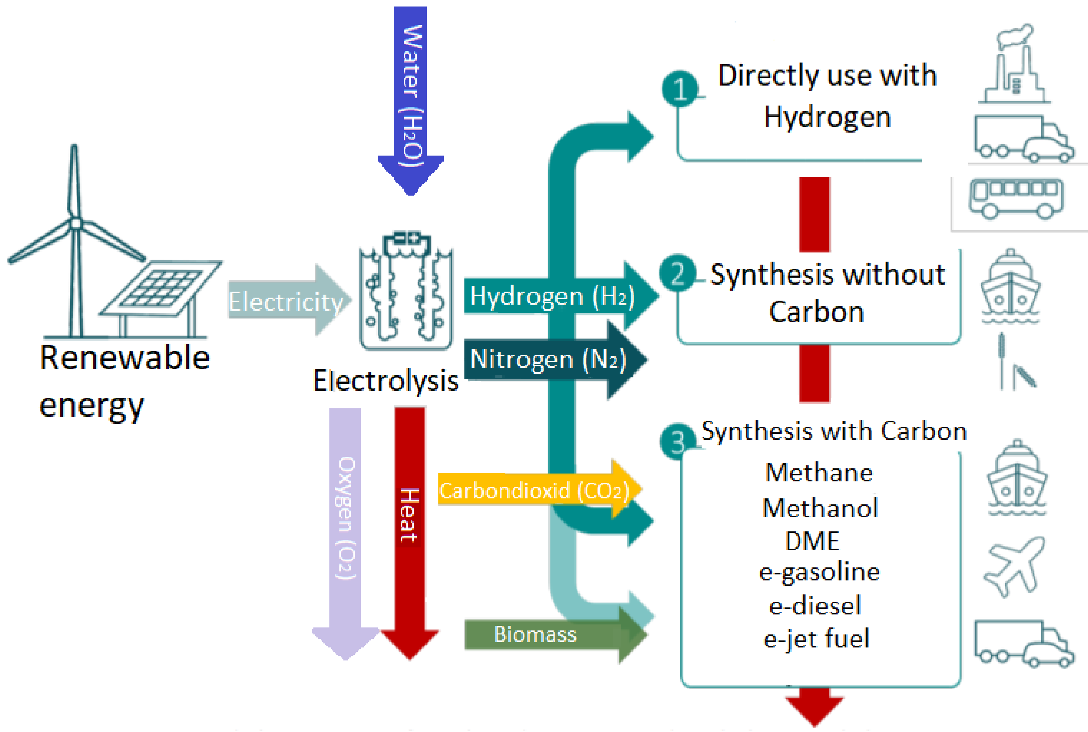

Figure 1.3: The production of green fuels by PtX [4]

The first step in the PtX process is the conversion of water (H2O) to hydrogen (H2), which is done by electrolysis. The electrolysis uses electricity to split the water molecules (H2O) into hydrogen (H2) and oxygen (O2). Thereby, the electrical energy is converted into chemically bound energy in the hydrogen molecules. And in order to have a sustainable process the electricity needs to come from renewable energy units such as wind turbines or solar cells. Once hydrogen has been produced this can be part of 3 different processes as seen in the figure 1.3. Firstly the hydrogen can be directly used for industrial purposes or smaller means of transport such as cars or busses. Secondly, the hydrogen can be part of a synthesis process with e.g. nitrogen which will produce the product ammonia that can be used for ships or in agriculture. Third, it is possible with the hydrogen in the synthesis process with carbon dioxide to produce many different fuels. These fuels can be categorized as green fuels as long as the CO2 emerge from a sustainability source. A sustainable CO2 source is for example when CO2 is captured from the flue gas emitted by incineration plants or biogas plants. When the CO2 originates from the combustion of biomass, it is considered climate neutral in the energy sector according to the UN's calculation methods, as the emissions are included in the carbon balance for forests and soils (LULUCF)[5]. This is called biogenic CO2 and if used for production of PtX fuels, these fuels can be considered green and CO2-neutral.

CO_2 can also be captured directly from Earth's atmosphere through a process called direct air capture (DAC). Direct air capture is essentially an unlimited resource but is today a more expensive solution than biogenic CO_2, but could in the future be an essential factor to the green transition. In the process of synthesis with CO_2 it is possible to recreate existing or similar fuels that can be used in the transport sector. But even though it is possible to produce e-gasoline or e-diesel, analyses from the Danish Energy Agency's have showed direct electrification e.g. through electric cars is the most cost-effective and optimal way to use electricity generated from renewable energy sources [5]. Therefore should PtX fuels be prioritised where direct electrification is not possible or resulting in very high costs, which has proven to be especially within the aviation and shipping sector. Besides the end fuel in the Power-to-X process, two usable by-products are also produced in the form of oxygen and heat, which can be used for industrial purpose and district heating.

Today, large amounts of electricity are produced from wind turbines and solar cells in Denmark and this will only increase in the future as far more capacity is being installed. But with large amounts of renewable energy sources in the electricity grid, this creates a kind of uncertainty due to the fluctuating pattern as you can not determine when the wind blows or the sun shines. This will create periods where overproduction of renewable electricity occurs and periods where it is less than electricity consumption. This is undesirable in an energy system because a high security of supply is desired which requires flexibility. Therefore, PtX facilities can play a crucial role in the electricity system by consuming large amounts of green electricity when the wind blowing and the sun shining, and shutting down when it is not and thereby provide with the needed flexibility [6]. Among other things, this is one of the reasons why the Danish government in 2021 came up with a strategy for PtX in Denmark *"The Government's strategy for POWER-TO-X [5]"* hence the potential of PtX becoming a new green utility sector in Denmark and thereby provide with green fuels in the transition of to being climate neutral. The strategy is based on analyses from the Danish Energy Agency which has estimated the potential for cost-effective CO_2 reductions within the transport and industry sectors by 2030 and 2050. Estimates for the use of PtX fuels in Denmark in sectors where they are forecasted to eventually become cost-effective is shown in figure 1.4

Estimates for the use of PtX fuels in Denmark in sectors where they are forecasted to eventually become cost-effective		
	Potential reduction (CO_2, million tonnes/year)	
Application	2030	2050
Robust potential		
Power-to-X for shipping	0.6 - 1.2	1.9 - 2.6
- Of which domestic transport	0.1 - 0.4	0.4 - 0.7
Power-to-X for aviation	0.3 - 2.5	1.5 - 3.0
- Of which domestic transport	0.02 - 0.13	0.08 - 0.15
Robust potential of indeterminate extent		
Hydrogen for light road transport, including vans	0.0 - 0.1	0.0 - 0.4
Hydrogen for trucks and buses	0.02 - 0.4	0.4 - 1.2
Hydrogen for industry, direct firing	0.0 - 0.1	0.0 - 0.5
Hydrogen or e-diesel for industry, internal transport	0.0 - 0.2	0.2 - 0.5
E-fuels for the Danish Defence (aircraft, ships, vehicles)	unknown	unknown
Hydrogen for biofuel production, etc. at refineries	unknown	unknown
Production of chemicals (fertiliser, plastics, etc.)	unknown	unknown
Uncertain potential for transitional solutions that are not cost-effective		
Methanol mixed with gasoline	0.03 - 0.05	0.00 - 0.01
Mixing e-fuels into diesel/gasoline	0.3 - 0.5	0.0 - 0.1
Sum	**1.3 - 5.1**	**4.1 - 8.2**
Of which contributes to the 70 percent target	**0.5 - 1.9**	**1.1 - 3.5**

Note:

1. 'Robust potential' is defined here as areas of application where direct electrification is not possible or expected to be more expensive than adopting PtX fuels.

2. 'Indeterminate extent' is defined as the degree of PtX adoption within the area of application being indeterminate/uncertain. This includes segments with significant electrification potential but where the use of PtX fuels will be the most cost-effective and practical solution in parts of the segment.

3. The technical gross reduction potential from the 2021 Climate Programme indicates that PtX has the potential to contribute with domestic CO_2 reductions amounting to approximately 9 million tonnes by 2030. This table shows the Danish Energy Agency's calculations of the cost-effective potential. The cost-effective potential is lower than the technical potential, which is partly due to an overlap between the use of PtX fuels and electrification, the latter of which is the more cost-effective choice in the indicated technical gross potential in the Climate Programme.

4. Blending e-fuels into diesel/gasoline is not believed to be cost-effective, as it is - albeit with considerable uncertainty - not likely to be competitive with 2nd generation fossil fuels.

Figure 1.4: Estimated potential CO2 reductions in the transport and industry sectors of PtX [5]

From figure 1.4 it can be seen that PtX within the transport and industry sector has the potential in 2030 to provide with cost-effective CO2 reductions of approximately 4.5 million tonnes. Approximately 1.5 million tonnes of the CO2 reduction would be within the Danish border and contribute towards the goal of 70% reduction. Whereas there is even greater potential to reduction within international shipping and aviation. The same pattern is seen in 2050 just with even bigger potential for reduction where combined within national and international, approximately 8 million tonnes of CO2 would be cost-effective. With these estimates the government has established four objectives to promote PtX in Denmark:

1. Power-to-X must be able to contribute to the realisation of the objectives in the Danish Climate Act.
2. The regulatory framework and infrastructure must be in place to allow Denmark's strengths to be utilised and for the Power-to-X industry to operate on market terms in the long run
3. The integration between Power-to-X and the Danish energy system must be improved.
4. Denmark must be able to export Power-to-X products and technologies

Today, there are only pilot projects in Denmark in relation to PtX, but with this new strategy presented by the Danish Government, there are now 21 announced PtX projects in Denmark, which together have a vision to deliver 6+ gigawatt (GW) electrolysis capacity by 2030. And one of these projects is set to be build in Aalborg municipality.

1.3 Power-to-Methanol in Aalborg municipality

As previously mentioned, the fuel of the future for ships and other heavy transport can be produced from renewable electricity that has been converted to hydrogen and combined with CO2, and that is exactly what the Power-to-Methanol plant in Aalborg will do. *"Copenhagen Infrastructure Partners, Reno-Nord and Aalborg Forsyning"* have formed a partnership with the project "Fjord PtX", with the ambition of Aalborg having one of the first commercial facilities in the world, where the end product is green methanol, which can be used directly in shipping. To produce green methanol, it requires a biogenic CO2 source which will be captured from the waste incineration at Reno-Nord. Instead of emitting CO2 into the atmosphere at Reno-Nord, the captured CO2 is used in the production of the green fuel methanol. The Power-to-Methanol plant in Aalborg will annually recycle 180.000 tonnes of waste-based CO2 from Reno-Nord, which corresponds to the annual CO2 emissions from approximately

15.000 Danish households. The facility will consist of a 300 MW electrolysis plant which converts green electricity into hydrogen, which in combination with CO2 is converted to methanol and is estimated the plant will produce 130.000 tons of methanol annually. Aalborg Forsyning supplies among other things the citizens of Aalborg Municipality with district heating, and the reason why they are a partner in the project is because the plant will produce excess heat that can be used to district heating. The plant is expected to be completed in 2028 and will from there contribute to the green transition in Denmark and especially for the heavy transport sector where the methanol is used for shipping [7].

2 Problem definition

From Chapter 1, the climate goal for Denmark was presented. It was shown that to reach the goal of 70% reduction within 2030 and climate neutral in 2050, action in sectors that have so far been seen as difficult to change from fossil to sustainable fuel needs to be taken. That is also why the Danish Government have come up with a strategy for PtX in Denmark and thereby provide with green fuels in the transition of being climate neutral. One of the sectors where direct electrification is not possible and it is believed to be more cost-effective to produce green fuels is the shipping sector. But the problem with these green fuels and PtX technology in general, is that it is very immature and unexplored. Despite this, is one of the first commercial facilities in the world producing methanol is to be build in Aalborg municipality. But, as there are no Power-to-Methanol systems on this scale, this rise to uncertainties about the system and the cost of producing green methanol which has led to this study's research question:

How can a Power-to-Methanol facility in Aalborg municipality be modelled to achieve a yearly production of 130.000 tons methanol and what is the socioeconomic feasibility of Power-to-Methanol.

The purpose of this study is to research the production of methanol from Power-to-Methanol and the feasibility of it. In order to due so, a feasibility study of Power-to-Methanol will be made to analyse the existing technological and institutional situation for Power-to-Methanol. This will provide the basis for economic calculations in the form of LCOE to analyze the cost of green methanol in relation to existing bunker oil used in the shipping sector.

Sub-questions have been made to narrow down and answer the underlying elements of the research question:

- What technologies and features are required in a Power-to-Methanol system?
- What is the present technical and institutional situation for Power-to-Methanol?
- How can a Power-to-Methanol facility be modelled in order to supply the demand of 130.000 tons methanol and what is the cost?

2.1 Delimitation

Since Power-to-Methanol is a broad topic and because of limited time for the project, some delimitation's have been made:

- In the process of producing methanol, hydrogen is produced. In the energy system of the future, hydrogen is predicted to be an important resource which has great value as it can be used in many different ways. Therefore, it is expected that hydrogen in a larger scale will become a commodity that is traded with. In this project, the hydrogen market has not been looked at and whether this would make sense in relation to the sale of hydrogen when there is overproduction.
- In addition, excess heat is also produced in the process. In this project, it is assumed that this excess heat is sold at the same price all year round, and that it can always be included in the district heating. This means that in this project, production patterns of the excess heat and the availability of the district heating network have not been looked at.
- Furthermore, the project is limited in relation to bilateral agreement with the potential for direct link between electricity production and consumption. The price of electricity is absolutely essential for the price of methanol, so the possibility of such bilateral agreements between wind farms and the Power-to-Methanol plant can be a crucial factor for such a plant. In this project, the possibility of such agreements in the Fjord PtX has not been looked at directly, but the idea itself will be discussed.

These delimitation's is expected to have an impact on the feasibility of Power-to-Methanol and how the plant will operate in the future.

2.2 Research design

The purpose of this section is to give an overview of the structure of the project, presented as the research design seen in figure 2.1.

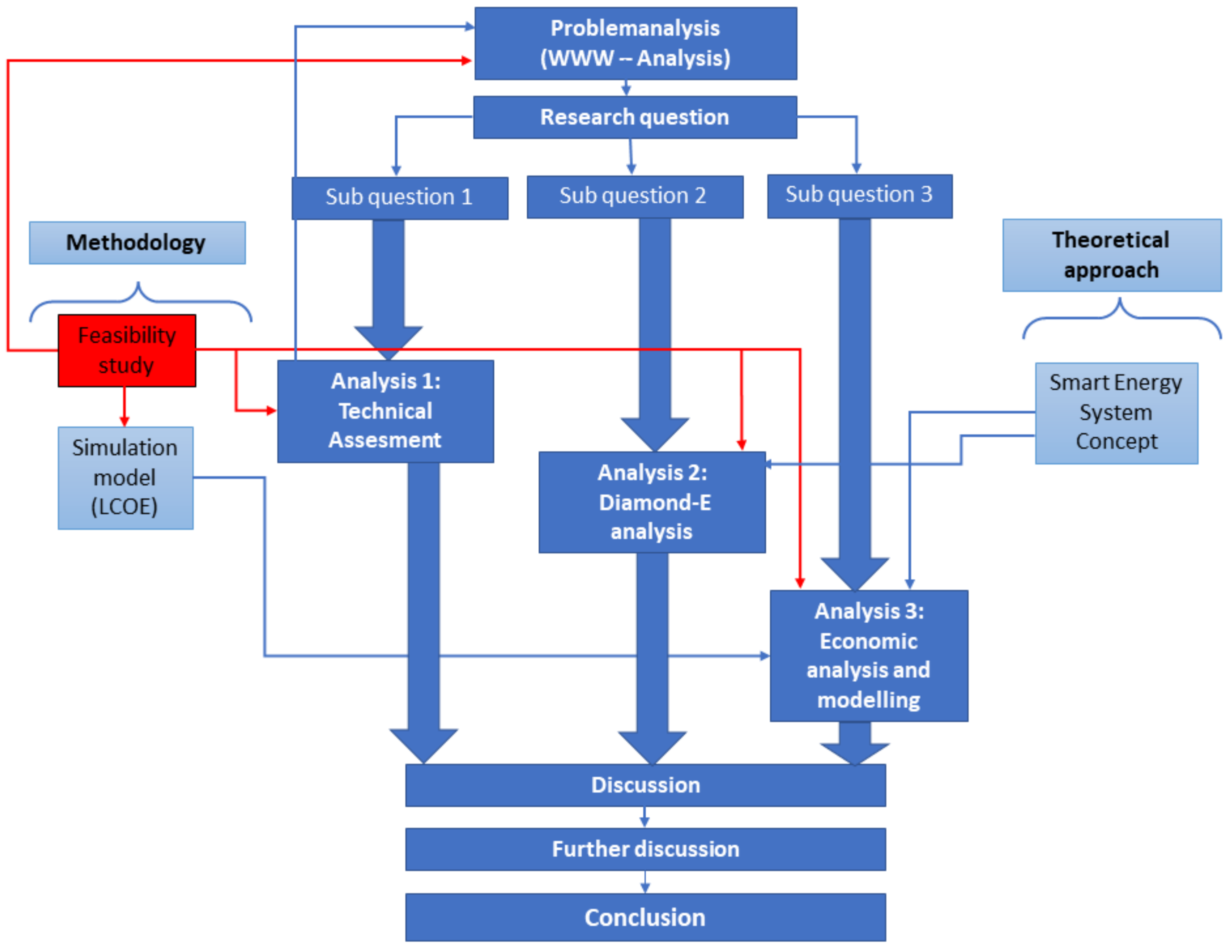

Figure 2.1: Research design for this project

From figure 2.1 it can be seen that the project starts with the problem analysis, that also can be described as the WWW-analysis of the feasibility study. The feasibility study is marked with red, because it is essentially the foundation and method used for the whole project. The problem analysis created the research question, which is answered by 3 different sub question. These 3 different sub questions are then answered by 3 analysis, which have been made with the theoretical approach and methodology. The results of the analyses are then discussed, which is followed up by the conclusion of the research question and project.

3 Theoretical Approach

In this chapter, the theoretical approach of the study is presented. The theoretical approach provides an overview of what perspective this study will take in relation to Power-to-Methanol. This overview is given with reference to smart energy system.

3.1 Smart Energy Systems

The green transition towards a 100% renewable energy system may face future challenges with the existing infrastructure. In a fossil-based energy system, the various energy sectors such as electricity, gas and heat have been primarily individual because it has been possible to have storage-able energy from fossils. This has ensured a stable energy system, but with an energy system consisting only of renewable energy, this stability can not be achieved in the same way. Renewable energy production is characterized by fluctuating and unpredictable energy from e.g. wind and solar. Therefore, it is necessary in a future energy system to have the different sectors to interact with each other in a "Smart energy system" to accommodate this inflexibility. And as it was presented previously in Chapter 1, Power-to-Methanol can provide with flexibility to the system. Therefore the 'Smart Energy Systems' is a necessary solution for transitioning from fossil fuels to renewable energy and how Power-to-Methanol can contribute to this can be seen in figure 3.1.

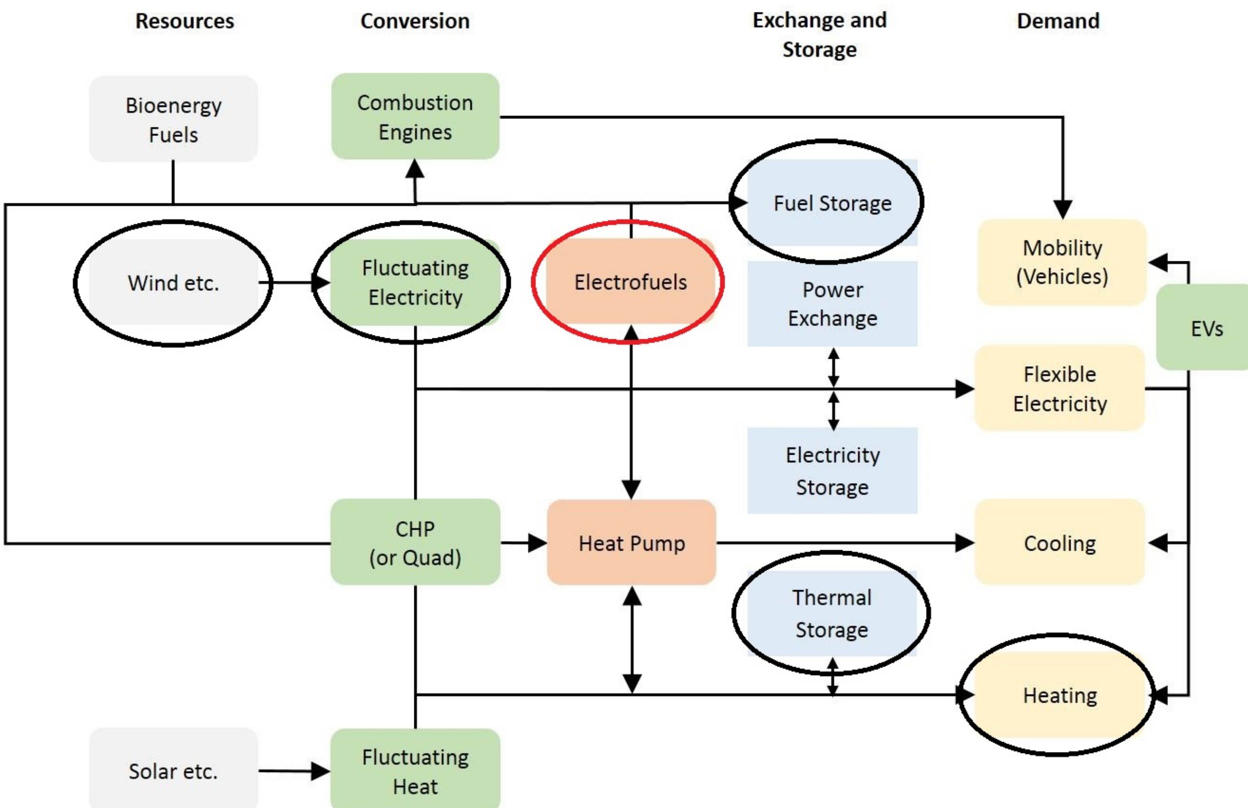

Figure 3.1: Smart energy system regarding Power-to-Methanol

Power-to-Methanol is a technology which are affecting different energy sectors. In order to produce methanol, electricity is needed which in the future Danish electricity grid will mostly consist of fluctuating wind power. Here, power-to-methanol can play an important role in minimizing this fluctuation in a flexible operation. In addition, excess heat is produced during the production of methanol which can thereby contribute with sustainable heat to the district heating and be stored as needed. In the production of methanol, hydrogen is also produced which can be stored for both own consumption but also a possible hydrogen market. As seen, Power-to-Methanol can contribute to a smart energy system since it is interacting with multiple sectors and can provide with flexibility. From figure 3.1 the different areas of which Power-to-Methanol is affecting can be seen with black and red rings. In relation to this study, these black rings mean that the study is aware that Power-to-Methanol involves many sectors and can be seen from different angles. But the main focus in this study will be on the production of electrofuel (Methanol) which is marked with the red circle. So the focus will be on understanding the production of methanol and the cost of this, but at the same time there will also be looked at the influence of electricity and the price of it.

4 Methodology

The purpose of this chapter is to present the methodology of the project, which consist of a feasibility study, and thereby explain how the analyses are made.

4.1 Feasibility study

Feasibility studies are being made to design feasible technical alternatives and an evaluation of social, environmental and economic costs of those alternatives. In relation to feasibility studies, there are generally two types: Socioeconomic feasibility and Business feasibility, where socioeconomic feasibility deals with whether the project is feasible for the society as a whole, whereas business feasibility analyzes the feasibility for a specific company. As a result, a feasibility study is based on a holistic examination of the effects of carrying out a certain project, rather than exclusively on economic benefit. In order to do a feasibility study, aspects such as economic, social, political and environmental impact must be considered. But in order to analyze these aspects, it is important to find out; *What should be studied? For whom should it be studied? Why should it be studied?* which is the first step in the feasibility study procedure.

4.1.1 Feasibility Study - Step 1: The WWW-Analysis

The WWW-analysis is very important to answer when making a feasibility study, which consists of the questions: **What** should be studied, for **Whom**, and **Why** (WWW). [8]

What should be studied?

In order to answer 'what should be studied?' the study consist of either a single project analysis or a system analysis. For the single project analysis, one single technology is introduced and analysed, whereas the system analysis consists of a scenario with a number of chosen technologies which is then analysed. In relation to the energy system that exists in Denmark today and how it will look in the future, it can be said that single project analysis is insufficient because technologies today affect several sectors. Therefore, in this project a system analysis will be made to answer the research question, because Power-to-Methanol contains several different technologies which affect several sectors at once, which is also related to the smart energy system approach.

For Whom and why are the feasibility study made?

A feasibility study can be made for a wide variation of actors such as governments, municipalities, private companies etc. The main objective of the feasibility may differ in relation to who the study is for. Therefore it is important to outline the different actors involved in the feasibility study. And looking at the implementation of Power-to-Methanol a lot of different actors are involved, where the most relevant have been mapped, which can be seen on figure 4.1.

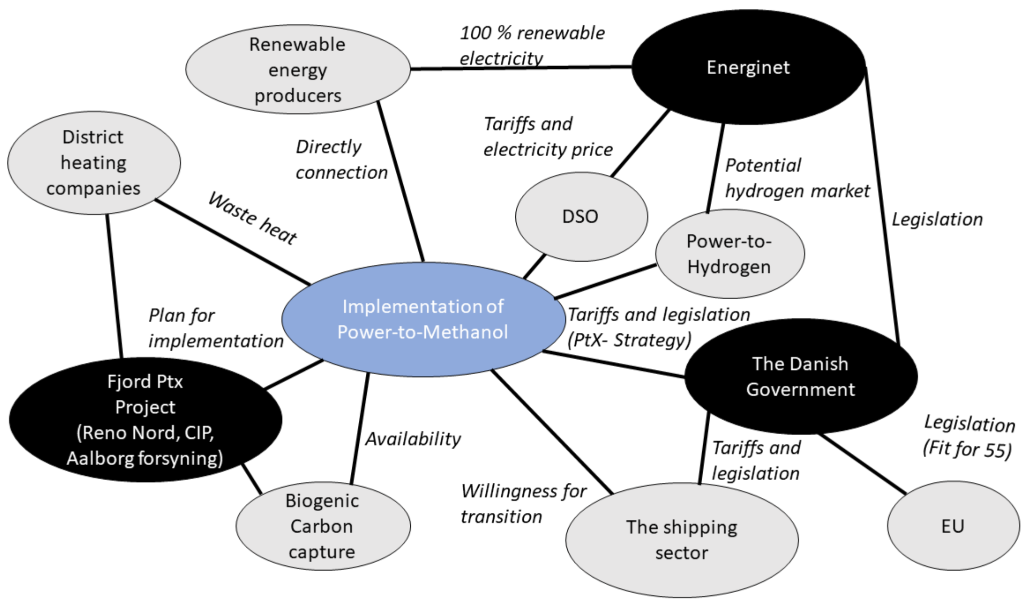

Figure 4.1: Mindmap of relevant actors and their interconnection for implementing power-to-Methanol

From figure 4.1 it can be seen that different organisations and actors are connected to the implementation of Power-to-Methanol. For this project the actors in the black boxes are seen as the main actors with directly influence on Power-to-Methanol. Whereas the actors in the gray boxes are seen as having less influence or indirectly. Therefore will main focus be given to, Fjord PtX project, the Danish Government and Energinet, throughout the feasibility study.

4.1.2 Feasibility Study - Step 2: The Diamond-E Analysis

After step 1, the WWW-analysis, it is important to establish a set of criteria explaining which consequences of a project there should be analysed and how. Here the Diamond-E analysis can be used as a systematic way of doing so. The framework for the Diamond-E analysis can be soon on figure 4.2.

Figure 4.2: The diamond-E framwork [8]

From figure 4.2 it can be seen that the feasibility study consists of *Organizational Resources, Organizational Goals and Financial Resources*, which is seen in relation the the *Natural and Socioeconomic Environment*. The Diamond-E analysis can be used to examine and analyse the present and institutional situation for the project, which in this case is Power-to-Methanol. The *Organisation Goals* consists of the investors and actors involved and their specific goal with the project which must be made explicit and open. Since the implementation of Power-to-Methanol includes a demand for technological innovation and environmental sustainability, then the feasibility will concentrate on these goals. The *Organisation Resources* are linked to the availability of implementation of the specific project, which could be e.g. is there good skilled workers and factories who can implement the desired project. If the availability is low then the project is rather complicated and also the corresponding investment. *Financial Resources* is obviously very important for a project to be implemented, therefore the feasibility study should also include the financial resources and how these could affect the project. And if the financial situation is characterized by turbulence, then the feasibility study should establish a sensitivity analysis. Furthermore, *Natural and Socioeconomic Environment* must be linked in the study, which means that the project must be placed in the context of political objectives and trends, as well as how the project fits within them.

A Diamond-E analysis will be used in order to analyse the present technical and institutional situation of Power-to-Methanol in relation to the main actors outlined previously. This analysis can be seen in chapter 6.

4.1.3 Feasibility Study - Step 3: LCOE

Step 3 can be seen as the concrete feasibility study and can be defined as the quantitative part of the feasibility study. To produce quantitative data, economic calculations can be made and evaluated. In this study the economic calculations consist of an evaluation of the Levelized Cost Of Energy for methanol. The general formula to calculate the LCOE can be seen in figure 4.3.

$$LCOE = \frac{\sum_{t}^{n} \frac{I_t + OM_t + F_t}{(1+i)^t}}{\sum_{t}^{n} \frac{E_t}{(1+i)^t}}$$

Where,

$LCOE = Levelised\ Cost\ of\ Energy$

$I_t = Investment\ cost\ in\ the\ year\ t$

$OM_t = Operation\ \&\ Maintenance\ cost\ in\ the\ year\ t$

$F_t = Fuel\ cost\ in\ the\ year\ t$

$E_t = Value\ of\ Energy\ generation\ in\ the\ year\ t$

$i = Discount\ rate$

$n = Economic\ lifespan\ of\ plant\ (number\ of\ years)$

Figure 4.3: Levelized Cost Of Energy [9]

The LCOE is a commonly used parameter for comparing and analysing various energy production units. It indicates the minimal price at which a unit of energy must be sold in order for the investment to be profitable. In this study the LCOE of methanol will be calculated and compared the cost of traditionally bunker oil, which is used in the shipping sector today.

Simulation Model

To calculate the LCOE a model of the Power-to-Methanol system has been set up in the modelling and simulation tool "Excel". Excel is used to simulate different scenarios for the Power-to-Methanol system. It is important to emphasize that excel is a simulation tool and not an optimization tool. This means that the calculations that are made in this feasibility study are not made to find the most optimal solution but thereby to simulate different scenarios and their effects.

5 Technical assessment of Power-to-Methanol

The purpose of this chapter is to give an overview of the technologies used in a Power-to-Methanol system and thereby answer the following subquestion:

What technologies and features are required in a Power-to-Methanol system?

Power-to-Methanol is a technology that can be regarded as a hybrid of several technologies that work together to produce Methanol. In this section these different technologies will be described and how they contribute for reaching the annually methanol production of 130.000 tons at Fjord X. As said, Power-to-Methanol consist of different technologies and these are shown on figure 5.1

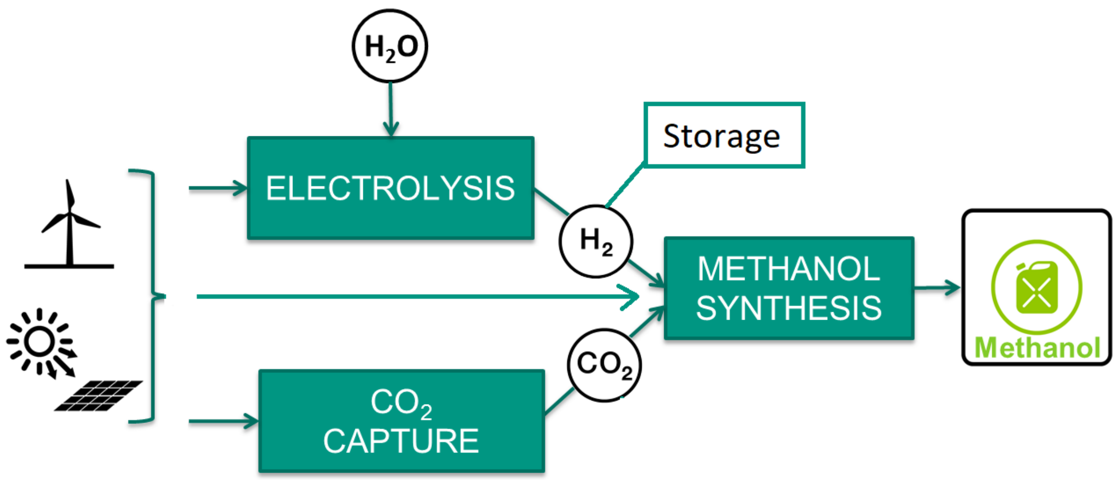

Figure 5.1: Different technologies in the Power-to-Methanol process [10]

From this figure the 3 essential technologies for producing e-methanol are shown, Electrolysis, CO2 capture and Methanol synthesis as well as hydrogen storage. And in order to produce green methanol, these technologies need to be powered by renewable energy sources like wind and solar. In addition if the system is to be flexible it is important to have storage units and especially for hydrogen which will also be described later. The chemical formula for methanol CH_3OH, where it can be seen that it consist of four parts hydrogen, one part oxygen and one part carbon.

5.1 Electrolysis

As seen from the chemical formula for methanol, hydrogen is an essential element in producing methanol, as methanol consists of hydrogen and CO2. Hydrogen can be made from a variety of different sources, such as fossil fuels, biomass, and electricity-powered water electrolysis. How hydrogen is created has an impact on the environment and its energy efficiency. And because of the environment, the production of renewable hydrogen has gained an increased focus, which is possible with electrolysis. The basic principle for the electrolysis technology is based splitting water by electricity, which can be described by the following equation:

$$2H_2O + Electricity \rightarrow 2H_2 + O_2$$

And if the electricity is produced by renewable energy sources, such as wind or solar, the hydrogen will also be considered renewable.

In order to produce renewable hydrogen three different electrolysis technologies are today considered appropriate, which is Alkaline Electrolysis Cells (AECs), Polymer Electrolyte Membrane (PEM), and Solid Oxide Electrolysis Cells (SOECs). In order to determine which technology there is most suitable for this project, the advantages and disadvantages has been looked at. Common to these technologies is that they are immature for commercial use at large scale (100 MW) plants. However, small MW scale systems (10 MW) are already being deployed both for AECs and PEM, which is promising. Whereas SOECs are still in demonstration phase for large scale applications for hydrogen production and are not readily commercially available, which therefore will not be considered further for the purposes of this study [11]. But when comparing the AEC and PEM electrolysis then there is one parameter in particular that separates the two technologies from each other and that is the regulation ability which can be seen in figure 5.2

	AEC	PEM
Cold start-up time (from 0 to 100%) [minutes]	<120	10 (5-10)
Warm start-up time (from 0 to 100%) [seconds]	240 (60-300)	<10
Power response signal [seconds]	<1 (<1-5)	<1 (<1-5)

Figure 5.2: Regulation ability for AECs and PEM [11]

From this figure it can be seen that the PEM electrolysis has a faster response time both from cold and warm start up compared to the AEC. And with a Danish energy system which consists of fluctuating electricity in the form of solar and wind power, it becomes essential to have flexible technologies that can be regulated in relation to this. Therefore, PEM electrolysis is chosen for this project as it has a warm start-up time of a few seconds, whereas AECs needs a few minutes.

The financial and technical data for PEM electrolysis, which will be used for the simulation model, can be seen in table 5.1.

PEM Electrolysis			
Financial Data		**Technical Data**	
Specific investment cost (M€/MW of total input)	0.65	Hydrogen efficiency (% of total input)	65.5
Fixed O&M (% of Capex/ year)	4	Hydrogen output (kg /MWh input)	19.7
Technical lifetime (Years)	25	Recoverable heat (% total input (MWh/MWh)	19.6%

Table 5.1: Financial and technical data for PEM electrolysis [11]

5.2 CO2 capture

The increasing amount of carbon dioxide (CO2) in the atmosphere has led to the changing climate of our planet. Creating new technologies to counter the ongoing climate crisis has gained significant focus in recent years and one of these technologies is Carbon Capture and Utilization (CCU). The use of carbon capture and utilization (CCU) to capture CO2 and produce electrofuels has been acknowledged as having a high potential for a more sustainable future. And in order to capture CO2 there are two methods; Carbon Capture at point source and Direct Air Capture (DAC).

5.2.1 Carbon Capture at point source

Carbon Capture at point source is where the CO2 is captured from large point sources, such as coal-fired power plant, a chemical plant or biomass power plant, where the flue gases emitted at these plants typically contains CO2. There exists different methods to separate the CO2 from other gases in the flue gas, but adsorption is the most common. Absorption processes work by contacting the CO2 to be captured with a chemical mixture and through a combination of temperature changes and pressure change the CO2 is captured and cleaned of other gases, which is released into the air [12]. In order to produce sustainable electrofuels, such as green methanol, the CO2 captured needs to be of a biogenic origin, such as a biomass plant. For this project the CO2 captured will originate from the waste incineration plant, Reno Nord I/S, which over the last 3 years have emitted approximately 216.000 tons CO2 per year. How the distribution between biogenic and fossil CO2 is will be analyzed in Chapter 6.

The technical and financial specification for a CCU plant can be seen in table 5.2

Carbon capture from point source			
Financial Data		**Technical Data**	
Specific investment cost (€/(t CO_2 capture capacity/yr))	180	Technical lifetime (Years)	20
Fixed O&M (% of Capex)	5	Electricity consumption (KWh/t CO_2	250
		Efficiency (%)	90

Table 5.2: Financial and technical data for carbon capture from point source [13] [14]

5.2.2 Direct Carbon Capture

Direct Carbon Capture (DAC) is another method to capture CO2. Direct air capture (DAC) technologies extract CO2 directly from the atmosphere. In a transition to net zero emissions, however, the CO2 used to produce electrofuels would increasingly need to be captured from sustainable bioenergy sources or from the atmosphere to avoid fossil-based CO2 when the fuel is combusted. One of the few technology options for removing CO2 from the atmosphere is Direct Air Capture and carbon removal is expected to be critical in the transition to a net zero energy system, in which the amount of CO2 released into the atmosphere equals the amount removed. Because some energy sectors, such as heavy transport, are difficult to decarbonize, carbon removal technologies can help offset emissions and speed up the transition. The financial and technical data can be seen in table 5.3

Direct Carbon Capture (DAC)			
Financial Parameters		**Technical Parameters**	
Specific investment cost (€/(t CO_2 capture capacity/yr))	550	Technical lifetime (Years)	25
Fixed O&M (% of Capex)	5	Electricity consumption (KWh/t CO_2)	550

Table 5.3: Financial and technical data for Direct Carbon Capture [13]

5.3 Methanol synthesis

The technologies to produce renewable hydrogen and capture sustainable CO_2 has now been introduced, but in order to produce methanol, the hydrogen and CO_2 has to combined, which is done in a synthesis process. Electricity is used in order for the methanol synthesis process to have the right temperature and pressure, about 300 C and 85 bar of pressure, which enables hydrogen and CO_2 to combine in a catalytic process. If this stage is not operated at a continuous rate there will be significant loss of overall efficiency for the process [11]. It is therefore important that there is a constant supply of hydrogen and CO_2 for the methanol synthesis process so that the system has the best working conditions.

Methanol synthesis			
Financial Data		**Technical Data**	
Specific investment cost (M€/1000 t Methanol)	0.16	CO_2 Consumption, t/t Methanol	1.37
Fixed O&M (% of Capex)	4	Hydrogen Consumption, t/t Methanol	0.192
Technical lifetime (years)	20	Electricity Consumption, MWh/MWh Total Inputs	1
		Methanol Output, MWh/MWh Input	0.61
		District heating Output, MWh/MWh Total Input	0.25
		Specific energy content (Mwh/ton) (Methanol)	5.58

Table 5.4: Financial and technical data for methanol synthesis [11] [15]

5.4 Storage

Energy Storage Systems are a technology used to store energy, where the stored energy can be used at a later time to perform useful operation. In the Power-to-Methanol system, there consist 3 different storage possibilities. First and foremost, there is storage of the methanol itself which is being produced. However, since methanol is a liquid energy carrier like petrol and diesel, which do not have special prerequisites, it is easy to store methanol in ordinary tanks. In this study, the storage of methanol will not be looked at further as it is a known technology and has no economic influence in relation to the whole system. Another type of storage that is part of the Power-to-Methanol system is the storage of CO2. However, in this study, it has been assumed that "Reno Nord" and DAC can deliver a constant flow of CO2 to the synthesis process and therefore there will be no closer look at CO2 storage.

The last form of storage that is part of the Power-to-Methanol system is the storage of hydrogen. In the process of producing hydrogen, large amount of electricity is needed and as known renewable power are fluctuating. Sometimes the production of renewable electricity is high, where a lot of hydrogen can be produced, and sometimes it is low. And that is why a hydrogen storage is needed in the Power-to-Methanol system, to give flexibility. Hydrogen H2 is the simplest element, consisting of only one proton and one electron, making it the smallest and lightest element of the periodic table. Its small size and its properties make hydrogen difficult to store in large quantities [16]. Storage of hydrogen in large scale, is a immature technology and is difficult because the hydrogen has to be pressurized at all times. But smaller hydrogen storage pressurized tanks exists, which will be used as the data in this study:

Hydrogen storage			
Financial Parameters		**Technical Parameters**	
Specific investment cost (€/kg hydrogen)	500	Technical lifetime (Years)	20
Fixed O&M (% of Capex)	4	Electricity consumption (KWh/kg)	4

Table 5.5: Financial and technical data for hydrogen storage [16]

5.5 Summary

From the technologies and their specifications presented in the technical assessment chapter, it is possible to calculate the demands for CO_2, hydrogen and electricity in order to fulfill the goal of a production of 130.000 tons methanol at the PtX fjord facility. The demands can be seen on figure 5.3 to produce 130.000 tons methanol with electrolysis, CO_2 capture at Reno Nord and methanol synthesis.

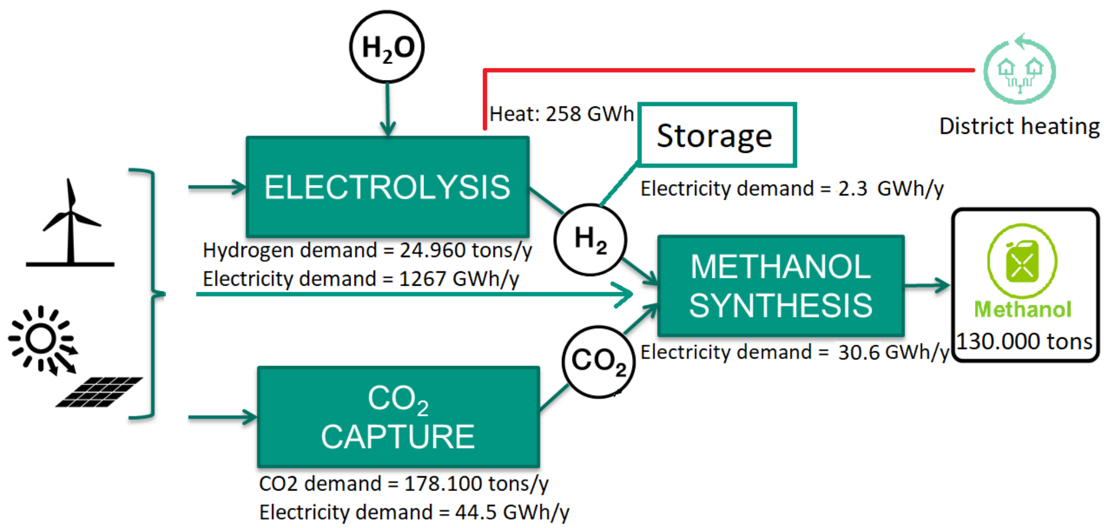

Figure 5.3: Demands for production of 130.000 tons methanol yearly at the PtX fjord facility

From this figure it can be seen that in order to produce methanol, electricity is an important resource especially for the electrolysis. Combined for the 4 technologies there is a yearly demand of 1344.4 GWh to produce the 130.000 tons of methanol. This gives the system an overall efficiency of approximately 54%. So for 1 MWh of electricity, 0.54 MWh of methanol is produced. In addition the process of electrolysis 258 GWh excess heat is generated yearly which can be utilized in the district heating network.

6 Diamond-E analysis of Power-to-Methanol in Denmark

The purpose of this chapter is to analyse the organizational goals, organizational resources, financial resources, natural and socioeconomic environment regarding the Fjord PtX and the PtX strategy from the Danish Government. This is done by answering the following subquestion:

What is the present technical and institutional situation for Power-to-Methanol?

6.1 Organizational goals

Technological development is taking place at a rapid pace, and PtX is a crucial technology for a green CO2-neutral future. When looking at the organizational goals regarding the PtX technology, it can be difficult to determine one specific goal as there are many different actors involved in a PtX facility. As it was presented in chapter 3 of the theoretical approach, Power-to-Methanol contribute to a smart energy system which is connecting different sectors and actors, which may have different goals with such a facility. Overall, it can be said that PtX in general is an immature technology but which has received increased attention recently in the green transition as this technology can contribute where direct electrification is not possible or associated with high costs such as parts of industry, parts of heavy road transport, shipping and aviation. This is also why, as it was presented in chapter 1, the danish government has a vision of 6+ GW PtX capacity by 2030. The Danish government plays an important role regarding the implementation of Power-to-X facilities in Denmark since it is a unknown and immature technology, and is also the reason why it is in the process of preparing a Danish strategy for Power-to-X and use Carbon Capture and Utilization. With *"The Government's strategy for POWER-TO-X [5]"* the Dansih government took the first important step towards the necessary framework conditions for PtX in Denmark. These framework conditions are aimed to make it easier for these technologies to contribute to the climate goals of 2030 and 2050, as well as to realize their commercial potential and to be integrated into the Danish energy system. This has resulted in announcements of PtX projects throughout Denmark and and one of them is Fjord PtX. As previously stated, there are many different actors involved in a PtX project, and this can also be seen at the Fjord PtX project, which consists of a partnership between *"Copenhagen Infrastructure Partners, Reno-Nord and Aalborg Forsyning"*. These actors have different roles in the project and can therefore in part also be said to have different goals. Reno Nord is an incineration plant in Aalborg municipality which process and burns waste from citizens and businesses. When burning waste this emits CO_2 which is subject to a taxation from the Danish government and the EU Emissions Trading System (EU ETS). These taxes are used to combat climate change and it is a key tool for reducing greenhouse gas emissions cost-effectively. In 2022 the Danish government came with a proposal for an increased CO2 tax, where in 2030 it will cost up to 750 DKK per tonne of CO2 as opposed to the 180 DKK it costs today [17]. As this tax becomes higher, it also becomes more expensive for companies to emit CO2, which provides an incentive to look for other solutions. Therefore, it must be believed that the main goal and solution for Reno Nord is carbon capture in order to avoid taxation of CO_2 emission. Another actor in the Fjord PtX project is "Aalborg Forsyning", which supplies the citizens of Aalborg Municipality with district heating, gas and water. Aalborg Forsyning is also constantly working to find new methods and technologies so that they can become CO2-neutral by optimizing and implementing green solutions [18]. Since Aalborg Forsyning supplies district heating, it must be believed that their main goal and focus in the project is the sustainable waste heat which the Fjord PtX facility will provide. The third partner of the project is "Copenhagen Infrastructure Partners" which is a fund management company specialized in offering renewable custom-made investments in the energy infrastructure. They have projects within offshore wind, onshore wind, solar power, biomass and energy-from-waste, transmission and distribution, storage, and recently Power-to-X. CIP are aiming to enable the green transition, while they build value for their investors, developers and local communities [19]. Common for the 3 partners is that they at this Fjord PtX project have found a technology that can meet their individual goals and at the same time create a new common goal which is to produce sustainable methanol which can contribute to the green transition.

6.2 Organizational resources

The organizational resources regarding this project implies the accessibility of skilled workers and factories who are able to build and maintain a Power-to-Methanol facility. The technology for producing green methanol is very immature and currently there are only exits 10 demonstration/pilot plants and 2 actually plants which can provide e-methanol [20]. These 2 plants have a maximum capacity of 4000 tons methanol per year, which is far from the 130.000 tons the Fjord PtX project wants to supply. Therefore, in relation to the organizational resources, it can be said that there is a shortage of experienced workers and factories within power-to-methanol. However, it is a technology that is under a lot of focus and several projects are underway, so therefore it is a matter of time before there are specialists in the field. But as it is right now, the technology is inexperienced on a large scale, which increases the risk associated by investing in Power-to-Methanol facilities.

6.3 Financial resources

The financial resources regarding are essential for an energy project to be carried out and especially for new technologies such as Power-to-Methanol. Therefore, it is absolutely fundamental that in order to establish this Fjord PtX, there will have to be financial support. This is also why the government has increased their public support from 750 million DKK to 1.25 billion DKK for operating support for the production of hydrogen and other PtX products, including methanol. Other than that, the Government will set aside 344 million DKK for innovative green technologies via funds from the REACT-EU initiative and the Just Transition Fund. And further more has the government with *Denmark can do more I* reform proposed a 6 billion DKK capital injection into the newly established Danish Investment Fund, of which 1.7 billion will be targeted for funding companies engaged in commercial large-scale projects in fields such as Power-to-Methanol [5]. This shows that the government is ready to support Power-to-Methanol projects which are essential for this immature technology to be implemented to the Danish energy system. But even though there is support from the government, there is still a high risk associated with an investment in Power-to-Methanol as there may be unforeseen challenges with the technology. Therefore, it may be difficult to get investors when there is a high risk, but here it is a good thing that CIP has experience in implementing energy projects and can thereby create trust for future investors in the Fjord PtX project.

Another financial opportunity for the Power-to-Methanol project, Fjord PtX, is the price for fuel which ships are using. Fuel costs constitute 50% or more of the operational cost of a ship and is therefore essential to the economy of shipping [21]. Today, almost all ships sail on fossil fuels (Oil and diesel) and the market for fossil marine fuel are characterized by significant fluctuations, and is generally the most unstable source of operation costs for the shipping sector. The fluctuations in the price is impacted from multiple different factors such as; supply and demand, natural disasters, political instability, production costs and storage [22]. These fluctuations can be seen on figure 6.1

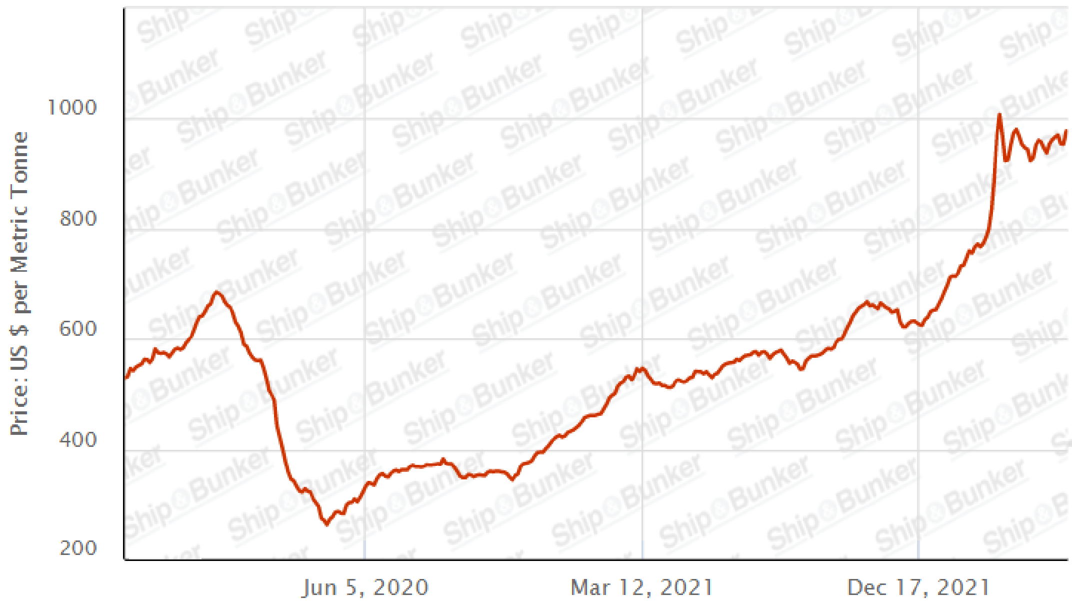

Figure 6.1: Price history for bunker oil which is used as fuel in the shipping sector [23]

Figure 6.1 shows the price history for bunker oil used as fuel in the shipping sector. Here it can be seen that the price for bunker oil have a lot of fluctuations, but in march 2022 it suddenly spiked up close to 1000 US dollars pr tonne and has kept this level. This sudden increase is due to the Russia-Ukraine war, because Russia is a major producer of gas and oil. This shows how unpredictable fossil fuel prices can be, which play a major role in the business economy of shipping. But this increase in price can also provide an incentive for the shipping sector to look for an alternative fuel which could be methanol and willingness to invest.

6.4 Power-to-X strategy from the Government

In recent years, there has been increased focus on the development of the PtX technology. This development has evolved at a speed which means that the existing legislation and framework conditions for PtX is not able to meet this and make the technology as competitive as possible. But this is, among other things, something that the government has looked at in their strategy for Power-to-X [5]. In addition to contributing to the green transition in the production of Power-to-X fuels, such as methanol, the government also has ambitions that the PtX facilities can provide flexibility to the electricity grid. As it was shown in Chapter 5 then large amounts of electricity is needed to be able to produce methanol. In total for the Fjord PtX project, 1344.4 GWh are needed to produce the 130,000 tonnes of methanol, where the electrolysis process accounts for almost all power consumption. As previously described, the electrolysis plant can be quickly adjusted up and down, whereas the synthesis process must be run continuously regarding the production. Therefore, the flexible unit in the Fjord PtX project is the electrolysis plant which will provide flexibility to the electricity grid, however, in order to provide this flexibility, it is essential for the facility to have hydrogen storage. And the reason why flexibility is important in the electricity grid is because renewable electricity capacity will continue to increase in Denmark the next many years. During periods of high renewable electricity generation, this will result in lower electricity prices. These periods can potentially result in more exports at very low electricity prices, or even force production shutdowns on a regular basis. Exporting electricity at low costs does not benefit the Danish market on its own, even though it may help other countries to electrify and transition to a greener future. Forced renewable energy production shutdowns, on the other hand, do not benefit the electricity market or the green transition. Therefor are large PtX and especially electrolysis plants, which can operate flexible, ideal partners for large-scale renewable electricity production. Because during periods when there is a lot of electricity in the grid, electricity can be transferred to these plants, hence increasing its value and settlement price. According to the Danish Energy Agency's research, constructing PtX facilities in geographically optimal places is a major precondition for them to operate in balance with the energy system and electricity grid. Electrolysis plants must be located in areas where already or new and significant amount of electricity can be integrated into the current grid. This means places where huge amounts of electricity are produced rather than areas where electricity consumption is already high. Such areas can be seen in figure 6.2 made by Energinet.

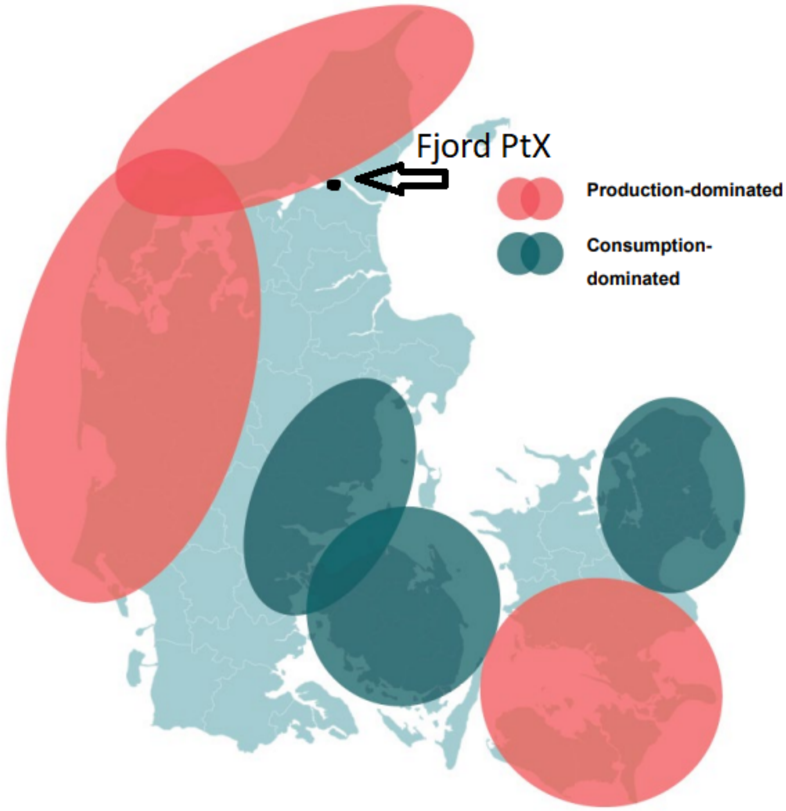

Figure 6.2: Capacity map of the Danish electricity grid. In order for the PtX plants to create value for the Danish electricity grid, large facilities would typically have to be placed in the production-dominated areas [5]

Here it can be seen that the Fjord PtX project is located right on the edge of the production-dominated area, which has certainly been part of the deliberations of the expected location of this Power-to-Methanol facility. The plant is to be built at Nordjyllandsværket, which is in the process of being transformed into a green test center, which with its location very close to production can contribute to developing and testing new supply solutions and improving the solutions already used today. But this location may also prove to have another advantage regarding the government's proposal to change consumer tariffs compared to how they are today.

Energinet are the owner and developer of electricity and gas networks in Denmark to incorporate more renewable energy, maintain security of supply and ensure equal market access to the networks. Energinet charges a number of different tariffs to cover the costs of establishing and operating the electricity grid, as well as of operating and balancing the electricity system. When electricity is consumed, tariffs are levied on this electricity which consists of a *Transmission tariff* which covers Energinet's costs for operation and maintenance of the overall electricity network (4.9 øre/kWh), *System tariff* which covers costs for security of supply and the quality of the electricity supply, including reserve capacity, system operation, etc. (6.1 øre/kWh), and lastly the *Balance tariff* which covers a share of Energinet's total costs for system services and management of the balance sheet market (0.229 øre/kWh) [24].

- Transmission tariff: 6.53 euro/Mwh
- System tariff: 8.13 euro/Mwh
- Balance tariff: 0.31 euro/Mwh

These tariffs are subject to all electricity consumers no matter the place and quantity, which means it is not possible today to make a geographical differentiation of consumption tariffs because of the Danish Electricity Supply Act. It prevents a cost-effective reflection of geographical certain net costs in the tariffs. But the use of geographically differentiated consumer tariffs can possible create socioeconomic value as it will encourage new major ones electricity consumers to place themselves appropriately in the electricity grid as it was seen on figure 6.2 and thereby contribute to that network capacity is used more efficiently, which also can reduce the need for investment in the electricity grid.

Another suggestion is to be able to establish direct links of electricity connection between electricity production and consumption to a greater extent. This could for example, be a wind farm directly connected to the Power-to-Methanol production without using the public electricity grid. This will not put load on the public electricity grid and thereby the electricity consumer can save on the tariff costs from the electricity supplied by the direct link from the producer to the consumer. The reduced tariff cost and the possibility of bilateral agreements could also increase the incentives for locating producers and consumers of electricity together and thereby reduce the need for expanding the public electricity grid. Of course there are costs associated with establishment of a direct link, but it is believed to be able to reduce the total production costs of e.g. Power-to-Methanol.

The possibilities for granting permission for geographically differentiated consumption tariffs and direct links have been included in the sensitivity analysis in chapter 7.

6.5 Natural and socio-economic Environment

As it was presented in the problem analysis in chapter 1, the Danish government has a goal of reaching climate neutrality in 2050, which implies net-zero CO2 emissions in Denmark within 2050. Then, CO2 emissions must be reduced in the shipping sector and subsequently be climate neutral. Therefore, the production of green methanol is essential to achieve this goal and for methanol to be green, it must be produced from renewable electricity and biogenic CO2. In the Fjord PtX project for producing methanol, CO2 will be captured from the waste incineration plant "Reno Nord", which have emitted approximately 216.000 tons CO2 in average over the last 3 years [25]. But at "Reno Nord" and in general at waste incineration, many different types of waste are incinerated which are both fossil and biogenic. Therefore, it is not only biogenic CO2 that is emitted at "Reno Nord" where the distribution is approximately 40% fossil CO2 and 60% biogenic CO2, respectively [25]. Thereby it can also be discussed whether it is green methanol which will be produced by the Fjord PtX project and the CO2 reduction, but this will be discussed further in Chapter 8. In addition, another thing to consider when producing methanol by CO2 capture of incineration plants is the amount of the emission in the future. The historical and expected CO2 emissions from the waste sector in Denmark is shown on figure 6.3.

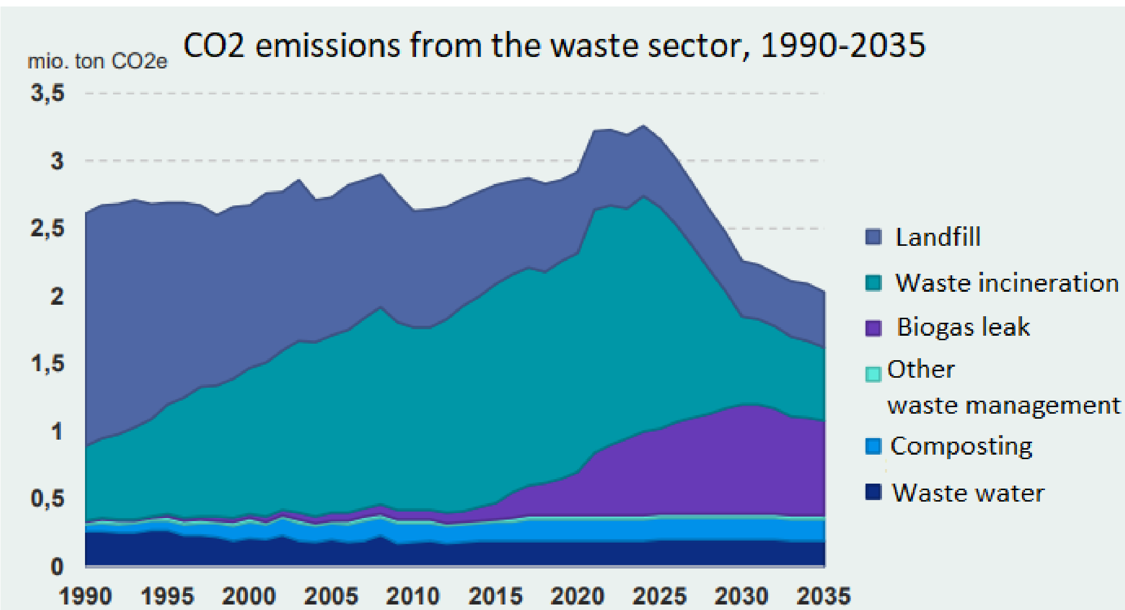

Figure 6.3: CO2 emissions from the waste sector in Denmark from 1990-2035 [26]

From figure 6.3 it can be seen that the CO2 emissions from incineration of waste consists today of approximately 1.7 million tonnes, whereas it is expected that in 2035 this will account of 0.5 million tonnes. The reason for this is, is an increased sorting and recycling of Danish waste, as well as a reduction in incineration capacity. Therefore, it can be argued that biogenic CO2 and generally CO2 from waste incineration plants is a limited resource which in the future will be less accessible. And this is one of the reasons why CO2 captured from "Direct Air Capture" is included in this project, as this technology can have a crucial role in the production of green methanol in the future energy system. But no matter if the CO2 is captured from the waste incineration or directly from the air for Power-to-Methanol production, it is a benefit to the climate.

Another benefit which the Power-to-Methanol project will deliver to the society is new jobs. Because with this Fjord PtX project, it is expected that the establishment of the Power-to-methanol plant is estimated to contribute 600-700 jobs during the construction phase and 50 permanent jobs when the plant is completed [7]. Therefore, the establishment of this Power-to-Methanol plant will create new jobs and thereby contribute to the socio-economics of Denmark.

7 Economic Analysis and Modelling of Power-to-Methanol

The purpose of this chapter is to make an analysis of the cost of producing methanol and thereby answer the following subquestion:

How can a Power-to-Methanol facility be modelled in order to supply the demand of 130.000 tons methanol and what is the cost?

This chapter contains of 4 different scenarios, which have been modelled and analyzed through the software "Excel". The 4 scenarios consists of a reference scenario with the cost of bunker oil and 3 different scenarios of the production of methanol, which will be described further. The scenarios will be evaluated on the Levelized Cost Of Energy of methanol and compared with reference scenario and with each other. Furthermore, a sensitivity analysis will be done to evaluate on the most important parameters affecting the cost of methanol.

7.1 Description of the scenarios

The 4 different Scenarios which will be analysed are:

- **Reference scenario**: Which is fossil-based bunker oil used as fuel in the shipping sector today
- **Scenario 1**: Which is the production of methanol with the use of PEM electrolysis, Carbon capture at point source and Methanol synthesis
- **Scenario 2**: Which is the production of methanol with the use of PEM electrolysis, Hydrogen storage, Carbon capture at point source and Methanol synthesis
- **Scenario 3**: Which is the production of methanol with the use of PEM electrolysis, Hydrogen storage, Direct Air Capture and Methanol synthesis

Reference scenario

The reference scenario for this project is the cost for bunker oil which is used by the shipping sector today. As it was seen on figure 6.1 the price for bunker oil is fluctuating and is today at a very high level due to the Russia-Ukraine war. In order to evaluate the price at a rationally and fair level it is determined that the price for the reference scenario is the average bunker price in 2019, which was before the effects of covid-19 and the Russia-Ukraine war. Therefore is the reference scenario price 390€/tonne bunker oil [27].

Scenario 1,2,3

Scenario 1,2 and 3 contain the production of methanol. The 3 scenarios have in common that they are fulfilling the demand of 130.000 tons methanol, which is the goal of the Fjord ptx project, but how the methanol is produced differs from the 3 scenarios in terms of strategy and technology.

Scenario 1: produces hydrogen from PEM electrolysis with a capacity of 300 MW and captures CO2 from the point source Reno Nord, which then are combined in the methanol synthesis process in order to make methanol. In this scenario the system are operating continuously, which means that no matter the electricity price, hydrogen is produced from the electrolysis.

Scenario 2: produces hydrogen from PEM electrolysis with a capacity of 300 MW and captures CO2 from the point source Reno Nord, which then are combined in the methanol synthesis process in order to make methanol. But in this scenario a hydrogen storage are implemented to run the system flexible. This means that a strategy for buying the electricity are implemented for the hydrogen production.

Scenario 3: also produces hydrogen from PEM electrolysis with capacity of 300 MW, but instead of CO2 from Reno Nord, the CO2 are captured from the air with DAC, which then combined in the methanol synthesis process in order to make methanol. This scenario is also running flexible regarding the hydrogen production.

The strategy for running the system both continuously and flexible in relation to the electricity price will be described in further detail in the results. But first some assumptions and working principle for the model are introduced.

7.2 Working principle and assumptions for the model

This section will provide an overview of the assumptions made for the model and important parameters in relation to the calculation of the levelized cost of methanol.

Data applied

The data which have been applied for the model in relation the the different technologies was introduced in chapter 5 "Technical assessment". Here the Investment cost, Fixed cost, Efficiencies, Input and Outputs for the different technologies will be used for the model.

Time horizon

The time horizon for the model is set to the technical lifetime of the methanol synthesis process which is 20 years.

Discount rate

In the calculations of the LCOE for methanol, the discount rate is used. The discount rate is set to 3.5% which is the recommended discount rate from the Danish Ministry of Finance. [28]

Electricity supply

Regarding the average electricity prices in east Denmark it has been up and down the last couple of years which also can be seen on figure 7.1.

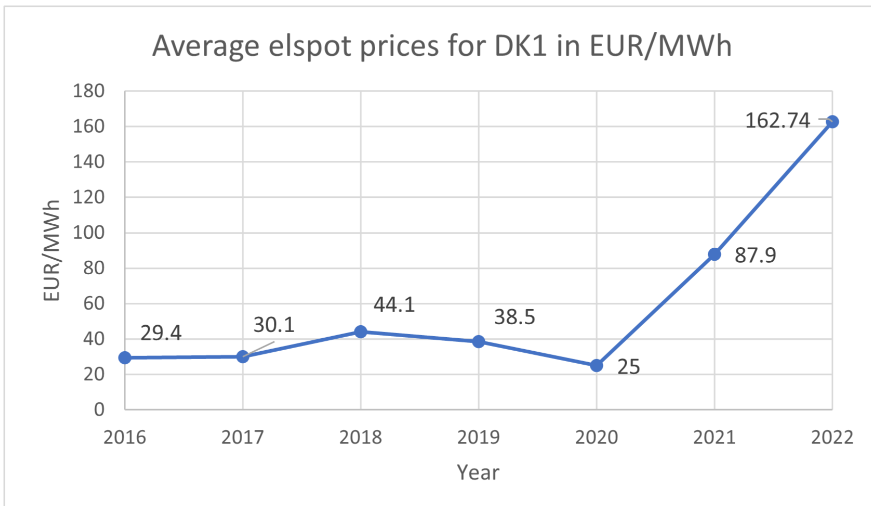

Figure 7.1: Average annual electricity prices in DK1 from Nord Pool

From this figure it can be seen that in 2021 and especially now in 2022 historical high electricity prices is a reality. The main reason for the increase in electricity prices is that the price of fossil natural gas. Because the market for electricity operates in such a way that it is the most expensive necessary electricity-producing unit that at all times determines the price of all electricity offered on the Nordpool market, also called the merit order effect. And as long the electricity grid is not 100% renewable, then there is often a need for an expensive gas-fired plant, which therefore sets the price in the electricity market. Due to lack of renewable electricity in 2021 and the Russia-Ukraine war in 2022 effecting the gas prices, has resulted in high electricity prices the last couple of years. Conversely, in 2020 a historically low record was set for the price of electricity because of the low power consumption in the Covid period. Therefore it is chosen in the project to use the electricity prices in 2019, which is believed to be a fair assumption because the electricity prices must in the best way reflect the prices in 2028 when the fjord Power-to-Methanol plant is set to be done. This assumption of using the electricity prices in 2019 with an average of 38.5 EUR/MWh is further supported by the estimation made of "Energinet", who estimates that the LCOE for onshore wind turbines are approx. 40 EUR/MWh and for offshore 53 EUR/KWh [29].

Further in relation to the electricity used, it is assumed that in 2028 the Danish electricity grid will consist of a 100% electricity mix, which is also the predictions from the Danish Energy Agency [30]. This means that renewable electricity will always be available in the grid, which can be used for the production of green methanol.

Excess Heat and O2

Regarding the excess heat for this project, then excess heat is produced in the process of making hydrogen in the PEM electrolysis. For the Fjord PtX it was showed in chapter 5 that 258 GWh of excess heat is being produced. This is a revenue for the project which Aalborg Forsyning can use in the district heating network of Aalborg. The price for the excess heat, which is an revenue for the project, is set at the price ceiling for excess heat that the Danish Energy Agency has set of 37€/MWh [31]. In addition, a assumption has been made that this excess heat can always be used in the district heating all year round, so there is no need for storage. Furthermore Oxygen is produced by the electrolysis unit and can be sold on the market for e.g. medical use. However, it is expected that this will have no substantial effect on the ultimate cost, thus it is not included.

Cost of water, land and transport

The same applies for the cost of water, land and transport. To produce hydrogen water is needed in the electrolysis process by splitting the water molecule, but in this project the cost of water is not included. Further the price of the land at Nordjyllandsværket where the Fjord PtX plant will be built is also not included. In addition it is believed that the electrolysis, hydrogen storage and methanol synthesis will be build close together at Nordjyllandsværket, which minimize the transportation and pipes needed for the fuels. However Reno Nord which is the supplier of CO2 is located on the other side of the limfjord, where a pipe connection is needed. But in relation to the entire project size, this is considered insignificant for the total cost of the project and is therefore not included.

7.3 Results

This section will present the results of modelling and analysing a Power-to-Methanol facility capable of producing 130.000 tons methanol in the Fjord PtX project.

For the Power-to-Methanol system, electricity is needed in every single step involving electrolysis, CO2 capture, synthesis process and storage. Therefore, it can be said that electricity is the primary input in this process to be able to produce methanol. The annual electricity consumption for the Power-to-Methanol facility in order to produce 130.000 ton methanol can be seen in figure 7.2.

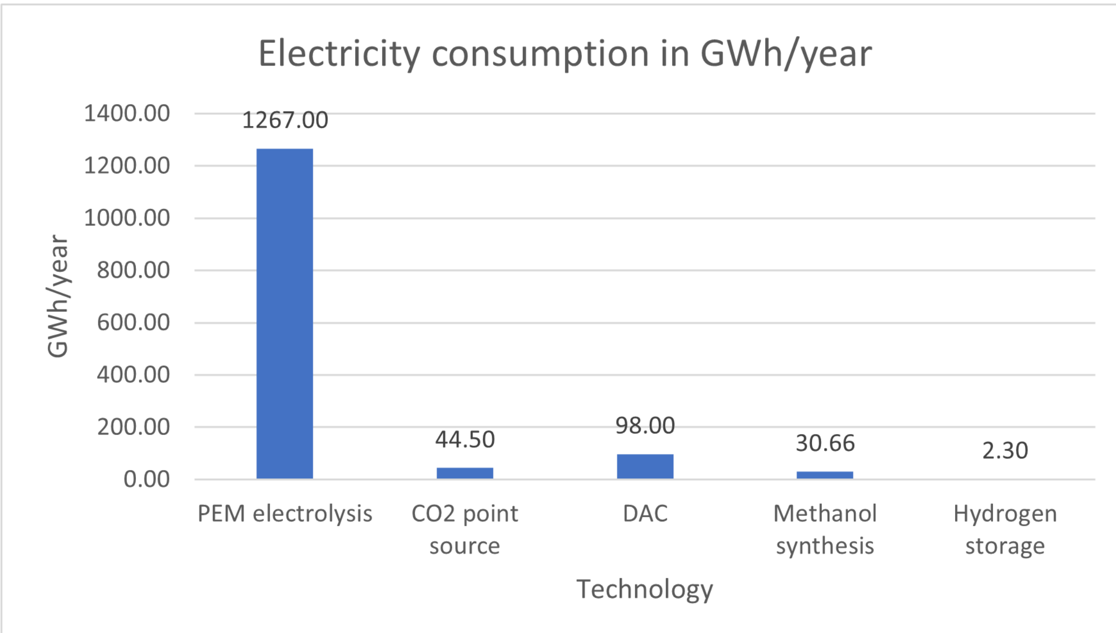

Figure 7.2: Annual electricity consumption for the technologies used in Power-to-Methanol

From figure it can be seen that the technology of PEM electrolysis consumes by far the most electricity per year with an annually consumption of 1267 GWh. Further it can be seen from the figure that the Direct Air Capture technology to capture CO2 consumes approximately twice the amount of CO2 capture at point source.

7.3.1 Results for Scenario 1

In scenario 1 the Power-to-Methanol plant is operating continuously, which means that the needed electricity is purchased every hour of the year. The yearly operation costs have been calculated for scenario 1 which can be seen on figure 7.3

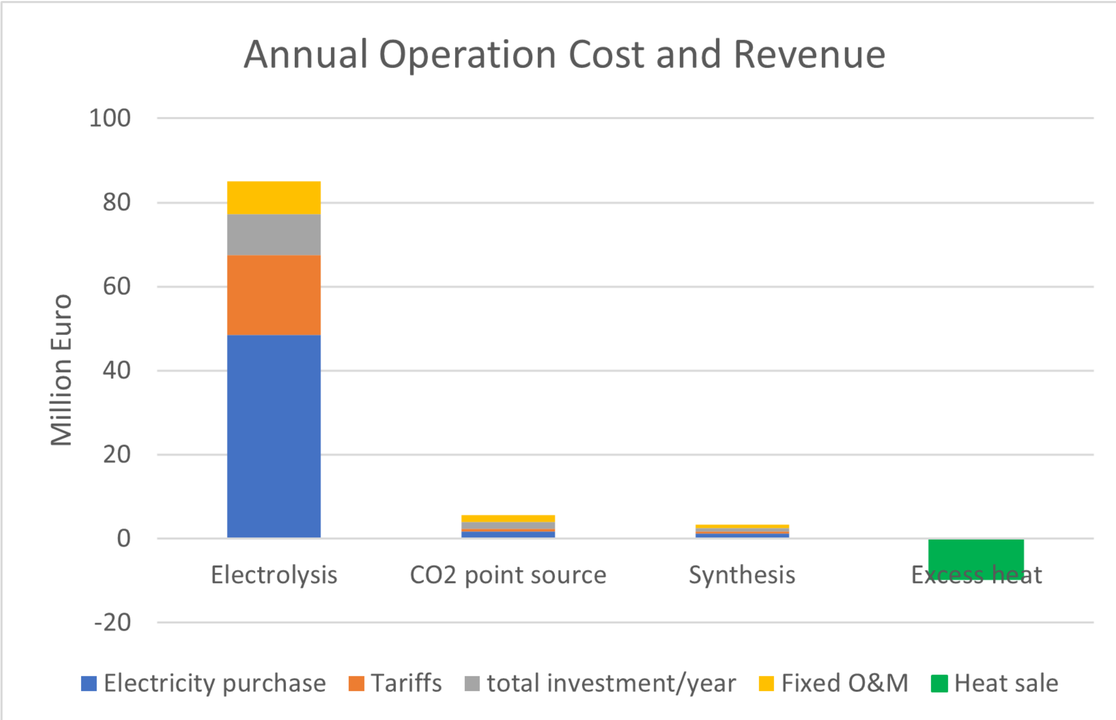

Figure 7.3: Annual Operation cost and revenue for scenario 1

From figure 7.3 it can be seen in relation to the annual operation for the Power-to-Methanol facility the electrolysis is by far the most expensive technology with annual operation cost of 83 Million Euro. And here it can be seen that over 50% of the cost of electrolysis is due to the electricity purchase. Further it can be seen that approximately 25% of the annual operation cost for the electrolysis is tariffs for Energinet. Whereas the last 25% is distributed in between the investment for electrolysis divided by lifetime and the fixed operation and maintenance costs. The total investment divided by lifetime is included in order to see how much it affects the total cost. Further it can be seen that the CO2 capture and synthesis process has a minor significance regarding the total cost. Furthermore it can be seen that in the excess heat produced in the process have a annual revenue of 9.5 Million Euro.

But since the purchase of electricity has such a significant influence on the total cost another operation strategy is introduced in scenario 2.

7.3.2 Results for Scenario 2

In scenario 2 the Power-to-Methanol plant is operated flexible which means that the technology of PEM electrolysis is operated flexible with a hydrogen storage connected. The synthesis process needs to operate continuously, therefore hydrogen needs to be provided for this process at anytime, either directly from the electrolysis or the hydrogen storage. The electricity price is fluctuating, which means that sometimes the electricity price is high and sometimes low as seen on figure 7.4

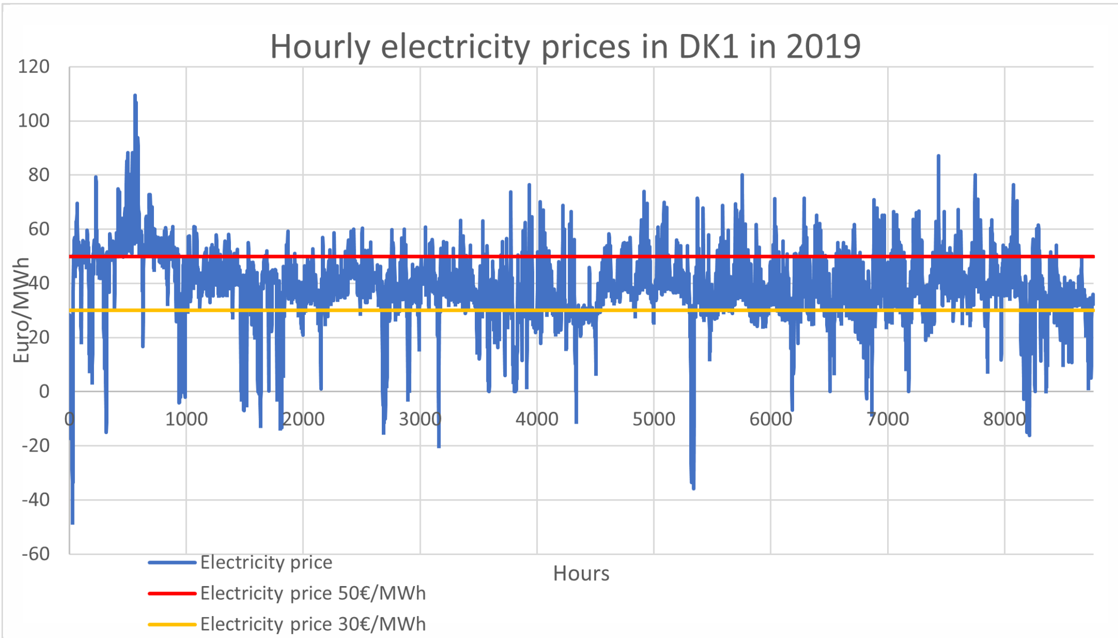

Figure 7.4: Electricity strategy for scenario 2

Here it can be seen that in some periods the electricity price is high and sometimes low, therefore are hydrogen storage unit is connected to scenario 2. Since the capacity of the electrolysis is 300 MW which is twice the amount needed to produce 130.000 ton hydrogen, it is possible to produce twice the amount of hydrogen needed in some periods and store it, and in some periods shut down the electrolysis and use hydrogen from the storage. The strategy which is used is that for the hours where the electricity price is under 30€/MWh, then the electrolysis is at full capacity and produces hydrogen both for the storage and the synthesis process. Whereas when the electricity price is over 50€/MWh the electrolysis shut down and hydrogen from the storage is used for the synthesis process. And when the electricity price is in between the two threshold the electrolysis run at half capacity and produces enough hydrogen for the synthesis process. With this strategy there are 1625 hours a year where the price is below 30 €/MWh and 1402 where it is above 50 €/MWh. The results of this strategy regarding the annual operation cost are shown on 7.5.

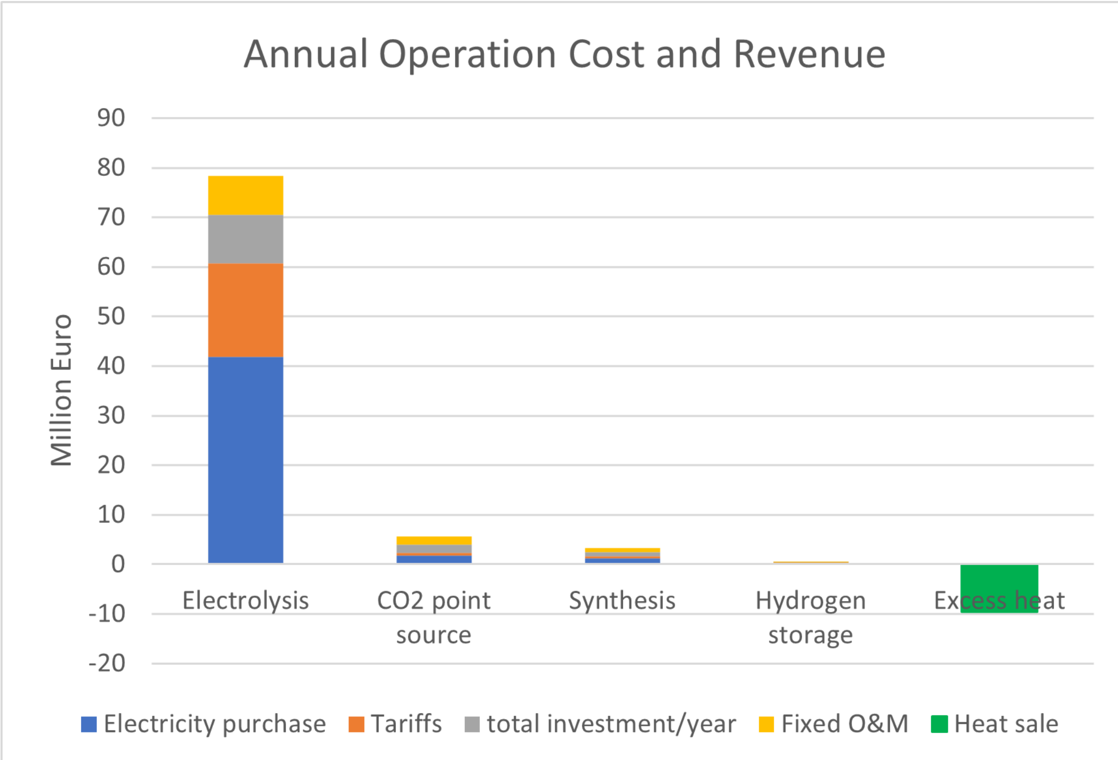

Figure 7.5: Annual operation cost and revenue for scenario 2

Here it can be seen that annual cost of electricity purchase have been reduced to 41.5 Million euro for scenario 2 compared to the 48.5 million euro in scenario 1. Further it can be seen that the total annual operation cost for the hydrogen storage is 0.5 million euro yearly, which means that the total annual cost reduction for scenario 2 is 6.5 million euro compared to scenario 1.

7.4 Results for scenario 3

In scenario 3 the Power-to-Methanol plant is operated in the same way as scenario 2, but in this scenario Direct Air Capture is used as CO2 capture. The results is shown in figure 7.6.

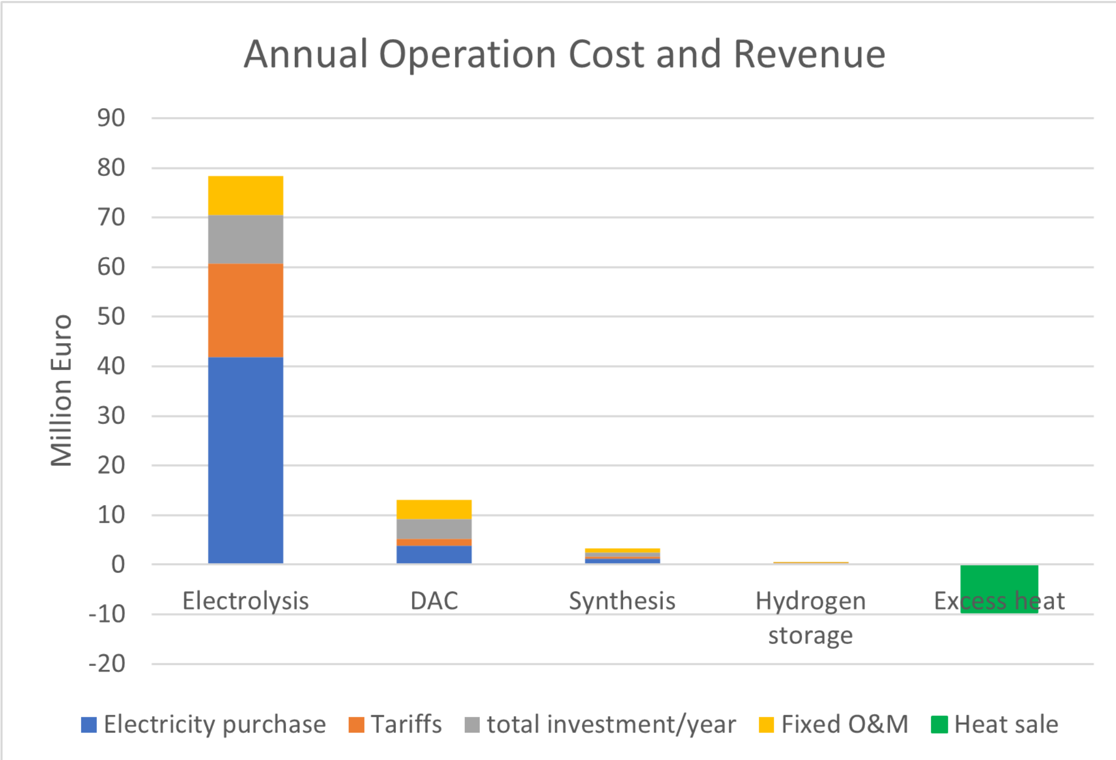

Figure 7.6: Annual operation cost and revenue for scenario 3

From figure 7.6 it can be seen that CO2 capture from the technology of Direct Air Capture have an annual cost of operation of 13.1 million euro, whereas in the previous scenarios the annual operation cost of CO2 capture at point source is 5.6 million euro. Therefore it can be said that it is more expensive to produce methanol from DAC, but exactly how much influence it has on the price of methanol will be calculated in the next section.

7.5 Levelized Cost Of Energy

In order to compare the different scenarios the Levelized Cost Of Energy for methanol has been calculated. The Levelized Cost Of Energy will be compared to the price of reference scenario fossil based bunker oil which is used as fuel in the shipping sector today. When comparing these two different types of fuel, Methanol and Bunker oil, it is important to take the energy density into account, which indicates the amount of energy stored in the fuel per unit volume. The energy density for methanol is 22 MJ/kg and the energy density for bunker oil is 44 MJ/kg [32, 33]. Therefore in order to compare the methanol and bunker oil on equally terms, then the LCOE for methanol is multiplied with a factor of 2. The results for the LCOE for methanol are shown on figure 7.7.

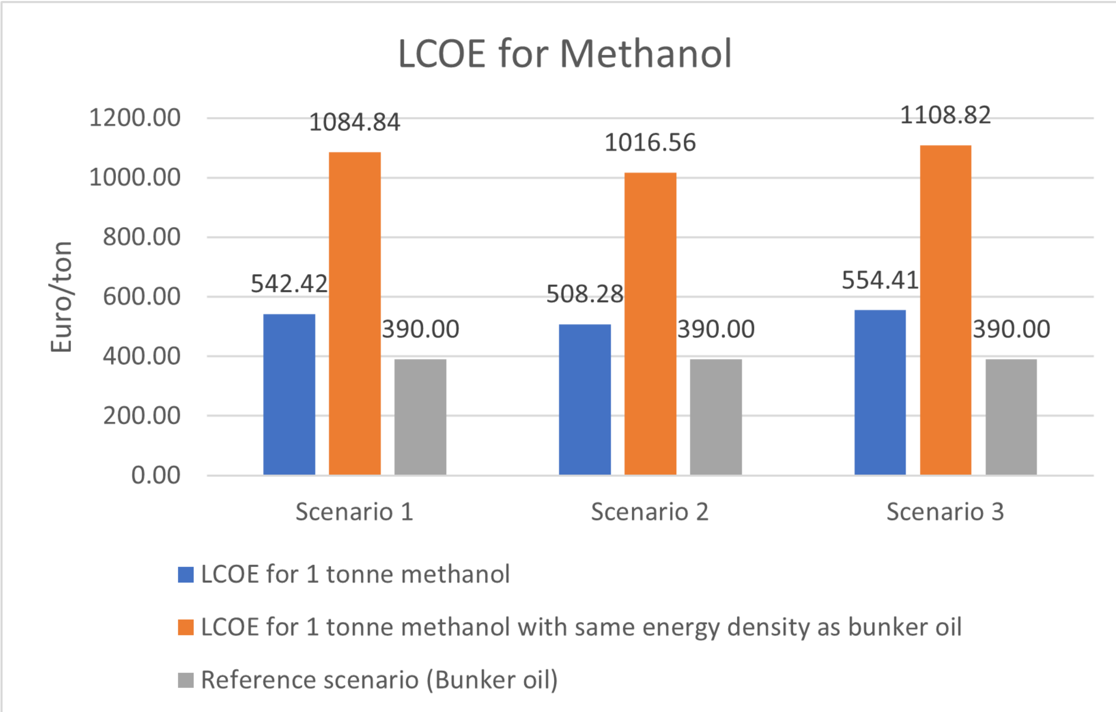

Figure 7.7: Comparison of Levelized Cost Of Energy for methanol with and without the same energy density as the reference scenario of bunker oil

From figure 7.7 it can be seen that with a flexible operation of the electrolysis in scenario 2 compared to the continuously operation in scenario 1 a cost reduction of 34 Euro/ton can be achieved. Further it can be seen that with the implementation of Direct Air Capture in scenario 3 compared to CO2 capture at a point source in scenario 2, makes the production of methanol 46 Euro/ton more expensive. Therefore it can be stated in order to produce the most cost effective methanol for this project scenario 2 is the most beneficial with a LCOE of 508 Euro/ton methanol. But when comparing the LCOE for the methanol production with the average bunker oil price in 2019 in scenario 2, it is noticeable that cost is approximately 160% more expensive with the same energy density taken into account.

As it has previously been shown, then there is different variables which are affecting the cost for the Power-to-Methanol production as well as cost for bunker oil. These variables are subject to some uncertainty because in the future energy system they may have a different impact on the LCOE for methanol. To investigate this uncertainty, a sensitivity analysis will be performed.

7.6 Sensitivity Analysis

A sensitivity analysis is performed in order to analysis the most important variables affecting the LCOE for methanol production from Power-to-Methanol. In the previously results for the annual operation cost and revenue it could be seen that the cost of electricity and tariffs accounted for the largest share of the total annual costs. Therefore, these two variables are seen as significant relative to the final LCOE for methanol and will be varied in the sensitivity analysis. Another significant variable in comparing green methanol with fossil based bunker oil is the price of bunker oil. Therefore, a CO2 tax will be added on bunker oil which could be part of the price for bunker oil in the energy system of the future.

These 3 variables will be varied according to the baseline of the LCOE which was found previously on 7.7. The parameters of the variations are as follows:

- Electricity price +20% and -20%
- Tariffs -50% and -100%
- CO2 Tax of 450€/ton bunker oil

These new variations result in new LCOEs for methanol and bunker oil and the result of this sensitivity analysis can be seen in figure 7.8

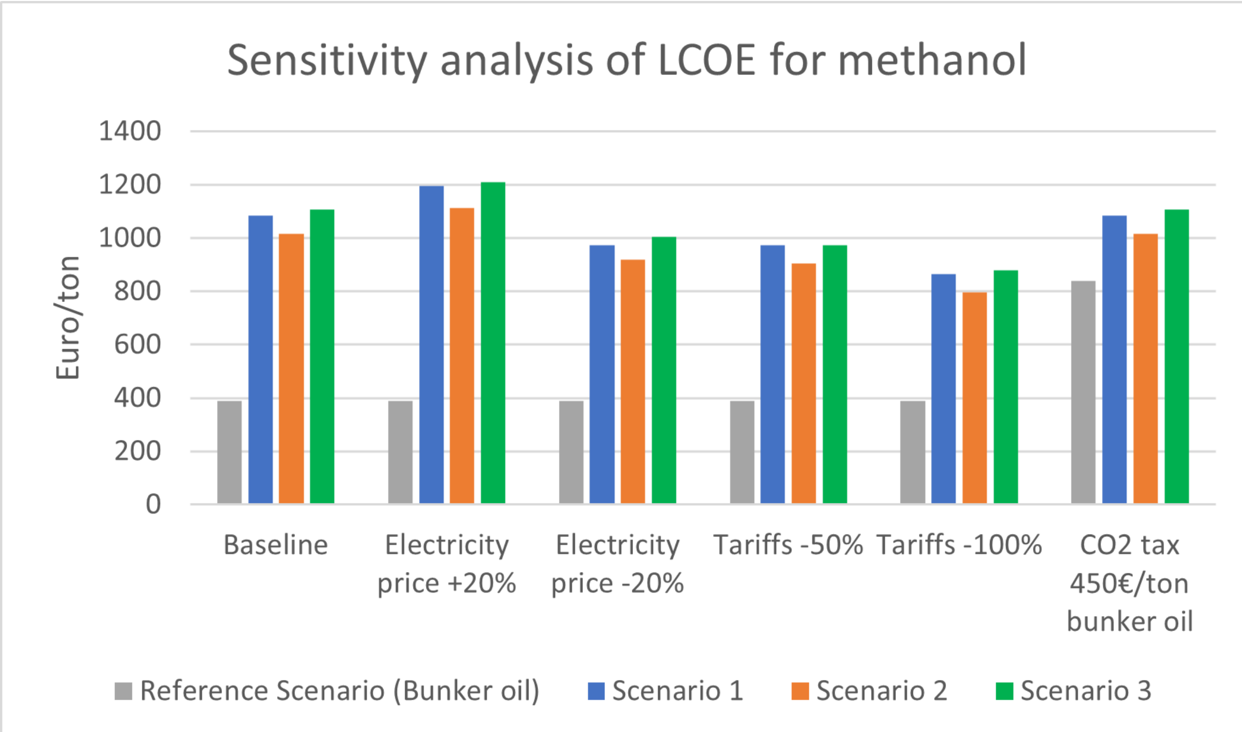

Figure 7.8: Sensitivity analysis of the LCOE for methanol and bunker oil with the same energy density.

As it was seen previously then the electricity purchase for the electrolysis have significant impact on the overall cost for producing methanol from the Power-to-Methanol system. This is also seen here in figure 7.8 where an increase in the electricity price of 20% and decrease of 20%, rises and reduces the LCOE for methanol with approximately 10% for scenario 2 in relation to the baseline. Further it can be seen that a reduction of LCOE for methanol can be achieved by lowering the tariffs of the electricity grid which may reflect the plans for geographical differentiated consumption tariffs and direct links for electricity consumption. Here it can be seen in figure 7.8 that with a reduction of 100% of the tariffs, an LCOE for methanol of 796 €/ton is achieved for scenario 2, which is the most feasible for the facility from an economic perspective. But even with this reduction in tariffs, the total LCOE for methanol is still about double the price of bunker oil. Although if a taxation of 450€/ton was added to the average cost of bunker oil in 2019, the price would then be 840 €/ton, and thereby be more expensive than the Power-to-Methanol production if no tariffs were paid.

The results of this economic analysis for power-to-methanol will be further discussed in the discussion

8 Discussion

This chapter provides with a discussion of the findings throughout the study. The purpose of the chapter is to discuss the socio-economic feasibility of Power-to-Methanol.

From the WWW-analysis in chapter 1 it was found that in order to reduce the CO2 emissions and reach the goal of Denmark being CO2 neutral within 2050, the Danish Government has come up with a strategy for implementing PtX and thus achieve CO2 reductions in difficult sectors such as shipping. A concrete project that wants to meet this goal is the Fjord PtX project in the production of green methanol. In chapter 5 it was shown that to produce green methanol from a Power-to-Methanol system, different technologies are needed. First and foremost, electricity from renewable resources must be used to operate the whole system where hydrogen is produced from electrolysis and biogenic CO2 is captured from either point source or directly from the air. Hydrogen and CO2 are thereby combined in a synthesis process to produce methanol. The Fjord PtX project has an ambition to produce 130.000 tons of methanol and an economic analysis of a Power-to-Methanol system of this size was made in chapter 7. The results of this economic analysis showed if no changes are made in relation to the electricity price, tariffs and bunker oil price, then the LCOE for methanol will be about 160% more expensive than the price of bunker oil. But whether it is fair that no changes are taken in relation to the production of green methanol can be discussed. Because such a Power-to-Methanol system will contribute to socio-economic benefits.

The first and obvious benefit that the production of green methanol will cause is the reduction of CO2 emissions and independence of fossil fuels which is actually the overall goal. For the Power-to-Methanol system, biogenic CO2 is needed in the process. In the Fjord PtX project, CO2 is to be captured from the incineration plant "Reno Nord", as it was shown in the Diamond-E analysis chapter 6 regarding the natural environment. Here it was shown that only 60% of the CO2 emitted from "Reno Nord" is biogenic whereas the last 40% is fossil based. Therefore, it can be discussed whether the production of methanol by the use of CO2 from "Reno Nord" is green. Today, bunker oil are used as fuel for the shipping sector, which emits approximately 3.0 tonne of CO2 for every tonne of bunker oil burned. And in figure 8.1 it can be seen that today, where no methanol or co2 is produced, fossil CO2 is emitted from both bunker oil and "Reno Nord" into the atmosphere.

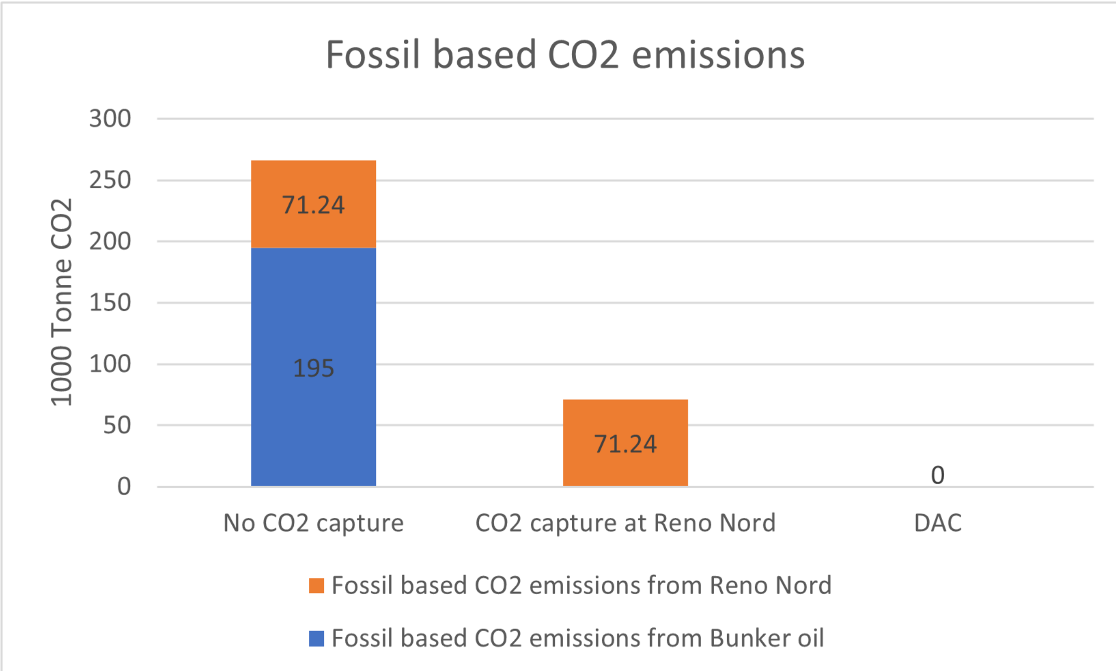

Figure 8.1: Fossil based CO2 emissions if methanol is not produced, is produced with CO2 from "Reno Nord", and produced with CO2 directly from the air (Same energy density).

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The emissions from bunker oil correspond to the amount that could be replaced by 130.000 tonnes of methanol. And here it can be seen that today where no methanol is produced a total of 266.000 tonne fossil based CO2 is emitted. But if the bunker oil is replaced by methanol with CO2 captured from "Reno Nord", the total CO2 emissions from fossils can be reduced to 71.240 tonne. In addition, it can be seen that if the production of methanol occurs by capturing CO2 directly from the air the process is CO2-neutral as there are no fossil emissions. Therefore, it can be said that the production of methanol by CO2 capture from "Reno Nord" is not 100% green, but it is a step in the right direction as it reduces the total emissions significantly. But in order to produce 100% green methanol, the CO2 emissions from "Reno Nord" has to be 100% biogenic or Direct Air Capture is needed.

However, with this reduction in CO2 emissions through the use of methanol, it can be discussed whether Power-to-Methanol is entitled to a compensation. This could, for example, be a price for the CO2 that the plant captures during CO2 capture. Because as it is today, the shipping sector does not pay a CO2 tax for their emissions. This means that there is no incentive to use methanol as a fuel as this is much more expensive. Therefore, a solution could be a compensation for the CO2 saved in methanol production or a CO2 tax must be introduced for the shipping sector. This is also the ambition of the EU as they in their "Fit-for-55" plans will include the shipping sector in the EU emissions trading scheme which will thereby give a CO2 tax on emissions. And this is also even suggested by the shipping giant AP Møller Mærsk, the largest consumer of bunker oil in the world, which proposes a global carbon tax of 450€ per tonne of bunker oil or equally 150€ per tonne CO2 emitted[34]. The reason why Mærsk wants to introduce this CO2 tax is because they want a CO2 neutral shipping sector where fossil fuels are not cheaper than green alternatives. And as it was shown in figure 7.8 for the sensitivity analysis that this CO2 tax will help make the LCOE for methanol competitive with bunker oil thereby provide an incentive to use green alternatives such as methanol.

Another socio-economic benefit which the Power-to-Methanol can provide is the stability of the electricity grid. As previously shown, large amounts of electricity must be used to produce methanol and especially in the electrolysis process. The smart thing about electrolysis is that it can operate flexibly, which means that when there are large amounts of renewable electricity and perhaps excess electricity, this can be used to produce extra hydrogen, whereas when there is a lack of electricity in the electricity grid, the electrolysis can be shut down and hydrogen from storage can be used. This will also contribute to a more stable electricity price on Nordpool and this flexibility will be absolutely essential in the smart energy system of the future as the production of renewable electricity is unpredictable. Therefore, it can also be argued that these Power-to-Methanol systems should be compensated for this stability and flexibility they can provide. This is also an proposal that the government has come up with in the form of geographically differentiated tariffs and direct links between production of renewable electricity and consumption at the Power-to-Methanol plant. The results of this were also seen in the sensitivity analysis figure 7.8, where this resulted in a reduction of LCOE for methanol. But the idea of being able to establish a direct link from e.g. a wind turbine farm to the production of power-to-methanol, a bilateral agreement, will most likely involve a contract with a fixed electricity price which can be beneficial for both partners. The electricity producers will be sure to get a fixed price per KWh and at the same time at the Power-to-Methanol plant what the price is. This gives the Power-to-Methanol plant a form of security of supply and avoids fluctuating electricity prices which will be a huge advantage over electricity prices today. As previously presented, electricity prices are about 4 times as expensive today as in the year 2019 due to the war in Ukraine. And if methanol were to be produced at this electricity price, it would increase LCOE significantly, which can be seen in the figure 8.2.

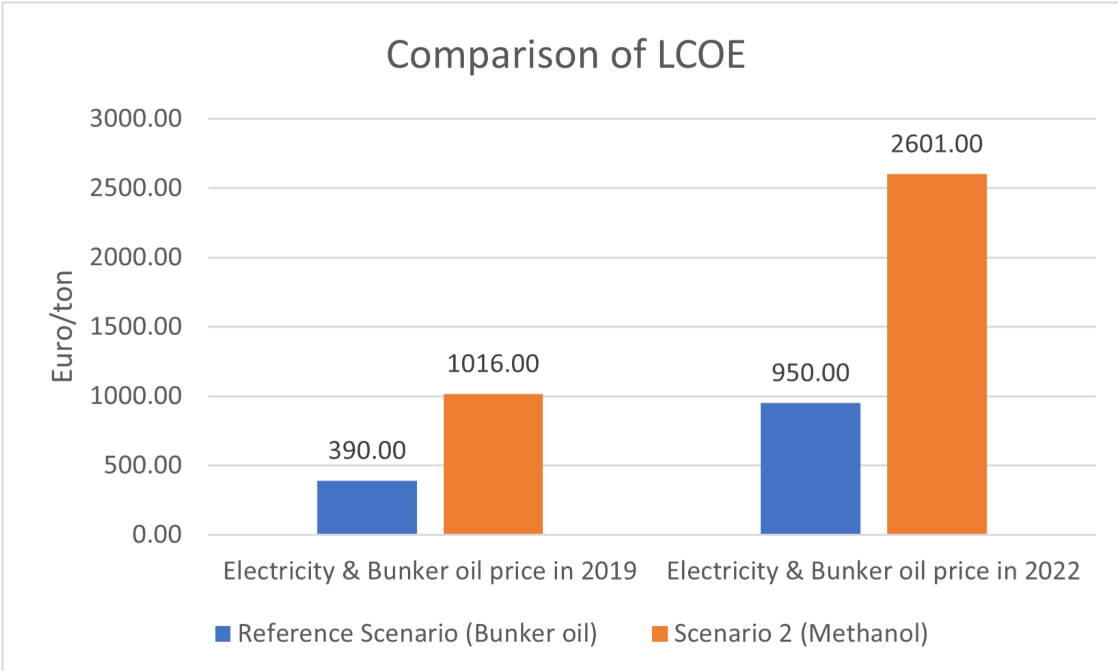

Figure 8.2: Comparison of Levelized Cost Of Energy for methanol and bunker oil with electricity and oil prices in 2019 and 2022 (Same energy density)

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Here it can be seen if methanol were to be produced with the electricity prices today, the LCOE of methanol would be 2601 Euro/ton with the same energy density as bunker oil. Further it can be seen that the price of bunker oil have increased to 950 Euro/ton instead of the average 390 Euro/ton in 2019. This shows an energy system in Denmark which is very dependent on what is going on in the rest of the world. Furthermore it can be seen if an electricity price of 2019 could have been achieved today, the LCOE of methanol would have approximately been the same as the price of bunker oil. This shows that direct links can be good for a Power-to-Methanol plant, but it also shows that the Danish electricity grid must be expanded and consist of a larger amount of renewable electricity so that it is not dependent on fossil fuels.

But it is not only the electricity sector a Power-to-Methanol plant will be able to provide benefits. Power-to-Methanol will also produce excess heat which can be used for district heating. And in the Fjord PtX project, Aalborg supply is also interested in this excess heat which contribute to their green transition. Furthermore it was shown in the Diamond-E analysis that Power-to-Methanol plants also will contribute to the socio-economics of Denmark by creating new jobs.

This shows that even though the LCOE for methanol is higher than the price for bunker oil, it must be remembered that such a Power-to-Methanol plant will contribute many different socio-economic benefits that bunker oil does not. In many ways, one can compare the establishment of this Power-to-Methanol technology with the historical establishment of wind turbines in Denmark. Because in the 1970s and 1980s, wind turbines were also an immature technology that could not compete with the prices of electricity at the time. Which is the same with the production of Power-to-Methanol which is an immature and limited technology that can not compete with today's prices for shipping fuel. But with various beneficial initiatives for wind turbines that the government undertook, wind turbines became more and more competitive and developed, where they are today the cheapest form of electricity in Denmark. This is very similar to what needs to be done for Power-to-Methanol to be established in a future energy system. The Danish government needs to provide financial support and favorable regulations for Power-to-Methanol for this technology to mature and develop, but in addition it is also crucial that a CO2 tax is included in the shipping sector in order to make methanol reasonably feasible at all.

But in relation to the maturity of Power-to-Methanol, it is also something that can be discussed in relation to the results of this project. As previously presented, there is no Power-to-Methanol facility at this capacity, and the technologies have not yet been tested on this scale. This gives an uncertainty to the simulation model which must be remembered. The financial and technical data for electrolysis, CO2 capture, methanol synthesis and storage are primarily found in energy catalogs made by the Danish Energy Agency. While this should be a reliable source, they also themselves describe the uncertainties in their data. The majority of the data comes from pilot projects with Power-to-Methanol on a smaller scale. So therefore it is estimates and projections by the Danish Energy Agency for how it will be. However, as there is no more concrete data that can be processed, this is the best estimate that can be made, however, one must be aware of the uncertainty in the data.

Finally, it can be discussed how the delimitation's of this project have affected the results as well as what influence it will have in a future system. As has previously been shown, the government has ambitions to implement 6+ GW PtX capacity by 2030, which will result in enormous hydrogen production in Denmark. Since hydrogen is predicted to be an important resource of the future energy system, it is also expected that hydrogen will become a commodity that in a larger scale can be traded with. Denmark is not the only country that has plans for PtX in the energy system, the EU has also laid out strategies. This means that in the future there may be a hydrogen market just as there is an electricity market where hydrogen is traded and transported across countries. This will mean that it can potentially become a business strategy to produce cheap hydrogen and sell it on the market. This could mean that at the Fjord PtX plant there will be an economic gain by producing more hydrogen than is needed and exporting it on a common market, which will affect the feasibility and LCOE for the production of methanol.

In addition, it can be discussed how the excess heat from this Power-to-Methanol plant will affect the feasibility for the real operation. In this project it was assumed that the excess heat could be sold to Aalborg district heating network at a price of 37€/MWh all year around at all times. However, if this is actually realistic have not been looked at, which could have influence on the LCOE for the Methanol.

But with these delimitation's and results in this project, this leads up to a further discussion of what might be interesting to investigate further for future studies.

8.1 Further Discussion

The following is a short list of subjects and concerns that were not included in this study but could be relevant for research:

- In the results of this study a simulation model was made, with a simple electricity strategy in order to only buy cheap electricity. But in a further study it could be interesting to look at a optimization model, which is optimized to operate the Power-to-Methanol plant at the lowest cost as possible. As it was seen by the results of the project, the electricity price has a huge impact of the total cost of a Power-to-Methanol plant. Therefore a optimized electricity strategy in relation to electricity market at Nordpool, could have a crucial role of the economic feasibility for such a plant.
- Further regarding the electricity price, it could also be relevant to further analyse if a possible bilateral agreement of wind farms, with a fixed electricity price, would be an option. If such agreement would be made, this could ensure a security of supply of the electricity price, which previously has been shown to be crucial. By this the fluctuating electricity prices can be avoided and huge price increases as was seen with the war.
- In Aalborg where the Fjord PtX project will be established, Denmark's largest company in terms of CO2 emissions is also found, Aalborg Portland. Aalborg Portland emit over 2 million tonnes of CO2 every year. Although this CO2 is fossil based, this could still reduce the total CO2 emissions if this was used for methanol production. Therefore, it would also be interesting to explore this possibility, which could be a step in the right direction for alternative fuels for the shipping sector.

9 Conclusion

In Chapter 1 of the problem analysis, the Danish Government's strategy of PtX was introduced with ambitions of reducing CO2 emissions in, among other things, the shipping sector. Despite unexplored and immature technology, one of the first commercial facilities in the world producing methanol is to be build in Aalborg municipality. With this uncertainty of the production of Power-to-Methanol, this resulted in the following research question:

How can a Power-to-Methanol facility in Aalborg municipality be modelled to achieve a yearly production of 130.000 tons methanol and what is the socioeconomic feasibility of Power-to-Methanol.

It can be concluded that to produce 130.000 tons methanol at the Fjord PtX project, the technologies of electrolysis, CO2 capture, methanol synthesis and hydrogen storage are needed. A simulation model of the Power-to-Methanol system showed that the LCOE of methanol would be 160% more expensive than the cost of bunker oil with the same energy density taken into account. But in the sensitivity analysis it was shown that with a reduction of tariffs by 100% and a CO2 tax of 450€/ ton bunker oil, the LCOE for methanol would have cost of 796 €/ton compared to the 840€/ton for bunker oil. Thereby it can be concluded that with the right strategies and regulations for Power-to-Methanol it can be competitive with the traditionally bunker oil used in the shipping sector today. Further it can be concluded that the Power-to-Methanol contributes with socio-economic benefits of stability of the electricity grid, job creation and CO2 reductions. But in relation to the CO2 reductions it can also be concluded that the production of methanol with CO2 capture at the incineration plant "Reno Nord" would still emit 71.24 tons fossil based CO2. Therefore it can only be called green methanol and CO2-neutral if the CO2 are captured by DAC. Furthermore it can be concluded that the electricity price have significant impact of the LCOE of methanol. Therefore, it will be advantageous to have an optimized pricing strategy in relation to the Nord pool market or bilateral agreements to ensure security of supply and low electricity prices.

Lastly it can be concluded that no Power-to-Methanol facility yet exists with this capacity. Therefore, the technology is still unexplored and immature on this scale which must be taken into account for the results of this project.

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